

Coastal Lagoonal Evolution within the Early Holocene Humber Estuary, eastern England

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ABSTRACT: Rapid sea-level rise during the Early Holocene around the North Sea coastal lowlands provided conditions under which estuarine and coastal features, with no modern equivalents, could be created. Investigation of nearshore sediments within the Outer Humber Estuary, UK, has identified a tidal lagoonal system, created between c. 9000 and 7800 cal a BP. These sequences show the initial flooding of a carr woodland, prior to the establishment of more saline conditions as the tidal lagoonal system developed. Inter-core comparisons, based on diatom and pollen analyses, suggest variations in the structure of a tidal lagoon setting, which probably lasted for only a brief period before being submerged by rising sea levels. The absence of an erosive contact in several of the sequences studied has permitted the creation of the oldest sea-level index points for the Outer Humber Estuary, providing validation for the current glacial isostatic adjustment models for the region. © 2023 The Authors. *Journal of Quaternary Science* Published by John Wiley & Sons Ltd.

KEYWORDS: diatom; Early Holocene; Humber; lagoon; sea level

Introduction

Studies of relative sea level (RSL) through the Lateglacial and Holocene are well established in many regions, with broad patterns of RSL change predicted by glacial isostatic adjustment (GIA) models (Lambeck, 1991; Shennan et al., 2002; 2018; Peltier et al., 2002; Kuchar et al., 2012; Bradley et al., 2011). Such models are reliant upon validation through the use of sea-level index points (SLIPs) and limiting data, but the availability and quality of these can be variable by region, depending upon availability and access to suitable sedimentary records and the history of eustatic sea-level change (e.g. Kirby et al., 2023). This is especially true for the Early Holocene in areas away from the Pleistocene ice caps, where the palaeoshoreline lay seaward of the modern coast (Sturt et al., 2013), resulting in onshore coring often only sampling mid- to late Holocene coastal deposits. For this reason, sea-level studies utilizing nearshore and offshore sedimentary sequences can be particularly important (Shennan et al., 2000a, 2000b, 2018) for understanding and constraining Late Devensian and Early Holocene sea-level change. This paper presents such a study from cores collected by Ørsted in association with the Hornsea Project Two Offshore Wind Farm, which has its transmission cable landfall within the Outer Humber Estuary, UK. Within the nearshore zone, conformable Early Holocene coastal deposits have been identified at Horse-shoe Point, East Lindsey, Lincolnshire.

Holocene RSL history of the Humber Estuary

The earliest investigations in the Humber Estuary that sought to establish regional sea-level change were conducted by Gaunt and Tooley (1974), investigating sequences containing basal peats at Market Place, Kingston upon Hull, and the Union Dock, Grimsby. Subsequent work was predominantly associated with archaeological investigations (e.g. Smith et al., 1981; Millett et al., 1987; McGrail, 1990), including the Humber Wetlands Project (van de Noort and Ellis 1995; 1998). A comprehensive review of these data was undertaken by Dinnin and Lillie (1995), Long et al. (1998) and Kirby (2001), also presenting new information from sites in Holderness, North Lincolnshire and the southern part of the Vale of York, providing the most comprehensive overview of the RSL history of the area. The subsequent Land-Ocean Evolution Perspective Study (LOEPS; see Shennan et al., 2000a) was conducted within the estuary, focused on collecting new data to refine the spatial and temporal gaps evident in the existing RSL record, which in turn generated a wide range of SLIPs along the estuary (Metcalf et al., 2000; Shennan et al., 2000a, b). These studies demonstrated that RSL rose at a rate of c. 7 mm a⁻¹ during the Early Holocene, slowing to c. 3.9 mm a⁻¹ during the early- to mid-Holocene (c. 7500–4000 cal a BP), with a further reduction to c. 1 mm a⁻¹ over the last 4000 years (Long et al., 1998; Metcalf et al., 2000; Shennan et al., 2018). While these studies provided significant insights into the structure, processes and timing of estuary development, sea-level rise and catchment processes through the Middle and Late Holocene, such conditions associated with the Early Holocene still remain poorly understood. This is due to the intertidal and subtidal environments from this period being either deeply buried and inaccessible with conventional hand-operated coring techniques or restricted

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to lower elevations situated in the outer portion of the estuary, seaward of the modern coastline.

Shennan et al. (2000a) undertook investigations at Sunk Island (HMB8), on the north side of the estuary, where deep Early Holocene peats were found over 15 m below the modern surface. Analysis of these showed that they contained an erosive contact between the peat and marine clay, with no evidence for saltmarsh development, rendering them unsuitable for the creation of SLIPs, instead only providing a freshwater (upper) limiting data point. Jelgersma (1961) and Shennan et al. (2000b) highlight this issue within the offshore zone, where marine transgression has the potential for significant erosion, with many sediment cores containing major hiatuses where significant sections of the Holocene record may be missing. Although marine inundation at Sunk Island had truncated the peat profile, laying down the clays unconformably over the eroded peat surface, it demonstrated that Early Holocene surfaces are to be found within the deeper areas of the Outer Humber Estuary. Therefore, there is the potential for non-eroded marine transgressive sediments suitable for the generation of SLIPs being preserved where more favourable depositional environments existed. Such sites would offer the opportunity to not only better constrain the Early Holocene RSL record for the region, but also improve the palaeogeographical mapping of the development of the estuary (e.g. Metcalfe et al., 2000; Dudley et al., 2021) and refine our understanding of the geomorphology and sedimentary architecture (Rees et al., 2000) of the outer estuary during this period of rapid sea-level rise.

Study site

Horseshoe Point, East Lindsey, on the Lincolnshire coastline of eastern England, is located within the Outer Humber Estuary (Fig. 1). It is the landfall site for the transmission cables from Ørsted's Hornsea One and Two Offshore Windfarms, whose arrays are situated c. 90 km east within the North Sea (Fig. 1a). During geotechnical site investigations for Hornsea Two, prior to cable installation, nine vibrocores were taken offshore of the Horseshoe Point landfall site in August 2019 by Fugro Marine Limited (Fig. 1c). Previous site investigations associated with Hornsea One (Heamagi, 2017) identified that organic deposits, related to Early Holocene semi-terrestrial environments, were present in the wider area, so sampling during the Hornsea Two investigative works was undertaken to obtain samples suitable for palaeoenvironmental analysis. The basement geology for Horseshoe Point is the Upper Cretaceous Flamborough Chalk Formation, on top of which the late Devensian Skipsea Till accumulated, overlain by several metres of Holocene deposits.

