Norfolk Boreas Offshore Wind Farm

Appendix 17.7

Norfolk Boreas Offshore Wind Farm Stage 3 Geoarchaeological Review

Environmental Statement

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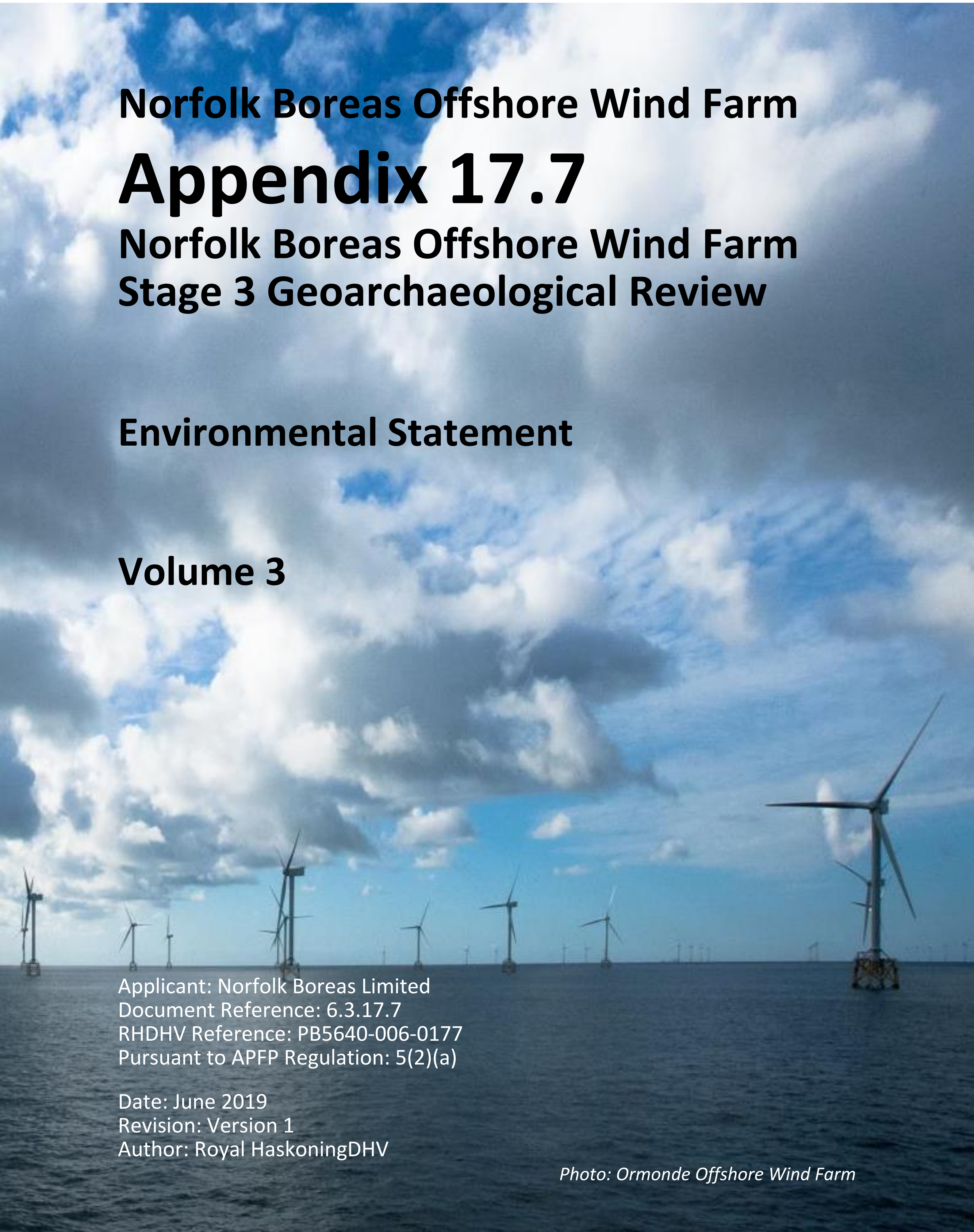
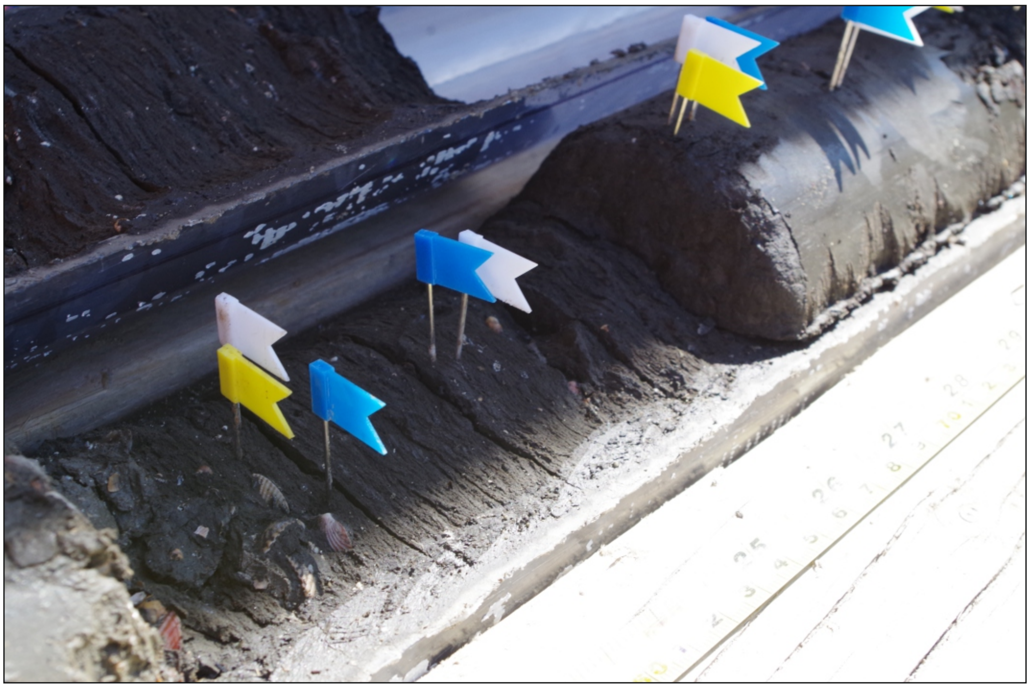


Photo: Ormonde Offshore Wind Farm

Norfolk Boreas Offshore Wind Farm

Stage 3 Geoarchaeological Assessment



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Summary

Wessex Archaeology (WA) were commissioned by Royal HaskoningDHV to undertake Stage 3 paleoenvironmental assessment of geotechnical vibrocores in support of the proposed Norfolk Boreas Offshore Wind Farm development, located in the southern North Sea.

During Stage 2 geoarchaeological recording, two geological units were identified as having geoarchaeological potential: **Unit 3**, Upper Brown Bank, comprising fine-grained sediments deposited in a shallow/intertidal lagoon during the early to Late Devensian; and **Unit 4**, Early Holocene pre-transgression peats and minerogenic deposits which formed in a terrestrial environment prior to post glacial sea-level rise. An additional “Undifferentiated” unit was identified as having the potential to be early Holocene in date.

Five vibrocores were subjected to Stage 3 palaeoenvironment assessment (VC016, VC028, VC032, VC039 and VC047). Deposits corresponding to **Unit 3** were targeted in VC016 and VC047 for OSL dating and accompanying assessment of foraminifera, ostracods and diatoms to determine age and palaeoenvironment. To help establish the depositional environment of an Undifferentiated unit, samples from VC016 and VC047 were submitted for foraminifera and ostracod assessment. Holocene pre-transgression peat deposits (**Unit 4b**) in VC028, VC032 and VC039 were selected for radiocarbon dating as they showed the greatest potential for preservation of pollen and plant macrofossils which would provide information on landscape development. Diatoms, foraminifera and ostracod assessment was also undertaken on these cores across transitions between peat and the over/underlying minerogenic sediments.

The Upper Brown Bank sediments (**Unit 3**) are the oldest deposits recovered in the vibrocores. Four sub-samples (VC016 and VC047) were submitted for OSL dating. The sub-samples from VC016 passed validity acceptance testing, whereas those from VC047 were considered tentative due to analytical behaviour. Accepted OSL results place deposition between 83.2 ± 9.5 ka and 69.8 ± 7.7 ka spanning Marine Isotope Stage (MIS) 5a to 4 (late Middle to Upper Palaeolithic).

A rich and diverse assemblage of foraminifera and ostracods were preserved within the Upper Brown Bank sediments. Observed species are typical of a cold-climate marine embayment to outer estuarine environments although the assemblage in VC047 suggests a more protected setting of less than normal salinity. Iron precipitates were observed in these sediments, possibly a sign of weathering and subaerial exposure. Diatoms were not preserved.

From the Undifferentiated unit in VC016, foraminifera and ostracod assemblages showed similar characteristics to the underlying **Unit 3**, Upper Brown Bank deposits. In contrast, the microfauna from this unit in VC047 are different and suggest a warmer interglacial climate. Being marine in origin, these deposits may date to the Holocene or to an interstadial during the early Devensian when temperatures would have been similar to today. While these deposits have a role in understanding the wider stratigraphy of the Norfolk Boreas site, their archaeological potential is considered low given their expected age and depositional environment.

Four sub-samples from **Unit 4** (early Holocene pre-transgression deposits) were submitted for radiocarbon dating, with two dates from VC032 and one each from VC028 and VC039. Calibrated results indicate that peat developed across the Norfolk Boreas site from as early as 12.9 ka in the Late Devensian, through the early Holocene until at least ~9.5 ka. The peat deposits across the Norfolk Boreas site therefore represent up to ~3,500 yrs of peat development, with results suggesting the sequence may represent continuous deposition with no erosive events.

Pollen was well preserved and present in high concentrations in the majority of samples, both in the peat and overlying and underlying minerogenic sediments, providing an important environmental

context for climatic and physical changes occurring across the Norfolk Boreas site, as well as the wider southern North Sea.

The pollen assessment from VC039 suggests peat started developing in the Late Devensian, in a sub-arctic environment with herbaceous fen and a sparse cover of trees. Under the influence of rising sea level and a warming climate, the top of the peat shows an increase in pine-dominated woodland. This pine-dominated woodland is also recorded at the base of the peat in VC032, gradually giving way to a greater hazel component accompanied by an increasing component of oak and elm. In VC028, the sequence extends further into the Early Holocene and shows the development of mixed deciduous-broadleaved woodland and wetland herb fen habitats.

In VC032, the peat gradually transitions to fine-grained minerogenic deposits indicative intertidal-brackish mudflats and creeks, supported by foraminifera, ostracod and diatom assessments, documenting inundation of the terrestrial landscape by rising sea levels sometime after ~9.7 ka.

Together, the peat and associated minerogenic deposits in vibrocores VC028, VC032 and VC039 represent the long-term (~3500 yr) development of a diachronous land surface forming under the background influence of climate, environmental and physical changes occurring across the Late Devensian and Early Holocene.

This is a significant and truly unique record from an area of the southern North Sea which formed the last land-bridge between Britain and continental Europe.

Based on the results of this Stage 3 palaeoenvironmental assessment, a series of recommendations are made for Stage 4 analysis works, focussing on **Units 3** and **4**, the Upper Brown Bank, and Late Devensian to Early Holocene deposits.

It is recommended that further OSL samples are analysed from VC016, in an attempt to improve the accuracy and precision of dates from Upper Brown Bank. This will allow us to assess if Upper Brown Bank sediments reflect continuous deposition through the early Devensian, or more punctuated phases separated by periods of sub-aerial exposure, which is significant given their age corresponds to a time when hominins were absent from Britain.

Given the significance of the Late Devensian to Early Holocene deposits, it is recommended further work is undertaken to provide a higher resolution chronology and statistically valid paleoenvironmental analysis comprising pollen, charcoal and diatom proxy techniques. This will provide a landscape context for any human activity in the area and enable assessments of the availability of resources and habitats for human settlement and exploitation.

It is also recommended that the results of Stage 4 analysis are integrated with geophysical data to produce a series of palaeogeographic maps for the Norfolk Boreas site from the early Devensian through to final inundation during the Early Holocene. These maps will provide a vital resource to assess archaeological potential.

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This work was commissioned by Royal HaskoningDHV. The report was compiled by Dr Claire Mellett and Dr Alex Brown. Diatom assessment was undertaken by Dr Nigel Cameron of University College London. Foraminifera and ostracod assessment was carried out by Dr John Whittaker. Optical stimulated luminescence dating was undertaken at University of Gloucestershire by Dr Phil Toms. Pollen assessment was carried out by Dr Alex Brown and macrofossil assessment by Dr Ines Lopez Doriga, both of Wessex Archaeology. Illustrations were prepared by Nancy Dixon. The project was managed on behalf of Wessex Archaeology by David Norcott.

Norfolk Boreas Offshore Wind Farm

Stage 3 Palaeoenvironmental Assessment

1 INTRODUCTION

1.1 Project background

1.1.1 Wessex Archaeology (WA) have been commissioned by Royal HaskoningDHV on behalf of Norfolk Boreas Ltd to undertake Stage 3 palaeoenvironmental assessment of sub-samples taken from five geotechnical vibrocores within the Norfolk Boreas Offshore Wind Farm, hereby referred to as the Norfolk Boreas site.

1.1.2 The Norfolk Boreas site is located approximately 73 km (39 nautical miles) northeast of Great Yarmouth within the southern North Sea (**Figure 1**). The proposed location of the windfarm is significant, as it occupies an area with known nationally and internationally important archaeological and geoarchaeological records from the last one million years (Bicket and Tizzard 2015). The region preserves Pleistocene and Holocene landforms and sediments formed during periods of lower than present-day sea level, when this part of the southern North Sea basin was a landscape suitable for human occupation.

1.2 Summary of previous work

1.2.1 A geotechnical survey campaign was undertaken in October 2017 during which a total of 61 vibrocores were recovered from 50 locations with the Norfolk Boreas site reaching depths of up to 6 m below sea floor (mbsf). These vibrocores provided a continuous record of the deposits within ~6 m of the seabed. Preliminary geotechnical logs and associated test results were subsequently provided to WA for a Stage 1 geoarchaeological review.

1.2.2 The Stage 1 geoarchaeological review identified deposits of potential archaeological interest in thirteen vibrocores, assigning them a high or medium priority status, with a further 48 vibrocores assigned low priority geoarchaeological status with no further work recommended (Wessex Archaeology 2018a).

1.2.3 Eight vibrocores (VC003, VC005, VC005a, VC010, VC013a, VC024, VC029 and VC033) were assigned medium priority status and were opened under supervision of a suitably trained geoarchaeologist at Fugro House, Wallingford (31st October - 1st November 2017). No deposits of geoarchaeological significance were noted during the monitoring of these medium priority vibrocores and no further work was recommended.

1.2.4 Five vibrocores (VC016, VC028, VC032, VC039 and VC047) were assigned high priority status due to the presence of organic material and thick sequences of fine grained deposits. These vibrocores were not split or subsampled for geotechnical testing and were delivered to WA for Stage 2 geoarchaeological recording. Descriptions of these high priority vibrocores, along with all vibrocore geotechnical logs, were used as a basis to construct a deposit model for the Norfolk Boreas site (Wessex Archaeology 2018b).

1.2.5 Stage 2 geoarchaeological recording and deposit modelling identified two units of geoarchaeological interest: Early Devensian sandy clays and silts of the Brown Bank Formation (**Unit 3**), and; Early Holocene pre-transgression peats and associated under/overlying minerogenic sediments (**Unit 4**). It was recommended that Stage 3 sub-sampling and palaeoenvironmental assessment be undertaken on these deposits of interest.

1.2.6 This report presents the results of this Stage 3 palaeoenvironmental assessment from five vibrocores from the Norfolk Boreas site.

1.3 Scope of document

1.3.1 To help frame geoarchaeological investigations of this nature, WA has developed a five-stage approach, encompassing different levels of investigation appropriate to the results obtained, accompanied by formal reporting of the results at the level achieved. The stages are summarised below (**Table 1**).

1.3.2 This report outlines the results from a Stage 3 paleoenvironmental assessment.

Table 1 Stages of geoarchaeological assessment and recording

Stage	Method	Description
1	Review	A desk-based archaeological review of the borehole, vibrocore and CPT logs generated by geotechnical contractors. Aims to establish the likely presence of horizons of archaeological interest and broadly characterise them, as a basis for deciding whether and what Stage 2 archaeological recording is required. The Stage 1 report will state the scale of Stage 2 work proposed.
2	Geoarchaeological Recording	Archaeological recording of selected retained or new core samples will be undertaken. This will entail the splitting of the cores, with each core being cleaned and recorded. The Stage 2 report will state the results of the archaeological recording and will indicate whether any Stage 3 work is warranted.
3	Sampling and Assessment	Dependent upon the results of Stage 2, sub-sampling and palaeoenvironmental assessment (pollen, diatoms and foraminifera) may be required. Subsamples will be taken if required. Assessment will comprise laboratory analysis of the samples to a level sufficient to enable the value of the palaeoenvironmental material surviving within the cores to be identified. Subsamples will also be taken and/or retained at this stage in case scientific dating is required during Stage 4. Some scientific dating (e.g. radiocarbon or Optically Stimulated Luminescence (OSL)) may be undertaken at this stage to provide chronological context. The Stage 3 report will set out the results of each laboratory assessment together with an outline of the archaeological implications of the combined results, and will indicate whether any Stage 4 work is warranted.
4	Analysis and Dating	Full analysis of pollen, diatoms and/or foraminifera assessed during Stage 3 will be undertaken. Typically, Stage 4 will be supported by scientific dating (e.g. radiocarbon or OSL) of suitable subsamples. Stage 4 will result in an account of the successive environments within the coring area, a model of environmental change over time, and an outline of the archaeological implications of the analysis.
5	Final Report	If required Stage 5 will comprise the production of a final report of the results of the previous phases of work for publication in an appropriate journal. This report will be compiled after the final phase of archaeological work, whichever phase that is.

2 GEOARCHAEOLOGICAL BACKGROUND

2.1 Geological baseline

2.1.1 The Norfolk Boreas site is located in an area characterised by Pleistocene and Holocene sediments (Cameron *et al.* 1992), comprising clays, silts, sands and gravels with occasional organic-rich deposits (peats), overlain by recent unconsolidated marine shelly sands.

2.1.2 The Pleistocene geological history of the North Sea basin is dominated by repeated glacial/interglacial cycles, resulting in rising and falling sea levels (**Figure 2**) and deposition of terrestrial, marine and glacially-derived sediments. The Norfolk Boreas site, and southern North Sea in general, is known to contain an important sedimentary archive including material dating from the earliest occupation of North Western Europe (Parfitt *et al.* 2010) up to more recent post-glacial reoccupation of Britain (Waddington 2015).

2.1.3 Only one glacial episode is thought to have directly affected the area. This was during the Anglian period (MIS 12, 480-423 ka) when ice extended into the southernmost North Sea (**Figure 3**). During subsequent glacial episodes, ice sheets terminated further north so did not directly affect the region. However, indirect affects resulting from changing sea levels and cold periglacial conditions will have influenced the site. The exact southern extent of the Anglian glaciation is debatable. However, bathymetric data suggests part of the Anglian ice sheet may have extended as far south as offshore from Felixstowe (Emu 2009), and Dix and Sturt (2011) argue for an Anglian glacial origin for over-deepened valleys (tunnel valleys) identified within the Outer Thames estuary.

2.1.4 As the area off East Anglia, including the study area, has only experienced at the most one glacial advance during the Pleistocene (**Figure 3**), palaeolandscape features from periods of low relative sea level are more likely to be preserved here rather than further north (approximately north of the north Norfolk coast), where they have been removed during the subsequent Saalian and Devensian glacial advances. Any surviving Pleistocene deposits may have been reworked or redeposited to a certain extent during subsequent marine transgressions (Hamblin et al. 1992), but there is potential for them to survive on the seabed.

2.1.5 Potential superficial deposits of geoarchaeological significance likely to be encountered within the Norfolk Boreas site area include the Brown Bank Formation, tentatively dating from the late Ipswichian interglacial to early Devensian glaciation (Limpenny *et al.* 2011).

2.1.6 The Brown Bank Formation includes deposits of silty sand, sandy silt and sandy silty clay, which is in places up to 20 m thick. The sandy silty clay deposits are here termed the Upper Brown Bank, to distinguish them from the underlying deposits of silty sand and sandy silt that characterise both the Lower Brown Bank (Lower Devensian) and underlying Eem Formation (Ipswichian) (Limpenny *et al.* 2011; Bicket and Tizzard 2015).

2.1.7 The Brown Bank Formation is present as a blanket deposit across the general area, and is interpreted to represent a shallow lagoon environment, comprising clayey silty sands (Cameron *et al.*1992; Limpenny *et al.* 2011). It remains unclear whether the Upper Brown Bank Formation was also deposited in the late Ipswichian, during a short period in the early Devensian, or over a much longer period extending into the Late Devensian, perhaps punctuated by hiatuses in sediment accumulation (Tizzard *et al.* 2015). The date of the Brown Bank Formation therefore has significant implications both for our understanding of the palaeogeographic development of the North Sea as well as the likelihood of encountering Palaeolithic archaeology.

2.1.8 In places across the southern North Sea a sequence of early Holocene pre- marine transgression deposits is mapped overlying Pleistocene sediments. The Holocene sediments include organic-rich peats along with more minerogenic fluvial and alluvial sediments, most often infilling channels (Limpenny *et al.* 2011; Tappin *et al.* 2011; Tizzard *et al.* 2015; Gearey *et al.* 2017; Brown *et al.,* 2018), but also preserved on the Brown Bank Formation or overlying periglacial aeolian sediment. The peats are of high geoarchaeological potential, preserving a range of palaeoenvironmental remains and material suitable for radiocarbon dating.

