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Palaeogeographical changes in response to glacial–interglacial cycles, as recorded in Middle and Late Pleistocene seismic stratigraphy, southern North Sea

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ABSTRACT: Offshore stratigraphic records from the North Sea contain information to reconstruct palaeo-ice-sheet extent and understand sedimentary processes and landscape response to Pleistocene glacial–interglacial cycles. We document three major Middle to Late Pleistocene stratigraphic packages over a 401-km^2 area (Norfolk Vanguard/Boreas Offshore Wind Farm), offshore East Anglia, UK, through the integration of 2D seismic, borehole and cone penetration test data. The lowermost unit is predominantly fluviatile [Yarmouth Roads Formation, Marine Isotope Stage (MIS) 19–13], including three northward-draining valleys. The middle unit (Swarte Bank Formation) records the southernmost extent of tunnel valley-fills in this area of the North Sea, providing evidence for subglacial conditions most likely during the Anglian stage (MIS 12) glaciation. The Yarmouth Roads and Swarte Bank deposits are truncated and overlain by low-energy estuarine silts and clays (Brown Bank Formation; MIS 5d–4). Smaller scale features, including dune-scale bedforms, and abrupt changes in cone penetration test parameters, provide evidence for episodic changes in relative sea level within MIS 5. The landscape evolution recorded in deposits of ~MIS 19–5 are strongly related to glacial–interglacial cycles, although a distinctive aspect of this low-relief ice-marginal setting are opposing sediment transport directions under contrasting sedimentary process regimes.

KEYWORDS: Brown Bank; palaeogeography; tunnel valley; Yarmouth Roads; Swarte Bank

Introduction

Throughout the Pleistocene, shallow continental shelves were periodically exposed and submerged in response to repeated glacial–interglacial cycles, respectively (Shennan *et al.*, 2000; Bridgland, 2002; Busschers *et al.*, 2007; Smith *et al.*, 2011; Hijma *et al.*, 2012). The resulting periods of terrestrial–marine–terrestrial transitions have resulted in a complicated stratigraphic record of depositional and erosional processes (Scourse *et al.*, 1998; Mellett *et al.*, 2013; Head and Gibbard, 2015; Emery *et al.*, 2019a). The Pleistocene basin-fill of the southern North Sea continental shelf is a valuable archive that has been used to reconstruct changes in palaeolandscapes (Gibbard, 1988; Cameron *et al.*, 1992; Funnell, 1996; Busschers *et al.*, 2007; Parfitt *et al.*, 2010; Hijma *et al.*, 2012; Murton and Murton, 2012; Cohen *et al.*, 2014; Peeters, 2018). Studies have highlighted periods of North Sea glaciation resulting in mapped ice-sheet limits (Praeg, 1996; Scourse *et al.*, 1998; Beets *et al.*, 2005; Carr *et al.*, 2006; Davies *et al.*, 2011; Murton and Murton, 2012; Cotterill *et al.*, 2017; Emery *et al.*, 2019b), developed palaeogeographical maps (Funnell, 1996; Fitch *et al.*, 2005; Hijma *et al.*, 2012; Bicket and Tizzard, 2015) and reconstructed the evolution of north-west European drainage networks (Gibbard, 1988; Bridgland and D'Olier, 1995; Peeters *et al.*, 2015). Despite this, arriving at robust reconstructions of successive landscape responses to glacial–interglacial cycles has remained a challenge due to the fragmentary nature of the evidence (Lee *et al.*, 2006), sparse boreholes and limited 2D-seismic reflection profiles. Advances in offshore submarine technologies and increased availability of high-resolution commercial data have greatly improved the potential to understand submerged and buried landscapes, and their evolution during the Middle and Late Pleistocene. Empirical evidence derived from these datasets of changing physiography can help to inform landscape evolution models.

Palaeogeographical reconstructions in high-relief settings make the reasonable assumption that catchments and adjacent sedimentary basins maintain simple source-to-sink configurations, and that overall sediment transport directions do not change, even if sediment flux varies significantly through time (e.g. Castelltort and Van Den Driessche, 2003; Sadler and Jerolmack, 2015; Romans *et al.*, 2016). However, in low-relief continental shelf settings this assumption needs to be treated with caution. This is particularly true in ice-marginal settings where major and abrupt change in sediment transport direction can occur, which complicates estimates of sediment flux and provenance studies. With sufficiently high-resolution 3D data over large areas, sediment transport pathways can be mapped through time, leading to more meaningful palaeogeographical reconstructions, particularly in low-relief landscapes that have been subject to a complex changes in climate and base level over relatively short periods.

This study aims to document a geologically constrained Middle to Late Pleistocene sedimentary sequence in the Vanguard wind farm zone offshore East Anglia, UK, using a densely spaced grid of 2D seismic reflection data, borehole

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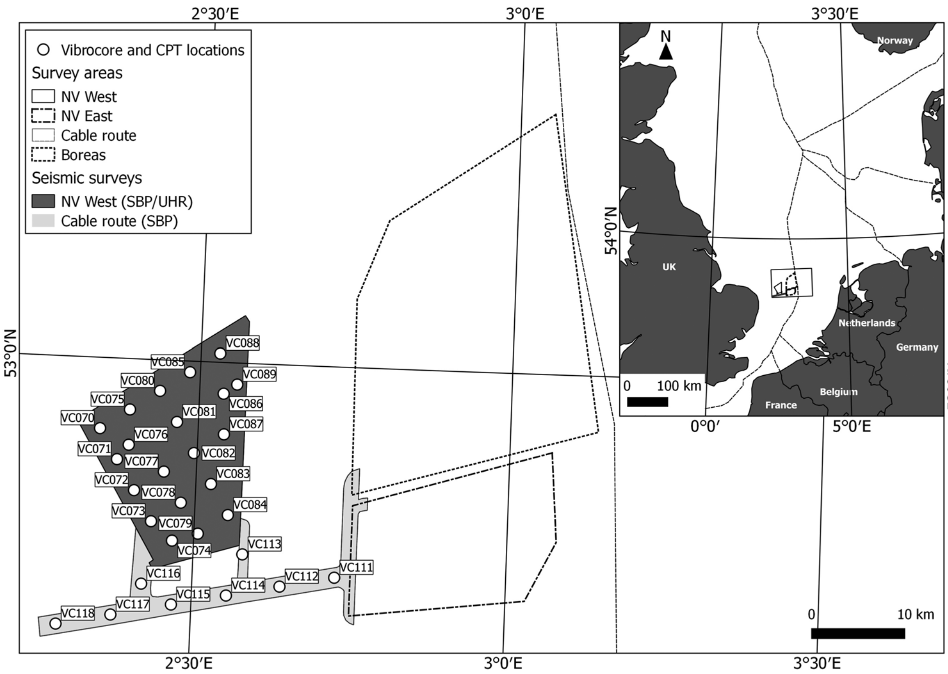


Figure 1. The Norfolk Vanguard survey areas are located within the UK sector of the southern North Sea. Norfolk Vanguard comprises three survey areas: NV West, NV East and the cable route. The Norfolk Boreas survey area sits to the north-east. Ultra-high-resolution (UHR) and sub-bottom profile (SBP) seismic reflection surveys acquired over NV West and the cable route survey areas that are used in this paper. Locations for 28 vibrocores and cone penetration tests (CPTs) over the NV West and cable route survey areas.

samples and geotechnical cone penetration tests (CPTs) acquired for industrial purposes (Fig. 1). We compare our detailed regional results with the current stratigraphic framework for the wider southern North Sea (Fig. 2D; Stoker *et al.*, 2011) to assess spatial and temporal similarities and differences. This paper sets out to: analyse the seismic facies and interpret the depositional environments through corroboration with core and CPT data; integrate our descriptions of

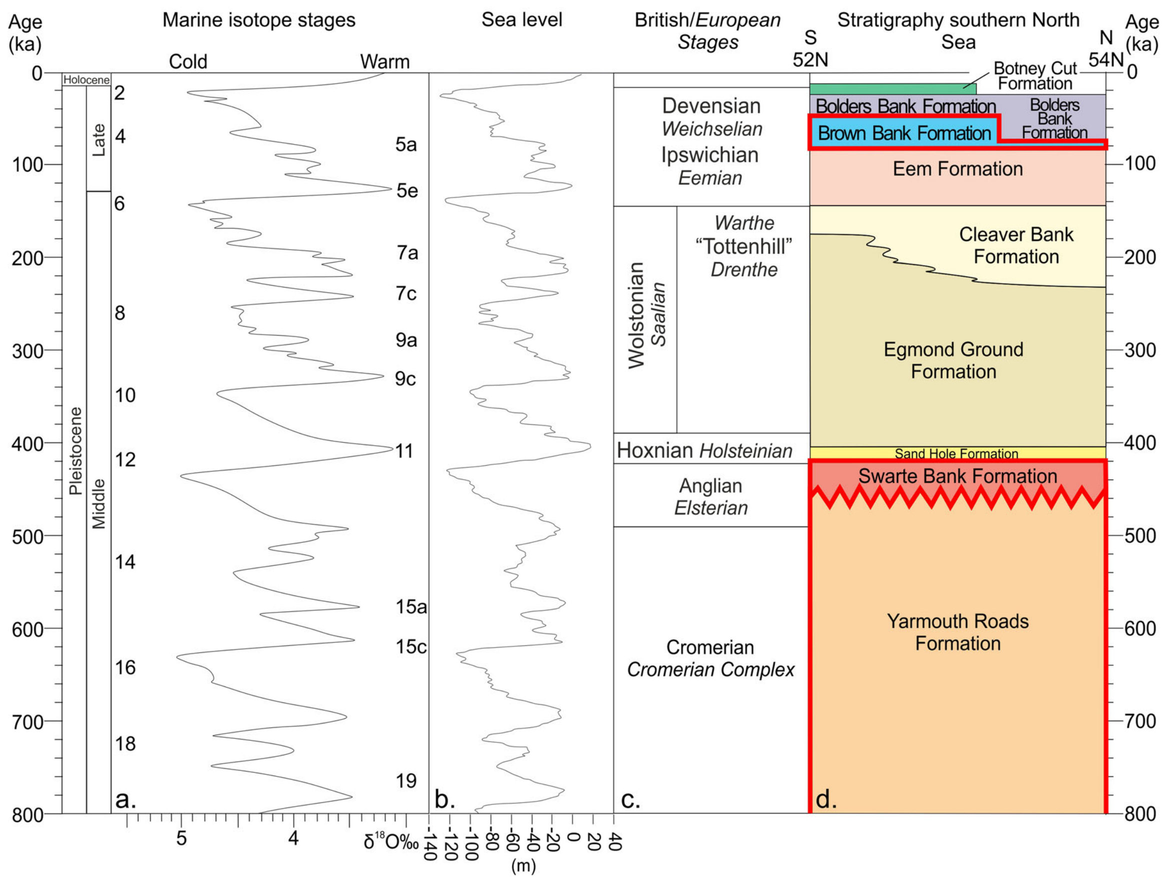


Figure 2. Stratigraphic correlation framework for the Quaternary of the study area. (A) Marine isotope stages (Lisiecki and Raymo, 2005), (B) global sea level estimates (Spratt and Lisiecki, 2016), (C) British and European Stages (italics) (based on Cohen and Gibbard, 2012), (D) Quaternary framework for the North Sea Basin (based on Stoker *et al.*, 2011). [Color figure can be viewed at wileyonlinelibrary.com]

marine, fluvial and glacial sequences to better understand the regional landscape response to climatic fluctuations; and embed these results into wider scale reconstructed palaeogeographies for the Middle to Late Pleistocene in the southern North Sea.

Study area

The study area is 401 km^2 and comprises the Norfolk Vanguard West (NV West), cable route, Norfolk Vanguard East (NV East) and Norfolk Boreas survey areas, and is in shallow water (<50 m) ~47 km east of the East Anglia coastline (Fig. 1). Local variations in seabed topography are mainly attributed to the presence of large sand banks that are interpreted to have formed during the late Holocene (Dyer and Huntley, 1999; Van Der Molen and De Swart, 2001; Liu *et al.*, 2007), or are relic features formed during a transgressive hydrodynamic regime (Cameron *et al.*, 1992; Uehara *et al.*, 2006; Van Landeghem *et al.*, 2009).