Methodology

Vibrocores were collected by Fugro Marine Limited at nine locations within the nearshore transmission cable corridor (see Figs 1 and 2). Coring was undertaken upon the *Roxane Z* utility vessel between the 8 and 17 August 2019 using Fugro's High Performance Corer. After acquisition, these cores were cut into 1-m-long sections onboard and then transported to Fugro's facilities in Wallingford, Oxfordshire, prior to longitudinal splitting, photographing and recording. Separate geoarchaeological recording of the vibrocore sequences was then undertaken, following the guidelines of Historic England (2015), with descriptions according to Hodgson (1997) and according to the Hornsea Two method statement for collection and

retention of geotechnical samples and Stage 1 and 2 geoarchaeological assessment (MSDS Marine, 2019; COWRIE, 2011). Four cores were identified as having the highest palaeoenvironmental potential, and were subsequently sampled for analysis and dating. Eleven radiocarbon ages were obtained across the four sequences using accelerator mass spectrometry (AMS) dating at Scottish Universities Environmental Research Centre (SUERC), following the method of Dunbar et al. (2016). Wherever possible, identifiable short-lived terrestrial plant macrofossils suitable for dating (following Bayliss and Marshall 2022) were selected. However, in some samples identifiable plant material was not present after sieving of sub-samples of the sediment, so a 1-cm slice of bulk sediment was sampled to allow extraction of the humic acid carbon fraction for dating. Dates have been calibrated against the IntCal20 Northern Hemisphere radiocarbon curve (Reimer et al., 2020) using OxCal 4.4 (Bronk Ramsey, 1995, 2001), with ranges quoted using the 2σ calibrated range and end points rounded outwards to 10 years (Mook, 1986). The results of the radiocarbon dating are provided in Table 1.

For diatom sample preparation, 0.5 g of wet sediment was required. Samples were treated overnight with sodium hexametaphosphate (5%) for minerogenic deflocculation, followed by hydrogen peroxide (30%) and weak ammonia (1%), as required. Samples were finally sieved using a 10- μ m mesh to remove fine minerogenic sediments. A minimum of 300 diatoms were identified for each sample depth. Diatom counting was undertaken at a magnification of $\times 400$ using a Motic C1-253 transmitted light microscope. Diatom species were identified with reference to van der Werff and Huls (1958–1974), Hendy (1964), and Krammer and Lange-Bertalot (1986–1991). Ecological classifications for the observed taxa were then achieved with reference to van der Werff and Huls (1958–1974), Vos and de Wolf (1988, 1993), Dam et al. (1994), Denys (1991–1992, 1994) and Round et al. (2007).

Standard procedures were used for the preparation of samples for pollen analysis (Moore et al., 1991) with 2 cm³ of sediment processed from each sample, to which a *Lycopodium* spike was added (one tablet from batch 100320201) to enable the calculation of pollen concentrations (Stockmarr, 1971). Pollen counting was undertaken at a magnification of $\times 400$ using a Nikon Eclipse Ci-L transmitted light microscope. Determinable pollen and spore types were identified to the lowest possible taxonomic level with the aid of a reference collection kept at COARS, University of Southampton. The pollen and spore types used are those defined by Bennett (1994) and Bennett, Whittington, et al. (1994), with the exception of Poaceae which followed the classification given by Küster (1988; see Waller and Grant 2012), with plant nomenclature following Stace (2010). A total land pollen (TLP) sum of 400 grains was sought for all samples, with the assemblage calculated as a percentage of total land pollen (%TLP). The TLP sum excluded aquatics and pteridophytes, which were calculated as %TLP + Group.

Results

The stratigraphy of the site has been determined through nine vibrocores, supplemented by cone penetration tests (CPTs), providing a sedimentary sequence up to 7.3 m in length at each location (Fig. 2). The sequence is characterized by pre-Holocene basal diamicton, the Skipsea Till, found within the base of the cores along the north-western edge of the study area, showing a reduction in elevation towards the east (Fig. 2). In the south-west, the base of the sequence in cores GT2-01-VC to GT2-03-VC contains a silty sand. Much of the sedimentary sequence, observed in all vibrocores, was a laminated clay

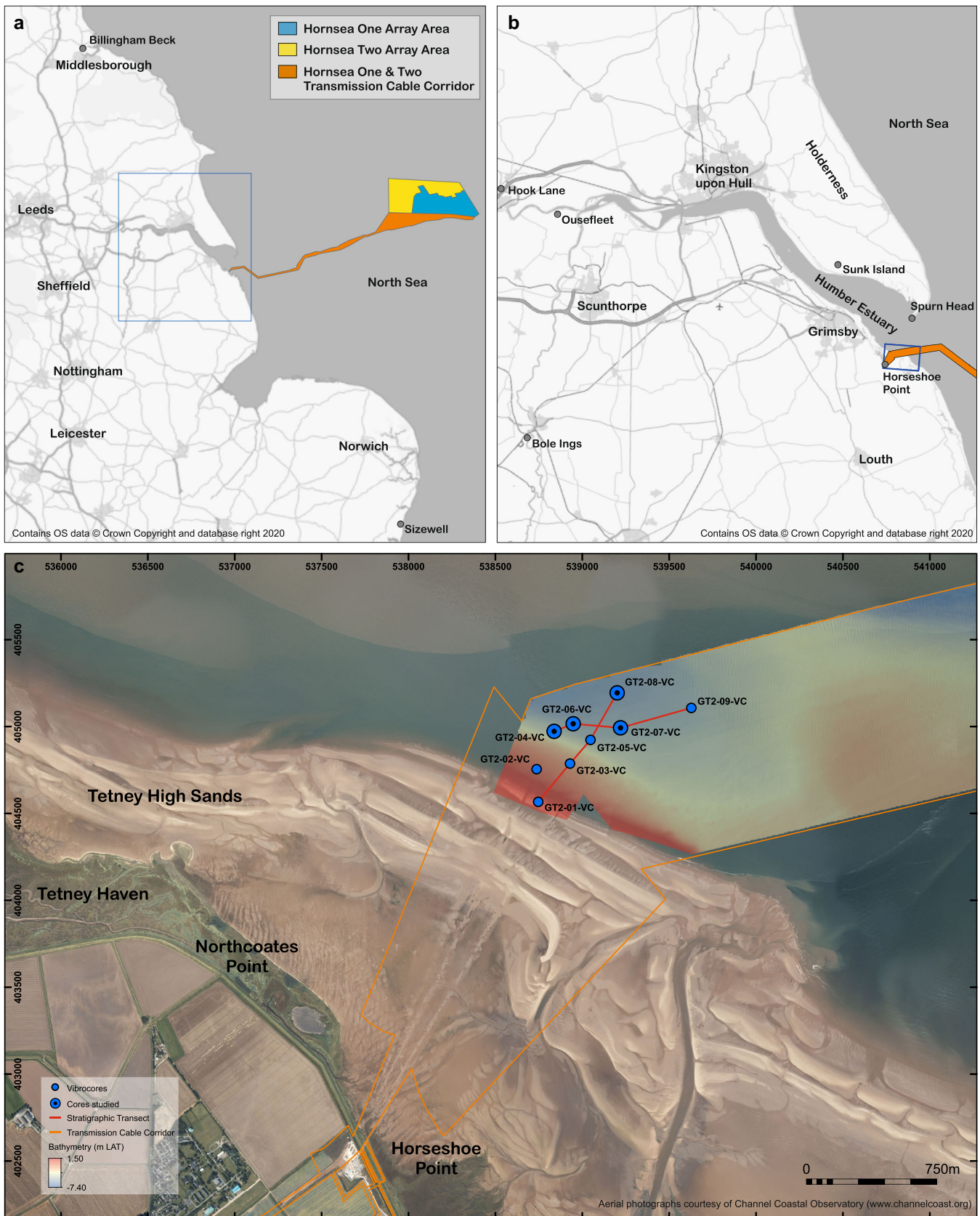


Figure 1. Location map of study area: (a) location of the Humber Estuary and extent of the Hornsea One and Two offshore windfarm arrays and export cable route, (b) Outer Humber Estuary, and (c) Horseshoe Point study area and coring locations.