2.1.9 Pleistocene and early Holocene sediments are capped by post-transgression marine sands. The progressive inundation of the North Sea occurred over an extended time scale, with particularly rapid sea-level rise during the early Holocene (11,500-7000 cal. BP), and with fully marine conditions occurring by around 6000 cal. BP (Sturt *et al.,* 2013).

2.1.10 Earlier geological reviews of the Norfolk Boreas site defined the site stratigraphy using previous geophysical and geotechnical assessments undertaken for the East Anglia One Offshore Project Area, and Cameron et al. (1992). Recent site specific geophysical and geoarchaeological assessments at the Norfolk Boreas site (Wessex Archaeology 2018b; 2018c) have allowed this stratigraphic model to be refined so it fully represents the deposits likely to be encountered in the shallow sub-surface (**Table 2**).

2.1.11 Note, the stratigraphic scheme presented here (**Table 2**) is based on interpretations of shallow geophysics and thus doesn't capture deeper, older deposits that are beyond the period of archaeological interest. A comparison between the stratigraphic scheme presented here and one developed by Fugro for geotechnical purposes is presented in **Appendix 1**. Both schemes are considered alongside the British Geological Survey lithostratigraphic framework for UK continental shelf deposits (Stoker *et al.* 2011).

Table 2 Stratigraphy of the Norfolk Boreas site based on site specific geophysical and geoarchaeological assessments (Wessex Archaeology 2018b; 2018c).

WA Litho-stratigraphic Unit	Geological Unit (Age)	Geophysical Characteristics (1)	Sediment Type (2)	Archaeological Potential
Unit 5	Holocene seabed sediments (post-transgression, MIS 1)	Generally observed as a veneer or thickening into large sand wave and bank features up to 20 m thick. Boundary between surficial sediments and underlying units not always discernible.	Medium to coarse sand with frequent shell fragments – marine	Considered of low potential in itself, but possibly contains re-worked artefacts and can cover wreck sites and other cultural heritage
Unit 4c	Holocene (pre-transgression, MIS 1)	Not identified within the geophysical data as deposit thickness is lower than geophysical data resolution	Coarsening upwards sequence of structureless clay overlain by laminated silt with evidence of crossbedding and organic laminations – transgression/intertidal	Potential to contain *in situ* and derived archaeological material, and palaeoenvironmental material

WA Litho-stratigraphic Unit	Geological Unit (Age)	Geophysical Characteristics [(1)]	Sediment Type [(2)]	Archaeological Potential
Unit 4b	Holocene (pre-transgression, MIS 1)	Extensive areas of intermittent, relatively flat, high amplitude reflectors. Often associated with shallow channelling	Peat ranging from strongly to weakly decomposed with plant fragments (reeds) roots and wood preserved – terrestrial land surface	Potential to contain *in situ* and derived archaeological material, and palaeoenvironmental material
Unit 4a	Holocene (pre-transgression, MIS 2-1)	Small, shallow, infilled channels with either seismically transparent fill, or fill characterised by sub-parallel internal reflectors	Fining upwards sequence of sand with silt laminations and plant/root fragments overlain by laminated to organic silt with roots and plant fragments – fluvial/intertidal	Potential to contain *in situ* and derived archaeological material, and palaeoenvironmental material
Undifferentiated	Holocene pre-transgression (MIS 1) or Upper Brown Bank (MIS 5d-3)	Acoustically chaotic unit at the top of Brown Bank Formation, potentially comprising numerous phases of cross cutting channels	Interbedded sand and silty clay with shell fragments and silt laminations (occasionally organic) – unknown, possible fluvial/intertidal	Unknown – potential will depend on precise age and depositional environment of unit
Unit 3	Upper Brown Bank Formation (MIS 5d-3)	Observed as a blanket deposit across much of the area, either acoustically transparent or characterised by sub-horizontal layered reflectors. Contains numerous internal erosion surfaces, occasional fluid escape structures, and areas of acoustic blanking	Silty clay and clayey silt with closely spaced fine laminations. May be sandy in places or comprise sand partings/laminations – lagoon/intertidal/sheltered embayment	*In situ* Lower Palaeolithic artefacts may be protected. Middle Palaeolithic *in situ* and derived artefacts may be associated, particularly with channel edges dependent on the age of the fill. Palaeoenvironmental information. Basal contact may cover old land surfaces
Unit 2	Lower Brown Bank Formation (MIS 5e-5d)	Observed within large topographically controlled depressions. Characterised by low relief basal reflector and either an acoustically transparent or well-layered fill	Silty sand and sandy silt - possible intertidal/shallow marine	*In situ* Lower Palaeolithic artefacts may be protected. Middle Palaeolithic *in situ* and derived artefacts may be associated, particularly with channel edges dependent on the age of the fill. Palaeoenvironmental information. Basal contact may cover old land surfaces

WA Litho-stratigraphic Unit	Geological Unit (Age)	Geophysical Characteristics (1)	Sediment Type (2)	Archaeological Potential
Unit 1	Yarmouth Roads Formation (>MIS 13)	Thick unit either seismically chaotic or containing numerous areas of well-defined cross cutting channel complexes characterised by layered sub-parallel internal reflectors. Top of unit generally a well-defined regional erosion surface	Silty sand with occasional shell fragments and occasional layers of clay. Generally becoming silty with depth - deltaic	Possibility of *in situ* finds in later part of formation if not eroded. Contemporaneous with terrestrial Cromer Forest Bed Formation (Pakefield and Happisburgh). Has been found to contain plant debris, wood and peat in some areas of possible palaeoenvironmental importance. Potential greatest where associated with river valleys.

(1) Based on geophysical data (Wessex Archaeology 2018c)

(2) Based on geoarchaeological recording of Norfolk Boreas vibrocores (Wessex Archaeology 2018b) and Cameron *et al.* (1992) in the case of Unit 1

2.2 Archaeological potential

2.2.1 The southern North Sea off the east coast of East Anglia is known to contain relatively well preserved palaeolandscape features such as fluvial channels, created during periods of lower sea level when landscapes were free of ice. The remains of these terrestrial landscapes are frequently recovered by dredging and fishing in numerous areas around the southern North Sea, generally in the form of the remains of extinct megafauna (e.g. mammoths, bison, horse etc.).

2.2.2 The discovery of actual human artefacts, such as hand axes and worked bone, is a rarer occurrence, but artefacts have been recovered. Reported finds from offshore activity has, to date, produced a range of early prehistoric lithic artefacts indicating early prehistoric activity in submerged palaeolandscapes from Lower, Middle, and Upper Palaeolithic periods (Tizzard *et al.* 2014; 2015; Wessex Archaeology 2011; 2013a), with notable collections of more recent Mesolithic artefacts from submerged palaeolandscape contexts (Momber *et al.* 2011; Wessex Archaeology 2013a).

2.2.3 Whilst the archaeology at Pakefield was created during a more Mediterranean climate, around MIS 17 (**Figure 2**), the remains at Happisburgh Site 3 are indicative of colder-than-present conditions at the edge the boreal zone (Candy *et al.* 2011), indicating that earlier hominins were capable of surviving in conditions previously thought to be too harsh for habitation (Parfitt et al. 2010).

2.2.4 The importance of these sites is international, as they are currently unique at this latitude for this early date (Wessex Archaeology 2013a). Cohen *et al.* (2012) have highlighted the North Sea basin as a key region for understanding Pleistocene hominins within a northerly, coastal environment. The east of England, particularly East Anglia, but also the southeast of England, are important regions for Lower Palaeolithic archaeology in the last 500,000 years during MIS 13 and 11 (Hoxnian interglacial, **Figure 2**) (Wymer 1999; Pettitt and White 2012).

2.2.5 During Middle Pleistocene interglacial periods (Hoxnian and Ipswichian), warmer climate conditions meant the UK was again available to be recolonised by hominin communities.

The foreshore, cliffs and hinterland at Clacton-on Sea (Essex) comprise an important Middle Pleistocene site and is a designated geological Site of Special Scientific Interest (SSSI). Channel sediments from the area are also an important site for the Lower Palaeolithic Clactonian flint industry, and have yielded a rare wooden spear alongside lithic artefacts. The site dates from the Hoxnian interglacial period (MIS 11, c. 423,000 - 380,000 BP, **Figure 2**) (Sumbler 1996; Bridgland *et al.* 1999), and the type site for the Hoxnian (the Hoxne Brick Pit) is located a relatively short distance inland outside of Diss, Suffolk.

2.2.6 During the Saalian glaciation (MIS 10, **Figure 2**) there was a hiatus in hominin activity in Britain (Pettitt and White 2012). When hominins returned, H. neanderthalensis, they brought a new lithic technology: the Levallois prepared core technique developing from MIS 9, c. 300,000 BP (Scott and Ashton 2011). They were hunters adapted to a 'mammoth steppe' environment (Ashton and Lewis 2002).

2.2.7 The international importance of early Middle Palaeolithic archaeology in the southern North Sea is highlighted by the numerous sites preserved within the Thames river terraces (White 2006; Scott *et al.* 2011) and, in particular, by the submerged prehistoric Levallois lithic assemblage from marine aggregates licence Area 240 in the palaeo-Yare catchment. Over 120 artefacts have now been recovered from this locale, some of which are identifiable as Levellois, with many recovered from in situ or near in situ contexts (Tizzard *et al.* 2014; 2015; Wessex Archaeology 2013a; 2013b).

2.2.8 The substantial, mixed assemblage of handaxes also recovered from Area 240 may be of older Lower Palaeolithic origin (e.g. >MIS 9, **Figure 2**), or may date to the Later Middle Palaeolithic when technologically similar artefacts were made (c. MIS 3, **Figure 2**) (Boismier *et al.* 2012). However, based on palaeoenvironmental and sedimentological evidence an Early Middle Palaeolithic date is most likely (Tizzard *et al.* 2015).

2.2.9 Palaeogeographically, Area 240 is one of the most northerly Neanderthal sites in northwest Europe and of primary archaeological importance for defining Middle Palaeolithic potential and the contemporary palaeogeography across the southern North Sea basin (Tizzard *et al.* 2014). The site highlights the archaeological potential of preserved Pleistocene fluvial deposits within the southern North Sea.

2.2.10 Currently there is no definitive evidence of a hominin presence in Britain during MIS 5 (Lewis *et al.* 2011). Within the context of early prehistory and submerged palaeogeography, however, substantial areas of the southern North Sea basin would have been dry land during the warming and cooling limbs of the various sub-stages (MIS 5a to 5e, **Figure 2**). Recent analysis has suggested that eight relatively brief phases of human activity within the UK are represented by the existing Upper Palaeolithic archaeological record (Jacobi and Higham 2011), with six occurring before the Devensian glacial maximum. Therefore, the potential exists for human activity to have occurred in Doggerland, the area of exposed terrestrial environment within the southern North Sea basin, during and after the Devensian glaciation.

2.2.11 Offshore locations may be the only source for testing this hypothesis (Wessex Archaeology 2013b), and the western European archaeological record is rich in comparison for MIS 5 (Lewis *et al.* 2011; Pettitt and White 2012). During the Late Glacial Maximum (LGM), the study area will have been close to the maximum Devensian ice margin (**Figure 3**).

2.2.12 Again, East Anglia provides early evidence for Neanderthal recolonisation of Britain after the hiatus between MIS 6 to 4, around 60,000 BP (**Figure 2**). The Lynford Quarry material highlights a new lithic technology visually similar to Lower Palaeolithic Acheulean lithics, so-called Mousterian of Acheulean Tradition handaxes and tools (Boismier *et al.* 2012).

2.2.13 Climatically, MIS 3 was significantly colder than now but did not attain the glacial conditions of later or earlier glacial periods (e.g. MIS 6 or 2, **Figure 2**) (Pettitt and White 2012). For the Neanderthals that may have occupied the region at this time, surviving in Doggerland during this period may have been subject to a variety of technological and cultural adaptations (White 2006).

2.2.14 In the Early Upper Palaeolithic, at the end of the Late Pleistocene, there was a transition period for hominins. Neanderthals died out around 40,000 BP, and modern humans then colonised Doggerland, arriving in Britain around 34,000 BP (Jacobi and Higham 2011; Bicket and Tizzard 2015). Archaeological evidence for this period is relatively sparse, but submerged palaeolandscapes provide key contextual evidence for recovered artefacts and provides a background landscape within which to place these human communities.

2.2.15 During the LGM, the environment within the southern North Sea was relatively poor for human colonisation and was situated at the north-western extents of possible habitation. However, there was increasing human exploitation after 15,000 BP. Humans at this time were hunting game, such as mammoth and deer, and evidence of these animals has been reported through marine aggregate dredging, and the associated reporting requirements (Bicket and Tizzard 2015).

2.2.16 The onshore archaeological record of Upper Palaeolithic activity is relatively sparse, and offshore locations may provide unique and important context for coastal and lowland human activity during this period (Wessex Archaeology 2013b). For example, a Maglemosian harpoon artefact from trawled peat in the early 20th century was subsequently radiocarbon dated to around 12,000 years ago (Housely 1991), and archaeological and palaeoenvironmental material has been reported from North Sea contexts for over a century (Reid 1913; Godwin and Godwin 1933).

2.2.17 The Mesolithic period began in the early Holocene. Around 10,000 BP, sea levels were still more than 60 m below current levels, and during this period, an extremely large area of the southern North Sea and English Channel was dry land, suitable for human occupation. Evidence of this environment has been identified from the foreshore at Jaywick, Essex, where layers of peat dating from the Early Holocene are present along with a preserved land surface from which Mesolithic artefacts have been recovered (Wilkinson and Murphy 1995).

2.2.18 Considerable attention has been paid to Mesolithic Doggerland in the last decade (Gaffney *et al.* 2007; Tappin *et al.* 2011) and the geoarchaeology (Boomer *et al.* 2007), submerged forests (Hazell 2008), and palaeo-river systems around the current North Sea coast (Wessex Archaeology 2013c; Limpenny *et al.* 2011; EMU 2009). Increasingly, a maritime perspective has developed for understanding the early prehistoric archaeological record, where coasts, estuaries and wetlands are key landscape elements (Ransley *et al.* 2013).

2.2.19 It is clear from numerous research and development-led investigations that postglacial marine transgression has not destroyed Pleistocene and Holocene palaeogeography by default (Wessex Archaeology 2013b). Areas of preserved palaeogeographic features do remain, and detailed reconstructions of palaeoenvironments and palaeogeography can be achieved for large parts of the North Sea basin (Tappin *et al.* 2011; Limpenny *et al.* 2011; Dix and Sturt, 2011). By the early Holocene, Mesolithic hunter-fisher-gatherers in Doggerland were active in a familiar ecosystem of mixed deciduous woodland with oak, elm, alder and lime populated by deer and a wide variety of other mammals (Tappin *et al.* 2011).

2.2.20 However, between 7,000 and 5,000 BP, much of the land was inundated by eustatically driven sea level change (Bicket and Tizzard 2015), and by 6,000 BP sea level was only approximately 7 m below the present level (Cameron *et al.* 1992). Around this time, Britain became an island again (Coles 1998). Settlements at the time were often transitory and seasonal, and therefore leave little trace in the archaeological record, however, new types of stone tools were introduced during this period. It is possible that the now submerged environment of which the study area was a part was occupied up until the final marine transgression between 7,000 and 5,000 BP.

3 AIMS AND OBJECTIVES

3.1.1 The principal aims of the Stage 3 palaeoenvironmental assessment were to:

- Determine the nature, depositional history and age of accumulated deposits;
- Determine the preservation potential and concentration of palaeoenvironmental remains (pollen, plant macrofossils, diatoms, foraminifera and ostracods) within the deposits;
- Interpret the results to inform reconstructions of past environmental and landscape change (e.g. vegetation and sea level), and;
- Assess archaeological and geoarchaeological potential of deposits.

3.1.2 A series of research questions were proposed in the Stage 2 report (Wessex Archaeology 2018b) which underpin the Stage 3 palaeoenvironmental assessment, taking into account the regional research framework (Medlycott 2011) and the national maritime research framework (Ransley *et al.* 2013).

3.1.3 Specific research questions include:

- What palaeoenvironments are represented by the deposits preserved across the site? How do these change through time?
- What is the age of the peat deposits? Do they represent a contemporary phase of peat formation across the site or separate phases of peat formation within environmental niches?
- What is the age of Upper Brown Bank Formation? Did it form relatively quickly in the early Devensian or accumulate over a longer period of time?
- What do the results mean for palaeolandscape development and palaeogeographic evolution of the southern North Sea, and what is the archaeological significance of this?

4 METHODOLOGY

4.1 Sampling strategy

4.1.1 Five vibrocores were selected for Stage 3 paleoenvironmental assessment (VC016, VC028, VC032, VC039 and VC047).

4.1.2 Deposits corresponding to Upper Brown Bank (**Unit 5**) were targeted in VC016 and VC047 for OSL dating and accompanying foraminifera, ostracod and diatom assessment, to determine the age and depositional environment. Overlying **Unit 5** in these cores was an Undifferentiated unit. Samples from this Undifferentiated deposit were submitted for foraminifera assessment to help determine the depositional context.

4.1.3 Holocene pre-transgression peat and over/underlying minerogenic deposits (Units 4a, 4b and 4c) in VC028, VC032 and VC039 were selected for radiocarbon dating as they showed the greatest potential for preservation of pollen within the peat. Diatoms, foraminifera and ostracod analysis was also undertaken on these cores across transitions between minerogenic and organic sediments.

4.1.4 Full sample preparation and analytical methods for each palaeoenvironmental and dating technique are described below. All sub-sample depths are quoted as metres below sea floor (mbsf). In some cases, the elevation of sub-samples has been corrected to Lowest Astronomical Tide (LAT). At this stage depths have not been corrected to meters Ordnance Datum. A full list of sub-samples is presented in **Appendix 2**.

4.2 Optical stimulated luminescence dating

Core handling and storage

4.2.1 Vibrocores had been collected in transparent liners, and were split offshore into ~1 m sections, which were then sealed for onshore analysis. Vibrocores with geoarchaeological potential, identified during a Stage 1 review (Wessex Archaeology 2018a), were transported to Wessex Archaeology for assessment.

4.2.2 At this stage, the ends of each core section and the outer surface of the core had already been exposed to light. Upon receipt, vibrocores were held in a dark core storage facility at Wessex Archaeology prior to geoarchaeological recording and sub-sampling.

4.2.3 When opened for geoarchaeological recording, plastic core liners were cut using a hand held vibrating multitool, cutting lengthways through the liner along either side of the core. Care was taken to minimise penetration into the sediment.

4.2.4 Depending on the nature of the sediment (cohesion, grain size etc.), the cores either naturally broke apart lengthways into two equal halves (2 x half round cores) or remained intact with minimal disturbance (whole round core).

4.2.5 During the geoarchaeological recording process, c.1-2 mm of sediment was removed from exposed core surfaces.

4.2.6 To avoid repeated disturbance of deposits, cores were opened and then immediately photographed and described. They were then sealed, wrapped in cling film and secured with Gorilla tape before being returned to the core storage facility. Unnecessary handling of cores was avoided.

Sample selection

4.2.7 Given the cohesive and compacted nature of the Brown Bank deposits recovered in cores, there was potential for these cores to be sub-sampled for OSL dating if a sample from the centre of the core could be extracted, avoiding the outer exposed surfaces.

4.2.8 Core photographs and geoarchaeological descriptions were used to identify potential core sections suitable for OSL dating, using the following criteria;

- Sediment must be undisturbed with no evidence of cracks, deformation slumping etc. as this could let light into the centre of the core or could allow reworked material to become incorporated into sample taken from the centre. By taking core photographs immediately after the core was opened, the opening/closing of any cracks could be monitored;

- Sediment must be cohesive to avoid movement or disturbance of loose grains minimising the potential of exposed material becoming mixed with material from the centre of the core during sampling, and;

- The core must not show evidence of drying out as this will affect water content calculations.

4.2.9 Four core sections were targeted for OSL dating to obtain a chronology for Brown Bank deposits (**Unit 3**), two from VC016 (2.65-3.00 and 1.70-2.00 mbsf) and two from VC047 (2.55-3.00 and 3.70-4.00 mbsf).

Sample preparation and analysis

4.2.10 Once suitable deposits were identified for OSL dating, a sub-section of the entire core was removed for delivery to the OSL lab. This was achieved by cutting through both the core liner and the sediment to create a ~30 cm cylinder of sediment still sealed within the core liner. Care was taken to minimise the exposure of new surfaces to light by taking a section from the top or bottom of a core where possible. These sub-sections were sealed in cling film and black liners for transport to the OSL laboratory for sample preparation and analysis.

4.2.11 All sample preparation and analysis was undertaken by OSL specialists at the University of Gloucester. Sub-sections were opened and prepared under controlled laboratory illumination provided by Encapsulite RB-10 (red) filters. To isolate any material potentially exposed to light, i.e. the outer core surface, sediment located within 10 mm of each core face was carefully removed to target the centre of the core that had been shielded from light. Once the OSL sample was isolated, the remaining core material was used to calculate Dose Rate (D_r) and moisture content.

4.2.12 The remaining sample was dried and then sieved. The fine sand fraction was segregated and subjected to acid and alkaline digestion (10% HCl, 15% H2O2) to attain removal of carbonate and organic components respectively. A further acid digestion in HF (40%) for 60 mins was used to etch the outer 10-15 μm layer affected by α radiation and degrade each samples' feldspar content. During HF treatment, continuous magnetic stirring was used to effect isotropic etching of grains. 10% HCl was then added to remove acid soluble fluorides. Each sample was dried, resieved and quartz isolated from the remaining heavy mineral fraction using a sodium polytungstate density separation at $2.68 g.cm^{-3}$. Twelve 8 mm multi-grain aliquots (c. 3-6 mg) of quartz from each sample were then mounted on aluminium discs for determination of Equivalent Dose (D_e) values.

4.2.13 All drying was conducted at 40°C to prevent thermal erosion of the signal. All acids and alkalis were Analar grade. All dilutions (removing toxic-corrosive and non-minerogenic luminescence-bearing substances) were conducted with distilled water to prevent signal contamination by extraneous particles.