Geological setting

The Quaternary succession within the study area provides a record for which landscape response to climatic and base level fluctuations can be investigated. The present-day configuration of the North Sea Basin is largely a result of Late Jurassic and Early Cretaceous rifting (Glennie and Underhill, 1998). Since the Late Cenozoic, there have been up to 3000 m of sediment deposited, of which 800 m was deposited during the Quaternary (Gatliff *et al.*, 1994; Lamb *et al.*, 2018). The Early Pleistocene sedimentation within the study area was dominated by shallow-marine facies (Cameron *et al.*, 1989). The Middle Pleistocene (Marine Isotope Stage (MIS) 19–13; Fig. 2) was a period of heightened climatic instability (Ehlers and Gibbard, 2007), driving regional-scale falls in relative sea level (RSL), river drainage configurations and glaciation cycles (Lee *et al.*, 2006). At least three major glacial advances have extended into the southern North Sea (Bowen *et al.*, 1986; Long *et al.*, 1988; Ehlers, 1990; Ehlers and Wingfield, 1991; Carr *et al.*, 2006; Graham *et al.*, 2011). The Anglian Stage (MIS 12) glaciation (Fig. 3) marks the most extensive of these glaciations (Cameron *et al.*, 1992; Clark *et al.*, 2004; Streif, 2004). The Hoxnian interglacial followed the Anglian Stage glaciation, a period (probably correlating to both MIS 11 and 9) in which the southern North Sea was flooded (Streif, 2004; Cohen *et al.*, 2014; Bogemans *et al.*, 2016). During the Wolstonian Stage (MIS 10–6) there were several ice sheet advances probably during MIS 10, 8 and 6 (Beets *et al.*, 2005; Pawley *et al.*, 2008; Toucanne *et al.*, 2009; Graham *et al.*, 2011; Moreau *et al.*, 2012), but these did not extend as far south as the study area (Fig. 3 – maximum ice limit). The Ipswichian interglacial (MIS 5e) followed the final Wolstonian Stage, during which the North Sea was inundated, with marine influence reaching extents similar to today (Streif, 2004; Konradi *et al.*, 2005). The subsequent Devensian Stage (Fig. 3 – maximum ice limit) was characterized by cycles of RSL rise (through MIS 5d–a, 4 and 3) and fall before final subaerial exposure by the time of the Last Glacial Maximum (LGM) within MIS 2 (Hijma *et al.*, 2012; Bicket and Tizzard, 2015).

Data collection

Seismic data acquisition and interpretation

Seismic reflection data were acquired by Fugro on behalf of Vattenfall Wind Power UK (Fig. 1), and along with data

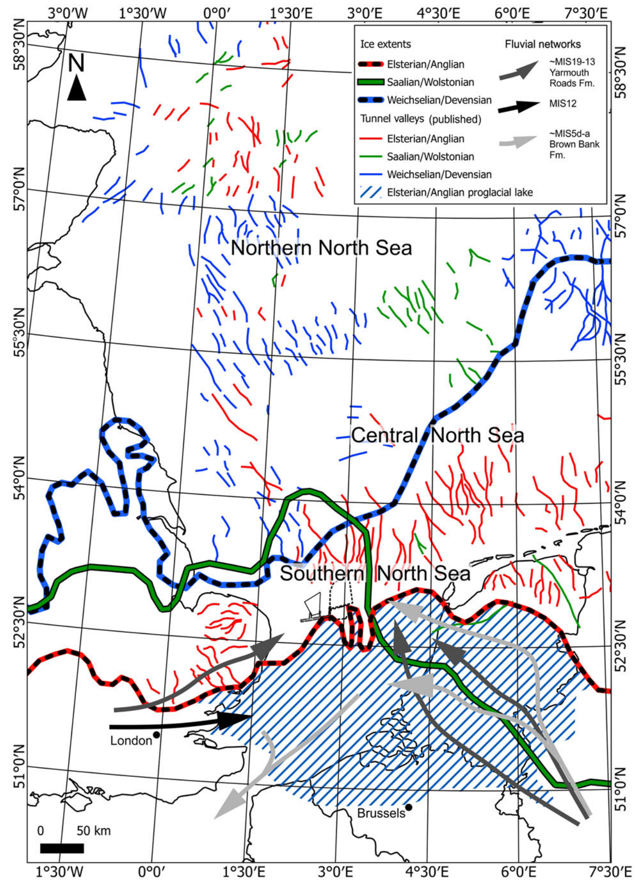


Figure 3. Composite map showing maximum ice extents for three major Pleistocene glaciations [Anglian and Wolstonian – Hijma *et al.* (2012) and references therein, Devensian – Ehlers and Wingfield (1991) and Sejrup *et al.* (2016). Tunnel valleys associated with the three major glaciations (Graham *et al.*, 2011). A glacial lake formed between 400 000 and 450 000 years ago and was dammed to the north by ice extending from the north (adapted from Gibbard, 2007; Cohen *et al.*, 2017). [Color figure can be viewed at wileyonlinelibrary.com]

acquisition reports, have been provided to the University of Leeds for an independent research project. A hull-mounted pinger [Massa TR-1075 pinger array, referred to here as sub bottom profile (SBP)], and a towed multichannel ultra-high-resolution (UHR) seismic system was used to image the shallow subsurface. The SBP seismic has a depth of investigation down to ~30 m below the seabed (bsb) and uses a relatively high frequency (4.5 kHz), which equates to a vertical resolution of 0.1–0.2 m. SBP seismic has been acquired in both the NV West and cable route survey areas. In the NV West survey area, the SBP seismic has inline spacing of 100 m and xline spacing of 1 km. Along the cable route survey area, the inline spacing is variable (80–100 m). The UHR seismic has a depth of investigation up to ~300 m bsb with a frequency of 4 Hz, which equates to a vertical resolution of 1–5 m. The seismic is minimum phase. Within the NV West survey area, UHR seismic inlines have been acquired at 100-m spacing, and xlines at 1-km spacing. UHR seismic has not been acquired along the cable route.

Both the UHR and the SBP seismic reflection data had been depth converted by Fugro Oceansismica SpA. A seismic velocity of 1600 m s^{-1} was used for the SBP seismic to convert from two-way travel time (TWTT) to depths in metres, and the UHR seismic was depth converted using a velocity field derived during seismic processing. The seismic reflection data have been interpreted on every available inline and xline by the authors using IHS Kingdom with characterization of seismic facies and stratigraphy (see Results) following Mellett *et al.* (2013) and Mitchum *et al.* (1977). Interpreted seismic surfaces were gridded using a minimum curvature algorithm, which provides geologically plausible surfaces. The cell size used for gridding was specified based on the data resolution (25 × 25 m for UHR and 20 × 20 m for SBP) so that each cell contains no more than one point.

Vibrocoring and cone penetration tests

Offshore investigations within the NV West survey area by Fugro recovered 28 vibrocores (maximum penetration 6 m) and data from 28 CPTs. Twenty-three of these vibrocores were destructively sampled for geotechnical analysis by Vattenfall, but five cores were kept intact for geoarchaeological assessment (Wessex Archaeology, 2018). These five cores were independently logged for this research project, and the remaining 23 vibrocores were logged using high-resolution photographs taken by Fugro before destructive geotechnical sampling. CPTs penetrate to a greater depth than the vibrocores, and therefore provide data for interpretation of the geotechnical properties and lithology of deeper (>6 m) sediments. Technical information pertaining to the geotechnical investigation of Norfolk Vanguard and the cable route came from confidential reports.

The raw data and technical reporting that support the findings of this study are not publicly available due to commercial restrictions.

Results

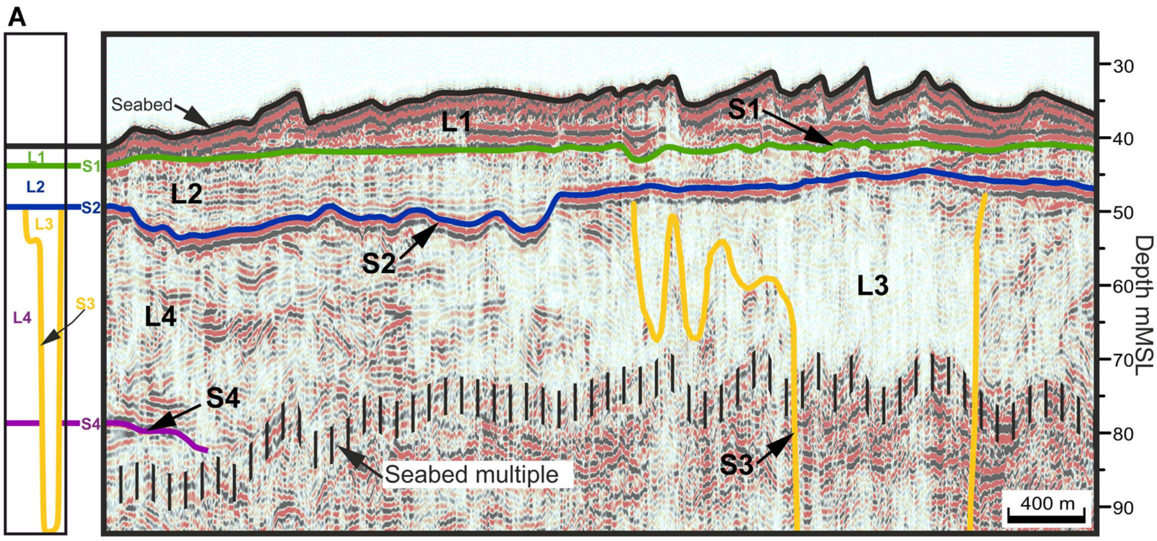
The Middle to Late Pleistocene sequence in the survey areas has been subdivided into four seismic units (L1–4) based on seismically mappable erosional surfaces/contacts (S1–4) that separate distinct seismic facies associations (Fig. 4). These seismic facies interpretations have been corroborated with vibrocores (contacts/change in lithofacies), and changes in CPT parameters as outlined in Fig. 4B.

Seismic stratigraphy

Eleven seismic facies (Table 1) have been defined based upon the seismic character, and bounding surfaces and their association. The UHR survey images down to ~300 m, enabling characterization of L4 and L3 and their bounding surfaces (S4 and S2). L1 and L2 are characterized using the SBP seismic, allowing a greater resolution of detail down to surface S2 compared with that of the UHR seismic. The seismic units and surfaces herein will be described starting with the lowermost surface and unit (S4/L4).

Surface 4 (S4) and seismic stratigraphic unit 4 (L4)

The L4 unit (average 41 m thick) is present over the entire NV West and cable route survey areas. The basal bounding surface, S4, is poorly defined across large parts of the survey area due to a coincident seabed multiple (Fig. 5i). Where S4 is imaged (NV West western margin), it is characterized by a laterally discontinuous and high-amplitude reflection, with truncated reflectors below, and is onlapped by the overlying L4 unit (sf1 – Table 1; Fig. 5i). The L4 unit is characterized by a range of seismic facies; the lower and middle L4 unit is seismically chaotic (sf3), comprising discontinuous seismic reflectors with sharp to transitional terminations (sf4). Inci-

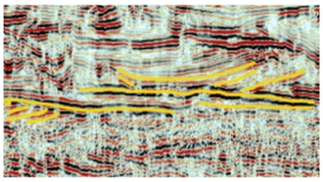
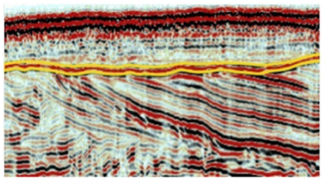
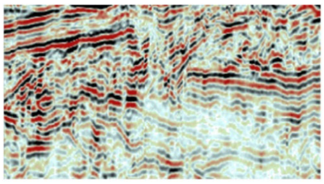
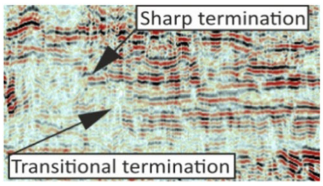
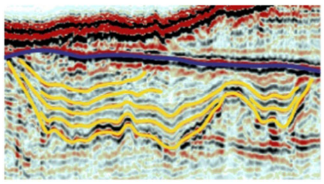
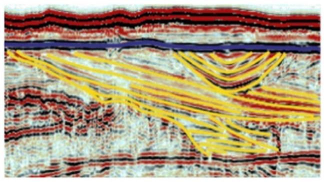
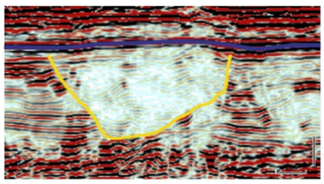
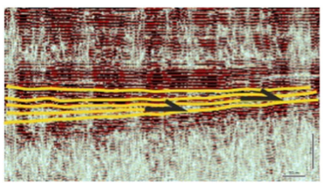
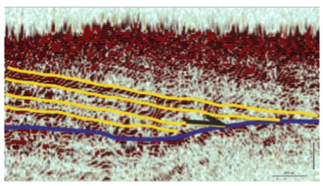


B

Seismic unit	Occurrence	External form	Seismic facies present	Interpretation	BGS regional stratigraphic framework equivalent
L1	Broad	Veneer	-	Shallow marine	
L2	Broad	Sheet	sf8, sf9, sf10, sf11	Marine/ lacustrine	Brown Bank Fm. Stoker et al., 2011
L3	North & central NV West	Channel fill	sf7	Glacial valley fill	Swarte Bank Fm. Stoker et al., 2011
L4	Broad	Sheet	sf3, sf4, sf5, sf6	Delta top	Yarmouth Roads Fm. Stoker et al., 2011