containing organic remains (see Fig. 3 for an example). These clays typically contained *Phragmites* remains, but in some cores (e.g. GT2-07-VC) this sequence also contained a basal wood-dominated laminated clay beneath the *Phragmites* one. In areas where the underlying diamicton was encountered, an organic

clay and/or peat was found overlying this surface. Elsewhere, in GT2-09-VC, a thin intercalated peat was present within the centre of the laminated clay sequence. Locally, the laminated clay graded into a weakly laminated clay and/or laminated sand, with marine sands topping the sequence in most cores,

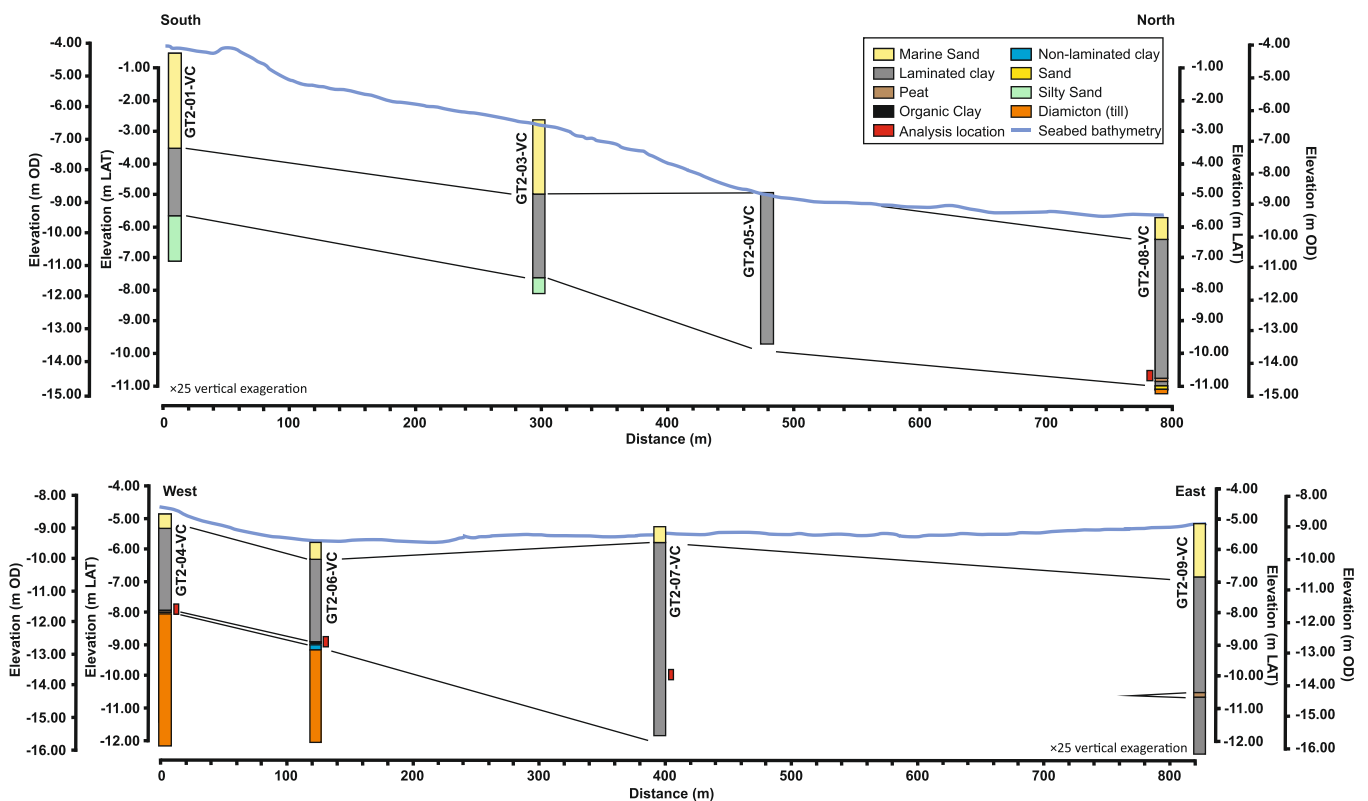


Figure 2. Simplified stratigraphy of vibrocores from Horseshoe Point. See Fig. 1(c) for core locations.

thickening in a south-western direction towards the beach. Sections from four of the vibrocores were selected for analysis.

GT2-04-VC

GT2-04-VC contained a basal weathered diamicton at 3.15 m [−7.95 m lowest astronomical tide (LAT), −11.64 m ordnance datum (OD)], overlain by a 0.10-m-thick basal peat and organic clay. These organic deposits suggest the presence of an intact semi-terrestrial marsh deposit, with evidence of rooting into the underlying diamicton. There is an initial organic clay over the diamicton that transitions into a thin laminated peat with *Phragmites australis*, that in turn gradually transitions to an overlying laminated clay, still containing *Phragmites* remains, probably indicating a non-eroded marine transgressive contact. Clays continue to the top of the sequence, though *Phragmites* is no longer present above 2 m, whereafter shells are much more prevalent in the sequence. Radiocarbon dating of the organic clay and overlying peat show that these date between 8380–8200 cal a BP (SUERC-101123) and 8010–7860 cal a BP (SUERC-101122). Sediment descriptions are provided in Supporting Information Table S1, with a photograph of this core shown in Fig. 3.

The basal diatom sample (Fig. 4a), taken from the top of the peat at 3.05 m (−7.86 m LAT, −11.54 m OD), is dominated by the marine-brackish aerophilous species *Diploneis interrupta*, contributing c. 68% total diatom valves (TDV), with the assemblage almost wholly dominated by mesohalobous marine-brackish species, with epipellic taxa including *Nitzschia navicularis*, *Diploneis smithii* and *Campylodiscus echeneis* encountered in relative abundance, in addition to a number of subordinate epipellic species (particularly of the genera *Nitzschia* and *Diploneis*). The immediately overlying sample within the base of the laminated clays, 3.04 m (−11.53 m OD), is also dominated by mesohalobous marine-brackish diatoms, contributing c. 92% TDV. However, marine-brackish epipellic species are now the most influential, with *Nitzschia navicularis*

now dominant (c. 49% TDV), supported by *Navicula peregrina*, *Campylodiscus echeneis* and *Diploneis smithii*, whilst the influence of the marine-brackish aerophilous species *Diploneis interrupta* is much lower.

The pollen (Fig. 5a) shows the effects of paludification at the base of the sequence, with a reduction in *Tilia cordata* across the organic clay–peat–clay transition, similar to that observed in other lowland coastal settings when lateral wetland expansion occurs (Waller 1994; Grant et al., 2011). Accompanying this is a reduction in *Alnus glutinosa* and Pteropsida (monolet) indet., with an increase in Poaceae, Cyperaceae and aquatic pollen, notably *Sparganium emersum*-type which is likely to be associated with slow-moving or standing water, signifying a shift from local carr woodland to open tall-herb wetland consisting of sedges and reeds, with Chenopodiaceae probably associated with local brackish communities.