4.2.14 D_e values were quantified using a single-aliquot regenerative-dose (SAR) protocol (Murray and Wintle 2000; 2003). Weighted (geometric) mean D_e values were calculated from 12 aliquots using the central age model outlined by Galbraith et al. (1999) and are quoted at 1σ confidence (**Table 3**). Lithogenic D_r values were defined through measurement of U, Th and K radionuclide concentration and conversion of these quantities into β and γ Dr values (Adamiec and Aitken, 1998), accounting for D_r modulation forced by grain size (Mejdahl, 1979) and present moisture content (Zimmerman, 1971) (**Table 3**). Cosmogenic D_r values were calculated on the basis of sample depth, geographical position and matrix density (Prescott and Hutton, 1994). Note, no in situ γ spectrometry was undertaken due to these samples being collected offshore, therefore the level of U disequilibrium was estimated by laboratory-based Ge γ spectrometry.

4.2.15 The accuracy with which D_e equates to total absorbed dose and that dose absorbed since burial was assessed. The former can be considered a function of laboratory factors, including feldspar contamination, preheating, irradiation and internal consistency, the latter, one of environmental issues such as incomplete zeroing and the influence of post-depositional turbation. Diagnostics were deployed to estimate the influence of these factors and criteria instituted to optimise the accuracy of D_e values. The analytical validity of each sample is presented in **Table 3**.

4.2.16 Ages reported in **Table 3** provide an estimate of sediment burial period based on mean D_e and D_r values and their associated analytical uncertainties. Full OSL results are presented in **Appendix 3**.

4.3 Radiocarbon dating

4.3.1 Four sub-samples were taken for radiocarbon dating (**Table 4**). Two sub-samples were taken from the top and bottom of a 0.32 m thick peat deposit (**Unit 4b**) in VC032. One sub-sample was taken at the base of the peat (**Unit 4b**) in VC028. Typically, a radiocarbon sample would also be taken near the top of the peat. However, in the case of VC028, the upper peat showed evidence of reworking and erosion with the inclusion of shelly sandy intraclasts, therefore, a sample for radiocarbon dating was not taken. Only one radiocarbon sub-sample was taken from VC039. In this case the peat deposit spanned two core sections and there was evidence of disturbance near the split faces. To avoid potential reworking, only one sample was taken at a location with no disturbance.

4.3.2 The sub-samples were assessed for plant macrofossils (see section **4.4**), three contained material suitable for dating (**Table 5**) but due to the highly decomposed nature of the peat in VC032, macrofossil preservation was low and a bulk sample was submitted for dating.

4.3.3 Radiocarbon dating was undertaken by the ^{14}CHRONO Centre at Queens University Belfast. Calibrated age ranges were calculated with OxCal 4.2 (Bronk-Ramsey 2013) using the IntCal13 curve (Reimer et al. 2013). All radiocarbon dates are quoted as uncalibrated years before present (BP), followed by the lab code and the calibrated date-range (cal. BP) at the 2σ (95.4%) confidence.

4.4 Macrofossils

4.4.1 Four sub-samples were processed and assessed for macrofossils to identify material suitable for radiocarbon dating. The sub-samples were processed by standard methods for the recovery of waterlogged plant remains; the flots were retained on a 0.25mm mesh. Flots were stored in sealed containers with water. The flots were scanned under a x10 – x40 stereo-binocular microscope and the preservation and nature of the plant remains recorded in **Table 5**. The presence of other macrofossils was also noted if observed. Nomenclature follows Stace (1997).

4.5 Pollen and spores

4.5.1 Twelve sub-samples of 1 ml volume were processed using standard pollen extraction methods (Moore et al 1991), comprising three sub-samples from VC028, six sub-samples from VC032 and three sub-sample from VC039. In VC028, the sub-samples were taken from the peat deposits (**Unit 4b**) while in VC032 and VC039, sub-samples were taken from the peat (**Unit 4b**) but also the over/underlying minerogenic deposits (**Unit 4a** and **Unit 4c**).

4.5.2 Pollen was identified and counted using a Nikon eclipse E400 biological research microscope. A total of 150 pollen grains was counted for each sub-sample in addition to aquatics and fern spores, and where 150 counts were not possible, all pollen and spores were counted from four transects. One Lycopodium tablet was added to enable calculation of pollen concentrations. Pollen and spores were identified to the lowest possible taxonomic level.

4.5.3 Plant nomenclature followed Stace (1997) and Bennett *et al.* (1994). Pollen sums are based on total land pollen (TLP) excluding aquatics and fern spores which are calculated as a percentage of TLP plus the sum of the component taxa within the respective category. Identification of indeterminable grains was according to Cushing (1967).

4.5.4 At assessment stage the results are not presented as pollen diagrams, but are presented in tabular form as raw data (**Table 6, Table 7 and Table 8**). Plant taxa are assigned to one of the following groups (trees and shrubs, dwarf shrubs, cultivated, field weeds, ruderals, herbaceous open/ undefined, fern spores and aquatics) based on their most likely ecological affinity, although many plant taxa occur in a range of environmental niches (see Stace 1997 for specific plant taxa).

4.6 Diatoms

4.6.1 Forty-two sub-samples were prepared for diatom assessment, comprising three sub-samples from VC028 (**Unit 4a**), ten sub-samples from VC032 (**Unit 4a** and **Unit 4c**), five sub-samples from VC039 (**Unit 4a** and **Unit 5**), fourteen sub-samples from VC016 (**Unit 3** and Undifferentiated deposit) and ten sub-samples from VC047 (**Unit 3** and Undifferentiated deposit) (**Table 9** and **Appendix 4**).

4.6.2 Diatom preparation followed standard techniques (Battarbee *et al.* 2001). Two coverslips were made from each sample and fixed in Naphrax for diatom microscopy. A large area of the coverslips on each slide was scanned for diatoms at magnifications of x400 and x1000 under phase contrast illumination.

4.6.3 Diatom floras and taxonomic publications were consulted to assist with diatom identification; these include Hendey (1964), Werff & Huls (1957-1974), Hartley *et al.* (1996), Krammer & Lange-Bertalot (1986-1991) and Witkowski *et al.* (2000). Diatom species' salinity preferences are indicated using the halobian groups of Hustedt (1953, 1957), these salinity groups are summarised as follows:

1. Polyhalobian: marine >30 gl^{-1} salinity

2. Mesohalobian: brackish 0.2-30 gl^{-1} salinity

3. Oligohalobian - Halophilous: optimum in slightly brackish water

4. Oligohalobian - Indifferent: optimum in freshwater but tolerant of slightly brackish water

5. Halophobous: exclusively freshwater

6. Unknown: taxa of unknown salinity preference.

4.6.4 Diatom assessment results are summarised in **Table 9** with comments on potential for full diatom analyses. Where diatom preservation was suitable, more detailed assessment was undertaken and is presented in **Appendix 4**.

4.7 Foraminifera and ostracods

4.7.1 Forty-two sub-samples were prepared for foraminifera and ostracod assessment, comprising three sub-samples from VC028 (**Unit 4a**), ten sub-samples from VC032 (**Unit 4a** and **Unit 4c**), five sub-samples from VC039 (**Unit 4a** and **Unit 5**), fourteen sub-samples from VC016 (**Unit 3** and Undifferentiated deposit) and ten sub-samples from VC047 (**Unit 3** and Undifferentiated deposit) **(Table 10-13**).

4.7.2 The sub-samples were weighed, then broken into small pieces by hand, placed into ceramic bowls, and dried in an oven. Boiling-hot water was then poured over them and a small amount of sodium carbonate added to help disaggregate the clay fraction. Each sub-sample was left to soak overnight. Washing was with hand-hot water through a 75 micron sieve, with the remaining residue being returned to the ceramic bowl for final drying in the oven. Most gave a good breakdown, but the more organic-rich silts often required processing twice. The residues were then stored in labelled plastic bags.

4.7.3 For examination, each sample was placed in a nest of sieves (>50, >250, >150µm, and base pan) and thoroughly shaken. Each grade was then sprinkled onto a picking tray, a little at a time, and viewed under a binocular microscope. "Contained material" were logged on a presence(x)/absence basis as shown in accompanying tables (**Table 10-13**).

4.7.4 The abundance of each foraminiferal and ostracod species was estimated semi-quantitatively (one specimen, several specimens, common and abundant/superabundant) by experience and by eye (**Appendix 5**). Species identification comes from Murray (2006) for the foraminifera, Athersuch et al. (1989) for the brackish and marine ostracods, and Meisch (2000) for the freshwater ostracods, in addition to expert judgement.

5 RESULTS

5.1 Optical stimulated luminescence dating

5.1.1 Four sub-samples from Upper Brown Bank deposits were submitted for OSL dating, comprising two sub-samples from VC016 (2.65-3.00 and 1.70-2.00 mbsf) and two from VC047 (2.55-3.00 and 3.70-4.00 mbsf). Age data are presented in **Table 3** and full results are given in **Appendix 3**.

5.1.2 Diagnostics were used to estimate the influence of laboratory and environmental factors on the results as a means of testing the analytical validity of the OSL age (**Table 3**). Of the four sub-samples analysed, those from VC016 were considered accurate representations of the burial age. Sub-samples from VC047 exhibit overdispersion of the regenerated signals which implies the effectiveness of sensitivity correction, a key part of the laboratory protocol, may be problematic. This is a function of the individual samples response to the SAR protocol and is not related to sample handling, storage or preparation. For these samples, ages have been accepted tentatively due to the potential for laboratory factors to influence the results.

5.1.3 The methodological approach to sub-sampling for OSL involved maximising the use of vibrocores recovered in transparent liners where the outer surface had been exposed to light (see section **4.2**). Measures were taken to reduce the risk of exposed grains from the outer surface of the cores becoming incorporated in the OSL sample that was taken from the centre of the core under controlled light conditions (see section **4.2**). The concern is that this would lead to partial bleaching and thus influence the final age.

5.1.4 Within this study, signal analysis was used to quantify the change in D_e value with respect to optical stimulation time for multi-grain aliquots. A statistically significant increase in natural D_e with time is indicative of partial bleaching, but this assumes certain laboratory conditions are met (see **Appendix 3**). The results from signal analysis from each of the Norfolk Boreas OSL sub-samples do not show an increase in natural D_e with time suggesting there is no evidence of partial bleaching. However, the utility of signal analysis is strongly dependent upon a samples pre-burial experience of sunlight's spectrum and its residual to post-burial signal ratio, and that all laboratory conditions are met.

5.1.5 Inter-aliquot D_e distributions studies may be used to test for partial bleaching. At present, it is contended that asymmetric inter-grain D_e distributions are symptomatic of partial bleaching (Murray *et al*. 1995; Olley *et al*. 1999; 2004 and Bateman *et al*. 2003). Samples GL17153 and GL17156 exhibit asymmetric distributions which may be indicative of partial bleaching (**Appendix 3**). However, distinguishing between partial bleaching caused by the sampling process and that which occurred naturally during deposition is problematic, especially in water lain sediments such as Upper Brown Bank where partial bleaching is prolific (Murray *et al.* 1995). Furthermore, the small aliquot number (12) and large aliquot size (8 mm) means these D_e distributions are not statistically robust, nor do they represent single grains. To account for this, additional aliquots of a smaller size (1 mm) would need to be analysed.

Table 3 Dose Rate (D_r), Equivalent Dose (D_e) and resulting OSL age estimates. Age estimates expressed in ka relative to year of sampling. Uncertainties in age are quoted at 1σ confidence and include combined systematic and experimental variability.

Laboratory id	Core	Depth mbsf (mLAT)	Total D_r (Gy.ka-1)	D_e (Gy)	Age (ka)	Considerations and analytical validity
GL17154	VC016	1.70-2.00 (-40.90 to -41.20)	2.19 ± 0.17	182.1 ± 15.0	83.2 ± 9.5	Accept
GL17153	VC016	2.65-3.00 (-41.85 to -42.20)	2.14 ± 0.17	149.6 ± 11.1	69.8 ± 7.7	Accept
GL17155	VC047	2.55-3.00 (-37.05 to -37.50)	2.23 ± 0.18	135.1 ± 7.2	60.5 ± 5.8	Overdispersed interpolated to applied regenerative-dose ratio, accept tentatively
GL17156	VC047	3.70-4.00 (-38.20 to -38.50)	2.38 ± 0.20	186.0 ± 11.6	78.9 ± 8.3	Overdispersed interpolated to applied regenerative-dose ratio, accept tentatively

VC016

5.1.6 Two OSL sub-samples were taken from Brown Bank deposits in VC016 at depths of 1.70-2.00 mbsf (central point at -41.05 mLAT) and 2.65-3.00 mbsf (central point -42.03 mLAT).

5.1.7 The basal sub-sample (GL17153) returned an age of 69.8 ± 7.7 ka with the overlying sub-sample (GL17154) giving an age of 83.2 ± 9.5 ka (**Table 3**). Both sub-samples have passed analytical validity tests and are therefore accepted. The dates are inverted as the age of the lowermost sub-sample (GL17153) is younger than the overlying sub-sample (GL17154) (see paragraph 6.2.8). However, the ages overlap within error margins.

5.1.8 The age range, including error margins, of samples from VC016 place deposition of Upper Brown Bank deposits at this location between MIS 5b and MIS 4 during the late-Middle Palaeolithic.

VC047

5.1.9 Two OSL sub-samples were taken from Brown Bank deposits in VC047 at depths of 2.55-3.00 mbsf (central point at -37.30 mLAT) and 3.70-4.00 mbsf (central point -38.35 mLAT).

5.1.10 The lowermost sub-sample (GL17156) gave an age of 78.9 ± 8.3 ka and the overlying sub-sample (GL171550) returned an age of 60.5 ± 5.8 ka indicating these ages are conformable (**Table 3**).

5.1.11 Sub-samples from VC047 did not fully pass analytical validity acceptance tests and are therefore only accepted tentatively (**Table 3**). However, the ages which span MIS 5b to MIS 4 lie within the same age range as VC016 increasing confidence in the results despite the analytical uncertainty.

5.2 Radiocarbon dates

5.2.1 Four sub-samples were taken for radiocarbon dating (**Table 4**), two from a peat deposit (**Unit 4b**) in VC032, and one sample from the peat deposits (**Unit 4b**) in VC028 and VC039.

5.2.2 Calibrated radiocarbon dates indicate peat developed across the Norfolk Boreas site from as early as 12.9 ka in the Late Devensian, transitioning into the early Holocene until at least ~9.5 ka. The peat deposits across the Norfolk Boreas site therefore represent up to ~3,500 yrs of peat development assuming deposition was continuous with no erosion.

Table 4 AMS Radiocarbon dates

Laboratory id	Material dated	Depth mbsf (mLAT)	Age BP	Age range cal. BP	Age range cal. BC
Vibrocore VC028					
UB-38188	Bud scales	2.59 to 2.62 (-33.79 to -33.82)	8749±40	9901-9564	7952-7615
Vibrocore VC032					
UB-38189	*Menyanthes trifoliata* seed	3.83 (-35.73)	8697±45	9884-9542	7935-7593
UB-38190	Bulk sediment	4.11 (-36.01)	9992±51	11707-11264	9758-9315
Vibrocore VC039					
UB-38191	*Menyanthes trifoliata* seed	3.07 (-35.77)	10881±60	12895-12685	10946-10736

All calibrated dates are expressed at 2 sigma confidence (95.4%)

VC028

5.2.3 One sub-sample was taken at the base of the peat (**Unit 4b**) in VC028. Typically, a radiocarbon sample would also be taken near the top of the peat. However, in the case of VC028, the upper peat showed evidence of reworking and erosion with the inclusion of shelly sandy intraclasts, therefore, a sample for radiocarbon dating was not taken.

5.2.4 The age at the base of the peat at -33.8 mLAT is 9901-9564 cal. BP (**Table 4**) indicating peat development commenced here during the early Holocene. Additional dates would be required to test if this peat was a relatively short-lived feature or a more persistent part of the landscape.

VC032

5.2.5 Two sub-samples were taken from VC032, one at the base and one at the top of a 0.32 m thick peat deposit (**Unit 4b**).

5.2.6 The basal date at -36.01 mLAT is 11707-11264 cal. BP (UB-38190) which corresponds to the beginning of the Holocene period, and the upper date at -35.73 mLAT is 9884-9542 cal. BP (UB-38189), again Holocene in age. Here, ~1700 yrs of deposition is represented by 0.32 cm of sediment suggesting low deposition and/or, high compaction/decomposition rates.

VC039

5.2.7 One radiocarbon sub-sample was taken from VC039. In this case the peat deposit spanned two core sections and there was evidence of disturbance near the split faces. To avoid potential reworking, only one sample was taken at a location with no disturbance.

5.2.8 The age of the peat in VC039 at -35.77 mLAT is 12895-12685 cal. BP which dates the Late Devensian (**Table 4**). This peat deposit likely represents very early phases of peat development after ice sheets retreated from the southern North Sea. As is the case with VC028, the age range represented by this 0.17 m thick deposit is unknown and additional date would be required to address this.

5.3 Macrofossils

5.3.1 For sub-samples were assessed for macrofossils with the primary aim of obtaining suitable material for radiocarbon dating from the peat (**Unit 4b**) (**Table 5**). Due to the relatively thin (0.17-0.35 m thickness), compact and highly decomposed nature of the peat, it was anticipated a large sample volume would be required for the assessment. Therefore, to preserve core material for further Stage 4 analysis, no additional macrofossil sub-samples other than those for radiocarbon dating were taken.

Table 5 Macrofossils

Vibrocore	Depth mbsf (mLAT)	Waterlogged plant remains		Invertebrates
		Uncharred vegetative plant parts	Uncharred other	Insects
VC028	2.59 to 2.62 (-33.79 to -33.82)	A*** inc. wood fragments	A - Betula sp. seeds, bud scales	C
VC032	3.83 (-35.73)	A*** inc. Bryophytae and Phragmites australis, leaves	A* - Menyanthes trifoliata, Cyperaceae, Typha latifolia, Betula sp., indets	-
VC032	4.11 (-36.01)	A*	-	-
VC039	3.07 (-35.77)	A**	A - Menyanthes trifoliata, Characeae, indets	-

Key: A*** = exceptional, A** = 100+, A* = 30-99, A = >10, B = 9-5, C = <5

5.3.2 Plant macrofossils were observed in all four sub-samples assessed (**Table 5**). Preservation and abundance of vegetative remains was exceptional in VC028 and the uppermost sample in VC032, with relatively lower abundance in VC039, and the basal sub-sample from VC032. Seeds and scales were recorded in all sub-samples with the exception of the basal sub-sample from VC032 which is highly decomposed. Insect remains were observed in small numbers in VC028.

5.3.3 The assessment of macrofossils suggests local to regional vegetation is reed swamp with sedges and tall grasses, and localised areas of birch (*Betula*) woodland. In VC039, the presence of the algae Characeae is an indicator of a freshwater environment.

5.4 Pollen and spores assessment

5.4.1 The results of pollen assessment of vibrocores VC028, VC032 and VC039 are presented here (**Table 6, Table 7 and Table 8**), accompanied by an outline interpretation (where results allow) of past vegetation environments and evidence for associated anthropogenic activity.

Vibrocore VC028

5.4.2 Three sub-samples were assessed for pollen preservation and concentration from the peat in VC028 (**Unit 4b**) (**Table 6**). Pollen preservation and concentrations is excellent in all three samples.

5.4.3 The basal sub-sample (2.60 mbsf) is dominated by arboreal pollen, principally *Pinus sylvestris* (pine) and *Corylus avellana* type (hazel) with a smaller proportion of *Salix* (willow), *Betula* (birch), *Ulmus* (elm) and *Quercus* (oak). Herb pollen largely comprises Poaceae (grass family). The subsequent two sub-samples include a greater quantity of Poaceae (roughly one-third of the count), with arboreal pollen declining, and *Corylus* becoming the dominant woodland species at 2.50 mbsf.

5.4.4 Pteridophyte spores occur in low quantities, largely Pteropsida undiff. (undifferentiated fern spores). A small number of aquatic pollen taxa were recorded comprising *Potamogeton natans* type (pondweed) and *Sparganium emersum* type (unbranched bur-reed).

5.4.5 The assessment from VC028 suggests a pine-dominated woodland initially, with an increasing influence of hazel-woodland and grasslands as the peat develops.

Table 6 Results of pollen assessment, vibrocore VC028.

Taxon	Depth (mbsf)	2.50	2.55	2.60
	Depth (mLAT)	-33.70	-33.75	-33.80
	Lithology	Peat		
	Unit	Unit 4b		
Betula (birch)		6	10	5
Pinus sylvestris (pine)		29	52	63
Corylus avellana type (hazel)		51	18	35
Ulmus (elm)		9	3	3
Quercus (oak)		5	9	6
Salix (willow)		1	-	12
Poaceae (grass family)		46	46	18
Cyperaceae (sedge family)		1	12	5
Rumex acetosa (common sorrel)		-	-	1
Chenopodiaceae (goosefoot family)		1	-	-
Rosaceae (rose family)		-	-	1
Filipendula (meadowsweet)		-	-	1
Aster type (daisies)		1	-	-
Pteropsida undiff. (undifferentiated fern spore)		9	1	8

Taxon	Depth (mbsf)	2.50	2.55	2.60
	Depth (mLAT)	-33.70	-33.75	-33.80
	Lithology	Peat		
	Unit	Unit 4b		
Pteridium aquilinum (bracken)		1	1	1
Thelypteris palustris (marsh fern)		2	-	-
Potamogeton natans type (pondweed)		5	7	1
Sparganium emersum type (unbranched bur-reed)		-	1	2
Total Land Pollen (TLP)		**150**	**150**	**150**
Pollen concentration		**1**	**1**	**1**
Pollen preservation		**1**	**1**	**1**

Preservation and Concentration: 1 = Excellent, 2 = Good, 3 = Moderate, 4 = Poor, 5 = Very poor/absent

Vibrocore VC032

5.4.6 Eight sub-samples were assessed for pollen preservation and concentration from vibrocore VC032 (**Table 7**). Pollen preservation and concentrations are excellent in the top four sub-samples 3.82 to 3.58 mbsf), with excellent concentrations and good preservation at 4.08 mbsf and 3.98 mbsf, moderate preservation and concentration at 3.90 mbsf, and moderate concentration and poor preservation in the basal sub-sample 4.13 mbsf.