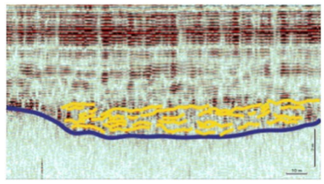
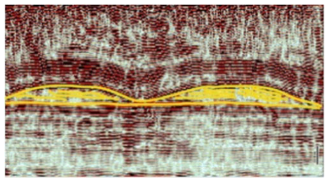
Figure 4. Summary of seismic stratigraphic surfaces and units in the survey areas. A. Type UHR seismic section with seismic stratigraphic surfaces interpreted. S4 is only partially interpreted due to a seabed multiple. B. Summary table of seismic stratigraphic units, their distribution, form, seismic facies present, environmental interpretation and the British Geological Survey (BGS) regional stratigraphic framework equivalent to seismic units. [Color figure can be viewed at wileyonlinelibrary.com]

Table 1. Summary of seismic facies identified and the seismic stratigraphic unit/surface they are associated with. Seismic descriptors used to characterize the facies are shown and seismic survey used to identify and characterize the facies are listed. Yellow is used to highlight seismic facies and the S2 surface is shown in blue

Seismic facies	Unit/ surface association	Seismic survey	Frequency	Amplitude	Continuity	Reflection termination	Structure or fill	Seismic example
Sf1	S4	UHR	Low	High	Discontinuous	Abrupt or masked by seabed multiple	Surface	
Sf2	S2	UHR	Low	High	Continuous	Not seen in survey area	Surface	
Sf3	L4	UHR	High to low	High to low	Discontinuous	Abrupt and transitional	Hummocky to chaotic	
Sf4	L4	UHR	High to low	High to low	Discontinuous	Abrupt and transitional	Parallel	
Sf5	L4	UHR	Medium to low	Medium to low	Continuous	Onlap	Valley with parallel draped and divergent	
Sf6	L4	UHR	High to low	Medium to low	Continuous to discontinuous	Onlap, downlap and truncation	Valley with complex fill	
Sf7	L3	UHR	Low	Low	Not applicable	Not applicable	Structureless	
Sf8	L2	SBP	High to low	High to low	Continuous	Onlap and truncation	Parallel	
Sf9	L2	SBP	Medium to low	Medium to low	Continuous	Base: downlap Top: truncation	Prograding, oblique parallel	

(*Continued*)

Table 1. (*Continued*)

Seismic facies	Unit/ surface association	Seismic survey	Frequency	Amplitude	Continuity	Reflection termination	Structure or fill	Seismic example
Sf10	L2	SBP	Medium to low	High to low	Discontinuous	Onlap and transitional	Hummocky and chaotic	
Sf11	L2	SBP	Medium to low	Low	Continuous	Downlap	Mounded structures with foresets	

sional geometries are common but are more clearly defined in the upper section of L4 (sf5 and sf6, Fig. 5i). The upper bounding surface of L4 corresponds to S2.

Three valley-fills (V1, V2 and V3) identified in the 2D sections have been mapped across the dataset (Fig. 6A) within the upper L4 unit. These valley-fills are larger and more continuous than those observed in the lower L4 unit. Valley-fills V2 and V3 are characterized by draped and divergent reflectors with maximum widths of 1.2 and 4 km, respectively, that onlap the valley margins and are truncated at the S2 surface (sf5 – Fig. 6A; Table 1). Valley V2 is cut by V1 in the south-west of the NV West survey area. V1 is the largest (deepest and widest) of the valley-fills, is orientated approximately NE–SW, and has a maximum width of at least 12 km (unknown due to seismic survey limits) and a maximum valley-fill thickness of 33 m. The valley-fill comprises a series of stacked progradational reflectors (sf6), with multiple truncation surfaces, and is interpreted as a channel complex (Colombera *et al.*, 2013). The youngest fill within V1 has a draped, divergent character. Overall, the valley axis for V1 deepens to the north-east.

Surface 3 (S3) and seismic stratigraphic unit 3 (L3)

The L3 unit is bounded laterally and at its base by surface S3, and at its upper surface by S2. Locally, surface S3 is truncated by S2 (Figs. 5ii and 6B). L3 is confined to linear erosional features defined by S3, orientated approximately N–S, with one exception that is orientated approximately E–W. Locally, S3 extends to ~290 m below mean sea level (MSL), with a maximum width of ~1.5 km and thickness of ~165 m. The flanks of these linear features are steep (~40°) with an undulating thalweg depth. The flanks of the L3 fill are defined as truncated L4 reflectors adjacent to the structureless L3 but in places become uncertain due to seismic blanking. The seismic character of unit L3 is largely structureless and/or chaotic (sf7), although locally the seismic character is masked by two seabed multiples (Fig. 5ii).

Surface 2 (S2) and seismic stratigraphic unit 2 (L2)

Unit L2 is present over the NV West and cable route survey areas, ranging in thickness from 17 to <0.5 m, with the exception of the south-west of NV West where the unit thins below seismic resolution. The basal bounding surface, S2, is a continuous, high-amplitude reflector, truncating underlying L4 and L3 reflectors. L2 has a variable thickness, largely attributed to the relief of the S2 surface. The L2 unit comprises laterally continuous, parallel dipping, draped, low- to high-amplitude, medium- to high-frequency reflectors (sf8 – Fig. 7i), which typically onlap on the S2 surface. Above the L2 unit, reflectors are truncated by the S1 surface. In the west of the cable route survey area, the seismic character of the L2 unit is not typical of that observed in the NV West survey area. Here, parallel reflectors (sf9 – Table 1; Fig. 7ii) downlap onto the S2 surface and are onlapped towards the east by sf8 reflectors. At the base of the L2 unit in the NV West survey area, sf10 is present (Table 1). The distribution of this seismic facies is patchy and associated with depressions in the S2 surface (sf10 – Fig. 7i). The character of sf10 is chaotic, hummocky and discontinuous, and it is draped by sf8.

Along the western margin, and in the south-west of the NV West survey area, the typical character of L2 (sf8) is disrupted by a change in seismic facies. Here, discrete mounded structures (sf11– Fig. 8; Table 1) are bounded by sf8. These structures are ~1–3 m high (crest-to-trough) with a wavelength of 20–50 m. The internal seismic character of these mounds is low frequency and low amplitude but with both planar parallel and dipping reflectors visible. The bedforms are both symmetrical and asymmetrical, with internal reflectors dipping southward and the crests orientated approximately E–W.

Surface 1 (S1) and lithostratigraphic unit 1 (L1)

L1 is bounded at the base by the S1 surface, which is characterized by truncation of L2 reflectors and a gradational stratigraphic change from low-amplitude and low-frequency to high-amplitude and low-frequency reflectors (Fig. 7i). The L1 unit forms a thin veneer, typically 1–2 m thick, but is locally up to 10.5 m thick where large bedforms are present on the seabed. Locally, the L1 unit is absent with the L2 unit cropping out at the seabed.

Synthesis of lithology and CPT data with seismic stratigraphy

Lithofacies have been defined for the L1 and L2 units using vibrocores and corroborated to seismic facies associated with the L1 and L2 units. In addition, cores, CPTs and seismic have been integrated to characterize the nature of the S1 surface and to better understand how and why CPT parameters vary across this surface.

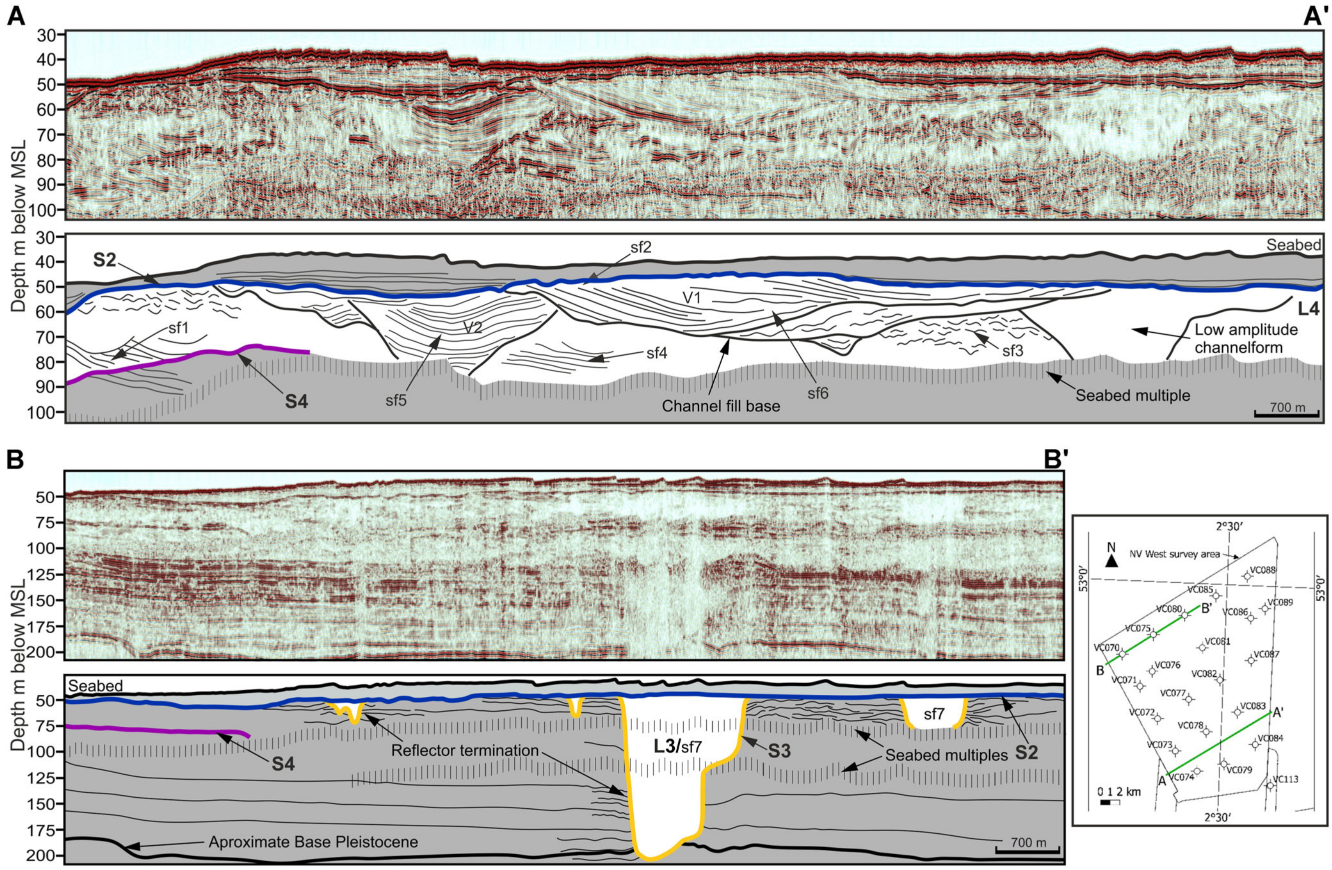


Figure 5. Seismic reflection profile and interpreted panels illustrating seismic facies character and association with seismic stratigraphic units and surfaces. Panel (i) shows the L4 unit and bounding surfaces S4 and S2. Surface S4 is mostly obscured by a seabed multiple. Upper L4 unit valley fill (V1 and V2) shown. Panel (ii) shows the L3 unit and bounding surfaces S3 and S2. Note the truncation of Middle to Late Pleistocene stratigraphy by the L3 unit. Seismic reflection profile A and B taken from the UHR survey. For location of seismic reflection profiles see inset map. [Color figure can be viewed at wileyonlinelibrary.com]

Vibrocores and CPT control

L2 unit and S2 surface

The L2 unit is largely characterized by clayey silt with no visible structure and rare shells (Slc – Fig. 9; Table 2), although in the west of the cable route survey area the L2 unit is largely characterized by sandy silt with clay (Ssf – VC117), which extends from the S1 to S2 surface. At the top and subdividing the L2 unit are silty clay intervals (<0.5–35 cm) with rare shells (Cl). In places, the sand content increases in lithofacies Slc towards lithofacies Cl. The contacts between lithofacies Slc and Cl are always sharp but these contacts and changes in lithofacies are not evident in the seismic reflection data, nor is there evidence in the cores for the parallel, continuous reflectors (sf8) that are characteristic of the L2 unit. This may be a result of seismic resolution. Black mottling is present in both Slc and Cl and is considered minerorgenic as opposed to organic in origin. At the base of the L2 unit, and confined to a topographic low in the S2 surface, is a coarse to fine, poorly sorted muddy sand with subangular to subrounded pebbles (<0.5–4 cm) and abundant disarticulated and fragmented shells (Scp – VC79), which is thought to be associated with sf10. CPT parameters [friction ratio (R_f) and cone resistance (q_c/p_a)] show that the L2 unit differs in mechanical properties. These changes in properties can be calibrated over NV West and the cable route survey areas [Intra L2 surface, Fig. 9 (CPT71 and 74) and Fig. 7i]. Changes in CPT parameters within the L2 unit are not evident in vibrocores.

Sf10 is sampled in one core (VC79 – Fig. 9) and is characterized by lithofacies Scp, which is a poorly sorted sand with silt, clay with subangular to subrounded pebbles (<0.5–4 cm in diameter) and occasional shells and overlies the S2 surface. The S2 surface is not penetrated by vibrocores, and therefore characterizing a change in lithofacies between L2 and L4 has not been possible. However, CPTs penetrate the S2 surface and show a clear change in CPT parameters between L4 and L2 that can be correlated across the survey areas (Fig. 9).