GT2-06-VC

GT2-06-VC contained a basal weathered diamicton at 3.40 m (−9.10 m LAT, −12.79 m OD), overlain by a basal clay and organic clay, c. 0.26 m thick. These basal organic deposits suggest the presence of an intact semi-terrestrial marsh deposit, with evidence of rooting into the underlying diamicton. The organic clay sits at the base of a 1.34-m laminated clay, featuring a transition from wood remains, including *Quercus* sp., at the base to *Phragmites*, which disappears above 1.50 m, whereafter shells are much more prevalent in the sequence. Radiocarbon dating of the organic clay and overlying laminated clay show that these date between 8370–8190 cal a BP (SUERC-101124) and 8010–7860 cal a BP (SUERC-101118), with a piece of *Quercus* sapwood from the base of the laminated clay dating to 8190–8030 cal a BP (SUERC-107856). Sediment descriptions are provided in Supporting Information Table S2.

Within the diatoms (Fig. 4b), the single sample from Local Diatom Assemblage Zone (LDAZ) VC06-1, within the organic clay, is typified by mesohalobous diatoms; the vast majority of

Table 1. Radiocarbon dates from vibrocores collected at Horseshoe Point, East Lindsey, Lincolnshire, UK.

Lab no.	Core	Depth*	Material	Radiocarbon age	$\delta^{13}\text{C}$ (‰)	Calibrated age (cal a BP) (95.4% probability)
SUERC-101122	GT2-04-VC	3.05 m bsb –7.85 m LAT –11.54 m OD	Leaf fragment: <i>Phragmites australis</i>	7120 ± 26	–25.0 [†]	8010–7860
SUERC-107852	GT2-04-VC	3.10 m bsb –7.90 m LAT –11.59 m OD	Bulk sediment: humic acid fraction	7478 ± 26	–27.3	8370–8190
SUERC-101123	GT2-04-VC	3.14 m bsb –7.94 m LAT –11.63 m OD	Bulk sediment: humic acid fraction	7499 ± 26	–27.4	8380–8200
SUERC-101118	GT2-06-VC	2.78 m bsb –8.48 m LAT –12.17 m OD	Leaf fragment: <i>Phragmites australis</i>	7112 ± 26	–25.0 [†]	8010–7860
SUERC-107856	GT2-06-VC	3.04–3.10 m bsb –8.74 to –8.80 m LAT –12.43 to –12.49 m OD	<i>Quercus</i> wood: stem/ branch, outer 5 rings	7331 ± 25	–27.5	8190–8030
SUERC-101124	GT2-06-VC	3.20 m bsb –8.90 m LAT –12.59 m OD	Bulk sediment: humic acid fraction	7468 ± 26	–28.5	8370–8190
SUERC-101125	GT2-07-VC	4.63 m bsb –9.83 m LAT –13.52 m OD	Leaf fragment: <i>Phragmites australis</i>	7217 ± 26	–28.8	8170–7960
SUERC-101126	GT2-07-VC	4.77 m bsb –9.97 m LAT 13.66 m OD	<i>Quercus</i> sp. stem/ branch, outer 5 rings	7316 ± 26	–27.5	8180–8030
SUERC-101127	GT2-08-VC	4.98 m bsb –10.68 m LAT –14.37 m OD	Bulk sediment: humic acid fraction	8179 ± 26	–27.5	9270–9020
SUERC-107857	GT2-08-VC	5.00 m bsb –10.70 m LAT –14.39 m OD	Bulk sediment: humic acid fraction	7825 ± 25	–28.1	8690–8540
SUERC-101128	GT2-08-VC	5.06 m bsb –10.76 m LAT –14.45 m OD	Bulk sediment: humic acid fraction	8879 ± 26	–27.0	10 180–9890

*Depth: below sea bed (bsb); lowest astronomical tide (LAT); ordnance datum (OD).

[†] Assumed $\delta^{13}\text{C}$ relative to VPDB.

these diatoms are marine–brackish epipellic in lifeform, with *Nitzschia navicularis*, *Nitzschia punctata* and *Campylodiscus echeneis* most common. Polyhalobous diatoms are restricted to occasional marine plankton (e.g. *Paralia sulcata*) and marine–brackish epiphytes (e.g. *Grammatophora oceanica*). Lower salinity diatoms are rare, with occasional frustules of fresh epiphytes, such as *Ulnaria ulna* and *Epithemia turgida*. Overlying this sample, within LDAZ VC06-2, mesohalobous diatoms continue to dominate the diatom assemblage, but their contribution falls to c. 70% TDV. Marine–brackish epipellic taxa continue to be the most influential and whilst *Nitzschia navicularis* remains the most common, its influence is reduced, while others, including *Navicula peregrina* and *Surirella striatula*, are relatively common. Polyhalobous marine plankton are also more influential, typified by *Paralia sulcata*, whilst marine epiphytes, such as *Ardissonea fulgens*, *Cocconeis scutellum* and *Grammatophora oceanica*, are also consistently encountered, collectively contributing up to 20% TDV. There is a small but distinct oligohalobous halophilous contribution, primarily from the brackish plankton *Cyclotella striata*. Fresh epiphytes now contribute up to c. 9% TDV within this zone. The uppermost sample, within LDAZ VC-03, maintains the trend for mesohalobous diatoms dominating, but there is an increase in the contribution of marine–brackish epipellic species to c. 80% TDV, with *Nitzschia granulata* dominating (c. 50% TDV), supported by *Nitzschia navicularis* and *Nitzschia punctata*. The marine–brackish epiphytes remain present but in lower numbers, typified by *Ardissonea*

fulgens. Marine plankton, brackish plankton, marine epipellic and fresh epiphytes all reduce in their relative influence when compared to the underlying zone.

The pollen record (Fig. 5b) is similar to that seen in GT2-04-VC, with a paludification signal, demonstrated by the decreasing *Tilia cordata*, seen at the transition from the organic clay to overlying clays, coinciding with a transition from local carr woodland to open tall-herb wetlands and some local brackish conditions, with *Gentianella campestris*-type possibly associated with grassland or dunes.

GT2-07-VC

GT2-07-VC contains a 4.30-m-long sequence of clays topped by a 0.50-m-thick loamy sand at the surface. Below 3.00 m (–8.20 m LAT, –11.89 m OD) the clay contains horizontal laminations with wood remains at the base, below 4.68 m (–9.88 m LAT, –13.57 m OD), transitioning to *Phragmites*, like that seen in GT2-06-VC. Within the upper silty clay some sandy horizontal laminations are present with no organic material. The 4.80-m sequence does not reach an underlying diamicton surface. Radiocarbon dating of the lowermost clay sampled dates between 8180–8030 cal a BP (SUERC-101126), where wood remains are present, and 8170–7960 cal a BP (SUERC-101125), where the wood has been replaced with *Phragmites* remains. Sediment descriptions are provided in Supporting Information Table S3.