5.4.7 The basal two sub-samples (4.13 to 4.06 mbsf) are characterised by large quantities of herbaceous pollen, dominated in the basal sub-sample by Cyperaceae (sedge family) and Poaceae in the overlying sub-sample. The basal sub-sample also includes a higher quantity of pollen grains of Chenopodiaceae (goosefoot family), declining thereafter.

5.4.8 Arboreal pollen increases in sub-samples from 3.98 mbsf, comprising large quantities of *Pinus sylvestris* at 3.98 and 3.90 mbsf, with a smaller component of *Corylus avellana* type, *Betula* and *Quercus*, with *Ulmus* appearing at 3.90 mbsf.

5.4.9 The arboreal component of the pollen assemblage changes from 3.82 mbsf with a sharp reduction in *Pinus sylvestris* and an increase in *Corylus avellana* type, along with a smaller increase in the quantities of *Ulmus* and *Betula*. Quantities of Corylus avellana type continue to increase within the silt and silty clay overlying the peat, accompanied by increasing quantities of Poaceae and Chenopodiaceae.

5.4.10 There is a significant spike in Pteridophyte spores at 3.82 mbsf, particularly Pteropsida undiff and *Thelypteris palustris* (marsh fern). Aquatic pollen also increases in this sub-sample, including *Typha latifolia* (bulrush), *Typha angustifolia* (lesser bur-reed), *Potamogeton natans* type and *Sparganium emersum* type. Pteridophyte spores and aquatic pollen otherwise occur in small quantities.

5.4.11 This sequence shows the progressive development of a tall herb swamp with and increasing influence of woodland, probably occupying areas of dryland locally. The woodland is pine-dominated initially, but transitions into a hazel-dominated woodland with time.

Table 7 Results of pollen assessment, vibrocore VC032.

Taxon	Depth (mbsf)	3.58	3.69	3.77	3.82	3.90	3.98	4.06	4.13
	Depth (mLAT)	-35.48	-35.59	-35.67	-35.72	-35.80	-35.88	-35.96	-36.03
	Lithology	Silt		Silty clay	Peat				Sandy silt
	Uni	4c			4b				4c
Betula (birch)		6	9	8	12	3	3	6	2

Taxon	Depth (mbsf)	3.58	3.69	3.77	3.82	3.90	3.98	4.06	4.13
	Depth (mLAT)	-35.48	-35.59	-35.67	-35.72	-35.80	-35.88	-35.96	-36.03
	Lithology	Silt		Silty clay	Peat				Sandy silt
	Uni	4c			4b				4c
Pinus sylvestris (pine)		22	17	21	33	117	125	57	32
Corylus avellana type (hazel)		82	84	70	77	12	11	1	-
Ulmus (elm)		4	6	10	7	1	-	-	-
Quercus (oak)		10	8	10	8	8	2	-	-
Salix (willow)		1	2	-	2	-	1	1	1
Hedera helix (ivy)		-	-	-	-	1	-	-	-
Poaceae (grass family)		12	22	23	6	5	7	68	11
Cyperaceae (sedge family)		-	1	-	3	2	5	14	87
Caryophyllaceae (pink family)		-	1	-	-	-	-	-	-
Chenopodiaceae (goosefoot family)		12	2	4	-	-	-	2	12
Rosaceae (rose family)		-	-	1	1	-	-	1	1
Filipendula (meadowsweet)		-	-	-	1	1	-	-	-
Apiaceae (carrot family)		-	-	-	-	-	1	-	-
Brassicaceae (cabbage family)		-	-	-	1	-	-	-	-
Lactuceae (lettuce family)		-	-	-	-	-	-	-	6
Aster type (daisies)		1	-	3	1	-	-	-	-
Pteropsida undiff. (undifferentiated fern spore)		9	25	22	270	6	4	18	2
Pteridium aquilinum (bracken)		1	-	-	2	1	1	1	-
Dryopteris filix-mas (male fern)		-	-	1	1	-	-	-	-
Thelypteris palustris (marsh fern)		1	-	-	165	1	-	-	-
Potamogeton natans type (pondweed)		1	-	3	16	7	9	10	-
Sparganium emersum type (unbranched bur-reed)		1	-	2	5	2	2	3	1
Typha latifolia (bulrush)		-	1	-	28	-	-	-	2
Typha angustifolia (lesser bulrush)		1	-	-	15	-	-	-	-
Menyanthes trifoliata (bogbean)		-	-	1	-	-	-	-	-
Sphagnum (bog moss)		-	1	-	-	-	-	-	-
Indeterminables		-	1	-	3	11	3	3	2
TLP		**150**	**152**	**150**	**152**	**150**	**155**	**150**	**152**
Pollen concentration		**1**	**1**	**1**	**1**	**3**	**1**	**1**	**3**
Pollen preservation		**1**	**1**	**1**	**1**	**3**	**2**	**2**	**4**

Preservation and Concentration: 1 = Excellent, 2 = Good, 3 = Moderate, 4 = Poor, 5 = Very poor/absent

Vibrocore VC039

5.4.12 Three sub-samples were assessed for pollen preservation and concentration from vibrocore VC039 (**Table 8**). Excellent preservation and concentrations were recorded from the basal sub-sample (3.15 mbsf), with good preservation but poor concentrations at 3.07 mbsf and good concentrations but poor preservation at 2.94 mbsf.

5.4.13 The basal sub-sample (3.15 mbsf) is dominated by herbaceous pollen, largely Poaceae, but with a large quantity of *Betula*. The basal sub-sample also includes a large quantity of aquatic pollen taxa, including *Typha latifolia*, *Menyanthes trifoliata* (bogbean), *Sparganium emersum* type and *Potamogeton natans* type. A full assessment count was not possible from 3.07 mbsf due to low concentrations, but what pollen is present comprises a large quantity of *Betula* and Poaceae.

5.4.14 The sub-sample at 2.94 mbsf differs, with a large increase in *Pinus sylvestris*, Cyperaceae and Pteropsida spores. Overall the diversity of the pollen assemblages is relatively restricted.

5.4.15 This pollen assemblage suggests tall herb swamp with birch-dominated woodland occupying dryland areas. As the peat develops there is an increasing influence of pine.

Table 8 Results of pollen assessment, vibrocore VC039.

Taxon				
	Depth (mbsf)	2.94	3.07	3.15
	Depth (mLAT)	-35.64	-35.77	-35.85
	Lithology	Peat		Sand
	Unit	4b		4a
Betula (birch)		2	13	36
Pinus sylvestris (pine)		115	3	3
Corylus avellana type (hazel)		2	1	3
Poaceae (grass family)		5	9	99
Cyperaceae (sedge family)		28	3	4
Rosaceae (rose family)		1	-	2
Filipendula (meadowsweet)		-	-	3
Pteropsida undiff. (undifferentiated fern spore)		38	2	2
Pteridium aquilinum (bracken)		-	-	1
Myriophyllum spicatum (spiked water-milfoil)		-	-	1
Potamogeton natans type (pondweed)		-	-	2
Sparganium emersum type (unbranched bur-reed)		-	-	5
Typha angustifolia (lesser bulrush)		-	-	18
Menyanthes trifoliata (bogbean)		-	-	5
Indeterminables		-	**1**	**2**
TLP		**153**	**29**	**150**
Pollen concentration		**2**	**4**	**1**
Pollen preservation		**4**	**2**	**1**

Preservation and Concentration: 1 = Excellent, 2 = Good, 3 = Moderate, 4 = Poor, 5 = Very poor/absent

5.5 Diatoms

5.5.1 Diatom assessment was undertaken on 42 sub-samples, comprising three sub-samples from VC028, ten from VC032, five from VC039, thirteen from VC016 and ten from VC047. A summary of the assessment results is presented in **Table 9** with comments on potential for full diatom analyses. Where diatom preservation was suitable, more detailed assessment was undertaken and is presented in **Appendix 4**.

Table 9 Summary of diatom assessment results

Sample No	Depth (mbsf)	Diatoms	Abundance	Quality of preservation	Diversity	Assemblage type	Potential for % count
VC028							
D1	2.75	-	-	-	-	-	none
D2	2.90	-	-	-	-	-	none
D3	3.05	-	-	-	-	-	none
VC032							
D4	3.50	+	mod high	poor to good	mod	mar bk fw	good
D5	3.58	+	mod	poor to mod	mod	bk fw mar	mod
D6	3.40	+	mod	poor to mod	mod	bk mar fw	mod
D7	3.30	+	low	poor	mod	mar bk fw	some
D8	3.69	+	mod	poor	mod	bk mar fw	mod
D9	3.77	+	mod	poor	mod	bk fw mar	mod
D10	4.17	-	-	-	-	-	none
D11	4.32	-	-	-	-	-	none
D12	4.44	-	-	-	-	-	none
D13	4.56	-	-	-	-	-	none
VC039							
D14	2.75	+	v low	ex poor	low	bk-mar, mar	none
D15	2.90	+	v low	ex poor	low	mar, bk-mar	none
D16	3.15	-	-	-	-	-	none
D17	3.31	-	-	-	-	-	none
D18	3.51	-	-	-	-	indet frag	none
VC016							
D19	0.20	-	-	-	-	-	none
D20	0.45	-	-	-	-	-	none
D21	0.70	-	-	-	-	-	none
D22	0.95	-	-	-	-	-	none
D23	2.18	-	-	-	-	-	none
D24	2.38	-	-	-	-	-	none
D25	2.58	-	-	-	-	-	none
D26	1.15	-	-	-	-	-	none
D27	1.40	-	-	-	-	-	none
D28	1.65	-	-	-	-	-	none
D29	3.35	-	-	-	-	Indet frag	none
D30	3.85	-	-	-	-	-	none
D31	4.40	-	-	-	-	-	none
D32	4.87	-	-	-	-	-	none
VC047							
D33	1.70	-	-	-	-	-	none
D34	1.90	-	-	-	-	-	none
D35	2.10	-	-	-	-	-	none

Sample No	Depth (mbsf)	Diatoms	Abundance	Quality of preservation	Diversity	Assemblage type	Potential for % count
D36	2.35	-	-	-	-	-	none
D37	2.60	-	-	-	-	-	none
D38	2.80	-	-	-	-	-	none
D39	3.35	-	-	-	-	-	none
D40	3.80	-	-	-	-	-	none
D41	4.35	-	-	-	-	-	none
D42	4.80	-	-	-	-	-	none
Key: + = present; - = absent; mod = moderate; ex = extremely; bk = brackish; mar = marine; fw = freshwater; aero = aerophilous; hal = halophilous; acid = acidophilous; oligtr = oligotrophic; non-planktonic = non-pk; indet frag = indeterminant fragment							

Vibrocores VC028, VC016 and VC047

5.5.2 Diatoms were not preserved in all sub-samples from VC028 and VC047, nor in VC016 with the exception of one sub-sample (D29) where an undetermined fragment was observed (**Table 9**).

5.5.3 The absence of diatoms from these cores can be attributed to taphonomic processes (Flower 1993, Ryves et al. 2001). This may be the result of diatom silica dissolution and breakage caused by factors such as extremes of sediment salinity, alkalinity or acidity, the under-saturation of sediment pore water with dissolved silica, cycles of prolonged drying and rehydration, movement of water, or physical damage to diatom valves from abrasion.

Vibrocore VC032

5.5.4 Ten samples from vibrocore VC032 were assessed for diatoms, four (D10, D11, D12 and D13) from the minerogenic deposits underlying peat (**Unit 4a**), three (D5, D8 and D9) from overlying minerogenic deposits (**Unit 4c**), and three (D4, D6, D7) from **Unit 5** which are interpreted as marine.

5.5.5 Diatoms are absent from sub-samples D10 to D13 (**Table 9**).

5.5.6 Diatom assemblages are present in the upper six sub-samples (D9 to D4; 3.50 to 3.77 mbsf). There are moderate or moderately high numbers of diatoms in these samples, with the exception of sample D7 (3.30 m) where the numbers of diatoms are low and the quality of preservation is poor. In the remaining five sub-samples, the quality of valve preservation varies from poor, poor to moderate, or poor to good. Diatom diversity in samples D9 to D4 is moderately high. With the exception of sample D7, where there is only some potential for further diatom analysis, there is moderate or good potential for percentage diatom counting of subsamples from **Unit 4c** (D5, D8 and D9) and **Unit 5** (D4 and D6).

5.5.7 The diatom assemblages of samples D9 to D4 are composed of mixtures of brackish, marine and freshwater diatom taxa (**Table 9** and **Appendix 4**). Girdle bands of the non-planktonic marine genus *Grammatophora* are present or common in all six samples and the marine planktonic species *Paralia sulcata* is common or present in all but sub-sample D8 (3.69 mbsf). The planktonic marine diatom *Podosira stelligera* is present or common in the top four samples. Other polyhalobous diatoms present in these samples include *Rhaphoneis surirella* and the benthic diatom *Trachyneis aspera*. The polyhalobous to mesohalobous diatom *Cocconeis scutellum* is abundant in five of the top samples and is also present in sample D7. The consistent importance of *Cocconeis scutellum*, a non-planktonic species, suggests that it is an autochthonous (formed in-situ) diatom and that the samples represent shallow water coastal environments. Other marine-brackish taxa include non-planktonic diatoms such as *Nitzschia constricta*, *Ardissonia crystallina* and *Synedra gaillonii*; and planktonic taxa such as *Actinoptychus undulatus* and *Hyalodiscus scoticus*.

5.5.8 A number of mesohalobous, mainly benthic and attached, diatoms are also present or common in sub-samples D9 to D4. These brackish water taxa include *Diploneis didyma*, *Rhopalodia musculus*, *Synedra tabulata*, *Nitzschia punctata*, *Nitzschia navicularis*, *Achnanthes brevipes*, *Achnanthes delicatula*, *Diploneis aestuari* and *Nitzschia granulata*. Again, the importance of non-planktonic taxa indicates the presence of shallow water, tidal habitats.

5.5.9 A number of freshwater diatoms are also present in samples D9 to D4. The epiphytic species *Cocconeis placentula* is common or abundant in three samples (D5, D8 and D9) and Aulacoseira sp. are present or common in three samples (D4, D6 and D7). Other oligohalobous indifferent diatoms that are present include *Amphora pediculus*, *Cocconeis disculus* and *Navicula scutelloides*. Diatoms with freshwater growth optima such as *Fragilaria brevistriata*, *Fragilaria construens* var. *binodis* and *Fragilaria pinnata* have wide salinity ranges.

5.5.10 The mixed diatom assemblages of samples D9 to D4 from **Unit 4c** and **Unit 5** in VC032, and the overall importance of marine and marine brackish taxa, with large numbers of shallow water taxa, is consistent with the preliminary interpretation that suggests that these samples represent intertidal deposits.

Vibrocore VC039

5.5.11 Five sub-samples were assessed for diatoms from vibrocore VC039, three (D16, D17 and D18) from a minerogenic deposit (**Unit 4a**) below peat and two (D14 and D15) from overlying marine sediments (**Unit 5**).

5.5.12 Diatom assemblages are absent from the bottom three samples (D16 to D18; 3.15 to 3.51 mbsf); a single indeterminate diatom fragment was recorded in sample D18.

5.5.13 In the top two samples (D14 and D15; 2.75 and 2.90 mbsf) there are very low numbers of extremely poorly preserved diatoms. There is no further potential for diatom analysis of the samples from vibrocore VC039. However, the fragmented and dissolved diatom assemblages of samples D14 and D15 do provide some useful environmental information.

5.5.14 The diatom assemblages of D14 and D15 are composed of marine-brackish and marine diatoms. The marine, planktonic diatom *Paralia sulcata* is present in both samples and is relatively common in D15. Other marine species include the planktonic diatom *Auliscus sculptus* in D15 and the polyhalobous to mesohalobous, non-planktonic species *Synedra gaillonii* in D14. The mesohalobous, benthic diatoms *Nitzschia navicularis* and *Diploneis didyma* are present or common in both samples. Freshwater and halophilous diatoms are absent from D14 and D15. The diatom assemblages of these samples represent coastal, marine habitats with no evidence of in wash from freshwater environments.

5.6 Foraminifera and Ostracod

5.6.1 The results of the foraminifera and ostracod assessment of vibrocores VC016, VC028, VC032, VC039 and VC047 are presented here, accompanied by an outline interpretation of past climatic and environmental conditions. Foraminifera and ostracods are recorded on a presence (x) or absence (-) basis, either as (o) one specimen, several specimen (x), abundant (xx) or superabundant (xxx). Where other palaeoenvironmental material (e.g. plant fragments) was observed within the sample residue, this was also noted in the assessment. Proxy ecological data for the ostracods and foraminifera, based on Athersuch *et al*. (1989) and Murray (2006), respectively, and expert judgment is used for the reconstructions.

5.6.2 The five vibrocores assessed will be discussed in two groups: the first comprises Units 4 and 5 recovered in VC028 (**Table 10**), VC032 (**Table 11 and Table 12**) and VC039 (**Table 15**); the second Brown Bank (**Unit 3**) and Undifferentiated deposits in VC016 (**Table 13** and **Table 14**) and VC047 (**Table 16**).

Table 10 Foraminifera and ostracod assessment, vibrocore VC028.

Contents	**Depth (mLAT)**	-33.95	-34.10	-34.25
	Depth (mbsf)	2.75	2.90	3.05
	Lithology	Sand		
	Unit	Unit 4a		
plant debris + seeds		**X**	**X**	**X**
peat (fragments)		**X**		
reworked marine foraminifera				**X**
ECOLOGY		Alluvial silts, initially with a few reworked marine foraminifera		
AGE		Devensian		

Vibrocores VC028, VC032 and VC039

5.6.3 Sub-samples from these vibrocores span the peat deposit (**Unit 4b**) and over/underlaying minerogenic units (**Units 4a**, **4c** and **5**), interpreted based on lithostratigraphy to document flooding of a terrestrial landscape during Holocene sea-level rise (Wessex Archaeology 2018b).

5.6.4 In VC028, three samples were taken from **Unit 4a** and of these only one preserved foraminifera (3.05 m; -34.25 mLAT) which are indicative of a cold climate marine environment (Table 9). However, these foraminifera showed evidence of reworking, most likely from underlying Brown Bank deposits (**Unit 3**), so do not represent environmental conditions at the time of deposition. In VC028, ostracods were absent, but plant debris and peat fragments were observed in samples.

5.6.5 Plant debris and cold climate reworked foraminifera were also observed in sub-samples from **Unit 4a** in VC032 and VC039 (**Table 11, Table 12 and Table 15**). However, in VC039 at depths 3.15 mbsf (-35.85 mLAT) and 3.31 mbsf (-36.01 mLAT) a promising freshwater ostracod fauna with cold/cool climate indicators were preserved which is the only *in situ* fossiliferous material from **Unit 4a**, therefore having the potential to be taken forward to an analytical stage.

5.6.6 Sub-samples from **Unit 4a** in VC028, VC032 and VC039 are interpreted to represent a vegetated channel or cut-off associated with a freshwater river in a terrestrial setting. The cool/cold climate ostracod fauna may suggest a Late Devensian age for these deposits, but chronological dating would be required to test this.

5.6.7 In VC032, overlying the peat (**Unit 4b**) were clay and laminated silt deposits interpreted to represent an intertidal environment (**Unit 4c**). The boundary at the top of **Unit 4c** was sharp and comprised a thin (3 cm) layer of broken shell, possibly a ravinement surface formed during marine transgression, this was then overlain by sands typical of seabed sediments **Unit 5**).

5.6.8 Sub-samples from **Unit 4c** in VC032 preserve brackish foraminifera and ostracods indicative of brackish tidal flat environments (**Table 11 and Table 12**). Outer estuarine/marine ostracods were observed in the uppermost sub-sample within **Unit 4c** (3.58 m; -35.48 mLAT) suggesting an increasing marine influence which would be expected during sea-level rise.

5.6.9 This increasing marine influence is also represented by the foraminifera and ostracods preserved in **Unit 5**. Again, brackish foraminifera and ostracods are present along with outer estuarine/marine foraminifera and ostracods. The palaeoecology of these deposits indicates a tidal flat environment with outer estuarine influences. This differs to the interpretation based on lithology, suggesting the sandy deposits of **Unit 5** are not seabed sediments but instead sandier units of **Unit 4c**.

5.6.10 In VC039, sub-samples from **Unit 5** were also taken and comprised brackish and outer estuarine/marine foraminifera and ostracods interpreted to represent a tidal flat to open estuarine environment (**Table 15**).

Table 11 Foraminifera and ostracod assessment, vibrocore VC032.

Contents	**Depth (mLAT)**	-35.20	-35.30	-35.40	-35.48	-35.59	-35.67
	Depth (mbsf)	3.30	3.40	3.50	3.58	3.69	3.77
	Lithology	Silty sand			Silt	Clay	
	Unit	5			4c		
outer estuarine/marine molluscs		X					
echinoderm remains		X	X				
fish remains		X					
outer estuarine/marine foraminifera		X					
brackish foraminifera		X	X	X	X	X	X
outer estuarine/marine ostracods			X	X			
plant debris + seeds			X	X	X	X	X
brackish molluscs (hydrobids, cockles, Littorina)			X	X	X	X	X
brackish ostracods			X	X	X	X	X
charophyte oogonia							
diatoms (>75µ)						X	
insect remains						X	X
reworked marine foraminifera							
ECOLOGY		Tidal mudflats; outer estuarine influences developing with sea-level rise				Brackish tidal mudflats and creeks	
AGE		Holocene					

Table 12 Foraminifera and ostracod assessment, vibrocore VC032 (continued from **Table 11**)

Contents	**Depth (mLAT)**	-36.07	-36.22	-36.34	-36.46
	Depth (mbsf)	4.17	4.32	4.44	4.56
	Lithology	Sand		Sand with silt lamination	
	Unit	4a			
outer estuarine/marine molluscs					
echinoderm remains					
fish remains					
outer estuarine/marine foraminifera					
brackish foraminifera					
outer estuarine/marine ostracods					
plant debris + seeds		**X**	**X**	**X**	**X**
brackish molluscs (hydrobids, cockles, Littorina)					
brackish ostracods					
charophyte oogonia					
diatoms (>75µ)					
insect remains				**X**	
reworked marine foraminifera				**X**	**X**
ECOLOGY		Alluvium		Alluvium with reworked marine cold climate foraminifera	
AGE		Devensian			

Table 13 Foraminifera and ostracod assessment, vibrocore VC016.