L1 unit and S1 surface

The L1 unit is characterized by well-sorted, medium-grained sand with shells dispersed throughout and occasional shell-rich intervals (Sm – Fig. 9; Table 2). In some vibrocores, the base of the L1 unit contains peats, organic-rich clays and fluvial sediments. These changes in lithofacies are clearly seen in the CPTs, and the S1 surface is readily correlated across the survey areas. Correlation of the S1 surface becomes challenging where either the upper L2 lithofacies (Slc) is more sand-rich, therefore decreasing the contrast in geomechanical properties, or where the L1 unit is thin.

Regional seismic stratigraphic context

The characteristics of the main seismic stratigraphic units identified in this study (L2 to L4) and surfaces (S4 to S1) have been used to assign depositional environments, which enables the units to be placed in a regional context within the previously defined formal lithostratigraphic framework (Fig. 2D; Stoker *et al.*, 2011).

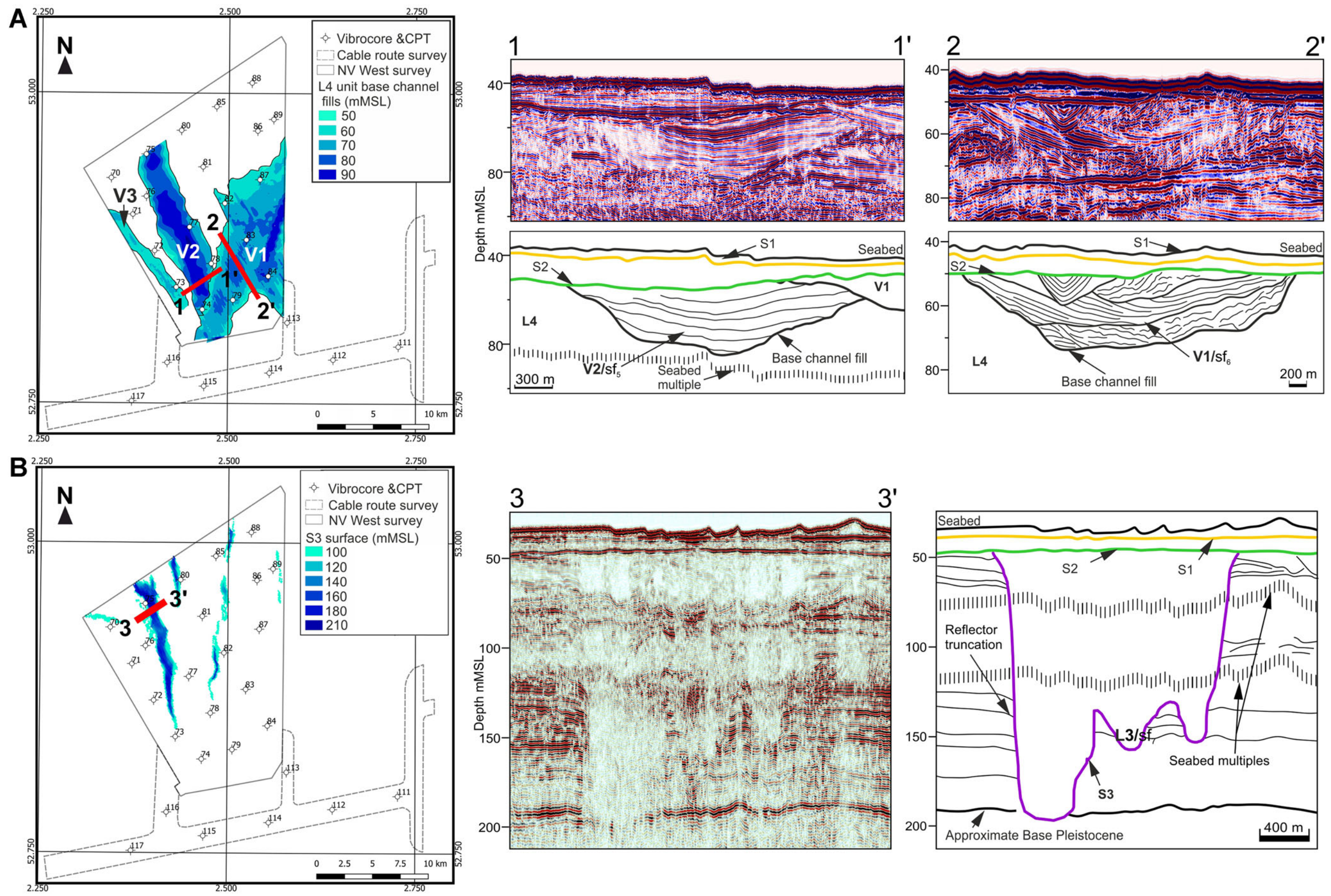


Figure 6. L3 and L4 fills. A. Depth map of the base valley-fills (V1, V2 and V3) present in the L4 unit with position and orientation of example seismic panels and interpretation (1–1′, 2–2′). B. Depth map of the S3 surface (base L3 unit fill) and position and orientation of an example seismic panel (3–3′). [Color figure can be viewed at wileyonlinelibrary.com]

The stratigraphic position of L4, which is incised by L3 and unconformably overlain by L2, supports deposition before formation of the regionally extensive Anglian Stage glaciogenic unconformity (MIS 12). The L4 unit shows stacked valley-fills, reflector terminations and laterally discontinuous high-amplitude reflectors, which are typical of depositional systems dominated by fluvial activity (Mitchum *et al.*, 1977). Therefore, L4 is interpreted to be the Yarmouth Roads Formation (Fm.), which has been described by Cameron *et al.* (1992), Van Kolfschoten and Laban (1995) and Funnell (1996), who considered this unit in this region to represent a fluvially dominated delta top environment. The Yarmouth Roads Fm. stratigraphy that is not confined to valley-fills shows truncated, discontinuous reflectors that are likely to be of fluvial, intertidal and coastal origin as previously observed in cores (Cameron *et al.*, 1992). The uppermost parts of the Yarmouth Road Fm. are likely to have been eroded by subsequent glaciations, and proglacial and periglacial fluvial activity (Cameron *et al.*, 1992; Cohen *et al.*, 2012).

The L3 unit is confined to linear features, predominantly orientated ~N–S, which incise the underlying L4 unit. Subglacial valley-fills of equivalent size and geometry have been identified north of the study area and have been assigned to the Swarte Bank Fm. (Praeg, 2003). The seismic character of the L3 unit is predominantly structureless, consistent with tunnel valley-fills assigned to the Swarte Bank Fm. elsewhere in the North Sea (Huuse and Lykke-Andersen, 2000; Praeg, 2003; Der Vegt *et al.*, 2012; Stewart *et al.*, 2013), but without an overlying draped seismic facies. The southern limit of the Anglian glaciation extends south of the study area, whereas the younger Wolstonian and Devensian glaciations do not extend to the study area, which supports formation and infilling of these tunnel valleys during the Anglian Stage (Figs. 2 and 3).

The L2 unit is a fine-grained, low-energy shallow-marine deposit with a uniform seismic facies extending across the entire study area. The character of L2 is consistent with the Brown Bank Fm., which is described at multiple locations across the southern North Sea as a fine-grained shallow-marine deposit (Cameron *et al.*, 1992; Limpenny *et al.*, 2011), and dated between MIS 5 and 3 (Bicket and Tizzard, 2015; Wessex Archaeology, 2018). No direct glaciogenic deposits nor deformation structures relating to the Wolstonian stage, or confirmed shallow-marine deposits relating to the marine transgressive Ipswichian stage, have been observed in the study area, supporting the suggestion that deposition of L2 occurred between MIS 5 and 3, equivalent to the Brown Bank Fm.

Discussion

The seismic stratigraphy, sedimentology and geotechnical data provide an integrated 3D architectural framework over a 401-km^2 study area. Corroboration with the literature supports extrapolation of this subregional architectural framework to the existing lithostratigraphic framework, chronostratigraphic ages and sequence stratigraphic positions (Cameron *et al.*, 1987; Stoker *et al.*, 2011). Within the study area the chronology of this framework extends from the Cromerian Stage (~MIS 19–13) to the present day, although some chronostratigraphic ages are not represented by deposits.

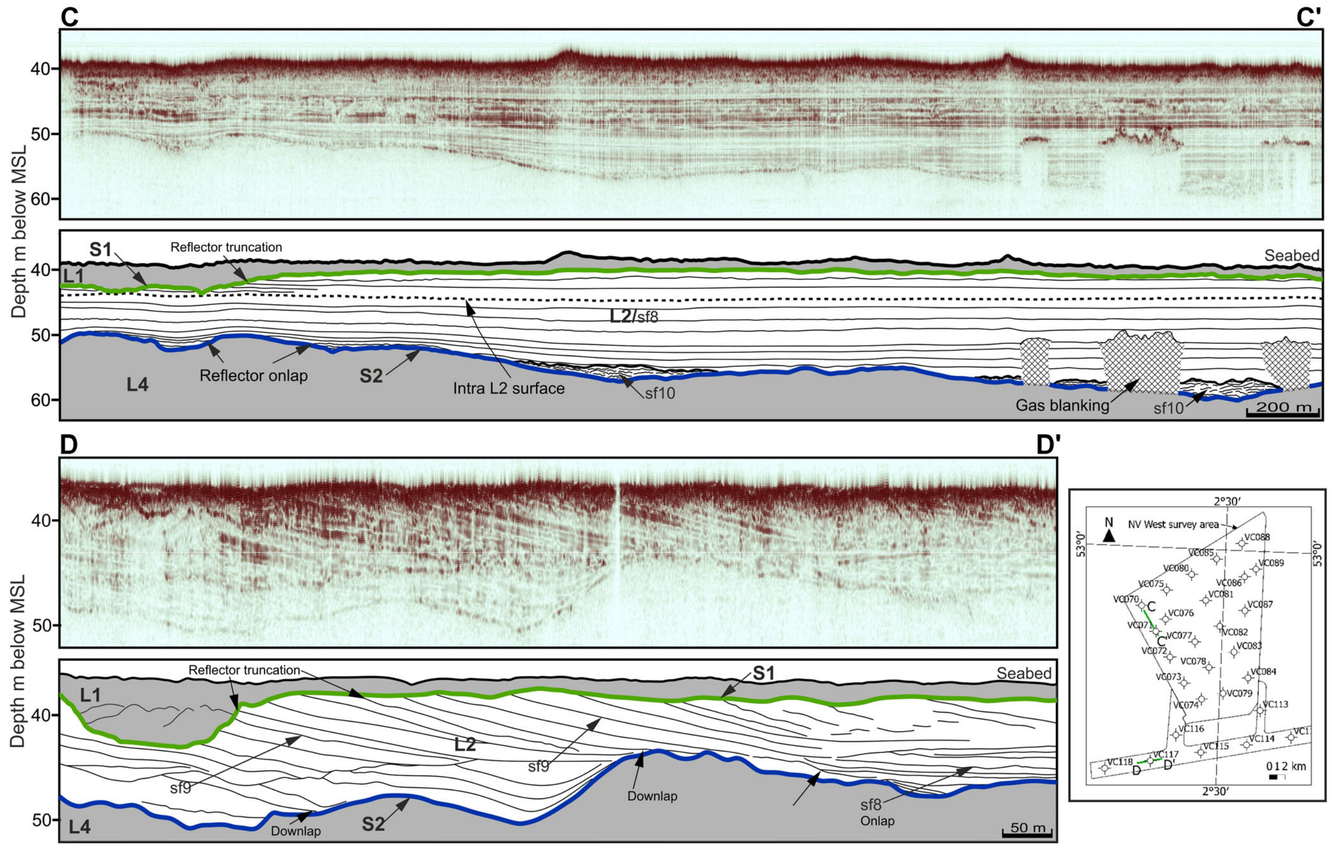


Figure 7. Seismic reflection profile and interpreted panels illustrating seismic facies character and association with seismic stratigraphic units and surfaces. Panel (i) shows sf10 associated with depressions in the S2 surface and sf8, the dominant seismic facies in L2 unit, draping the S2 surface. Panel (ii) shows dipping/prograding reflectors that characterize sf9 that are present in the west of the cable route survey area. Profiles C and D were taken from the SBP survey. For location of seismic reflection profiles see inset map. [Color figure can be viewed at wileyonlinelibrary.com]

MIS ~19 to 13 (L4) depositional environment

The seismic stratigraphy of the L4 succession is interpreted as a fluvially dominated delta top environment (Yarmouth Roads Fm.), as suggested by the presence of composite valley-fill features and adjacent, subhorizontal high-amplitude reflectors that may indicate adjacent peat or salt-marsh deposits. River systems were the primary agents of sediment transport during MIS 19–13 in the basin, and the presence of NE–SW- and N–S-trending valleys mapped in seismic reflection data support the proposed model of the expansion and increased influence of mainland European (e.g. Rhine-Meuse) and British (e.g. Thames and/or Bytham) rivers at this time (Gibbard, 1988; Moorlock *et al*., 2002; Hijma *et al*., 2012). A north and north-eastward drainage direction is supported by a deepening thalweg in V1 to the north-east. An increase in composite valley size (height and width) and preservation from base to top in L4 indicate that fluvial networks were increasing in size in the area, either due to increased precipitation (Gibbard, 1988; Funnell, 1996), or because they were part of an overall prograding distributive fluvial system (e.g. Hartley *et al*., 2010; Gulliford *et al*., 2014).