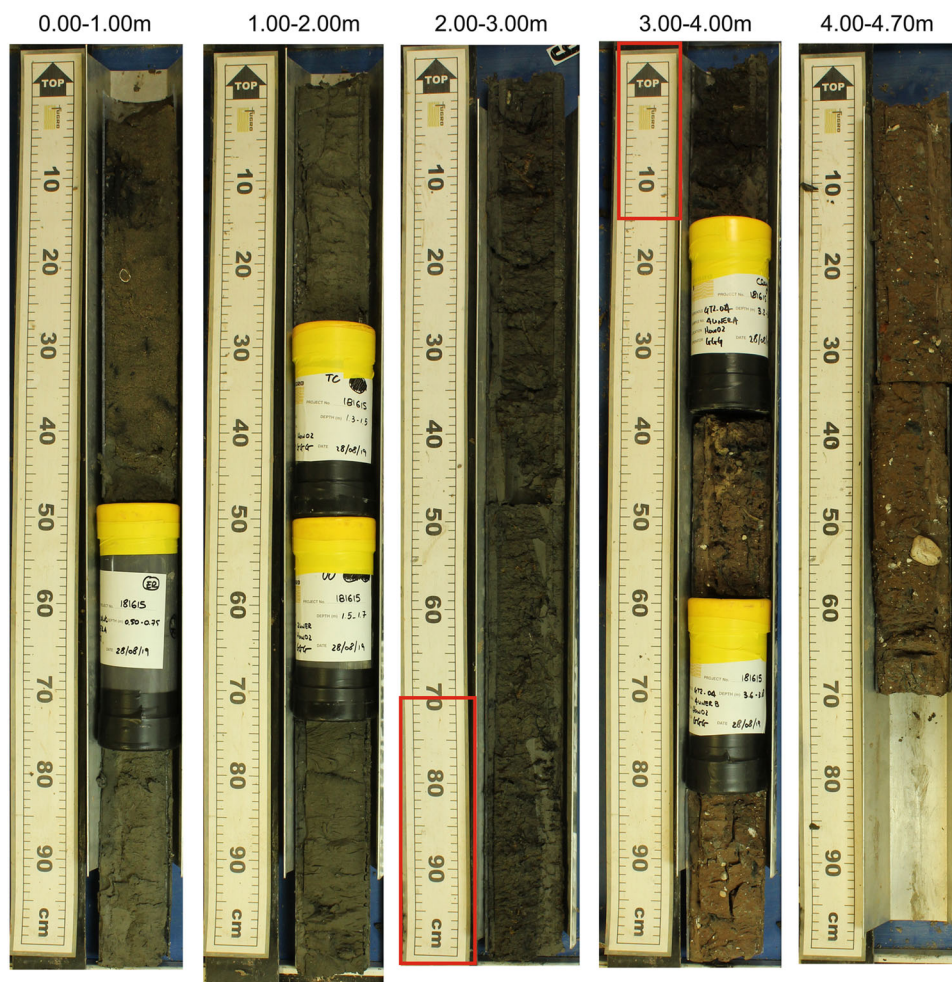


Figure 3. Photograph of core GT2-04-VC. Gaps are samples taken for destructive laboratory testing. Red outline highlights section of the core used for analysis.

The basal zone of this sequence (Fig. 4c), LDAZ VC07-1, comprises samples typified by a mixture of polyhalobous, mesohalobous and oligohalobous diatoms. Mesohalobous diatoms are most common, contributing on average 40–45% TDV. Polyhalobous diatoms contribute c. 35% TDV, whilst oligohalobous halophilous and indifferent taxa contribute 13% and 20% TDV respectively. The mesohalobous diatoms are mainly marine–brackish epipellic species such as *Nitzschia navicularis* and *Nitzschia punctata*, with an epiphytic component from species such as *Ardissonea fulgens*. Polyhalobous diatoms are mainly represented by marine plankton (e.g. *Paralia sulcata*, *Thalassiosira decipiens*), in addition to benthic species including *Grammatophora oceanica*, *Cocconeis scutellum* and *Rhabdonema arcuatum*, all of which are epiphytes. Oligohalobous diatoms are typified by the brackish planktonic diatom *Cyclotella striata* in addition to the freshwater epiphytic diatoms, including *Ulnaria ulna* and *Epithemia turgida*, which collectively contribute c. 20% TDV at the base of the zone. The diatom assemblages in LDAZ VC07-2 show an increase in the influence of mesohalobous diatoms, primarily with increases in the abundance of marine–brackish epipellic (e.g. *Nitzschia navicularis*, *Nitzschia punctata*) and marine–brackish epiphytic species (e.g. *Ardissonea fulgens*). This shift is reflected in a reduction in oligohalobous indifferent diatoms to 10% TDV in the centre of this zone, though values do increase to 15% TDV in the uppermost sample. Oligohalobous halophilous and polyhalobous diatoms also show reductions in abundance, but these are more subtle. Planktonic diatoms of varying salinity preferences (e.g. *Paralia sulcata*, *Thalassiosira decipiens*,

Cyclotella striata) appear to retain consistent numbers throughout respective zones.

The pollen record (Fig. 5c) from GT2-07-VC differs from that observed in GT2-04-VC and GT2-06-VC as there is no transition from carr to tall-herb communities, possibly due to the absence of an organic clay/peat in the sequence. Instead, *Tilia cordata* is already low in the record implying that some lateral wetland expansion has already occurred, but local woodland components still deliver the main pollen component to the site, which suppresses the representation of local dwarf shrub and herb communities. Nonetheless, Poaceae, Cyperaceae and *Sparganium emersum*-type remain the best represented, suggesting local tall-herb wetland communities, with Chenopodiaceae also present throughout, again indicative of local brackish communities, as seen in the other sequences.

GT2-08-VC

GT2-08-VC contains a basal rooted silty clay, below 5.43 m (–11.13 m LAT, –14.84 m OD), overlain by a loamy sand upon which sits a laminated clay at 5.32 m (–11.02 m LAT; –14.71 m OD) with *Phragmites* remains to 3.00 m (–8.70 m LAT, –12.39 m OD), on top of which sits a laminated silty clay with sandy clay horizons, and a loamy sand topping the sequence in the upper 0.69 m. Although a diamicton surface is not present, the rooted clay at the base of the sequence may represent the weathered/bioturbated till surface. Within the centre of the laminated clay sequence, at 5.00–5.08 m, a thin