Contents	**Depth (mLAT)**	-39.42	-39.67	-39.92	-40.17	-40.37	-40.62
	Depth (mbsf)	0.22	0.47	0.72	0.97	1.17	1.42
	Lithology	Sand	Silty sand				
	Unit	5	Undifferentiated				
plant debris + seeds + megaspores		**X**	**X**	**X**	**X**	**X**	**X**
echinoderm remains		**X**					
molluscs		**X**		**F**	**F**		
outer estuarine/marine foraminifera		**X**	**X**	**X**	**X**	**X**	**X**
outer estuarine/marine ostracods		**X**	**X**	**X**	**X**	**X**	**X**
insect remains			**X**				
iron minerals			**X**	**X**	**X**	**X**	
charophyte oogonia							

Contents	**Depth (mLAT)**	-39.42	-39.67	-39.92	-40.17	-40.37	-40.62
	Depth (mbsf)	0.22	0.47	0.72	0.97	1.17	1.42
	Lithology	Sand	Silty sand				
	Unit	5	Undifferentiated				
ECOLOGY		Outer estuarine/ marine	Outer estuarine/marine environment developed in (?shallow) embayment. Microfauna of cold climate aspect but probably no younger than MIS 3; however much of it is reworked/derived and contains at least one Ipswichian (MIS 5e) component.				
AGE		Holocene	Ipswichian to Early Devensian				

Vibrocores VC016 and VC047

5.6.11 Sub-samples from VC016 and VC047 targeted Brown Bank deposits (**Unit 3**) between 1.67 and 4.85 mbsf in VC016, and between 2.65 and 4.85 mbsf in VC047, overlain in both cores by a coarser-grained Undifferentiated deposit that was difficult to interpret according to depositional setting. Foraminifera and ostracod assessment was undertaken with the aim of determining palaeoenvironment, and to establish if the Undifferentiated deposit was related to Brown Bank (**Unit 3**) or to Holocene pre-transgression sediments (Unit 4).

5.6.12 In VC016, all sub-samples in both Brown Bank (**Unit 3**) and Undifferentiated deposits preserve outer estuarine/marine foraminifera and ostracod species indicative of a cold/cool climate (**Table 13, Table 14** and **Appendix 5**). Both foraminifera and ostracods are highly diverse, but no single species is particularly common. The similarities between the microfauna of Brown Bank (**Unit 3**) and the Undifferentiated Unit suggest this deposit is likely part of Brown Bank Formation rather than an early Holocene deposit.

5.6.13 Brown Bank (**Unit 3**) deposits in VC047 have a similar microfauna to that of VC016, but slightly less diverse (**Table 16**). These microfauna suggest a protected lagoon or large embayment of possibly less than normal marine salinity. Microfauna for the most part indicate a cold climate (Devensian).

5.6.14 The upper three sub-samples in the Undifferentiated deposits (1.70; 1.90 and 2.15 mbsf) appear different from underlying Brown Bank (**Unit 3**), and Undifferentiated deposits in VC016. These sub-samples contain three species in particular that suggest a living fauna (biocenosis) and a warmer climate. These are very large and ornate *Ammonia batavus* (which would be clinging to marine algae and/or sea-grass) and which according to Funnell (1989) are restricted in the North Sea to interglacial periods, along with the ostracods *Pontocythere elongata* and *Elofsonella concinna*, all in large numbers. The ecology of the two ostracods is outlined in **Appendix 5**– both are sublittoral (below intertidal zone) species living on sandy-silty substrates, although the latter would not be found offshore of Norfolk today, its southernmost occurrence being further north. In this vibrocore, the upper part of the Undifferentaited deposits require dating, to see whether these microfauna are substantially younger (early Holocene) or where living within an interstadial of the Devensian when temperatures would have been similar to today.

5.6.15 Brown Bank (**Unit 3**) deposits in VC016 and VC047 comprise, at depth (3.85-4.85 mbsf VC047; 0.97-3.87 mbsf), the ostracod *Roundstonia globulifera* which has been extinct in Britain since MIS 3 in the early Devensian (**Appendix 5**). This is a possible biostratigraphic marker placing the age of Brown Bank sediments as no earlier than MIS 3.

5.6.16 In VC016, the ostracod *Callistocythere curryi* was recorded in two samples (0.72 and 1.17 mbsf), although only one specimen was observed in each case and it was possibly reworked. This species has not been recorded in Britain since MIS 5e.

5.6.17 During foraminifera and ostracod assessments, the presence of plant fragments was noted in all samples, but more so in VC047 at depth (from 2.65– 4.85 mbsf). This organic material looks finely disseminated, typical of that found washed up on a strand line in a coastal setting.

5.6.18 The presence of iron minerals was also noted throughout Brown Bank and Undifferentiated deposits in VC016, and in Brown Bank (**Unit 3**) in VC047. Two types of iron appear to be present distinguishable by colour (black and orange). These iron precipitates may be associated with weathering or near-surface groundwaters (Ashton *et al.,* 2005), formed prior to the onset of fully terrestrial conditions. These iron rich intervals within the Brown Bank may indicate periods of drying out and weathering in shallow water-subaerial settings.

Table 14 Foraminifera and ostracod assessment, vibrocore VC016 (continued from **Table 13**)

Contents	**Depth (mLAT)**	-40.87	-41.40	-41.60	-41.80	-42.57	-43.07	-43.58	-44.05
	Depth (mbsf)	1.67	2.20	2.40	2.60	3.37	3.87	4.38	4.85
	Lithology	Sandy silt						Silt and clay	
	Unit	3							
plant debris + seeds + megaspores		X	X	X	X	X	X	X	X
echinoderm remains									
molluscs									
outer estuarine/marine foraminifera		X	X	X	X	X	X	X	
outer estuarine/marine ostracods		X	X	X	X	X	X	X	
insect remains		X	X					X	
iron minerals		X	X	X			X		
charophyte oogonia								X	
ECOLOGY		Outer estuarine/marine environment developed in (?shallow) embayment. Microfauna of cold climate aspect but probably no younger than MIS 3; however much of it is reworked/derived and contains at least one Ipswichian (MIS 5e) component.							
AGE		Ipswichian to Early Devensian							

Table 15 Foraminifera and ostracod assessment, vibrocore VC039.

Contents	**Depth (mLAT)**	-35.45	-35.60	-35.85	-36.01	-36.21
	Depth (mbsf)	2.75	2.90	3.15	3.31	3.51
	Lithology	Silty sand		Silty sand		
	Unit	Unit 5		Unit 4a		
plant debris + seeds		X	X	x	X	X
brackish molluscs (hydrobids, cockles, Littorina)		X	X			
brackish foraminifera		X	X			

Contents	Depth (mLAT)	-35.45	-35.60	-35.85	-36.01	-36.21
	Depth (mbsf)	2.75	2.90	3.15	3.31	3.51
	Lithology	Silty sand		Silty sand		
	Unit	Unit 5		Unit 4a		
brackish ostracods		X	X			
diatoms (>75µ)		X				
insect remains		X		X		
outer estuarine/marine foraminifera		X	X			
outer estuarine/marine ostracods		X	X			
freshwater ostracods		X		X	X	
peat			X	X	X	X
charophyte oogonia			x	X	X	
reworked marine foraminifera					x	X
ECOLOGY		Brackish tidal flats, becoming more open estuarine		Freshwater cold-climate vegetated river alluvium, initially with reworking		Alluvial silts with reworked foraminifera
AGE		Holocene		Devensian		

Table 16 Foraminifera and ostracod assessment, vibrocore VC047.

Contents	Depth (mLAT)	-36.20	-36.40	-36.65	-36.90
	Depth (mbsf)	1.70	1.90	2.15	2.40
	Lithology	Silty clayey sand			
	Unit	Undifferentiated			
outer estuarine/marine molluscs		X	X	F	F
echinoderm remains		X	X		X
outer estuarine/marine foraminifera		X	X	X	X
outer estuarine/marine ostracods		X	X	X	X
plant debris + megaspores			X	X	
iron minerals					
ECOLOGY		Climate ameliorating (interstadial), sea-grass/sand-silt community			Protected lagoon or large embayment of possibly less than normal salinity. Microfauna for the most part indicate a cold climate
AGE		Devensian			

Table 17 Foraminifera and ostracod assessment, vibrocore VC047 (continued from **Table 15**)

Contents	**Depth (mLAT)**	-37.15	-37.35	-37.90	-38.35	-38.90	-39.35
	Depth (mbsf)	2.65	2.85	3.40	3.85	4.40	4.85
	Lithology	Clayey sandy silt					
	Unit	3					
outer estuarine/marine molluscs		**F**		**F**			**F**
echinoderm remains							
outer estuarine/marine foraminifera		**X**	**X**	**X**	**X**	**X**	**X**
outer estuarine/marine ostracods		**X**	**X**	**X**	**X**	**X**	**X**
plant debris + megaspores		**X**	**X**	**X**	**X**	**X**	**X**
iron minerals		**X**	**X**	**X**	**X**	**X**	
ECOLOGY		Protected lagoon or large embayment of possibly less than normal salinity. Microfauna for the most part indicate a cold climate					
AGE		Devensian					

6 DISCUSSION

6.1 Introduction

6.1.1 The palaeoenvironmental assessment results are considered collectively with reference to the aims and objectives outlined in **Section 3**, and to the regional research agenda (Medlycott 2011) and the national maritime research framework (Ransley *et al.* 2013), with recommendations for Stage 4 analysis presented in **Section 7** below.

6.1.2 Deposits identified as being of geoarchaeological interest (Wessex Archaeology 2018b) include pre-transgression peats and over/underlying minerogenic deposits (**Unit 4**), Upper Brown Bank (**Unit 3**) and an Undifferentiated deposit that lies between **Unit 3** and **Unit 4**. Each of these deposits is discussed here in relation to paleoenvironmental evolution of the Norfolk Boreas site.

6.2 Upper Brown Bank (Unit 3)

6.2.1 Deposits interpreted as belonging to the Upper Brown Bank Formation were identified as having geoarchaeological potential during Stage 2 recording (Wessex Archaeology 2018b). These comprised fine-grained sediments interpreted to have been deposited in a lagoon to intertidal environment, indicating shallow water in close proximity to a coast which may have been suitable for human exploitation. The Upper Brown Bank sediments are considered to have the potential to preserve in situ Lower Palaeolithic artefacts, depending on its age.

6.2.2 Chronological information from Brown Bank Formation deposits is rare; and those dates that do exist suggest deposition during the Early/Middle Devensian (MIS 5d-MIS 3), potentially extending into the Late Devensian (Limpenny et al. 2011; Wessex Archaeology 2018d). It is unknown if these dates represent continuous deposition, and thus continuous presence of a shallow lagoon in the southern North Sea over a long period of time, or if they represent punctuated shorter phases of deposition where the lagoon dried out periodically.

6.2.3 The full extent of the lagoon is also unknown, making it difficult to locate or target the margins which would have greater potential for occupation, and thus preservation of in situ artefacts.

6.2.4 To better assess the archaeological potential of this Formation, we need greater age control by way of absolute dating, and a stronger understanding of the paleogeographic configuration of this landscape. This is particularly important as it appears to correspond with a period of human absence from Britain, raising the question as to whether migration pathways from mainland Europe were obstructed by the presence of the Brown Bank lagoon.

6.2.5 Upper Brown Bank sediments are likely present across the Norfolk Boreas site, although they are not always clearly visible on geophysical data due to being overlain by large sand banks or dissected by younger shallow channels (Fugro 2018). The base of Upper Brown Bank deposits within the site area is generally sub-horizontal, except where dissected by two large channel features in the south-eastern part of the site (Fugro 2018). The recorded thickness of Upper Brown Bank deposits on site range from 3 m up to 38 m where they infill one of the large channel features. Geophysical interpretation suggests a complex depositional history, with strong reflectors possibly indicating surfaces within the Upper Brown Bank deposits which may have formed during periods of exposure or drying out (Wessex Archaeology 2018c).

6.2.6 Upper Brown Bank deposits were recovered in VC016 and VC047 of a sufficient thickness to allow palaeoenvironmental assessment (4.14 m and 2.89 m respectively). VC016 is located in the mid-western part of the site and VC047 is located in the north-east corner (**Figure 4**). Both vibrocores are located in the troughs separating marine sediment banks, where present-day erosion is expected to have removed overlying Holocene deposits (if present), and possibly part of the Upper Brown Bank. The top of Upper Brown Bank in VC047 is at an elevation of -36.91 mLAT, which is shallower than in VC016 where the top of Upper Brown Bank is at -40.80 mLAT.

6.2.7 To establish the age of Upper Brown Bank deposits, four sub-samples were submitted for OSL dating, two from VC016 and two from VC047. Considering the analytical validity of the ages, only two ages were fully accepted, these being GL17153 and GL17154 from VC016 (**Table 3**).

6.2.8 The results from VC016 suggest deposition of Upper Brown Bank between 83.2 ± 9.5 ka (MIS 5a) and 69.8 ± 7.7 ka (MIS 4). However, these ages are not conformable as the older date (83.2 ± 9.5 ka) came from a sub-sample at -41.05 mLAT, whereas the younger age came from a sub-sample located below at an elevation of -42.03 mLAT. Despite the inversion, the dates overlap within error margins.

6.2.9 The inversion of OSL dates in VC016 may be the result of environmental factors such as reworking or could be due to analytical uncertainty. There is evidence of bioturbation and possible deformation in VC016 between 3.68 mbsf and 5.75 mbsf. However, the samples submitted for OSL dating were not taken from this interval to avoid possible reworking and were instead taken from overlying finely laminated clayey silts which did not show any signs of disturbance. Therefore, it is proposed this inversion is a function of analytical factors.

6.2.10 Full OSL results, specifically inter-aliquot D_e distributions and age cumulative frequency plots (**Appendix 3**), were examined to assess inter-aliquot variability which may influence the final age. The upper sub-sample from VC016 at a depth of 1.70-2.00 mbsf (GL17154) exhibits an asymmetric distribution that is skewed towards higher D_e values. As ages are calculated based on mean D_e, this skewness may be influencing the final age, possibly giving an erroneously older date.

6.2.11 The D_e distribution from the lower sub-sample in VC016 at a depth of 2.65-3.00 mbsf (GL17153) is multi-modal suggesting there are two populations of D_e. Calculating an age by taking the mean D_e from a multi-modal distribution will be giving an average of both populations and further analysis would be required to determine which of the two populations is representative of dose history, and thus the age of the deposit.

6.2.12 OSL results have been assessed qualitatively at this stage due to the relatively small (12) number of aliquots analysed. To improve the accuracy and precision of the OSL ages from VC016, additional aliquots need to be analysed to determine if D_e variability is a result of heterogenous dose history or analytical inaccuracies.

6.2.13 OSL dates from VC047 have only tentatively been accepted as the interpolated to applied regenerative-dose ratio was overdispersed indicating sensitivity correction, a key part of the SAR protocol, may not have been effective. This is a function of inherent sample behaviour and properties.

6.2.14 The ages from VC047 are conformable and place deposition of Upper Brown Bank between 78.9 ± 8.3 ka (MIS 5a) and 60.5 ± 5.8 ka (MIS 4) (**Table 3**). Although there is evidence of analytical uncertainty, these dates lie within the same age range as VC016. They also lie within the range of Upper Brown Bank deposits recovered from the adjacent Norfolk Vanguard site where OSL dates place deposition between 82.4 ± 8.5 ka (MIS 5a) and 57.2 ± 6.4 ka (MIS 3) (Wessex Archaeology 2018d).

6.2.15 The depositional history of Upper Brown Bank was initially interpreted from core descriptions (Wessex Archaeology 2018b) where laminated clays and silts with occasional detrital organic inclusions and evidence of bioturbation suggested deposition in a low energy, possibly tidally influenced water body such as a lagoon. To test this interpretation, sub-samples from Upper Brown Bank in VC016 and VC047 were assessed for foraminifera, ostracods and diatoms to characterise depositional environment and paleoenvironmental change.

6.2.16 Diatoms are absent, or in two sub-samples represented by indeterminate silica fragments, from Upper Brown Bank deposits in cores VC016 and VC047. There is no further potential for diatom analysis of these deposits.

6.2.17 Within Upper Brown Bank from VC016 and VC047, both foraminifera and ostracods are preserved, and species diversity is high, but no single species is ever very common making interpretation difficult. According to Cameron and Holmes (1999), the Brown Bank Formation comprises “largely unfossiliferous silty clays”. In contrast, Upper Brown Bank deposits in VC016 and VC047 are highly fossiliferous as is the case for Brown Bank Formation deposits assessed from the Norfolk Vanguard site (Wessex Archaeology 2018d).

6.2.18 Foraminifera and ostracods in VC016 and VC047 are characterised as being outer estuarine to marine species indicative of a cold/cool climate. In VC016, the microfauna suggest deposition in a marine embayment, possibly shallow water, whereas in VC047, a slightly less diverse assemblage suggests a more protected lagoon or embayment of less than normal salinity. At present it is not possible determine if the sequences represent distinct environmental niches within a contemporaneous landscape, or if they formed at different times and thus document evolving palaoegeography of a restricted marine basin.

A refined chronology may address this, but further work would be required to reduce the error margins of the OSL dates.

6.2.19 The age of Upper Brown Bank from OSL dating extends from MIS 5a to MIS 4. In VC016 and VC047, the ostracod *Roundstonia globulifera* has been identified. This species has been extinct in Britain since MIS 3 suggesting Upper Brown Bank deposits were deposited before MIS 3 which corroborates the OSL dates. In VC016, the ostracod *Callistocythere curryi* was observed. This species went extinct in Britain MIS 5e, suggesting Upper Brown Bank deposits predate MIS 5e. However, this species showed evidence of reworking and was likely incorporated into Upper Brown Bank deposits through erosion of older sediments.

6.2.20 During foraminifera and ostracod assessment, iron precipitates, both orange and black (goethite?) in colour, were observed in some samples from VC016 and VC047. These suggest oxidation of the sediment, possibly through burrowing, pedogenic process or weathering which would occur if water depths were shallow or the embayment/restricted lagoon dried out. These iron rich intervals may correlate to reflectors seen in geophysical data that have been interpreted to represent periods of drying out or subaerial exposure.

6.2.21 Upper Brown Bank deposits within the Norfolk Boreas site are early to mid Devensian in age (MIS 5a-4) and represent deposition in a cold-climate open embayment to restricted lagoon. Environmental change may be related to fluctuating sea levels (**Figure 2**), with formation of a restricted lagoon during periods of lower sea level and a more open embayment during periods of relatively higher sea level. Changes in salinity may also be related to meltwater input from large river systems such as the Rhine-Meuse.

6.2.22 At present, it is not known if the embayment/lagoon was a persistent feature in the landscape or if it intermittently dried out. There is macrofaunal evidence to suggest periods of lower salinity and iron precipitates may represent weathering or bioturbation in a shallow water or subaerial environment.

6.2.23 If the Brown Bank embayment/lagoon was a persistent feature in the landscape through the early to mid Devensian, it may explain the apparent absence of hominins from Britain until MIS 3 (**Figure 3**), with the embayment/lagoon creating a geographic barrier to migration across the southern North Sea. If this is the case, the potential for finding in-situ artefacts within Upper Brown Bank is considering low as the Norfolk Boreas site would not have been suitable for occupation during the early to mid Devensian.

6.2.24 However, understanding the palaeogeographic configuration of this embayment/lagoon is important to help identify the location of coastal margins suitable for occupation, but also to locate alternative migration pathways into Britain.

6.2.25 Key questions about the extent of the embayment/lagoon remain; for example, was there a marine connection to the north and/or south of the embayment i.e. when did Britain reconnect with the European continental landmass after last interglacial?

6.3 Undifferentiated

6.3.1 During Stage 2 geoarchaeological recording, a deposit comprising fine sand with occasional silt/clay laminations, occasional organic partings and mottles, and rare shell, was observed overlying Upper Brown Bank in VC016 and VC047. Based on descriptions alone it was not possible to determine if this deposit, termed Undifferentiated, was part of Brown Bank Formation or a Late Devensian to Early Holocene in age.

6.3.2 Due to the sandy nature of the deposit, it was not possible to sub-sample the deposit for OSL dating as the core had been exposed to light. Therefore, foraminifera, ostracod and diatom assessment were required to reconstruct depositional environment.

6.3.3 Diatoms were not preserved in sub-samples from Undifferentiated deposits and there is no potential for further work.

6.3.4 The foraminifera and ostracod assemblage from Undifferentiated deposits in VC016 show similar characteristics of Upper Brown Bank deposits, i.e. cold climate outer estuarine to marine species suggesting the Undifferentiated deposits in this core are a sandier part of the Upper Brown Bank, possibly reflecting higher energy shallow water.

6.3.5 In contrast, the microfauna from VC047 are different. The Undifferentiated deposits in this core comprise three species that suggest a living fauna and warmer climate. These are very large and ornate *Ammonia batavus* which are restricted in the North Sea to interglacial periods (Funnell 1989), and the ostracods *Pontocythere elongata* and *Elofsonella concinna*, all in large numbers. Both ostracod species are sublittoral species living on sandy-silty substrates, although the latter would not be found off Norfolk today, its southernmost occurrence being further north.