The age relationship between valley-fills V1 and V2 is clearly defined by cross-cutting relationships, with V1 being younger than V2, but there are no chronostratigraphic constraints to place the channel evolution more precisely in the MIS 19–13 period. V3 has the same fill character as V2 but an age relationship with respect to V1 and V2 cannot be determined with this dataset. Allogenic controls on sedimentation at this time would largely have been a result of climatic instability, with cycles of glaciation/deglaciation resulting in times of increased precipitation and changes in RSL. The difference in valley-fill types between V2 and V3 and the younger V1 (with respect to V2) support a marked change in depositional style. The draped, divergent fill characteristic of V2 and V3 are typical of a low-energy environment, such as estuaries, with fine-grained deposition under low-energy tidal conditions (Fig. 10A). In contrast, the multistorey V1 fill suggests a higher energy depositional environment with a coarser grained sediment load and repeated cut-and-fill cycles. This change in sedimentation style may be accounted for by a regional base-level fall resulting in northward shoreline migration and increased terrestrial influence (Fig. 10B). Alternatively, changes in climate may have resulted in increased sediment supply, and subsequent progradation of the fluvial system, leading to northwards shoreline migration and continued progradation of both the Rhine-Meuse and the Thames fluvial systems (Funnell, 1996; Cohen *et al*., 2012; Hijma *et al*., 2012). Therefore, it is considered highly likely that valleys V1, V2 and V3 reflect the northwards progradation of these systems. The multiple stages of glaciation from MIS 19 to 13, resulting in several RSL cycles (Hijma *et al*., 2012), suggest that allogenic controls were a major influence on the sedimentary systems in the southern North Sea during this time. Alternatively, V1, V2 and V3 may support deposition during a relatively short period during the later parts of the Cromerian Stage, whereby channel style and position reflect internally generated autogenic changes. The truncation of the channel-fills at the S2 surface prohibits understanding of the age relationship between these channel systems. However, uncertainty remains as to whether allogenic or autogenic controls were the primary driver for the changes in channels fill types seen in V1, V2 and V3 due to the absence of chronostratigraphic constraints. Consequently, support for

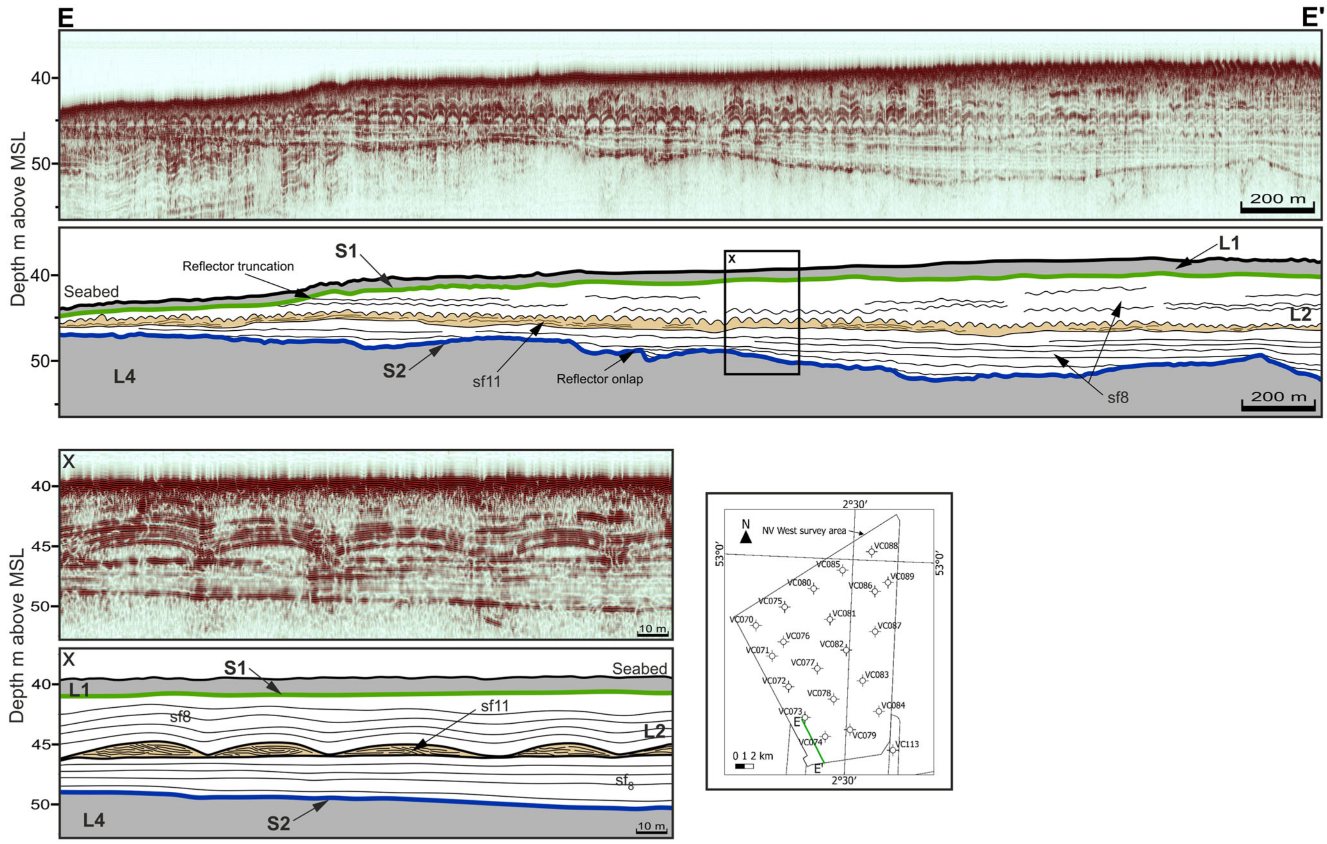


Figure 8. Seismic reflection profile and interpreted panels illustrating seismic facies character and association with seismic stratigraphic units and surfaces. Panel (i) shows dune-scale bedforms (sf11) seen in the south-west of NV West and in the cable route survey area. Panel (ii) shows zoom in of inset on panel (i). Note that these bedforms are bound between sf8 facies. Panel (i) is taken from the SBP survey. For location of seismic reflection profiles see inset map. [Color figure can be viewed at wileyonlinelibrary.com]

either a landscape responding to changes in the climate and base level, which drove significant increases in climate and sediment supply, and northward shoreline migration, and/or normal regression from progradation of a fluvial distributive system, remain unresolved.

MIS 12 (L3) depositional environment

The structureless character of the seismic facies infilling the deep narrow erosion surfaces constituting the L3 unit are consistent with the Swarte Bank Fm. (Stoker *et al.*, 2011), which have been widely documented in the North Sea Basin (e.g. Praeg, 2003; Davies *et al.*, 2011; Graham *et al.*, 2011). The fill character in conjunction with the geomorphological characteristics of the deep erosive bounding surfaces [asymmetrical and steep sides (>40°)], over-deepened and irregular thalwegs are consistent with tunnel valleys (O'Cofaigh, 1996; Stewart *et al.*, 2012) and their fills. These are common features northward of 53°N (Fig. 3; Graham *et al.*, 2011). However, we document the most southerly tunnel valley-fills for this time in the offshore domain. The orientation (N–S) of the tunnel valleys, the E–W-trending fill (Figs. 3 and 6B), the depth of incision, and their position with respect to the upper and lower units is consistent with tunnel valley-fills that formed during the Anglian glaciation elsewhere in the region (Huuse and Lykke-Andersen, 2000; Praeg, 2003; Graham *et al.*, 2011), and support previous estimates of MIS 12 ice sheet limits in the southern North Sea (Laban, 1995; Laban and van der Meer, 2004; Graham *et al.*, 2011). In many cases in the North Sea, the Swarte Bank Fm. tunnel valley-fills comprise multiple seismic facies (Praeg, 2003; Mellett *et al.*, 2020). Typically, a lower structureless unit is overlain by a layered unit, which have been interpreted to be basal glaciofluvial sands and/or glacial diamicts that transition into lacustrine muds (Long *et al.*, 1988; Cameron *et al.*, 1989; Balson and Jeffery, 1991; Praeg, 2003). Within the NV West survey area, the tunnel valley-fills comprise a single structureless seismic facies. This may indicate a predominantly glaciofluvial sand and/or diamict-fill. However, a structureless seismic facies could be the result of both lithology and/or seismic blanking. Where the Swarte Bank Fm. is present, the overlying L2 unit shows no increased thickening, in contrast to documented thickening of sediments overlying tunnel valley-fills north of the survey area (Cameron *et al.*, 1992). This suggests that either the tunnel valleys were filled or that the S2 surface represents an erosion surface that planed off the L3 unit tunnel valley shoulders and neighbouring L4 delta top palaeosurfaces. Given that the tunnel valley-fills are always truncated by S2, we interpret a major planar erosion surface that removed some Swarte Bank Fm. stratigraphy, probably a result of polycyclic events (ice-marginal–proglacial–transgression) culminating in marine transgression. The lithology and the infilling history of the tunnel-valleys remains unclear, due to both the limits of seismic imaging (blanking and structureless character) and the absence of core and CPT data penetrating the fills. However, given the diversity and complexity of fills documented to the north (Praeg, 2003), and to the north-west (Mellett *et al.*, 2020) of the study area it would be unwise to assign a fill history and lithology to these tunnel-valley fills based on the data available.

MIS 5d to 2 (L2) depositional environment

The L2 unit blankets the study area and is predominantly composed of clayey silt and silty clay lithologies, which are

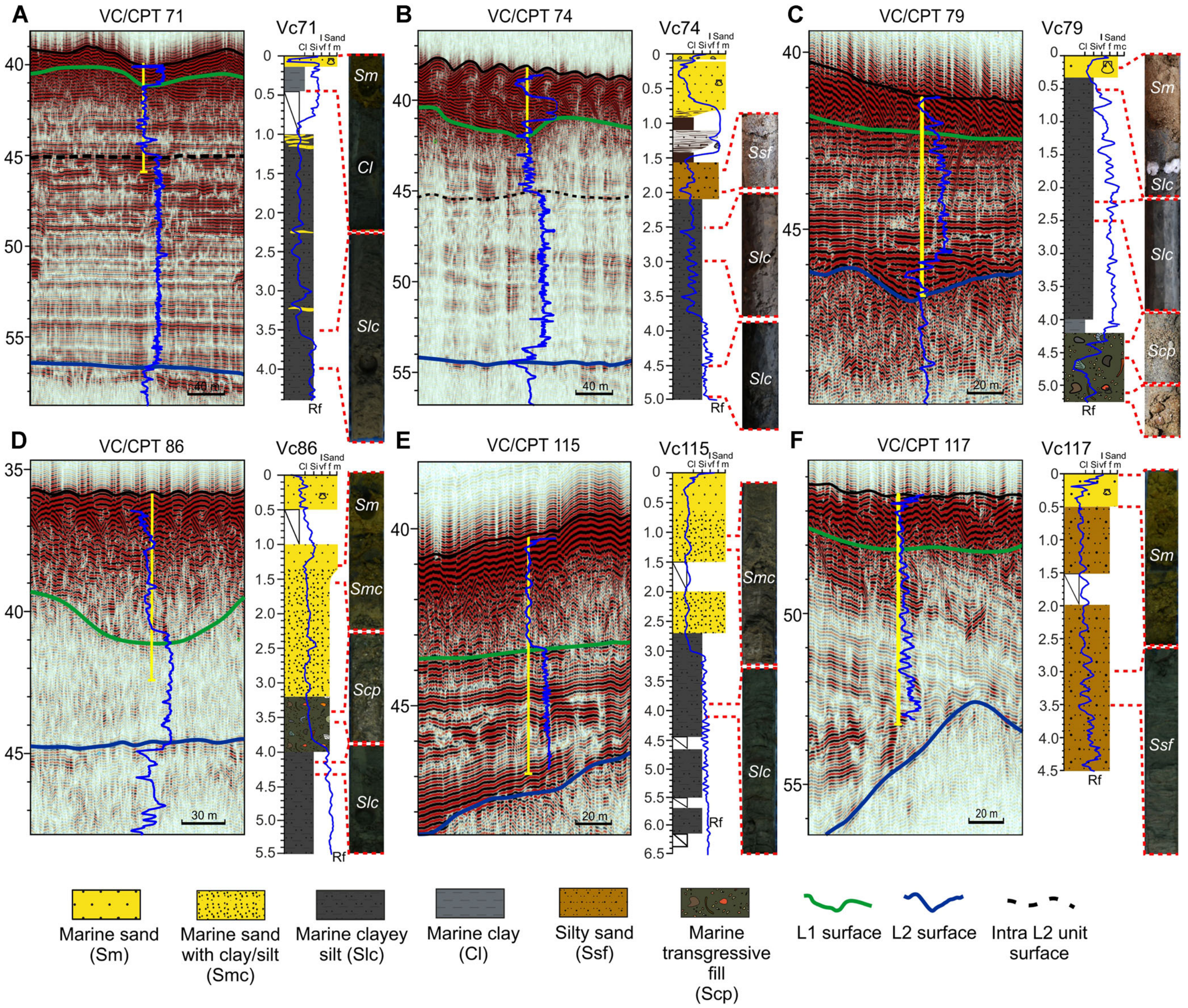


Figure 9. Calibration of SBP seismic, core logs and CPT data. Vibrocore path overlain on seismic (yellow). CPT parameter (Rf) overlain on seismic in blue. Core photographs are shown alongside lithological core logs. See Fig. 1 for locations of vibracores. [Color figure can be viewed at wileyonlinelibrary.com]