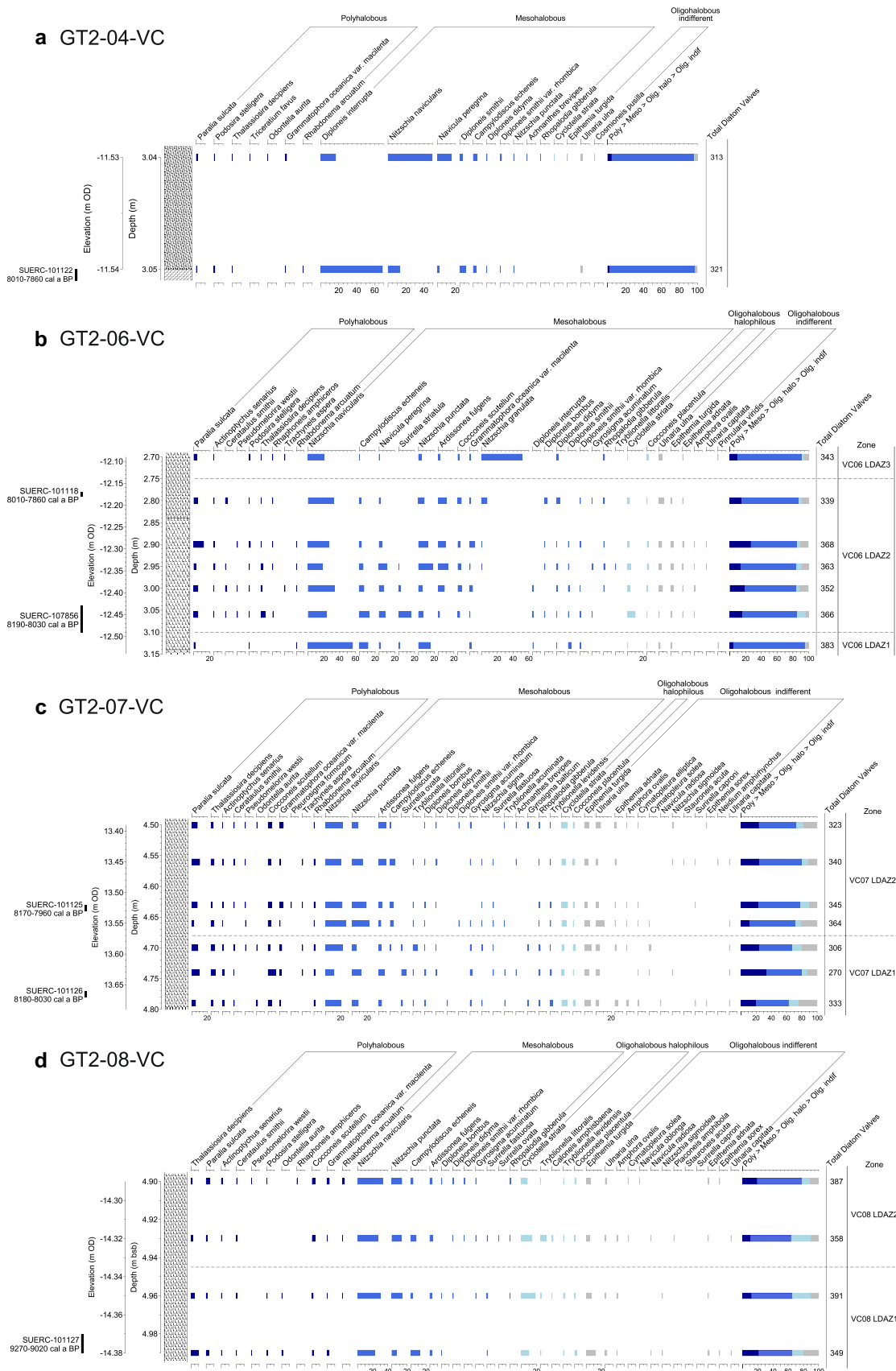


Figure 4. Diatom flora encountered during analysis of vibrocores: (a) GT2-04-VC, (b) GT2-06-VC, (c) GT2-07-VC and (d) GT2-08-VC. Taxa have been subdivided by the halobian salinity classification of Hustedt (1953) and so, in some instances, planktonic and benthic taxa have been grouped together according to their salinity requirements (marine to left, reducing salinity towards the right). The cumulative salinity preference graph towards the right of the diagram ('polyhalobous > Oligo. Indiff') displays the broad salinity changes through the profile, with the darker blues inferring the abundance of the more saline taxa, and lighter blues inferring lower salinity taxa. Lithology follows Troels-Smith (1955); full descriptions are provided in Supplementary Material 1.

pre-dates the other three sampled sequences from this area. Sediment descriptions are provided in Supporting Information Table S4.

The basal diatom zone (Fig. 4d), LDAZ VC08-1, is dominated by mesohalobous diatoms, collectively contributing c. 45% TDV, typified by *Nitzschia navicularis*, *Nitzschia punctata* and *Campylodiscus echeensis*. Polyhalobous diatoms are also influential, contributing a further 20% TDV, but show a slight reduction in influence with height through the zone. The remaining 35% TDV comprises a mixture of oligohalobous halophilous and oligohalobous indifferent diatoms. However, there is a shift in their abundances relative to one another with height through the zone. At the base of the zone, oligohalobous indifferent diatoms contribute c. 20% TDV, reflected through species such as the fresh epiphytes *Epithemia turgida* and *Ulnaria ulna*, reducing up-sequence to be replaced by oligohalobous halophilous diatoms in greater numbers, typified by *Cyclotella striata*. Mesohalobous diatoms continue to dominate in the overlying LDAZ VC08-2, increasing to c. 60% TDV, with increases in polyhalobous species and a reduction in oligohalobous diatoms. Fresh epiphytes remain present in low but consistent numbers, again typified by *Epithemia turgida* and *Ulnaria ulna*.

Pollen (Fig. 5d) preservation and concentrations were low in the silty peat, limiting the counting, but was dominated by *Tilia cordata*, *Corylus avellana*-type, Poaceae and Pteropsida (monolete) indet. These are significantly reduced in the overlying clay, again probably the result of paludification, with Poaceae, *Sparganium emersum*-type and *Typha latifolia* becoming more abundant, with Chenopodiaceae and *Armeria maritima* suggesting the presence of some saltmarsh, similar to that recorded in the other three sequences. Seeds of *Carex* sp. and *Ranunculus* sp. were also present, alongside the remains of *Phragmites australis*.

Discussion

Early Holocene lagoonal development

The pollen record from all four sequences is consistent, with organic deposits typically associated with a fen carr community close to the terrestrial margin, prior to paludification, clearly shown by the reduction of *Tilia cordata* and expansion of tall-herb and brackish communities across the organic–inorganic sediment boundaries. Paludification, related to regional groundwater and sea-level rise, is already well established within the Humber Estuary from c. 9200 cal a BP at Ousefleet and Bole Ings (Brayshay and Dinnin, 1999; Metcalfe et al., 2000), consistent with the pattern seen at Horseshoe Point. The local proximity of woodland at this site is also confirmed by the presence of wood remains, identified as *Quercus*, within the clays/organic silts towards the base of the sequences, indicating that *Quercus* forms part of the local carr woodland. Previous studies within the Holderness area, to the north, have shown an expansion of *Quercus* from c. 9000 cal a BP, with *Alnus* and *Tilia* from c. 7500 cal a BP (Tweddle 2000, 2001). The pollen sequences from the current study at Horseshoe Point confirm a much earlier arrival and expansion of both *Alnus* and *Tilia*, with both established within the GT2-08-VC record prior to at least 9270–9020 cal a BP (SUERC-101128). A similar woodland assemblage is also recorded in the pollen record from Union Dock, Grimsby, dated 9280–9000 cal a BP (SRR-4747; Long et al., 1998), suggesting that mixed deciduous woodland and carr communities were established along the southern margins of the Humber several centuries before their expansion within the Holderness area. The record of *Alnus* within GT2-08-VC is

also comparable to *Alnus* being recorded in the lower Trent area, dated c. 9200 cal a BP (Brayshay and Dinnin 1999).

Within the diatom record, all sequences contain a mixture of polyhalobous, mesohalobous and oligohalobous diatoms, with a general increase in salt-tolerant taxa with height through each sequence. The sequences from GT2-06-VC, GT2-07-VC and GT2-08-VC all contain similar records, with an overall dominance of mesohalobous diatoms (primarily marine–brackish epipelton, supported by marine–brackish epiphytes), a supporting polyhalobous (marine plankton) component, an absence of aerophilous species and a consistent oligohalobous signal throughout all samples. Fresh–brackish and fresh diatoms, comprising a balanced mixture of epipellic and epiphytic taxa, reduce within the uppermost samples, where a subtle increase in saline influence is recorded. The classification scheme of Vos and de Wolf (1993) suggests that, for the duration of sedimentation taking place in the locale surrounding these three vibrocores, between c. 9100 and 8100 cal a BP, deposition took place in a tidal lagoon. The presence of laminated deposits supports the interpretation of a lagoonal deposit, similar to that observed by Best et al. (2022) within the Inner Estuary. Taking into account the location of the offshore vibrocores, there is an apparent fall in taxa associated with freshwater conditions further landward, from GT2-08-VC through to GT2-06-VC. There is also a stronger brackish–fresh signal encountered in the older sequence (GT2-08-VC), which probably alludes to lower RSL at the time, given that this peat is c. 1000 years older than the other three sequences. This would have in turn allowed for a stronger oligohalobous signal to be recorded. In contrast, the ages of the two sequences from GT2-06-VC and GT2-07-VC are indistinguishable, and hence the slightly stronger brackish–freshwater signal in GT2-07-VC may indicate closer proximity to a source of freshwater drainage. In addition to the apparent spatial shifts in saline influence between the cores, there are also subtle temporal shifts within cores. Although small timeframes are being analysed in each stratigraphic sequence, there is evidence of increasing saline influence over time, as a consequence of rising RSL during the early to mid-Holocene.