6.3.6 Being marine in origin, these deposits may date to the Holocene or to an interstadial during the early Devensian when temperatures would have been similar to today. However, these deposits are younger than Upper Brown Bank that has been dated to MIS 4 in VC047 and there are no known interstadials after MIS 4 as the climate deteriorated into the Last Glacial Maximum (MIS 2).

6.3.7 While these deposits have a role in understanding the wider stratigraphy of the Norfolk Boreas site, there archaeological potential is considered low given their expected age and depositional environment.

6.4 Early Holocene (Unit 4)

6.4.1 Early Holocene pre-transgressive deposits were recovered in VC028, VC032 and VC39, and they were identified as having high geoarchaeological potential due to their potential to preserve palaeoenvieonmental material (Wessex Archaeology 2018b). These deposits comprise terrestrial peats and associated minerogenic deposits interpreted as being deposited in palaeochannels, and/or, low-lying wetland and saltmarsh environments, and they have the potential to document the progressive inundation of a terrestrial landscape suitable for hominin occupation.

6.4.2 Vibrocores VC032 and VC039 are located in the northern part of Norfolk Boreas in an area where extensive peat deposits have been mapped from geophysical data (**Figure 4**). These two vibrocores are not located within palaeochannel features but instead lie 0.5-1 km away from the nearest mapped channel feature. In comparison, VC028 lies 12 km to the southwest of VC032 in an area where the mapped distribution of peat is more fragmentary (**Figure 4**). The elevation range of the peat in VC028 ranges from -33.52 to 33.87 mLAT, wheras in VC032 and VC039 further to the north, it ranges from -36.02 mLAT at the base of VC033 and -35.63 mLAT at the top of VC039.

6.4.3 Radiocarbon dating of peat deposits in vibrocores VC028, VC032 and VC039 demonstrate that collectively peat formation occurred across Norfolk Boreas over a period of as much as 3,500 years from the Late Devensian to Early Holocene. The majority of peats thus far studied from the southern North Sea basin comprise relatively short-lived Holocene peats preserved within palaeochannels (e.g. Tappin *et al.* 2011; Gearey *et al.* 2017).

6.4.4 Consequently, the organic deposits from Norfolk Boreas are highly significant in covering the transition from the end of the last ice age into the current Holocene warm period providing a near-continuous record of palaeoenvironmental change of the southern North Sea landscape before it was submerged by sea-level rise.

6.4.5 Pollen was well preserved and present in high concentrations in the majority of samples, both in the peat and overlying and underlying minerogenic sediments, providing an important environmental context for climatic and physical changes occurring across the Norfolk Boreas site, and the wider North Sea.

6.4.6 The earliest peat started forming in vibrocore VC039 during the Late Devensian, with a date of 12895–12685 cal. BP from the base of the peat. Pollen assessment from the peat and underlying sandy deposits confirm the Late Devensian date of these deposits, including pollen of birch and grasses typical of an open grassland sub-arctic environment with herbaceous fen and a sparse cover of trees (most likely dwarf birch).

6.4.7 The Late Devensian date of these deposits is further supported by the freshwater cool/cold climate species ostracods recorded from 3.15 mbsf (-35.85 mLAT) and 3.31 mbsf (-36.01 mLAT). Foraminifera from these depths appear to be reworked, probably from the underlying Upper Brown Bank deposits. Ostracods, however, are preserved in situ and suggest deposition in a vegetated channel or cut-off associated with a river floodplain. Diatoms were not preserved in sub-samples from these deposits. Therefore, as the only in situ macrofaunal assemblage from **Unit 4a**, further ostracod analysis on VC039 will refine the paleoenvironmental characterisation of this Late Devensian landscape to determine if it may have been suitable for occupation.

6.4.8 The peat in vibrocore VC039 shows a change in vegetation signal towards the top of the peat with a significant increase in pine frequencies, reflecting the increase in woodland habitats during the initial stages of the early Holocene as the climate ameliorated. The migration of pine into the area probably occurs around 11,000 cal. BP, suggesting the peat in VC039, although heavily compacted, may represent as much as 2000 years of peat growth.

6.4.9 The base of the peat in vibrocore VC032 (4.11mbsf) is dated to 11707-11264 cal. BP, corresponding to the beginning of the Early Holocene - as much as a thousand years after initial peat formation in vibrocore VC039. The top of the peat in VC032 (3.83mbsf) is dated to 9884-9542 cal. BP, suggesting the peat may have accumulated over as much as 1400 to 2100 years.

6.4.10 Pollen preservation and concentrations were excellent to good in vibrocore VC032, showing key changes in vegetation composition characteristic of the ameliorating climate during the initial centuries of the early Holocene. Pine frequencies also increase in VC032, demonstrating that the peat in vibrocores VC039 and VC032 overlap to form an extended record of environmental change of as much as 3,300 years covering the Late Devensian and Early Holocene (approximately 12,900–9550 cal. BP). Pine-dominated woodlands gradually give way to a greater hazel component, perhaps from around 10,000 cal. BP, accompanied by an increasing component of oak and elm.

6.4.11 The peat in vibrocore VC032 is overlain by laminated clays and silts (**Unit 4c**) containing foraminifera and ostracod assemblages indicative of intertidal-brackish mudflats and creeks. Diatoms assemblages comprise mixtures of brackish, marine and freshwater taxa that indicate an intertidal environment. Collectively, these assemblages mark a shift to tidal flat environment under the influence of rising sea levels. The pollen from towards the top of the peat also include increasing frequencies of Chenopodiaceae, a family of pollen taxa including plants characteristic of saltmarsh environments. As **Unit 4c** transitions to **Unit 5**, the foraminifera and ostracod microfauna suggest a shift to a more outer estuarine environment as sea level continues to rise and the area becomes fully marine.

6.4.12 The base of the peat in vibrocore VC028 is dated to 9901–9564 cal. BP, suggesting that this sequence further extends the deposits preserved in vibrocore VC032 and VC039. As VC028 is located at higher elevations than VC032 and VC039, the onset of transgression occurred later at this location (assuming similar compaction rates). Pollen preservation and concentrations are excellent in VC028 and show the development of mixed deciduous-broadleaved woodland and wetland herb fens habitats. It is worth noting that peat deposits 34 km to the south-west from the Norfolk Vanguard site (VC074) date as late as 8250 cal. BP (Wessex Archaeology 2018d).

6.4.13 Together, the peat and associated minerogenic deposits in vibrocores VC028, VC032 and VC039 represent the long-term development of a diachronous land surface forming under the background influence of climate, environmental and physical changes occurring across the Late Devensian and Early Holocene. The available radiocarbon dates for these three sequences suggest that they collectively cover 3500 years or more, representing an exceptional and unique record of sediment deposition and environmental history for the southern North Sea basin.

6.4.14 Furthermore, exceptional preservation of a sequence documenting early Holocene sea-level rise in VC039 has the potential to provide valuable data to constrain the timing and rate of landscape inundation in the southern North Sea. At present, only 18 sea-level index points (SLIPs) are available from the British offshore sector (Hazell 2008), and of these, only three are located within 150 km of the Norfolk Boreas site. There is potential to increase the available sea-level data from this part of the southern North Sea by maximising the use of the early Holocene sequences assessed here.

6.4.15 Regional palaeogeographic models for the time period from 13-9 ka (Sturt *et al.* 2013) were reviewed to understand palaeolandscape evolution of the Norfolk Boreas site over the timescale of peat development (approximately 12,900–9550 cal. BP). The model shows a terrestrial landscape that is inundated from the south during early Holocene sea-level rise. The location of Norfolk Boreas is significant in that it is located in an area that was the last land bridge between Britain and continental Europe before final inundation.

6.4.16 The low-lying riverine and coastal landscapes represented by early Holocene deposits across the Norfolk Boreas site would have been suitable for hominin occupation during the early Holocene. There is potential for the extensive (possibly 85 km^2) peat deposits to comprise or bury archaeology, and there is potential for in situ or derived artefacts within, or along the margins of the palaeochannels. The results here demonstrate that preservation of material for palaeoenvironmental analysis in the peat, but also overlying minerogenic deposits, is high. Therefore, the archaeological significance of early Holocene palaeolandscape features across the Norfolk Boreas site are considered high.

7 RECOMMENDATIONS

7.1 Introduction

7.1.1 Based on the results of the palaeoenvironmental assessment and preliminary chronological information presented here, a series of recommendations are made for further Stage 4 targeted palaeoenvironmental analysis and supporting dating, as discussed below and itemised in **Table 18**.

7.1.2 The selection of samples for Stage 4 analysis is based on the geoarchaeological significance of the deposits preserved, the suitability of sediments for the palaeoenvironmental and dating techniques available, and the research questions proposed, taking into account the regional research agendas (Medlycott 2011) and the national maritime research framework (Ransley et al. 2013).

Table 18 Recommendations for Stage 3 palaeoenvironmental analysis and scientific dating

Core	Deposit	Analysis				
		Pollen	C^{14}	Macros	Diatom	OSL
VC028	Unit 4b	2	1	1	-	-
VC032	Unit 4b	25	2	1	2	-
	Unit 4c	10	-	-	8	-
VC039	Unit 4b	12	2	2	-	-
VC016	Unit 3	-	-	-	-	2
Total		**49**	**4**	**4**	**10**	**2**

7.1.3 The rationale behind recommendations for analysis are discussed below by Unit.

7.2 Brown Bank Formation (Unit 3)

7.2.1 The results of foraminifera and ostracod analysis indicate Upper Brown Bank sediments were deposited in an open estuary or lagoon in a cold-climate sometime between MIS 5e and MIS 3. The diversity of foraminifera and ostracod species was high, but no single species was common. This limits the potential for further analysis and the assessment results are considered sufficient to characterise depositional environment. No further foraminifera or ostracod analysis is recommended for Upper Brown Bank deposits.

7.2.2 Of the four OSL dates submitted, two passed analytical validity tests (69.8 ± 7.7 ka 83.2 ± 9.5 ka) and place deposition of Brown Bank in VC016 between MIS 5b and MIS 4 during the Early Devensian. The ages are not in stratigraphic sequence as the upper age is older than the basal age, but they do overlap within error margins. A qualitative assessment of D_e distributions suggests multi-modal or skewed distributions which may explain the discrepancy between the two ages.

7.2.3 It is recommended sub-samples GL17153 and GL17154 are analysed further in an attempt to improve the accuracy and precision of the dates. The exact scope of works will be decided in consultation with an OSL specialist but may include measuring additional and smaller (1 mm) aliquots, statistical analysis and age modelling.

7.2.4 Improving the accuracy and precision of the OSL chronology will help refine the age of Upper Brown Bank and allow us to assess if the deposits reflect continuous deposition through the early Devensian or more punctuated phases separated by periods of sub-aerial exposure.

7.3 Late Devensian-Early Holocene pre-transgressive deposits (Unit 4)

7.3.1 Peat and over- and underlying minerogenic deposits from VC028, VC032 and VC039 collectively provide an exceptional near-continuous record of almost 3,500 years of landscape development before inundation by rising sea sometime after 9,700 BP.

7.3.2 This is the most extensive and long-lived record of a terrestrial landscape within the North Sea mapped to date, and it represents relatively stable environmental conditions in a terrestrial-coastal environment, which would have been suitable for occupation, on what would have been the last land-bridge between Britain and continental Europe during the Holocene.

7.3.3 Pollen preservation is typically excellent to good through the peat (**Unit 4b**) and overlying minerogenic deposits (**Unit 4c**), with moderate to good diatom preservation, the presence of foraminifera and conformable radiocarbon dates, together indicating the potential for paleoenvironmental analysis is high.

7.3.4 The sequence preserved in VC032 is unique as it documents the gradual transition from a terrestrial to marine environment with no signs of erosion. This may provide key information on the timing of marine transgression across the Norfolk Boreas site, but also the wider southern North Sea where sea-level data points are rare.

7.3.5 Given the archaeological significance of these deposits, it is recommended further work is undertaken to provide a higher resolution chronology and statistically valid paleoenvironmental analysis comprising pollen, charcoal and diatom proxy techniques. This will provide a landscape context for any human activity in the area and enable assessments of the availability of resources and habitats for human settlement and exploitation.

7.3.6 The highly compact nature of the peat means that although they are relatively thin (<0.5 m), they represent a long period of time, as much as 1400 to 2100 yrs in VC032. This means a high-resolution sample interval (2-3 cm) would be required to capture any environmental changes at a scale of 100 yr intervals.

7.4 Palaeolandscape reconstructions

7.4.1 The results from Stage 4 palaeoenvironmental analysis will provide the evidence base and age information required for palaeogeographic reconstructions.

7.4.2 It is recommended that palaeogeographic maps for the Early Devensian, Late Devensian and Early Holocene are produced for the Norfolk Boreas site. This can be achieved by integrating geophysical assessments (Wessex Archaeology 2018c and Fugro 2018) with) the results of the Stage 4 paleoenvironmental analysis to refine the deposit model proposed during Stage 2 works (Wessex Archaeology 2018b).

7.5 Stage 5 publication

7.5.1 It is recommended the final results from the Norfolk Boreas site are disseminated publicly through publication in a peer reviewed journal.

7.5.2 Typically, we would advise all results are published in a single manuscript. However, here we recommend the results from Norfolk Boreas are integrated with those from Norfolk Vanguard due to their close proximity, the nature of the deposits investigated, and the techniques employed.

7.5.3 We propose submitting two manuscripts as follows;

- Late Devensian to Early Holocene landscape development and inundation
- A reappraisal of Brown Bank Formation - Implications for palaeogeography and hominin occupation

7.5.4 This approach will produce regional scale palaeolandscape reconstructions driven by period specific research questions, thus having a wider impact than more localised site-specific data driven reconstructions.

7.6 Research questions

7.6.1 The results of this Stage 3 palaeoenvironmental assessment are summarised in **Table 19** with reference to the research questions proposed in Wessex Archaeology (2018b).

7.6.2 Considering the results presented here, a series of additional research questions are posed as follows;

- What is the palaeogeographic configuration of the Brown Bank embayment/lagoon?
- Did the Brown Bank embayment/lagoon create an obstacle for human migration through the southern North Sea during the early to mid-Devensian?
- When did Britain reconnect with continental Europe after the last interglacial, during MIS 3 or earlier?
- What is the early Holocene vegetation and landscape history?
- What is the sea-level history? Was transgression rapid occurring at a similar time across the Norfolk Boreas site or was it more gradual and spatially variable?

7.6.3 These questions, along with those presented in the Stage 2 report (Wessex Archaeology 2018b) will be addressed as part of the Stage 4 final report.

Table 19 Summary of progress against research questions proposed during Stage 2 (Wessex Archaeology 2018b)

What palaeoenvironments are represented by the deposits preserved across the site? How do these change through time?	
Answer	The deposits represent a marine embayment/lagoon environment which may have dried out periodically through time (Unit 3) and a cold-climate terrestrial alluvial plain that became a freshwater-brackish marsh which was inundated to create tidal flats/creeks and later, estuarine to shallow marine environments, all of which occurred under rising sea level (Unit 4).
Archaeological importance	The site preserves a ~3500 year record of palaeoenvironmental change documenting development, and later inundation of, terrestrial landscapes suitable for hominin occupation in an area that was the last land connection between Britain and continental Europe.
Further work	Higher resolution chronological control and quantitative palaeoenvironmental analysis to underpin palaeogeographic, landscape and sea-level reconstructions.
What is the age of peat deposits? Do they represent a contemporary phase of peat formation across the site or separate phases of peat formation within environmental niches?	
Answer	The peat deposits date from 9542 to 12895 and are Late Devensian to Early Holocene in age representing broadly continuous formation across the site, but over a long time (3,500 yrs) period.
Archaeological importance	The peat preserves a paleoenvironmental record that will provide a landscape context for any human activity in the area and enable assessments of the availability of resources and habitats for human settlement and exploitation.
Further work	Higher resolution pollen sample interval and statistically valid analysis, combined with higher resolution age control.
What is the age of Upper Brown Bank Formation? Did it form relatively quickly in the early Devensian or accumulate as a more gradual deposit over a longer period of time?	

Answer	OSL results suggest deposition occurred between 60.5 and 83.2 (MIS 5b to MIS 4) during the early to mid-Devensian.
Archaeological importance	If deposition was continuous it suggests the Brown Bank embayment was persistent in the landscape for ~25 ka corresponding to a time period when humans were absent from Britain.
Further work	Improve the precision and accuracy of the OSL dates.
What do the results mean for palaeolandscape development and palaeogeographic evolution of the southern North Sea, and what is the archaeological significance of this?	
Answer	The results suggest the presence of an embayment/lagoon during the Early Devensian which may have created a barrier to hominin migration into Britain, at least via terrestrial routes. However, there may have been periods of drying out which could have been exploited. The wider geography of this embayment/lagoon is unknown. The Late Devensian to Early Holocene sequences are significant in providing the palaeoenvironmental record to reconstruct landscape and vegetation history at a regional scale. They document inundation of the southern North Sea in the Early Holocene.
Archaeological importance	The Holocene sequences are potentially the best preserved, continuous record of environmental change recovered to date from the southern North Sea. They are a potential “type sites” to benchmark other palaeoenvironmental reconstructions. The palaeogeography of the Brown Bank embayment/lagoon is key for understanding if the North Sea as a migration pathway, was open or closed throughout the early Devensian, corresponding to a period when hominins were absent from Britain.
Further work	Higher resolution chronological control and quantitative palaeoenvironmental analysis to underpin palaeogeographic, landscape and sea-level reconstructions.

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APPENDIX 1

WA Lithostratigraphy					**Fugro Soil Stratigraphy[3]**		**BGS Lithostratigraphy[4]**
Unit No	**Unit Name (age)**	**Geophysical Characteristics[1]**	**Sediment Type[2]**	**Archaeological Potential**	**Soil Unit**	**Soil Unit Name**	**Formation**
5	Holocene Seabed Sediments (post-transgression MIS 1)	Generally observed as a veneer or thickening into large sand wave and bank features. Boundary between seabed sediments and underlying units not always discernible.	Medium to coarse sand with frequent shell fragments – marine	Low archaeological potential in areas of mobile sediments; basal contact may cover old land surfaces. Mobile sediment could cover wreck sites.	A1	Bligh Bank	Southern Bight Formation
4	Holocene (pre-transgression MIS 1)	Small shallow infilled channels with either seismically transparent fill, or fill characterised by sub-parallel internal reflectors.	Sands silt and clay intercalated with peat and organic clay – fluvial, terrestrial and intertidal (transgressive)	Shallow infilled depressions or channels have potential for *in situ* or derived artefacts if deposited during occupation. Preserved organic material of interest to palaeoenvironmental studies.	A2	Elbow	Elbow Formation
Undiff	Undifferentiated	Not identified in shallow geophysical data	Interbedded sand and silty clay with shell fragments and silt laminations (occasionally organic) – unknown, possible fluvial/intertidal	Unknown – potential will depend on precise age and depositional environment of unit	-	-	-
-	Twente (Upper Devensian MIS 2)	Not identified in shallow geophysical data	Not identified in geotechnical logs	Thin layer of aeolian periglacial sand deposited when the southern North Sea was a glaciated terrestrial landscape. Potential to contain *in-situ* and derived archaeological and palaeoenvironmental material.	B	Twente	Twente Formation
3	Upper Brown Bank (Lower Devensian MIS 5d-3)	Observed as a blanket deposit across the whole area, generally acoustically transparent or characterised by relatively poorly defined sub-horizontal layered reflectors.	Silty clay and clayey silt with closely spaced fine laminations. May be sandy in places or comprise sand partings/laminations – lagoon/intertidal/sheltered embayment	*In situ* Lower Palaeolithic artefacts may be protected; Middle Palaeolithic *in situ* and derived artefacts may be associated particularly with channel edges dependent on the age of the fill; palaeoenvironmental information;	C	Brown Bank	Brown Bank Formation

WA Lithostratigraphy					Fugro Soil Stratigraphy[3]		BGS Lithostratigraphy[4]
Unit No	**Unit Name (age)**	**Geophysical Characteristics[1]**	**Sediment Type[2]**	**Archaeological Potential**	**Soil Unit**	**Soil Unit Name**	**Formation**
				basal contact may cover old land surfaces.			
2	Lower Brown Bank/Eem Formation (Ipswichian or Lower Devensian MIS 5e - 5d)	Observed within large topographically controlled depressions. Characterised by low relief basal and either an acoustically transparent or well-layered fill.	Silty sand and sandy silt, possible intertidal or shallow marine deposits.	*In situ* Lower Palaeolithic artefacts may be protected; Middle Palaeolithic *in situ* and derived artefacts may be associated particularly with channel edges dependent on the age of the fill; palaeoenvironmental information; basal contact may cover old land surfaces.	C	Brown Bank	Brown Bank Formation and Eem Formation
-	Swarte Bank (Anglian MIS 12)	Not identified in shallow geophysical data	Not identified in geotechnical logs	Low archaeological potential as associated with glacial processes	D	Swarte Bank	Swarte Bank Formation
1	Yarmouth Roads Formation (Lower to Middle Pleistocene MIS >13)	Thick unit either seismically chaotic or containing numerous areas of well-defined cross cutting channel complexes characterised by layered sub-parallel internal reflectors. Top of unit generally a well-defined regional erosion surface.	Silty sand with occasional shell fragments with occasional layers of clay. Generally becoming silty with depth. Sediments deposited as part of delta complex.	Possibility of *in situ* finds in later part of formation if not eroded. Contemporaneous with terrestrial Cromer Forest Bed Formation (Pakefield and Happisburgh). Has been found to contain plant debris, wood and peat in some areas of possible palaeoenvironmental importance. Potential greatest where associated with river valleys.	E	Yarmouth Roads	Yarmouth Road Formation
-	Winterton Shoal/Smith's Knoll (Lower Pleistocene)	Not identified in shallow geophysical data	Not identified in geotechnical logs	Pre-date earliest occupation; of no archaeological interest.	F	Winterton Shoal/Smith's Knoll	Winterton Shoal Formation and Smith's Knoll Formation