Table 2. Classification and interpretation of sedimentary facies according to lithological composition

Lithofacies	Description	Depositional environment	Facies photographs
Sm	Well-sorted, medium-grained sand with occasional coarse grains and shells. Sand grains are subangular to subrounded	Shallow marine	
Slc	Dark grey silt with sand and clay and occasional shells. Sand and clay content <15%. Homogenous with no visible structure.	Shallow marine/intertidal/lagoon	
Cl	Dark grey clay with occasional shells. Homogenous with no visible structure.	Shallow marine/intertidal/lagoon	
Ssf	Dark grey sandy silt with clay. Sand grains are fine and well sorted.	Shallow marine/intertidal/lagoon	
Scp	Dark brown grey, coarse to fine, poorly sorted sand with silt, clay and pebbles (<0.5–4 cm) and occasional shells. Pebbles are distributed throughout and are subangular to subrounded.	Transgressive marine	

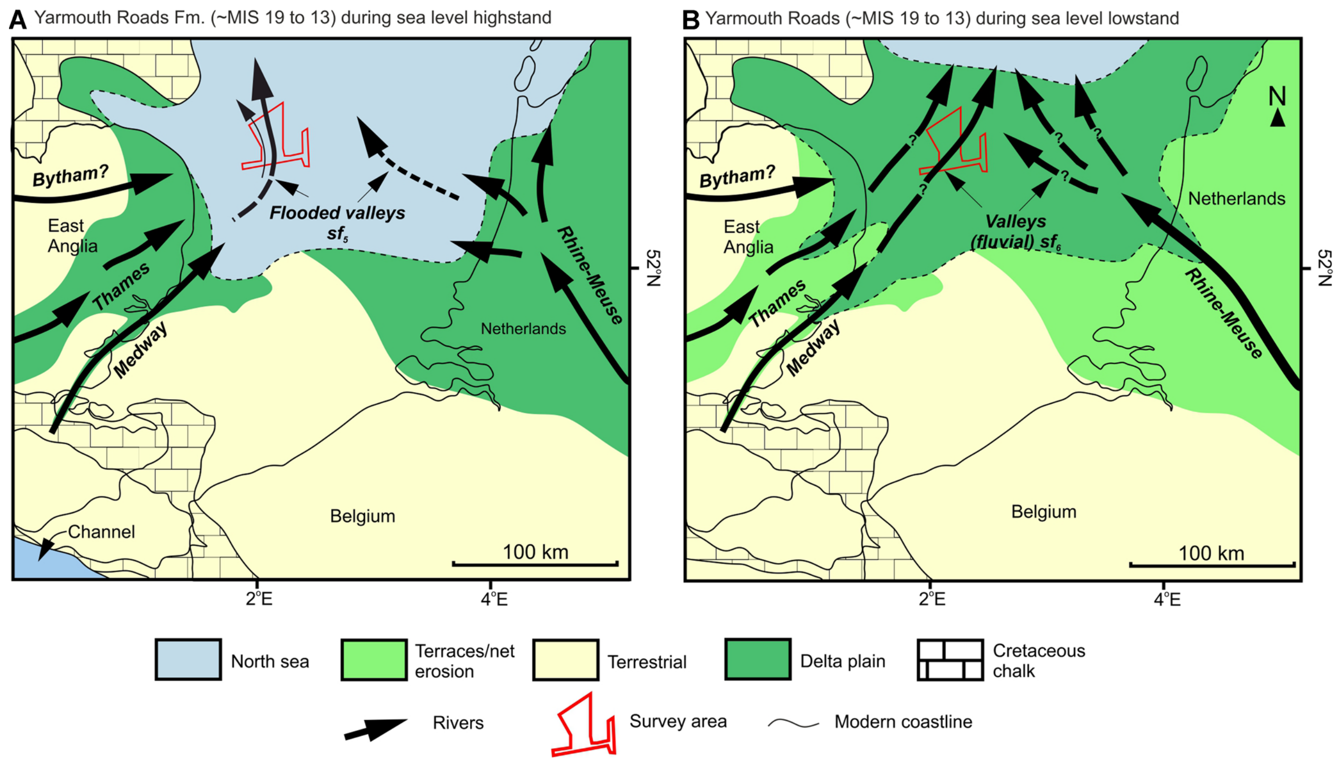


Figure 10. Palaeoenvironmental maps depicting highstand and lowstand scenarios at the time of Yarmouth Roads Fm. deposition. A. Interglacial conditions and flooding of valleys V2 and V3 and draped deposition of fine-grained marine/estuarine sediments. B. Glacial conditions with northwards expansion of fluvial networks and infilling of valley V1 with coarser grained terrestrial sediments (modified from Gibbard, 1988; Funnell, 1996; Cohen *et al.*, 2012; Hijma *et al.*, 2012). [Color figure can be viewed at wileyonlinelibrary.com]

consistent with the interpretation of the Brown Bank Fm. (Cameron *et al.*, 1992; Stoker *et al.*, 2011). The Brown Bank Fm. has been subdivided by previous workers into an upper and lower unit (Bicket and Tizzard, 2015, and references therein), with the lower unit being sandier and associated with topographic lows, and the underlying marine transgressive Eem Fm. (Limpenny *et al.*, 2011). The fine-grained lithology, the seismic character and the flat nature to S2 suggests that only the upper Brown Bank Fm. is present in the study area. The core sedimentology and faunal assemblages (Wessex Archaeology, 2018) support deposition under a low-energy, shallow-marine and/or lagoonal environment in which regional changes in RSL may be superimposed (Fig. 2A,B). However, given that the study area is located towards the northern limits of where the Brown Bank Fm. deposits are distributed (Cameron *et al.*, 1992), it may suggest that Brown Bank Fm. deposits seen in the study area are of a slightly different genesis and age than seen in the Belgian, British and Dutch areas south of the study area.

The CPT data calibrated to seismic reflection data provide compelling evidence for subdivision within the Brown Bank Fm. Soil behaviour type (SBT) plots reveal that the fine-grained lithofacies that characterize the upper Brown Bank Fm. have two distinct distributions (Fig. 11), with geomechanical parameters predicting a silt-dominated lithology overlain by a clay-dominated lithology. This subdivision is further supported by seismic reflection data where a marked change in seismic facies is coincident with a change in CPT character. The change in CPT character supports a change in sediment supply and/or energy regime because of RSL change. Evidence for a multi-stage fill is not supported by all CPTs. This may be explained by erosive processes and/or spatial variability in contemporaneous sedimentary depositional environments.

The Brown Bank Fm. has been interpreted to represent a widespread lagoon-type system, with limited connection to open marine conditions, which extended across the southern North Sea, and became increasingly restricted during the early Devensian (Cameron *et al.*, 1989; Laban, 1995). Seismic and core data in the study area support regional deposition of fine-grained sediments onto a gently undulating lower bounding surface (S2), probably during a time of fluctuating RSL. Figure 12 estimates the position of the palaeo-coastlines, with the overlying sediment fill stripped back. When sea level is 50 m below present (Fig. 12A), most of the study area is subaerial with only enclosed and semi-enclosed lagoons. However, when RSL is ~46 m below present (Fig. 12B) a more complex coastal configuration is revealed. At 44 m below present the area is predominantly flooded, with a small area in the north-east remaining subaerial. These flooding and exposure scenarios suggest that minor changes in RSL would have resulted in major shifts from open marine through estuarine to restricted lagoonal conditions and challenges the idea of a long-lived and widespread lagoonal environment. Cores from the study area support periods of submersion and exposure with iron sulphide indicative of a restricted marine and/or subaerially exposed landscape. Work by Wessex Archaeology (2018) on changes in faunal assemblages in the region adds further support to the idea of restriction and/or isolation of water bodies through time.

Further evidence for an environment controlled by localized topography and RSL change are the dune-scale bedforms [symmetrical and asymmetrical, 1–3 m high (crest-to-trough) with a wavelength of 20–50 m] present in the south-west of the study area. The bedforms are not channel-confined, which discounts a fluvial or estuarine origin. Given the uniform crest-line orientation and scale of the bedforms, and their stratigraphic position between marine fines, a tidal origin on an open shelf is the preferred interpretation. Examples of similar bedforms are identified both on modern shelf environments (Passchier and Kleinhans, 2005) and in the stratigraphic

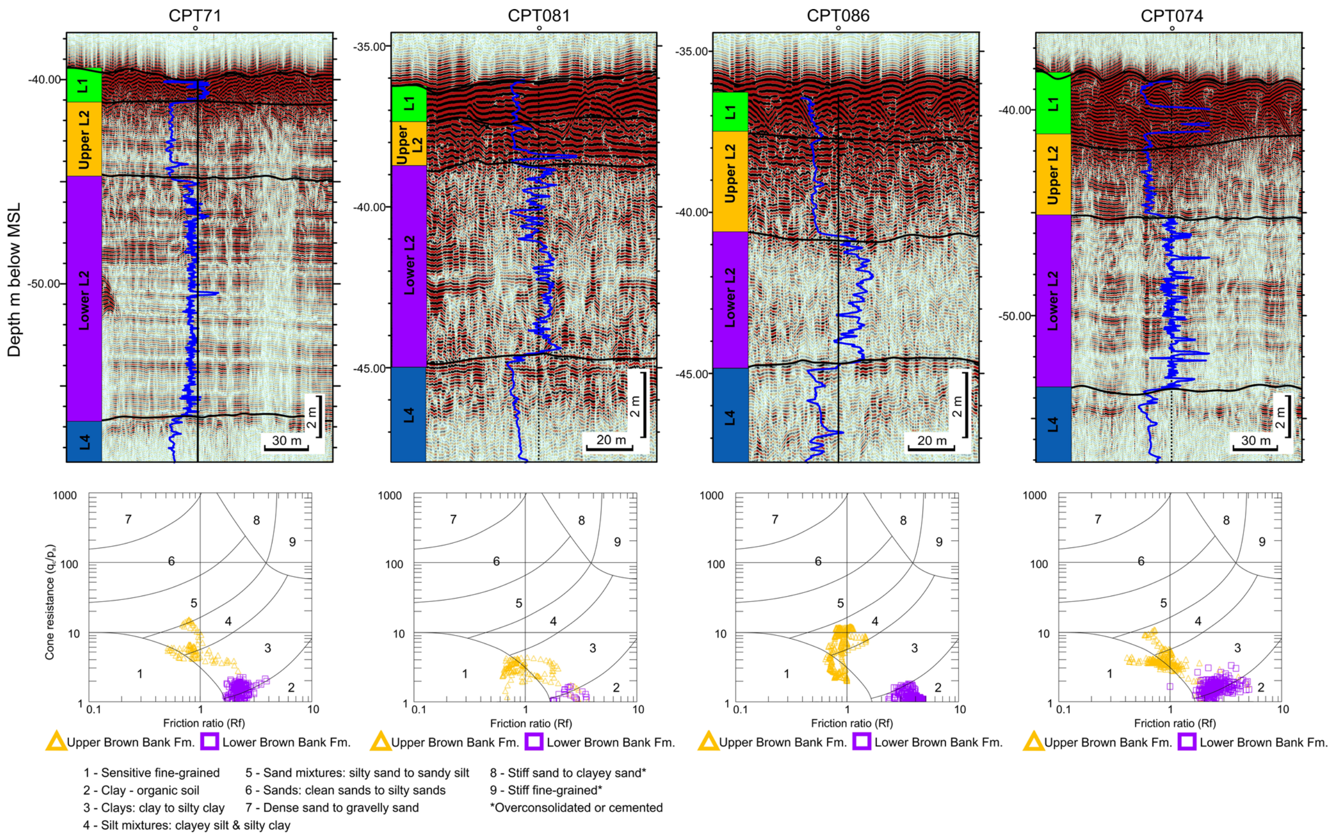


Figure 11. Seismic reflection profiles with CPT friction ratio (Rf) overlain and SBT plot showing data for the L2 unit interval. The SBT plot shows two distributions interpreted to support a subdivision of the L2 unit. Using the SBT plot, the lower L2 unit is predicted to be predominantly clay (organic soils) and the upper L2 unit predominantly silt with clay. [Color figure can be viewed at wileyonlinelibrary.com]

record (Brew, 1996). An aeolian origin is unlikely given their size, preservation and bounding by marine fines. The net southward-migration direction would support an overall E–W-trending contemporary shoreline with available sand supply. Their patchy distribution is probably due to be a combination of the S2 surface topography, grain-size availability and water depth. The symmetrical and asymmetrical geomorphology of the tidal bedforms could support an interpretation of an estuarine environment where ebb and flood tides were both symmetrical and asymmetrical (Reynaud, 2012). However, without core calibration their composition and process origin remain equivocal. A rising and falling RSL during MIS 5 (Zagwijn, 1983; Long *et al.*, 2015) presents one scenario for bedform development. In this scenario, the landscape would fluctuate from open marine to increasingly restricted, with estuarine processes becoming more dominant during periods of lower sea level. During RSL fall tidal processes could become more dominant, and sand supply increase, leading to the development of tidal bedforms. Subsequent RSL rise led to burial of the tidal bedforms by fine-grained marine sediments. The exceptional preservation of these tidal bedforms suggests that burial was rapid and under relatively low-energy conditions.