The diatom assemblage in GT2-04-VC contrasts with that from the other three vibrocores by the presence of marine–brackish aerophilous species within the clay directly overlying the peat surface. Aerophilous species are most often associated with meso-macrotidal open coastal settings, restricted to deposition in the supratidal realm towards highest astronomical tide (Vos and de Wolf, 1988; 1993), with *Diploneis interrupta* indicative of high-intertidal/supratidal conditions, typically associated with an upper salt marsh. The almost total absence of marine plankton is, however, somewhat contrary to what would be expected within an open coastal setting in which salt marshes are most often encountered. This was perhaps a depositional setting in which regular tidal inundation was somewhat restricted. Saline waters remained heavily influential in the coastal setting, and probably in proximity to the terrestrial realm. Indeed, Vos and de Wolf (1988) described how aerophiles, such as *Diploneis interrupta*, are encountered within supratidal settings such as in tidal levees or back levee marshes, which are somewhat protected from tidal flooding, especially during neap tides. The overlying laminated clay was also dominated by a mesohalobous signal, with a predominance of marine–brackish epipellic diatoms, replacing the aerophilous species, inferring deposition now lower in the inter-tidal frame, such as inter-tidal flats. The occurrence of Early Holocene depositional contexts containing aerophilous diatoms from around the North Sea basin is rare. Previous offshore studies

across this area (e.g. Hill, 2021; Mellett, 2019) have shown them to be absent, with the only comparable assemblage found in Lower Saxony, Germany (Watermann et al., 2004), where aerophilous taxa were abundant in saltmarsh/mudflat settings within the East Frisian barrier islands from c. 7000 BP onwards.

The Horseshoe Point deposits can be compared with the recently discovered Early Holocene site at Hook Lane, within the Inner Humber Estuary, where Best et al. (2022) identified the development of perimarine tidal lagoonal deposits. Like the record from Horseshoe Point, an initial short-lived fen carr environment is replaced by an influx of inorganic sediment corresponding with a reduction in *Alnus* pollen. Best et al. (2022) attributed this to the rapid rise in RSL, creating increased accommodation space, leading to flooding, submergence and eventually the creation of an expansive tidal lagoonal system, dated c. 7800 cal a BP at Hook Lane. The discovery of perimarine tidal lagoonal sites is uncommon, lacking any modern equivalent in NW Europe today, so evidence for two locations within the Humber Estuary, close in age, may be significant, suggesting that different coastal lowland conditions prevailed within this area during the Early Holocene. Further afield, similar lagoonal conditions have also been encountered within the upper reaches of the Tees estuary at Billingham Beck (Plater et al., 2000a, 2000b). Diatom records, in which marine-brackish epipellic and epiphytic diatoms prevail, are also encountered within borehole sequences from Sizewell, Suffolk (Grant et al., 2018), and the Norfolk Boreas Offshore Wind Farm development (Mellett, 2019) between c. 9700 and 8500 cal. a BP. Further afield, van der Woude (1984) has described the presence of freshwater 'fluviolagoon' deposits within the Rhine–Meuse delta during the Early Holocene, though these lack a brackish tidal influence.

These Early Holocene lagoonal settings may have been subject to continuous reworking and associated movement of sediments along the coastal margins, developing temporary barrier islands, like those encountered in Lower Saxony, protecting some of the coastal lowlands from significant marine inundation and encouraging the development of back-barrier lagoons. Work by Hamilton et al. (2019) supports such a suggestion, where they propose that localized factors explain the considerable spatial variability in marine transgressions experienced along the Suffolk/Norfolk coastline, with sediment availability and barrier dynamics highly influential for the evolution of the East Anglian coastline. Although this study does focus on the later Holocene when RSL rise was moderate to slow, therefore permitting system controls rather than RSL to dominate coastal evolution, recent work in the offshore zone at Sizewell has identified Early Holocene lagoonal diatom and foraminifera assemblages are present (Grant et al., 2018). For coastal lagoonal features to form, the primary controls are the climatic conditions, hydrodynamic setting, pre-existing topography and substrate materials, and sea level history (Wanless, 1976). Since barrier islands form during rises in RSL, lagoons have the potential to be a common feature along coasts experiencing such conditions (Duck and de Silva 2012). Where sediment accretion keeps pace with RSL, coastal lagoon deposits are able to accrete upwards and form thick sequences. However, when the rate of RSL rise exceeds that of sediment accretion, these lagoonal features will be short-lived and rapidly undergo marine transgression (e.g. Stevenson et al., 1986; Nichols, 1990).

Another key factor that might have influenced the formation of coastal lagoons at this time are contemporary tidal conditions and the palaeogeography. Today, the Humber Estuary is macrotidal, with an average tidal range of 6.83 m