[1] Based on geophysics data (Wessex Archaeology 2018b)
[2] Based on geoarchaeological recording of Norfolk Boreas vibrocores (Wessex Archaeology 2018b) and Cameron et al. (1992) in the case of Unit 1
[3] Fugro (2018)
[4] Stoker et al. (2011)

APPENDIX 2

VC	Easting (m)	Northing (m)	Water Depth (m LAT)	Depth (m down core)		Depth (m LAT)		Assessment
				From	To	From	To	
VC28	485146	5873305	-31.2	2.50		-33.70		Pollen
VC28	485146	5873305	-31.2	2.55		-33.75		Pollen
VC28	485146	5873305	-31.2	2.60		-33.80		Pollen
VC28	485146	5873305	-31.2	2.59	2.62	-33.79	-33.82	Radiocarbon
VC28	485146	5873305	-31.2	2.75		-33.95		Foraminifera & Ostracod
VC28	485146	5873305	-31.2	2.75		-33.95		Diatom
VC28	485146	5873305	-31.2	2.90		-34.10		Foraminifera & Ostracod
VC28	485146	5873305	-31.2	2.90		-34.10		Diatom
VC28	485146	5873305	-31.2	3.05		-34.25		Foraminifera & Ostracod
VC28	485146	5873305	-31.2	3.05		-34.25		Diatom
VC032	494379	5880618	-31.9	3.30		-35.20		Foraminifera & Ostracod
VC032	494379	5880618	-31.9	3.30		-35.20		Diatom
VC032	494379	5880618	-31.9	3.40		-35.30		Foraminifera & Ostracod
VC032	494379	5880618	-31.9	3.40		-35.30		Diatom
VC032	494379	5880618	-31.9	3.50		-35.40		Foraminifera & Ostracod
VC032	494379	5880618	-31.9	3.50		-35.40		Diatom
VC032	494379	5880618	-31.9	3.58		-35.48		Foraminifera & Ostracod
VC032	494379	5880618	-31.9	3.58		-35.48		Diatom
VC032	494379	5880618	-31.9	3.58		-35.48		Pollen
VC032	494379	5880618	-31.9	3.69		-35.59		Foraminifera & Ostracod
VC032	494379	5880618	-31.9	3.69		-35.59		Diatom
VC032	494379	5880618	-31.9	3.69		-35.59		Pollen
VC032	494379	5880618	-31.9	3.77		-35.67		Foraminifera & Ostracod
VC032	494379	5880618	-31.9	3.77		-35.67		Diatom
VC032	494379	5880618	-31.9	3.77		-35.67		Pollen
VC032	494379	5880618	-31.9	3.82		-35.72		Pollen
VC032	494379	5880618	-31.9	3.83		-35.73		Radiocarbon
VC032	494379	5880618	-31.9	3.90		-35.80		Pollen
VC032	494379	5880618	-31.9	3.98		-35.88		Pollen
VC032	494379	5880618	-31.9	4.06		-35.96		Pollen
VC032	494379	5880618	-31.9	4.11		-36.01		Radiocarbon
VC032	494379	5880618	-31.9	4.13		-36.03		Pollen
VC032	494379	5880618	-31.9	4.17		-36.07		Diatom
VC032	494379	5880618	-31.9	4.17		-36.07		Foraminifera & Ostracod
VC032	494379	5880618	-31.9	4.32		-36.22		Diatom
VC032	494379	5880618	-31.9	4.32		-36.22		Foraminifera & Ostracod
VC032	494379	5880618	-31.9	4.44		-36.34		Diatom

VC	Easting (m)	Northing (m)	Water Depth (m LAT)	Depth (m down core)		Depth (m LAT)		Assessment
				From	To	From	To	
VC032	494379	5880618	-31.9	4.44		-36.34		Foraminifera & Ostracod
VC032	494379	5880618	-31.9	4.56		-36.46		Diatom
VC032	494379	5880618	-31.9	4.56		-36.46		Foraminifera & Ostracod
VC039	493714	5884543	-32.7	2.75		-35.45		Diatom
VC039	493714	5884543	-32.7	2.75		-35.45		Foraminifera & Ostracod
VC039	493714	5884543	-32.7	2.90		-35.60		Diatom
VC039	493714	5884543	-32.7	2.90		-35.60		Foraminifera & Ostracod
VC039	493714	5884543	-32.7	2.94		-35.64		Pollen
VC039	493714	5884543	-32.7	3.07		-35.77		Pollen
VC039	493714	5884543	-32.7	3.07		-35.77		Radiocarbon
VC039	493714	5884543	-32.7	3.15		-35.85		Foraminifera & Ostracod
VC039	493714	5884543	-32.7	3.15		-35.85		Diatom
VC039	493714	5884543	-32.7	3.15		-35.85		Pollen
VC039	493714	5884543	-32.7	3.31		-36.01		Diatom
VC039	493714	5884543	-32.7	3.31		-36.01		Foraminifera & Ostracod
VC039	493714	5884543	-32.7	3.51		-36.21		Diatom
VC039	493714	5884543	-32.7	3.51		-36.21		Foraminifera & Ostracod
VC016	488684	5869659	-39.2	0.20		-39.40		Diatom
VC016	488684	5869659	-39.2	0.22		-39.42		Foraminifera & Ostracod
VC016	488684	5869659	-39.2	0.45		-39.65		Diatom
VC016	488684	5869659	-39.2	0.47		-39.67		Foraminifera & Ostracod
VC016	488684	5869659	-39.2	0.70		-39.90		Diatom
VC016	488684	5869659	-39.2	0.72		-39.92		Foraminifera & Ostracod
VC016	488684	5869659	-39.2	0.95		-40.15		Diatom
VC016	488684	5869659	-39.2	0.97		-40.17		Foraminifera & Ostracod
VC016	488684	5869659	-39.2	1.15		-40.35		Diatom
VC016	488684	5869659	-39.2	1.17		-40.37		Foraminifera & Ostracod
VC016	488684	5869659	-39.2	1.40		-40.60		Diatom
VC016	488684	5869659	-39.2	1.42		-40.62		Foraminifera & Ostracod
VC016	488684	5869659	-39.2	1.65		-40.85		Diatom
VC016	488684	5869659	-39.2	1.67		-40.87		Foraminifera & Ostracod
VC016	488684	5869659	-39.2	1.70	2.00	-40.90	-41.20	OSL
VC016	488684	5869659	-39.2	2.18		-41.38		Diatom
VC016	488684	5869659	-39.2	2.20		-41.40		Foraminifera & Ostracod
VC016	488684	5869659	-39.2	2.38		-41.58		Diatom
VC016	488684	5869659	-39.2	2.40		-41.60		Foraminifera & Ostracod
VC016	488684	5869659	-39.2	2.58		-41.78		Diatom
VC016	488684	5869659	-39.2	2.60		-41.80		Foraminifera & Ostracod
VC016	488684	5869659	-39.2	2.65	3.00	-41.85	-42.20	OSL

VC	Easting (m)	Northing (m)	Water Depth (m LAT)	Depth (m down core)		Depth (m LAT)		Assessment
				From	To	From	To	
VC016	488684	5869659	-39.2	3.35		-42.55		Diatom
VC016	488684	5869659	-39.2	3.37		-42.57		Foraminifera & Ostracod
VC016	488684	5869659	-39.2	3.85		-43.05		Diatom
VC016	488684	5869659	-39.2	3.87		-43.07		Foraminifera & Ostracod
VC016	488684	5869659	-39.2	4.38		-43.58		Foraminifera & Ostracod
VC016	488684	5869659	-39.2	4.40		-43.60		Diatom
VC016	488684	5869659	-39.2	4.85		-44.05		Foraminifera & Ostracod
VC016	488684	5869659	-39.2	4.87		-44.07		Diatom
VC047	502211	5896931	-34.5	1.70		-36.20		Foraminifera & Ostracod
VC047	502211	5896931	-34.5	1.70		-36.20		Diatom
VC047	502211	5896931	-34.5	1.90		-36.40		Foraminifera & Ostracod
VC047	502211	5896931	-34.5	1.90		-36.40		Diatom
VC047	502211	5896931	-34.5	2.10		-36.60		Diatom
VC047	502211	5896931	-34.5	2.15		-36.65		Foraminifera & Ostracod
VC047	502211	5896931	-34.5	2.35		-36.85		Diatom
VC047	502211	5896931	-34.5	2.40		-36.90		Foraminifera & Ostracod
VC047	502211	5896931	-34.5	2.55	3.00	-37.05	-37.50	OSL
VC047	502211	5896931	-34.5	2.60		-37.10		Diatom
VC047	502211	5896931	-34.5	2.65		-37.15		Foraminifera & Ostracod
VC047	502211	5896931	-34.5	2.80		-37.30		Diatom
VC047	502211	5896931	-34.5	2.85		-37.35		Foraminifera & Ostracod
VC047	502211	5896931	-34.5	3.35		-37.85		Diatom
VC047	502211	5896931	-34.5	3.40		-37.90		Foraminifera & Ostracod
VC047	502211	5896931	-34.5	3.70	4.00	-38.20	-38.50	OSL
VC047	502211	5896931	-34.5	3.80		-38.30		Diatom
VC047	502211	5896931	-34.5	3.85		-38.35		Foraminifera & Ostracod
VC047	502211	5896931	-34.5	4.35		-38.85		Diatom
VC047	502211	5896931	-34.5	4.40		-38.90		Foraminifera & Ostracod
VC047	502211	5896931	-34.5	4.80		-39.30		Diatom
VC047	502211	5896931	-34.5	4.85		-39.35		Foraminifera & Ostracod

APPENDIX 3

University of Gloucestershire

Luminescence dating laboratory

Optical dating of sediments: Boreas Offshore Windfarm

to

Dr C. Mellett

Wessex Archaeology

Analysis & Reporting, Dr P.S. Toms
Sample Preparation & Measurement, Mr J.C. Wood
14 August 2018

Contents

Scope of Report

This is a standard report of the Luminescence dating laboratory, University of Gloucestershire. In large part, the document summarises the processes, diagnostics and data drawn upon to deliver Table 1. A conclusion on the analytical validity of each sample's optical age estimate is expressed in Table 2; where there are caveats, the reader is directed to the relevant section of the report that explains the issue further in general terms.

Field Code	Lab Code	Overburden (m)	Grain size (μm)	Moisture content (%)	NaI γ-spectrometry (*in situ*) γ D_r (Gy.ka^{-1})	Ge γ-spectrometry (*ex situ*)			β D_r (Gy.ka^{-1})	γ D_r (Gy.ka^{-1})	Cosmic D_r (Gy.ka^{-1})	Preheat (°C for 10s)	Low Dose Repeat Ratio	Interpolated:Applied Low Regenerative-dose D_e	High Dose Repeat Ratio	Interpolated:Applied High Regenerative-dose D_e	Post-IR OSL Ratio
						K (%)	Th (ppm)	U (ppm)									
NBOWF_VC016: 2.65-3.00 m	GL17153	2.83	125-180	16 ± 4	-	1.45 ± 0.10	8.23 ± 0.54	1.96 ± 0.14	1.22 ± 0.14	0.79 ± 0.10	0.13 ± 0.01	260	1.03 ± 0.01	1.05 ± 0.02	1.00 ± 0.01	1.03 ± 0.03	1.00 ± 0.01
NBOWF_VC016: 1.70-2.00 m	GL17154	1.85	125-180	15 ± 4	-	1.50 ± 0.10	7.81 ± 0.53	1.93 ± 0.14	1.25 ± 0.14	0.79 ± 0.10	0.15 ± 0.01	220	1.04 ± 0.01	1.07 ± 0.02	1.01 ± 0.01	1.05 ± 0.03	1.01 ± 0.01
NBOWF_VC047: 2.55-3.00 m	GL17155	2.78	125-180	16 ± 4	-	1.55 ± 0.10	8.25 ± 0.53	1.92 ± 0.14	1.29 ± 0.14	0.82 ± 0.11	0.13 ± 0.01	240	1.04 ± 0.02	1.08 ± 0.03	1.02 ± 0.02	1.11 ± 0.05	1.04 ± 0.02
NBOWF_VC047: 3.70-4.00 m	GL17156	3.85	125-180	17 ± 4	-	1.73 ± 0.11	8.95 ± 0.57	1.97 ± 0.14	1.38 ± 0.16	0.87 ± 0.11	0.11 ± 0.01	240	1.06 ± 0.03	1.12 ± 0.04	1.04 ± 0.02	1.21 ± 0.09	1.05 ± 0.02

Field Code	Lab Code	Total D_r (Gy.ka^{-1})	D_e (Gy)	Age (ka)
NBOWF_VC016: 2.65-3.00 m	GL17153	2.14 ± 0.17	149.6 ± 11.1	69.8 ± 7.7 (6.9)
NBOWF_VC016: 1.70-2.00 m	GL17154	2.19 ± 0.17	182.1 ± 15.0	83.2 ± 9.5 (8.7)
NBOWF_VC047: 2.55-3.00 m	GL17155	2.23 ± 0.18	135.1 ± 7.2	60.5 ± 5.8 (5.0)
NBOWF_VC047: 3.70-4.00 m	GL17156	2.38 ± 0.20	186.0 ± 11.6	78.9 ± 8.3 (7.4)

Table 1 D_r, D_e and Age data of submitted samples located at c. 53°N, 3°E, 0m. Age estimates expressed relative to year of sampling. Uncertainties in age are quoted at 1σ confidence, are based on analytical errors and reflect combined systematic and experimental variability and (in parenthesis) experimental variability alone (see 6.0). **Blue** indicates samples with accepted age estimates, **red**, age estimates with caveats (see Table 2).

Generic considerations	Field Code	Lab Code	Sample specific considerations
Absence of *in situ* γ spectrometry data (see section 4.0)	NBOWF_VC016: 2.65-3.00 m	GL17153	None
	NBOWF_VC016: 1.70-2.00 m	GL17154	None
	NBOWF_VC047: 2.55-3.00 m	GL17155	Overdispersed interpolated to applied regenerative-dose ratio (see section 3.1.4 and Table 1) Accept tentatively
	NBOWF_VC047: 3.70-4.00 m	GL17156	Overdispersed interpolated to applied regenerative-dose ratio (see section 3.1.4 and Table 1) Accept tentatively

Table 2 Analytical validity of sample suite age estimates and caveats for consideration

1.0 Mechanisms and principles

Upon exposure to ionising radiation, electrons within the crystal lattice of insulating minerals are displaced from their atomic orbits. Whilst this dislocation is momentary for most electrons, a portion of charge is redistributed to meta-stable sites (traps) within the crystal lattice. In the absence of significant optical and thermal stimuli, this charge can be stored for extensive periods. The quantity of charge relocation and storage relates to the magnitude and period of irradiation. When the lattice is optically or thermally stimulated, charge is evicted from traps and may return to a vacant orbit position (hole). Upon recombination with a hole, an electron's energy can be dissipated in the form of light generating crystal luminescence providing a measure of dose absorption.

Herein, quartz is segregated for dating. The utility of this minerogenic dosimeter lies in the stability of its datable signal over the mid to late Quaternary period, predicted through isothermal decay studies (e.g. Smith *et al*., 1990; retention lifetime 630 Ma at 20°C) and evidenced by optical age estimates concordant with independent chronological controls (e.g. Murray and Olley, 2002). This stability is in contrast to the anomalous fading of comparable signals commonly observed for other ubiquitous sedimentary minerals such as feldspar and zircon (Wintle, 1973; Templer, 1985; Spooner, 1993)

Optical age estimates of sedimentation (Huntley *et al*., 1985) are premised upon reduction of the minerogenic time dependent signal (Optically Stimulated Luminescence, OSL) to zero through exposure to sunlight and, once buried, signal reformulation by absorption of litho- and cosmogenic radiation. The signal accumulated post burial acts as a dosimeter recording total dose absorption, converting to a chronometer by estimating the rate of dose absorption quantified through the assay of radioactivity in the surrounding lithology and streaming from the cosmos.

$$\text{Age} = \frac{\text{Mean Equivalent Dose } (D_e\text{, Gy})}{\text{Mean Dose Rate } (D_{r,}\ \text{Gy.ka}^{-1})}$$

Aitken (1998) and Bøtter-Jensen *et al*. (2003) offer a detailed review of optical dating.

2.0 Sample Preparation

Four sediment samples were submitted within cores for Optical dating. To preclude optical erosion of the datable signal prior to measurement, all samples were opened and prepared under controlled laboratory illumination provided by Encapsulite RB-10 (red) filters. To isolate that material potentially exposed to daylight during sampling, sediment located within 10 mm of each core face was removed.

The remaining sample was dried and then sieved. The fine sand fraction was segregated and subjected to acid and alkaline digestion (10% HCl, 15% H_2O_2) to attain removal of carbonate and organic components respectively. A further acid digestion in HF (40%, 60 mins was used to etch the outer 10-15 μm layer affected by α radiation and degrade each samples' feldspar content. During HF treatment, continuous magnetic stirring was used to effect isotropic etching of grains. 10% HCl was then added to remove acid soluble fluorides. Each sample was dried, resieved and quartz isolated from the remaining heavy mineral fraction using a sodium polytungstate density separation at $2.68 g.cm^{-3}$. Twelve 8 mm multi-grain aliquots (*c*. 3-6 mg) of quartz from each sample were then mounted on aluminium discs for determination of D_e values.

All drying was conducted at 40°C to prevent thermal erosion of the signal. All acids and alkalis were Analar grade. All dilutions (removing toxic-corrosive and non-minerogenic luminescence-bearing substances) were conducted with distilled water to prevent signal contamination by extraneous particles.

3.0 Acquisition and accuracy of D_e value

All minerals naturally exhibit marked inter-sample variability in luminescence per unit dose (sensitivity). Therefore, the estimation of D_e acquired since burial requires calibration of the natural signal using known amounts of laboratory dose. D_e values were quantified using a single-aliquot regenerative-dose (SAR) protocol (Murray and Wintle 2000; 2003) facilitated by a Risø TL-DA-15 irradiation-stimulation-detection system (Markey *et al*., 1997; Bøtter-Jensen *et al*., 1999). Within this apparatus, optical signal stimulation is provided by an assembly of blue diodes (5 packs of 6 Nichia NSPB500S), filtered to 470±80 nm conveying 15 mW.cm^{-2} using a 3 mm Schott GG420 positioned in front of each diode pack. Infrared (IR) stimulation, provided by 6 IR diodes (Telefunken TSHA 6203) stimulating at 875±80nm delivering ~5 mW.cm^{-2}, was used to indicate the presence of contaminant feldspars (Hütt *et al*., 1988). Stimulated photon emissions from quartz aliquots are in the ultraviolet (UV) range and were filtered from stimulating photons by 7.5 mm HOYA U-340 glass and detected by an EMI 9235QA photomultiplier fitted with a blue-green sensitive bialkali photocathode. Aliquot irradiation was conducted using a 1.48 GBq ^{90}Sr/^{90}Y β source calibrated for multi-grain aliquots of 125-180 μm quartz against the 'Hotspot 800' ^{60}Co γ source located at the National Physical Laboratory (NPL), UK.

SAR by definition evaluates D_e through measuring the natural signal (Fig. 1) of a single aliquot and then regenerating that aliquot's signal by using known laboratory doses to enable calibration. For each aliquot, five different regenerative-doses were administered so as to image dose response. D_e values for each aliquot were then interpolated, and associated counting and fitting errors calculated, by way of exponential plus linear regression (Fig. 1). Weighted (geometric) mean D_e values were calculated from 12 aliquots using the central age model outlined by Galbraith *et al*. (1999) and are quoted at 1σ confidence (Table 1). The accuracy with which D_e equates to total absorbed dose and that dose absorbed since burial was assessed. The former can be considered a function of laboratory factors, the latter, one of environmental issues. Diagnostics were deployed to estimate the influence of these factors and criteria instituted to optimise the accuracy of D_e values.

3.1 Laboratory Factors

3.1.1 Feldspar contamination

The propensity of feldspar signals to fade and underestimate age, coupled with their higher sensitivity relative to quartz makes it imperative to quantify feldspar contamination. At room temperature, feldspars generate a signal (IRSL; Fig. 1) upon exposure to IR whereas quartz does not. The signal from feldspars contributing to OSL can be depleted by prior exposure to IR. For all aliquots the contribution of any remaining feldspars was estimated from the OSL IR depletion ratio (Duller, 2003). The influence of IR depletion on the OSL signal can be illustrated by comparing the regenerated post-IR OSL D_e with the applied regenerative-dose. If the addition to OSL by feldspars is insignificant, then the repeat dose ratio of OSL to post-IR OSL should be statistically consistent with unity (Table 1). If any aliquots do not fulfil this criterion, then the sample age estimate should be accepted tentatively. The source of feldspar contamination is rarely rooted in sample preparation; it predominantly results from the occurrence of feldspars as inclusions within quartz.

3.1.2 Preheating

Preheating aliquots between irradiation and optical stimulation is necessary to ensure comparability between natural and laboratory-induced signals. However, the multiple irradiation and preheating steps that are required to define single-aliquot regenerative-dose response leads to signal sensitisation, rendering calibration of the natural signal inaccurate. The SAR protocol (Murray and Wintle, 2000; 2003) enables this sensitisation to be monitored and corrected using a test dose, here set at 5 Gy preheated to 220°C for 10s, to track signal sensitivity between irradiation-preheat steps. However, the accuracy of sensitisation correction for both natural and laboratory signals can be preheat dependent.

The Dose Recovery test was used to assess the optimal preheat temperature for accurate correction and calibration of the time dependent signal. Dose Recovery (Fig. 2) attempts to quantify the combined effects of thermal transfer and sensitisation on the natural signal, using a precise lab dose to simulate natural dose. The ratio between the applied dose and recovered D_e value should be statistically concordant with unity. For this diagnostic, 6 aliquots were each assigned a 10 s preheat between 180°C and 280°C.