The detailed timing of Brown Bank Fm. deposition has remained a subject of discussion and chronological evidence

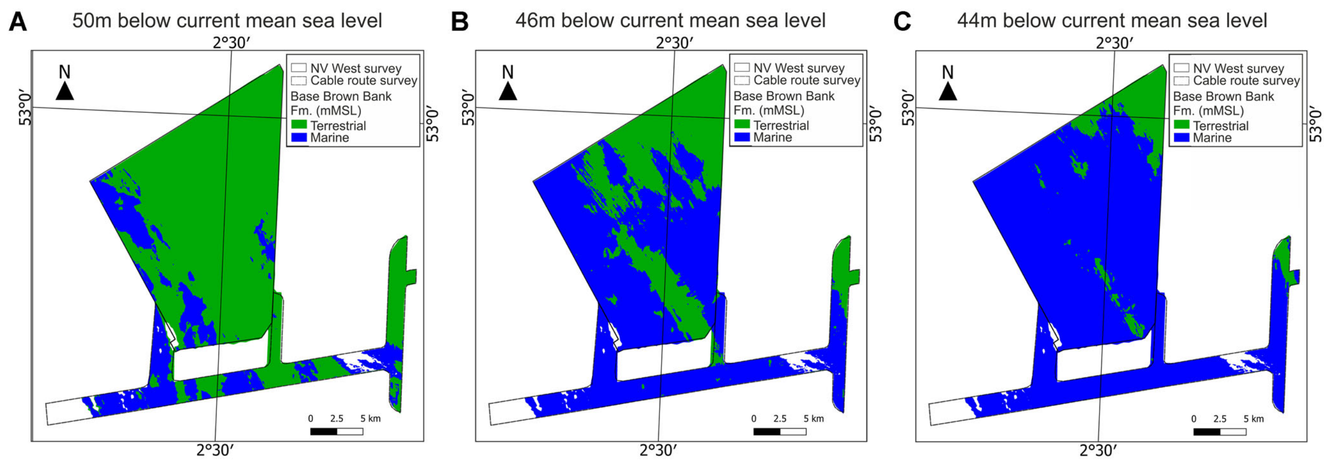


Figure 12. Flooded landscape scenarios for hypothetical stages in the Last Interglacial and Early Glacial (L2 unit; Eem and Brown Bank Fms., MIS 5). A. At 50 m below current mean sea level most of the area is subaerial with small enclosed and semi-enclosed lagoons, lakes and peninsulas. B. At 46 m below current mean sea level a less restricted, more open marine landscape is revealed. C. At 44 m below current mean sea level the survey area is predominantly flooded with the exception of the north-east with some islands. [Color figure can be viewed at wileyonlinelibrary.com]

is scarce. The Brown Bank Fm. drapes the S2 surface, which is coincident with the top of the Swarte Bank Fm. In rare exceptions, for example in VC79, coarse-grained marine sediments overly the S2 surface. These coarse-grained marine sediments are considered to represent a marine transgressive lag (i.e. a wave ravinement surface), probably deposited during the Ipswichian transgression, and therefore part of the Eem Fm. Dates obtained by Limpenny *et al.* (2011) and the stratigraphic position of the Brown Bank Fm. fill (overlying MIS 12 stratigraphy and suspected Eem Fm. transgressive sediments) support a time of deposition between MIS 5d and 3, with the S2 surface representing major erosion and/or a hiatus of ~0.4 Ma. Any sediment accumulation in the study area most probably occurred during the Hoxnian interglacial (Fig. 2), followed by a hiatus and/or erosion during the following Wolstonian glaciations (Fig. 3 – maximum ice extent), with eroded sediment probably transported south away from the ice front (Toucanne *et al.*, 2009).

Opposing sediment transport directions

Over short timescales, most catchments and adjacent sedimentary basins have simple source-to-sink configurations driven by the direction of slope, meaning the net direction of sediment flux does not change. During the Middle to Late Pleistocene, the southern North Sea underwent major changes in sedimentary process regime under the influence of glacial and interglacial cycles. Associated with these changes are marked shifts in the primary direction of sediment flux. During Yarmouth Roads Fm. deposition the primary sediment transport direction was to the north (Fig. 10), with sediment transported from catchments to the west (England) and south-east (mainland Europe) (Fig. 3). During the Anglian glaciation, northward fluvial and westward ice-marginal glaciofluvial transport of sediment was towards a proglacial lake (Fig. 3) and the previously fluvial-dominated landscape became glaciated with evidence for subglacial conditions preserved in the stratigraphy as tunnel-valley fills (Fig. 3), with net sediment transport to the south via meltwater conduits (Gibbard *et al.*, 2009). Significant erosion and/or a hiatus took place before marine transgression during the Eemian period (although the direction of this erosion is unknown) and following this, marine sediments including those of the Brown Bank Fm. were deposited in a highly dynamic low-relief environment that was highly responsive to cycles of RSL. This environment probably shifted from open marine to more restricted, with embayments and lagoons being the main environments of deposition. During deposition of the Brown Bank Fm. sediments are considered to come from the west, a result of the Rhine Delta progradation into the basin (Hijma *et al.*, 2012; Peeters *et al.*, 2016). These marked changes in sediment transport directions over relatively short periods reflect the low-relief continental shelf environment and proximity to an ice-marginal setting. The low-relief physiography in the study area contrasts with more typical high-relief source-to-sink configurations. The results caution against applying simple estimates of sediment flux and provenance signals even over short durations, particularly in ice-marginal continental shelf settings.

Conclusions

The availability of high-resolution seismic reflection data acquired for the offshore windfarm industry alongside a complementary dense network of cores and CPTs allows the development of a detailed and integrated view of the stratigraphy and depositional environments of the middle and late Pleistocene in a 401-km^2 area of the southern North Sea, 47 km off the coast of East Anglia. The patterns of deposition are strongly related to periods of glacial/interglacial cycles but record a far more spatially and temporally complex fill rather than a simple record of alternating warm and cool climate periods.

Imaged within the lower units are the topsets associated with the Yarmouth Roads Fm. Changes in valley-fill architecture and scale record changes in the influence of terrestrial, fluvial and marine depositional environments during the Cromerian period (MIS ~19–13), because of allogenic controls (climate and base level change) and/or autogenic control. The expansion and increasing influence of European and British rivers are the predominant control on the N–S orientation of the fluvial network, which drained northwards.

The extensive Anglian glaciation (MIS 12) altered the mode of sediment erosion and deposition by 180°, with N–S-trending subglacial tunnel valleys under a southward advancing ice sheet (the Swarte Bank Fm.). Currently, the tunnel valley-fills mapped here are the most southern subglacial expression of the extensive MIS 12 ice sheet documented in the southern North Sea. Following MIS 12, a stratigraphic hiatus of ~0.4 Ma is marked by an unconformity that is overlain by sediments closely related to the upper Brown Bank Fm. (Cameron *et al.*, 1989).

Shallow-marine/estuarine sediments that form the latter part of MIS 5 record a phase of fluctuating RSL, within a low-relief shelf setting. Dune-scale bedforms preserved within these fine-grained sediments are interpreted as tidal in origin, and suggest at least one phase of lower or stable RSL, probably during cool conditions approaching the onset of the Devensian glaciation (MIS 4–2). Previously, Brown Bank Fm. deposits have been thought to represent a single estuarine phase at the culmination of the sea-level highstand following the Last Interglacial. However, our analysis shows that there were periods of alternating sediment deposition suggesting change in RSL and sediment supply.

Data availability statement

The raw data and technical reporting that support the findings of this study are not publicly available due to commercial restrictions.

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Abbreviations. bsb, below the seabed; CPT, cone penetration test; LGM, Last Glacial Maximum; MIS, Marine Isotope Stage; MSL, mean sea level; RSL, relative sea level; SBP, sub bottom profile; SBT, soil behaviour type; TWTT, two-way travel time; UHR, ultra-high-resolution.

References

Balson PS, Jeffery DH. 1991. The glacial sequence of the southern North Sea. In Glacial deposits in Great Britain and Ireland. Rotterdam, Netherlands: A.A. Balkema, 245–253.

Beets DJ, Meijer T, Beets CJ *et al.* 2005. Evidence for a Middle Pleistocene glaciation of MIS 8 age in the southern North Sea. *Quaternary International* **133–134**: 7–19.

Bicket A, Tizzard L. 2015. A review of the submerged prehistory and palaeolandscapes of the British Isles. *Proceedings of the Geologists' Association* 126: 643–663.

Bogemans F, Roe HM, Baeteman C. 2016. Incised Pleistocene valleys in the Western Belgium coastal plain: age, origins and implications for the evolution of the southern North Sea Basin. *Palaeogeography, Palaeoclimatology, Palaeoecology* **456**: 46–59.

Bowen DQ, Rose J, McCabe AM *et al.* 1986. Correlation of quaternary glaciations in England, Ireland, Scotland and Wales. *Quaternary Science Reviews* **5**: 299–340.

Brew DS. 1996. Late Weichselian to Early Holocene subaqueous dune formation and burial off the North Sea Northumberland coast. *Marine Geology* **134**: 203–211.

Bridgland DR. 2002. Fluvial deposition on periodically emergent shelves in the Quaternary: example records from the shelf around Britain. *Quaternary International* **92**: 25–34.

Bridgland DR, D'Olier B. 1995. The Pleistocene evolution of the Thames and Rhine drainage systems in the southern North Sea Basin. *Geological Society Special Publication* **96**: 27–45.

Busschers FS, Kasse C, van Balen RT *et al.* 2007. Late Pleistocene evolution of the Rhine-Meuse system in the southern North Sea basin: imprints of climate change, sea-level oscillation and glacio-isostacy. *Quaternary Science Reviews* **26**: 3216–3248.

Cameron TDJ, Crosby A, Balsonn PS *et al.* 1992. United Kingdom Offshore Regional Report: the Geology of the Southern North Sea. London.

Cameron TDJ, Laban C, Schuttenhelm RTE. 1989. Upper Pliocene and Lower Pleistocene stratigraphy in the Southern Bight of the North Sea. In *The Quaternary and Tertiary Geology of the Southern Bight, North Sea*, Henriet JP, De Moor G (eds). Ministry of Economic Affairs——Belgian Geological Survey, 97–110.

Cameron TDJ, Stoker MS, Long D. 1987. The history of Quaternary sedimentation in the UK sector of the North Sea Basin. *Journal of the Geological Society* **144**: 43–58.

Carr SJ, Holmes R, van der Meer JJM *et al.* 2006. The Last Glacial Maximum in the North Sea Basin: micromorphological evidence of extensive glaciation. *Journal of Quaternary Science* **21**: 131–153.

Castelltort S, Van Den, Driessche J. 2003. How plausible are high-frequency sediment supply driven cycles in the stratigraphic record? *Sedimentary Geology* **157**: 3–13.

Clark C, Evans D, Khatwa A *et al.* 2004. Map and GIS database of glacial landforms and features related to the last British Ice Sheet. *Boreas* **33**: 359–375.

Cohen KM, Gibbard PL. 2012. Regional chronostratigraphical correlation table for the last 270,000 years: North Atlantic–Greenland–West, North, East, Central Europe–Russia. In Abstract INTIMATE Workshop Utrecht, Netherlands, March.

Cohen KM, Gibbard PL, Weerts HJT. 2014. North Sea palaeogeographical reconstructions for the last 1 Ma. *Netherlands Journal of Geosciences - Geologie en Mijnbouw* **93**: 7–29.

Cohen KM, MacDonald K, Joordens JCA *et al.* 2012. The earliest occupation of north-west Europe: A coastal perspective. *Quaternary International* **271**: 70–83.

Cohen KM, Westley K, Erkens G *et al.* 2017. The North Sea. In *Submerged Landscapes of the European Continental Shelf Vol. 1 Quaternary Paleoenvironments*, Flemming NC, Harff J, Moura D, Burgess A, Bailey GN (eds). John Wiley & Sons Ltd: New York; 147–186.

Colombera L, Mountney NP, Mccaffrey WD. 2013. A quantitative approach to fluvial facies models: methods and example results. *Sedimentology* **60**: 1526–1558.