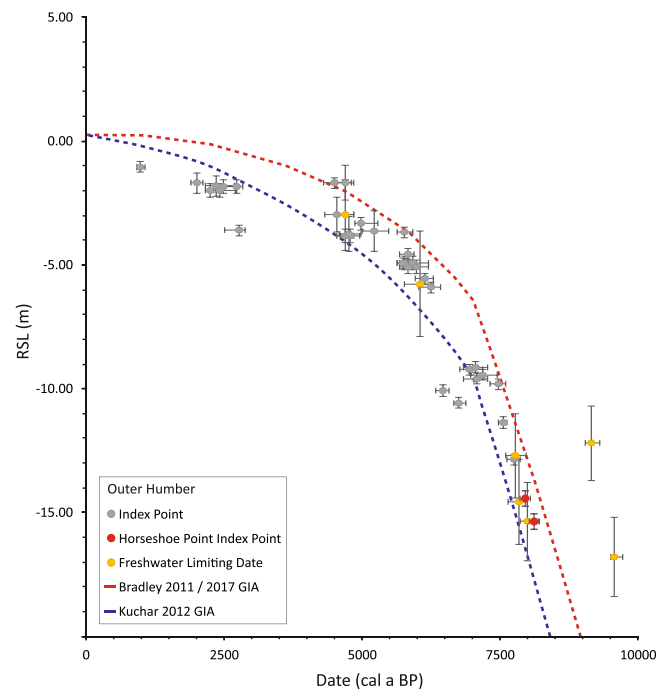
recorded at Immingham, and contains strong flood currents that bring sediments into the estuary from the North Sea (Pethick, 1990). Several studies have suggested that tidal amplitude for the east coast of Britain has remained close to its present-day size since 8k cal a BP (Gehrels et al., 1995; Uehara et al., 2006; Ward et al., 2016; Hamilton et al., 2019), but coastlines fronted by a wide shallow shelf or semi-enclosed are more susceptible to changes in tidal range through time (Hamilton et al., 2019). For the Humber, it has been proposed that the palaeotidal regime during the Early to Middle Holocene consisted of a spring tidal range only 63% of its present magnitude at c. 8k cal a BP (Shennan et al., 2000a, 2000b, 2003), with Shennan et al., (2000b, 2002) using model predictions to show that tidal range increased by 0.60 m between c. 8k and 6k cal a BP, in response to variations in tidal prism, accommodation space and estuary configuration. Palaeogeographical reconstructions of the Humber Estuary by Metcalfe et al. (2000) and Dudley et al. (2021) have demonstrated that during the Early Holocene, the intertidal limit of the Humber Estuary would have been constrained to the Outer Humber Estuary, therefore placing sites such as Horseshoe Point within a wide eutrophic wetland situated at the limits of the tidal influence and with a large accommodation space during flooding. In addition, Berridge and Pattison (1994) predict that the main channel of the Humber was situated further north during the Early Holocene, flowing under the modern Spurn Head, resulting in an increased distance between Horseshoe Point and the open estuary mouth. They also propose that the Lincolnshire coast contained several till headlands, now eroded, which extended north from the modern coastline; such landforms might have also facilitated barrier formation and lagoonal development. At Hook Lane, Best et al. (2022) proposed that the initial flooding of the fen carr environment, in response to RSL rise, was coupled with an expansion of accommodation space as water levels rose but sedimentation rates were unable to keep pace with this rise, leading to flooding, submergence and eventually the creation of expansive tidal lagoonal conditions. At both Hook Lane and Horseshoe Point, *Alnus* pollen declines across the transition from organic to inorganic deposition and lagoonal initiation, along with a change in the diatom biostratigraphy from initially freshwater and perimarine in nature, reflecting the role of rising water tables and impeded fluvial drainage in the creation of these features.

Holocene RSL change

New SLIPs are presented from Horseshoe Point, constructed on the organic–inorganic contacts within GT2-04-VC and GT2-06-VC, where the indicative meaning and a positive tendency can be established. The dated organic deposits sit immediately above an incompressible diamicton substrate, resulting in these deposits having been subject to limited compaction, making them the equivalent of 'top of basal' SLIPs (Brain, 2015; Shennan et al., 2018). The SLIPs have been constructed following the guidelines of Shennan (1986), with vertical errors calculated following the method of Hijma et al. (2015). This has provided index points at -14.3 and -15.3 m for c. 7940 and c. 8110 cal a BP respectively (Table 2). No index points were attempted on the records from GT2-07-VC and GT2-08-VC, where there was less certainty over the indicative meaning. In addition, the sequence from GT2-07-VC is from the middle of the laminated clay sedimentary sequence and therefore vertical compaction is highly likely, whereas the eroded silty peat at the base of GT2-08-VC contains a hiatus along with poor pollen preservation and an

Table 2. Sea-level index points calculated for Horseshoe Point, East Lindsey, Lincolnshire, UK.

Core	Depth (m bsb)	Elevation (m OD)	Calibrated date (cal a BP) (weight mean)	Date positive error	Date negative error	Positive/negative tendency	Reference water table	Palaeo-RSL (m OD)	Total upper error (m)	Total downward error (m)
GT2-04-VC	3.05	-11.54	7940	70	80	Positive	MHWS - 20 cm	-14.295	0.299	0.293
GT2-06-VC	3.14	-12.53	8110	80	80	Positive	MHWS - 20 cm	-15.285	0.301	0.295

**Figure 6.** Relative sea-level curve for the Outer Humber Estuary, with the new index points from Horseshoe Point combined with published sea-level index points and terrestrial limiting data, as compiled in Shennan et al. (2018).

absence of diatoms that would permit characterization of the indicative meaning.

The new index points are of particular importance for the Outer Humber Estuary as the current sea-level record only contains SLIPs dating back to c. 7700 cal a BP, with older dated deposits only representing freshwater (upper) limiting points (Metcalf et al., 2000; Shennan et al., 2018). The new index points are in good agreement with the existing record for the outer estuary, supporting the GIA models of Bradley et al. (2011) and Kuchar et al. (2012), where there is an Early Holocene RSL rise rate of c. 7 mm a^{-1} until c. 7400 cal a BP, after which the rate of RSL rise begins to reduce (Fig. 6). This average rate of RSL rise is comparable with those from across the southern North Sea during the early Holocene, c. 11 700–8200 cal a BP, where Waller and Kirby (2021) suggest that landward encroachment of coasts and a dominance of tidal sedimentation led to formation of wetlands occurring in only the most marginal areas, with the subsequent slowing of RSL in the middle Holocene leading to the more widely observed formation of peat and establishment of coastal wetlands.

Conclusion

The sedimentary sequences from the nearshore zone at Horseshoe Point provide a unique glimpse into the Early Holocene dynamics of the Outer Humber Estuary during a period of rapid RSL rise. Like the record from Hook Lane (Best et al., 2022), the environmental transition that occurred was in response to the Early Holocene rapid RSL rise, with a significant increase in accommodation space, that inundated the existing wetland surface, leading to the formation of a tidal lagoonal system. Shifts in saline influence between and within cores infer that, although discrete and short timeframes are being analysed in each stratigraphic sequence, evidence of increasing saline influence over time is apparent, being driven by the rapid rate of Early Holocene RSL. Further complexity within the structure of this lagoonal system is also introduced

by the presence of aerophilous diatoms within GT2-04-VC, providing a rare Early Holocene diatom assemblage. Traditionally studies within the Outer Humber Estuary have focused on Holocene fluvial–estuarine–wetland sediments accessible from on land, which are typically associated with the Middle to Late Holocene sedimentary sequences (Rees et al., 2000). The study from Horseshoe Point, however, demonstrates that exploration of the sedimentary sequences within the nearshore and offshore zone does provide opportunities to locate and study non-eroded Early Holocene wetlands, permitting an improved understanding of the interplay between rapid RSL rise and the evolving palaeogeography of the Humber Estuary at that time.

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Data availability statement

Pollen and diatom data has been deposited with the European Pollen Database (EPD) (<https://epdweblog.org/>) and Diatom Palaeolinology Data Cooperative (DPDC) (<https://diatom.ansp.org/dpdc/>), both of which are accessible through the Neotoma Paleocology database (<https://www.neotomadb.org/>). Datasets collected through the site investigation (geotechnical and geophysical) will be deposited with The Crown Estate's Marine Data Exchange (<https://www.marinedataexchange.co.uk/>).

Supporting information

Additional supporting information can be found in the online version of this article.

Table S1. Sediment description for core GT2-04-VC.

Table S2. Sediment description for core GT2-06-VC.

Table S3. Sediment description for core GT2-07-VC.

Table S4. Sediment description for core GT2-08-VC.

Abbreviations. GIA, glacial isostatic adjustment; LAT, lowest astronomical tide; LDAZ, local diatom assemblage zone; LOEPS, Land-Ocean Evolution Perspective Study; LPAZ, local pollen assemblage zone; OD, Ordnance datum; RSL, relative sea level; SLIP, sea-level index point; TDV, total diatom valves; TLP, total land pollen; VC, vibrocore.

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