Cotterill CJ, Phillips E, James L *et al.* 2017. The evolution of the Dogger Bank, North Sea: A complex history of terrestrial, glacial and marine environmental change. *Quaternary Science Reviews* **171**: 136–153.

Davies BJ, Roberts DH, Bridgland DR *et al.* 2011. Provenance and depositional environments of Quaternary sediments from the western North Sea Basin. *Journal of Quaternary Science* **26**: 59–75.

van der Vegt P, Janszen A, Moscariello A. 2012. Tunnel valleys: current knowledge and future perspectives. *Geological Society, London, Special Publications* **368**: 75–97.

Dyer KR, Huntley DA. 1999. The Origin, Classification and Modelling of Sand Banks and ridges. *Continental Shelf Research*, Elsevier. **19**: 1285–1330.

Ehlers J. 1990. Reconstructing the dynamics of the North-west European Pleistocene ice sheets. *Quaternary Science Reviews* **9**: 71–83.

Ehlers J, Gibbard PL. 2007. The extent and chronology of Cenozoic Global Glaciation. *Quaternary International* **164–165**: 6–20.

Ehlers J, Wingfield R. 1991. The extension of the Late Weichselian/Late Devensian ice sheets in the North Sea Basin. *Journal of Quaternary Science* **6**: 313–326.

Emery AR, Hodgson DM, Barlow NLM *et al.* 2019a. Topographic and hydrodynamic controls on barrier retreat and preservation: an example from Dogger Bank, North Sea. *Marine Geology* **416**(105981), 1–20.

Emery AR, Hodgson DM, Barlow NLM *et al.* 2019b. Left high and dry: deglaciation of Dogger Bank, North Sea, recorded in proglacial lake evolution. *Frontiers in Earth Science* **7**.

Fitch S, Thomson K, Gaffney V. 2005. Late Pleistocene and Holocene depositional systems and the palaeogeography of the Dogger Bank, North Sea. *Quaternary Research* **64**: 185–196.

Funnell BM. 1996. Plio-Pleistocene Palaeogeography of the southern North Sea basin (3.75–0.60 Ma). *Quaternary Science Reviews* **15**: 391–405.

Gatliff RW, Richards PC, Smith K *et al.* 1994. *United Kingdom Offshore Regional Report: the Geology of the Central North Sea*. British Geological Survey.

Gibbard PL. 2007. Palaeogeography: Europe cut adrift. *Nature* **448**: 259–260.

Gibbard PL, Pasanen AH, West RG *et al.* 2009. Late Middle Pleistocene glaciation in East Anglia, England. *Boreas* **38**: 504–528.

Gibbard PL. 1988. The history of the great northwest European rivers during the past three million years. *Philosophical Transactions of the Royal Society of London. B, Biological Sciences* **318**: 559–602.

Glennie KW, Underhill JR. 1998. Origin, development and evolution of structural styles. In *Petroleum Geology of the North Sea: Basin Concepts and Recent Advances*, Glennie K (ed). Blackwell Science Ltd: Oxford; 42–84.

Graham AGC, Stoker MS, Lonergan L *et al.* 2011. The Pleistocene glaciations of the North Sea basin. *Developments in Quaternary Sciences* **15**: 261–278.

Gulliford AR, Flint SS, Hodgson DM. 2014. Testing applicability of models of distributive fluvial systems or trunk rivers in ephemeral systems: reconstructing 3-D fluvial architecture in the Beaufort Group, South Africa. *Journal of Sedimentary Research* **84**: 1147–1169.

Hartley AJ, Weissmann GS, Nichols GJ *et al.* 2010. Large distributive fluvial systems: characteristics, distribution, and controls on development. *Journal of Sedimentary Research* **80**: 167–183.

Head MJ, Gibbard PL. 2015. Early-Middle Pleistocene transitions: linking terrestrial and marine realms. *Quaternary International* **389**: 7–46.

Hijma MP, Cohen KM, Roebroeks W *et al.* 2012. Pleistocene Rhine-Thames landscapes: geological background for hominin occupation of the southern North Sea region. *Journal of Quaternary Science* **27**: 17–39.

Huuse M, Lykke-Andersen H. 2000. Overdeepened Quaternary valleys in the eastern Danish North Sea: morphology and origin. *Quaternary Science Reviews* **19**: 1233–1253.

Konradi PB, Larsen B, Sørensen AB. 2005. Marine Eemian in the Danish eastern North Sea. *Quaternary International* **133–134**: 21–31.

Laban C. 1995. *The Pleistocene Glaciations in the Dutch Sector of the North Sea: A Synthesis of Sedimentary and Seismic Data*. University of Amsterdam: Amsterdam.

Laban C, van der Meer JJM. 2004. Pleistocene glaciations in the Netherlands. *Developments in Quaternary Science*. Elsevier, 251–260.

Lamb RM, Harding R, Huuse M *et al.* 2018. The early Quaternary North Sea Basin. *Journal of the Geological Society* **175**: 275–290.

Lee JR, Rose J, Candy IAN *et al.* 2006. Sea-level changes, river activity, soil development and glaciation around the western margins of the southern North Sea Basin during the Early and early Middle Pleistocene: evidence from Pakefield, Suffolk, UK. *Journal of Quaternary Science* **21**: 155–179.

Limpenny SE, Barrio Frojan C, Cotterill C *et al.* 2011. The East Coast Regional Environmental Characterisation. *Cefas Open Rep* **08/04**: 287.

Lisiecki LE, Raymo ME. 2005. A Pliocene-Pleistocene stack of 57 globally distributed benthic δ 18O records. *Paleoceanography* **20**: 1–17.

Liu Z, Berné S, Saito Y *et al*. 2007. Internal architecture and mobility of tidal sand ridges in the East China Sea. *Continental Shelf Research* **27**: 1820–1834.

Long AJ, Barlow NLM, Busschers FS *et al*. 2015. Near-field sea-level variability in northwest Europe and ice sheet stability during the last interglacial. *Quaternary Science Reviews* **126**: 26–40.

Long D, Laban C, Streif H *et al*. 1988. The sedimentary record of climatic variations in the southern North Sea. *Philosophical Transactions of the Royal Society of London* **318**: 523–537.

Mellett CL, Hodgson DM, Plater AJ *et al*. 2013. Denudation of the continental shelf between Britain and France at the glacial–interglacial timescale. *Geomorphology* **203**: 79–96.

Mellett CL, Phillips ER, Lee JR *et al*. 2020. Elsterian ice-sheet retreat in the southern North Sea: antecedent controls on large-scale glaciotectonics and subglacial bed conditions. *Boreas* **49**: 129–151.

Mitchum RM Jr, Vail PR, Sangree JB. 1977. Stratigraphic interpretation of seismic reflection pattern in depositional sequences. In *Seismic Stratigraphy – Applications to Hydrocarbon Exploration AAPG Memoires*, Payton CE (ed). American Association of Petroleum Geologists: Tulsa; 117–134.

Moorlock BSP, Riding JB, Hamblin RJO *et al*. 2002. The Pleistocene College Farm Silty Clay at Great Blakenham, Suffolk, England – additional information on the course of the early River Thames. *Netherlands Journal of Geosciences - Geologie en Mijnbouw* **81**: 9–17.

Moreau J, Huuse M, Janszen A *et al*. 2012. The glaciogenic unconformity of the southern North Sea. *Geological Society, London, Special Publications* **368**: 99–110.

Murton DK, Murton JB. 2012. Middle and Late Pleistocene glacial lakes of lowland Britain and the southern North Sea Basin. *Quaternary International* **260**: 115–142.

Ó Cofaigh C. 1996. Tunnel valley genesis. *Progress in Physical Geography: Earth and Environment* **20**: 1–19.

Parfitt SA, Ashton NM, Lewis SG *et al*. 2010. Early Pleistocene human occupation at the edge of the boreal zone in northwest Europe. *Nature* **466**: 229–233.

Passchier S, Kleinhans MG. 2005. Observations of sand waves, megaripples, and hummocks in the Dutch coastal area and their relation to currents and combined flow conditions. *Journal of Geophysical Research: Earth Surface* **110**.

Pawley SM, Bailey RM, Rose J *et al*. 2008. Age limits on Middle Pleistocene glacial sediments from OSL dating, north Norfolk, UK. *Quaternary Science Reviews* **27**: 1363–1377.

Peeters J. 2018. The Last Interglacial Rhine Estuary: Sedimentary Architecture, Chronostratigraphy, Preservation and Analogue Potential (Doctoral dissertation, University Utrecht).

Peeters J, Busschers FS, Stouthamer E. 2015. Fluvial evolution of the Rhine during the last interglacial-glacial cycle in the southern North Sea basin: a review and look forward. *Quaternary International* **357**: 176–188.

Peeters J, Busschers FS, Stouthamer E *et al*. 2016. Sedimentary architecture and chronostratigraphy of a late Quaternary incised-valley fill: A case study of the late Middle and Late Pleistocene Rhine system in the Netherlands. *Quaternary Science Reviews* **131**: 211–236.

Praeg D. 1996. *Morphology, Stratigraphy and Genesis of Buried Mid-Pleistocene Tunnel-Valleys in the Southern North Sea Basin*. University of Edinburgh.

Praeg D. 2003. Seismic imaging of mid-Pleistocene tunnel-valleys in the North Sea Basin—high resolution from low frequencies. *Journal of Applied Geophysics* **53**: 273–298.

Reynaud JY, Dalrymple RW. 2012. Shallow-marine tidal deposits. In Principles of Tidal Sedimentology (pp. 335–369). Springer, Dordrecht.

Romans BW, Castelltort S, Covault JA *et al*. 2016. Environmental signal propagation in sedimentary systems across timescales. *Earth-Science Reviews* **153**: 7–29.

Sadler PM, Jerolmack DJ. 2015. Scaling laws for aggradation, denudation and progradation rates: the case for time-scale invariance at sediment sources and sinks. *Geological Society, London, Special Publications* **404**: 69–88.

Scourse JD, Ansari MH, Wingfield RTR *et al*. 1998. A Middle Pleistocene shallow marine interglacial sequence, inner silver pit, southern North Sea. *Quaternary Science Reviews* **17**: 871–900.

Sejrup HP, Clark CD, Hjelstuen BO. 2016. Rapid ice sheet retreat triggered by ice stream debuttressing: evidence from the North Sea. *Geology* **44**: 355–358.

Shennan I, Lambeck K, Flather R *et al*. 2000. Modelling western North Sea paleogeographies and tidal changes during the Holocene. *Geological Society, London, Special Publications* **166**: 299–319.

Smith DE, Harrison S, Firth CR *et al*. 2011. The Early Holocene sea level rise. *Quaternary Science Reviews* **30**: 1846–1860.

Spratt RM, Lisiecki LE. 2016. A Late Pleistocene sea level stack. *Climate of the Past* **12**: 1079–1092.

Stewart M, Lonergan L, Hampson G. 2012. 3D seismic analysis of buried tunnel valleys in the Central North Sea: tunnel valley fill sedimentary architecture. *Geological Society, London, Special Publications* **368**: 173–184.

Stewart MA, Lonergan L, Hampson G. 2013. 3D seismic analysis of buried tunnel valleys in the central North Sea: morphology, cross-cutting generations and glacial history. *Quaternary Science Reviews* **72**: 1–17.

Stoker M, Balson PS, Long D *et al*. 2011 *An Overview of the Lithostratigraphical Framework for the Quaternary Deposits on the United Kingdom Continental Shelf*. British Geological Survey Research Report RR/11/03, 48.

Streif H. 2004. Sedimentary record of Pleistocene and Holocene marine inundations along the North Sea coast of Lower Saxony, Germany. *Quaternary International* **112**: 3–28.

Toucanne S, Zaragosi S, Bourillet JF *et al*. 2009. Timing of massive 'Fleuve Manche' discharges over the last 350 kyr: insights into the European ice-sheet oscillations and the European drainage network from MIS 10 to 2. *Quaternary Science Reviews* **28**: 1238–1256.

Uehara K, Scourse JD, Horsburgh KJ *et al*. 2006. Tidal evolution of the northwest European shelf seas from the Last Glacial Maximum to the present. *Journal of Geophysical Research* **111**: 1–15.

Van Der Molen J, De Swart HE. 2001. Holocene wave conditions and wave-induced sand transport in the southern North Sea. *Continental Shelf Research* **21**: 1723–1749.

Van Kolfschoten T, Laban C. 1995. Pleistocene terrestrial mammal faunas from the North Sea. *Meded-Rijks Geol D* **52**: 135–151.

Van Landeghem KJJ, Wheeler AJ, Mitchell NC *et al*. 2009. Variations in sediment wave dimensions across the tidally dominated Irish Sea, NW Europe. *Marine Geology* **263**: 108–119.

Wessex Archaeology. 2018. *Norfolk Vanguard Offshore Wind Farm: Stage 3 Geoarchaeological Sampling and Assessment*. Wessex Archaeology: Salisbury.

Zagwijn WH. 1983. Sea-level changes in the Netherlands during the Eemian. *Geol en Mijnb* **62**: 437–450.