That preheat treatment fulfilling the criterion of accuracy within the Dose Recovery test was selected to generate the final D_e value from a further 12 aliquots. Further thermal treatments, prescribed by Murray and Wintle (2000; 2003), were applied to optimise accuracy and precision. Optical stimulation occurred at 125ºC in order to minimise effects associated with photo-transferred thermoluminescence and maximise signal to noise ratios. Inter-cycle optical stimulation was conducted at 280ºC to minimise recuperation.

3.1.3 Irradiation

For all samples having D_e values in excess of 100 Gy, matters of signal saturation and laboratory irradiation effects are of concern. With regards the former, the rate of signal accumulation generally adheres to a saturating exponential form and it is this that limits the precision and accuracy of D_e values for samples having absorbed large doses. For such samples, the functional range of D_e interpolation by SAR has been verified up to 600 Gy by Pawley *et al*. (2010). Age estimates based on D_e values exceeding this value should be accepted tentatively.

3.1.4 Internal consistency

Abanico plots (Dietze *et al*., 2016) are used to illustrate inter-aliquot D_e variability (Fig. 3). D_e values are standardised relative to the central D_e value for natural signals and are described as overdispersed when >5% lie beyond $\pm 2\sigma$ of the standardising value; resulting from a heterogeneous absorption of burial dose and/or response to the SAR protocol. For multi-grain aliquots, overdispersion of natural signals does not necessarily imply inaccuracy. However where overdispersion is observed for regenerated signals, the efficacy of sensitivity correction may be problematic. Murray and Wintle (2000; 2003) suggest repeat dose ratios (Table 1) offer a measure of SAR protocol success, whereby ratios ranging across 0.9-1.1 are acceptable. However, this variation of repeat dose ratios in the high-dose region can have a significant impact on D_e interpolation. The influence of this effect can be outlined by quantifying the ratio of interpolated to applied regenerative-dose ratio (Table 1). In this study, where both the repeat dose ratios and interpolated to applied regenerative-dose ratios range across 0.9-1.1, sensitivity-correction is considered effective.

3.2 Environmental factors

3.2.1 Incomplete zeroing

Post-burial OSL signals residual of pre-burial dose absorption can result where pre-burial sunlight exposure is limited in spectrum, intensity and/or period, leading to age overestimation. This effect is particularly acute for material eroded and redeposited sub-aqueously (Olley *et al*., 1998, 1999; Wallinga, 2002) and exposed to a burial dose of <20 Gy (e.g. Olley *et al*., 2004), has some influence in sub-aerial contexts but is rarely of consequence where aerial transport has occurred. Within single-aliquot regenerative-dose optical dating there are two diagnostics of partial resetting (or bleaching); signal analysis (Agersnap-Larsen *et al*., 2000; Bailey *et al*., 2003) and inter-aliquot D_e distribution studies (Murray *et al*., 1995).

Within this study, signal analysis was used to quantify the change in D_e value with respect to optical stimulation time for multi-grain aliquots. This exploits the existence of traps within minerogenic dosimeters that bleach with different efficiency for a given wavelength of light to verify partial bleaching. D_e (t) plots (Fig. 4; Bailey *et al*., 2003) are constructed from separate integrals of signal decay as laboratory optical stimulation progresses. A statistically significant increase in natural D_e (t) is indicative of partial bleaching assuming three conditions are fulfilled. Firstly, that a statistically significant increase in D_e (t) is observed when partial bleaching is simulated within the laboratory. Secondly, that there is no significant rise in D_e (t) when full bleaching is simulated. Finally, there should be no significant augmentation in D_e (t) when zero dose is simulated. Where partial bleaching is detected, the age derived from the sample should be considered a maximum estimate only. However, the utility of signal analysis is strongly dependent upon a samples pre-burial experience of sunlight's spectrum and its residual to post-burial signal ratio. Given in the majority of cases, the spectral exposure history of a deposit is uncertain, the absence of an increase in natural D_e (t) does not necessarily testify to the absence of partial bleaching.

Where requested and feasible, the insensitivities of multi-grain single-aliquot signal analysis may be circumvented by inter-aliquot D_e distribution studies. This analysis uses aliquots of single sand grains to quantify inter-grain D_e distribution. At present, it is contended that asymmetric inter-grain D_e distributions are symptomatic of partial bleaching and/or pedoturbation (Murray *et al*., 1995; Olley *et al*., 1999; Olley *et al*., 2004; Bateman *et al*., 2003). For partial bleaching at least, it is further contended that the D_e acquired during burial is located in the minimum region of such ranges. The mean and breadth of this minimum region is the subject of current debate, as it is additionally influenced by heterogeneity in microdosimetry, variable inter-grain response to SAR and residual to post-burial signal ratios.

3.2.2 Turbation

As noted in section 3.1.1, the accuracy of sedimentation ages can further be controlled by post-burial trans-strata grain movements forced by pedo- or cryoturbation. Berger (2003) contends pedogenesis prompts a reduction in the apparent sedimentation age of parent material through bioturbation and illuviation of younger material from above and/or by biological recycling and resetting of the datable signal of surface material. Berger (2003) proposes that the chronological products of this remobilisation are A-horizon age estimates reflecting the cessation of pedogenic activity, Bc/C-horizon ages delimiting the maximum age for the initiation of pedogenesis with estimates obtained from Bt-horizons providing an intermediate age 'close to the age of cessation of soil development'. Singhvi et al. (2001), in contrast, suggest that B and C-horizons closely approximate the age of the parent material, the A-horizon, that of the 'soil forming episode'. Recent analyses of inter-aliquot D_e distributions have reinforced this complexity of interpreting burial age from pedoturbated deposits (Lombard *et al*., 2011; Gliganic *et al*., 2015; Jacobs *et al*., 2008; Bateman *et al*., 2007; Gliganic *et al*., 2016). At present there is no definitive post-sampling mechanism for the direct detection of and correction for post-burial sediment remobilisation. However, intervals of palaeosol evolution can be delimited by a maximum age derived from parent material and a minimum age obtained from a unit overlying the palaeosol. Inaccuracy forced by cryoturbation may be bidirectional, heaving older material upwards or drawing younger material downwards into the level to be dated. Cryogenic deformation of matrix-supported material is, typically, visible; sampling of such cryogenically-disturbed sediments can be avoided.

4.0 Acquisition and accuracy of D_r value

Lithogenic D_r values were defined through measurement of U, Th and K radionuclide concentration and conversion of these quantities into β and γ D_r values (Table 1). β contributions were estimated from sub-samples by laboratory-based γ spectrometry using an Ortec GEM-S high purity Ge coaxial detector system, calibrated using certified reference materials supplied by CANMET. γ dose rates can be estimated from *in situ* NaI gamma spectrometry or, where direct measurements are unavailable as in the present case, from laboratory-based Ge γ spectrometry. *In situ* measurements reduce uncertainty relating to potential heterogeneity in the γ dose field surrounding each sample. The level of U disequilibrium was estimated by laboratory-based Ge γ spectrometry. Estimates of radionuclide concentration were converted into D_r values (Adamiec and Aitken, 1998), accounting for D_r modulation forced by grain size (Mejdahl, 1979) and present moisture content (Zimmerman, 1971). Cosmogenic D_r values were calculated on the basis of sample depth, geographical position and matrix density (Prescott and Hutton, 1994).

The spatiotemporal validity of D_r values can be considered a function of five variables. Firstly, age estimates devoid of *in situ* γ spectrometry data should be accepted tentatively if the sampled unit is heterogeneous in texture or if the sample is located within 300 mm of strata consisting of differing texture and/or mineralogy. However, where samples are obtained throughout a vertical profile, consistent values of γ D_r based solely on laboratory measurements may evidence the homogeneity of the γ field and hence accuracy of γ D_r values. Secondly, disequilibrium can force temporal instability in U and Th emissions. The impact of this infrequent phenomenon (Olley *et al.*, 1996) upon age estimates is usually insignificant given their associated margins of error. However, for samples where this effect is pronounced (>50% disequilibrium between ^{238}U and ^{226}Ra; Fig. 5), the resulting age estimates should be accepted tentatively. Thirdly, pedogenically-induced variations in matrix composition of B and C-horizons, such as radionuclide and/or mineral remobilisation, may alter the rate of energy emission and/or absorption. If D_r is invariant through a dated profile and samples encompass primary parent material, then element mobility is likely limited in effect. Fourthly, spatiotemporal detractions from present moisture content are difficult to assess directly, requiring knowledge of the magnitude and timing of differing contents. However, the maximum influence of moisture content variations can be delimited by recalculating D_r for minimum (zero) and maximum (saturation) content. Finally, temporal alteration in the thickness of overburden alters cosmic D_r values. Cosmic D_r often forms a negligible portion of total D_r. It is possible to quantify the maximum influence of overburden flux by recalculating D_r for minimum (zero) and maximum (surface sample) cosmic D_r.

5.0 Estimation of Age

Ages reported in Table 1 provide an estimate of sediment burial period based on mean D_e and D_r values and their associated analytical uncertainties. Uncertainty in age estimates is reported as a product of systematic and experimental errors, with the magnitude of experimental errors alone shown in parenthesis (Table 1). Cumulative frequency plots indicate the inter-aliquot variability in age (Fig. 6). The maximum influence of temporal variations in D_r forced by minima-maxima in moisture content and overburden thickness is also illustrated in Fig. 6. Where uncertainty in these parameters exists this age range may prove instructive, however the combined extremes represented should not be construed as preferred age estimates. The analytical validity of each sample is presented in Table 2.

6.0 Analytical uncertainty

All errors are based upon analytical uncertainty and quoted at 1σ confidence. Error calculations account for the propagation of systematic and/or experimental (random) errors associated with D_e and D_r values.

For D_e values, systematic errors are confined to laboratory β source calibration. Uncertainty in this respect is that combined from the delivery of the calibrating γ dose (1.2%; NPL, pers. comm.), the conversion of this dose for SiO_2 using the respective mass energy-absorption coefficient (2%; Hubbell, 1982) and experimental error, totalling 3.5%. Mass attenuation and bremsstrahlung losses during γ dose delivery are considered negligible. Experimental errors relate to D_e interpolation using sensitisation corrected dose responses. Natural and regenerated sensitisation corrected dose points (S_i) were quantified by,

$$S_i = (D_i - x.L_i) / (d_i - x.L_i) \quad \textbf{Eq.1}$$

where D_i = Natural or regenerated OSL, initial 0.2 s

L_i = Background natural or regenerated OSL, final 5 s

d_i = Test dose OSL, initial 0.2 s

x = Scaling factor, 0.08

The error on each signal parameter is based on counting statistics, reflected by the square-root of measured values. The propagation of these errors within Eq. 1 generating σS_i follows the general formula given in Eq. 2. σS_i were then used to define fitting and interpolation errors within exponential plus linear regressions.

For D_r values, systematic errors accommodate uncertainty in radionuclide conversion factors (5%), β attenuation coefficients (5%), a-value (4%; derived from a systematic α source uncertainty of 3.5% and experimental error), matrix density (0.20 $g.cm^{-3}$), vertical thickness of sampled section (specific to sample collection device), saturation moisture content (3%), moisture content attenuation (2%), and burial moisture content (25% relative, unless direct evidence exists of the magnitude and period of differing content) and Ge gamma spectrometer calibration (3%). Experimental errors are associated with radionuclide quantification for each sample by Ge gamma spectrometry.

The propagation of these errors through to age calculation was quantified using the expression,

$$\sigma y\ (\delta y/\delta x) = (\Sigma\ ((\delta y/\delta x_n).\sigma x_n)^2)^{1/2} \qquad \textbf{Eq. 2}$$

where y is a value equivalent to that function comprising terms x_n and where σy and σx_n are associated uncertainties.

Errors on age estimates are presented as combined systematic and experimental errors and experimental errors alone. The former (combined) error should be considered when comparing luminescence ages herein with independent chronometric controls. The latter assumes systematic errors are common to luminescence age estimates generated by means identical to those detailed herein and enable direct comparison with those estimates.

Fig. 1 Signal Calibration

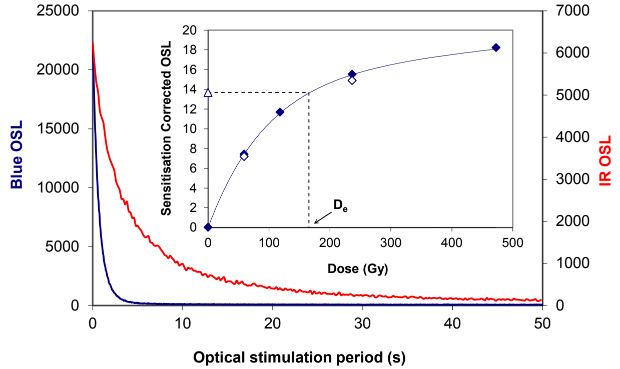

Fig. 2 Dose Recovery

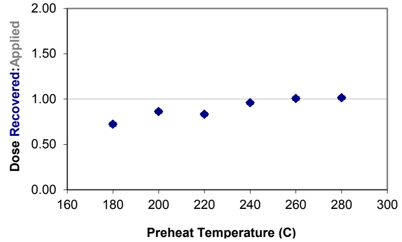

Fig. 4 Signal Analysis

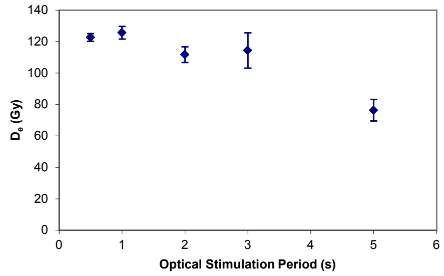

Fig. 3 Inter-aliquot D_e distribution

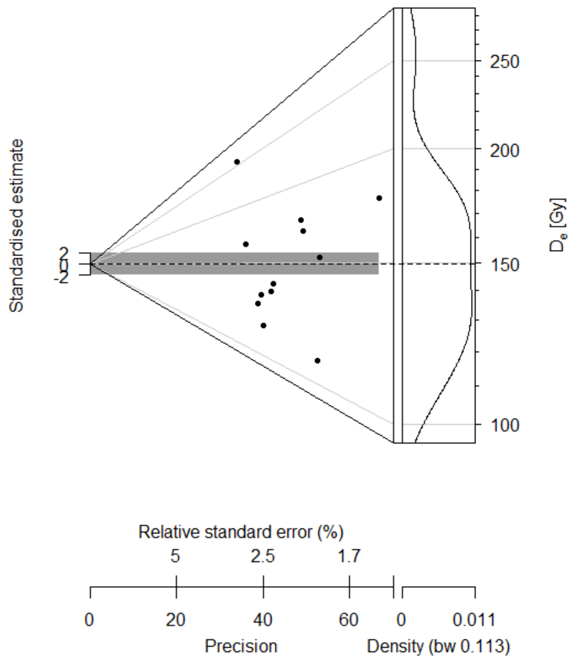

Fig. 5 U Decay Activity

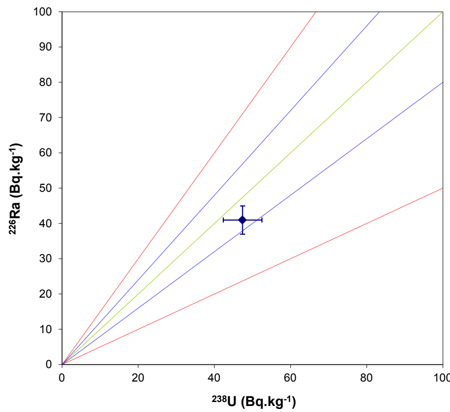

Fig. 6 Age Range

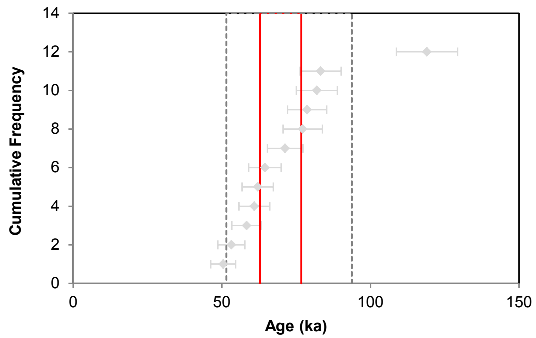

Fig. 1 Signal Calibration Natural blue and laboratory-induced infrared (IR) OSL signals. Detectable IR signal decays are diagnostic of feldspar contamination. Inset, the natural blue OSL signal (open triangle) of each aliquot is calibrated against known laboratory doses to yield equivalent dose (D_e) values. Repeats of low and high doses (open diamonds) illustrate the success of sensitivity correction.

Fig. 2 Dose Recovery The acquisition of D_e values is necessarily predicated upon thermal treatment of aliquots succeeding environmental and laboratory irradiation. The Dose Recovery test quantifies the combined effects of thermal transfer and sensitisation on the natural signal using a precise lab dose to simulate natural dose. Based on this an appropriate thermal treatment is selected to generate the final D_e value.

Fig. 3 Inter-aliquot D_e distribution Abanico plot of inter-aliquot statistical concordance in D_e values derived from **natural** irradiation. Discordant data (those points lying beyond **±2 standardised ln D_e**) reflect heterogeneous dose absorption and/or inaccuracies in calibration.

Fig. 4 Signal Analysis Statistically significant increase in **natural** D_e value with signal stimulation period is indicative of a partially-bleached signal, provided a significant increase in D_e results from **simulated partial bleaching** followed by insignificant adjustment in D_e for simulated **zero** and **full bleach** conditions. Ages from such samples are considered maximum estimates. In the absence of a significant rise in D_e with stimulation time, simulated partial bleaching and zero/full bleach tests are not assessed.

Fig. 5 U Activity Statistical concordance (equilibrium) in the activities of the daughter radioisotope ^{226}Ra with its parent ^{238}U may signify the temporal stability of D_r emissions from these chains. Significant differences (disequilibrium; >50%) in activity indicate addition or removal of isotopes creating a time-dependent shift in D_r values and increased uncertainty in the accuracy of age estimates. A 20% disequilibrium marker is also shown.

Fig. 6 Age Range The Cumulative frequency plot indicates the inter-aliquot variability in age. It also shows the **mean age range**; an estimate of sediment burial period based on mean D_e and D_r values with associated analytical uncertainties. The **maximum influence** of temporal variations in D_r forced by minima-maxima variation in moisture content and overburden thickness is outlined and may prove instructive where there is uncertainty in these parameters. However the combined extremes represented should not be construed as preferred age estimates.

Sample: GL17153

Fig. 1 Signal Calibration

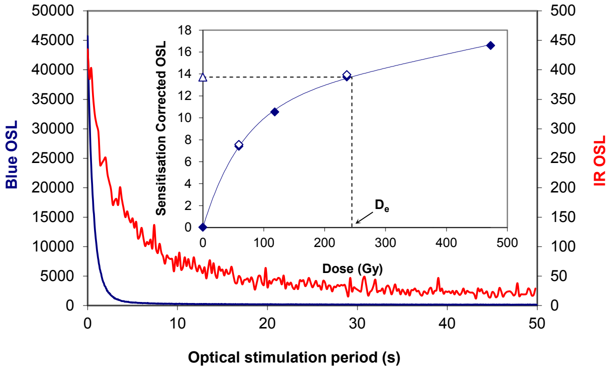

Fig. 2 Dose Recovery

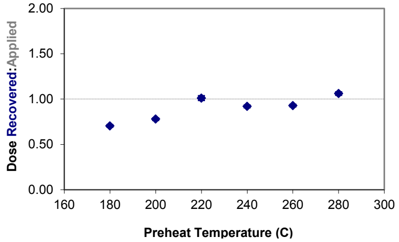

Fig. 4 Signal Analysis

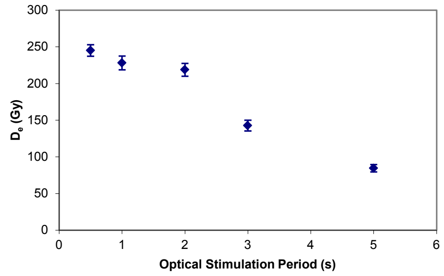

Fig. 3 Inter-aliquot D_e distribution

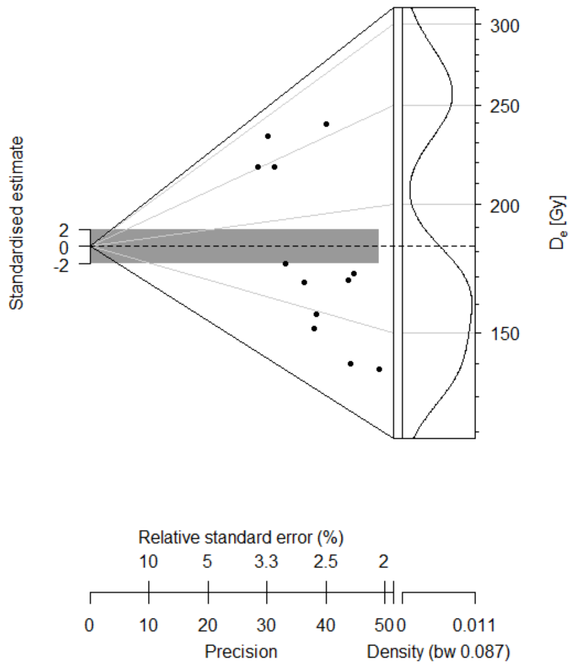

Fig. 5 U Decay Activity

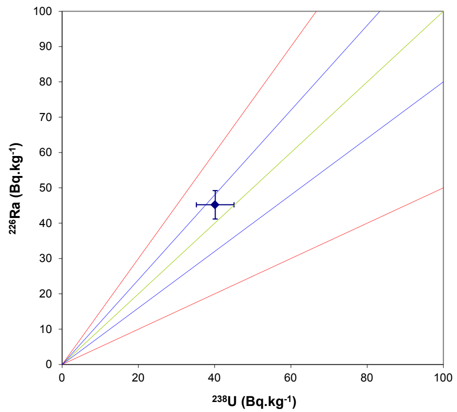

Fig. 6 Age Range

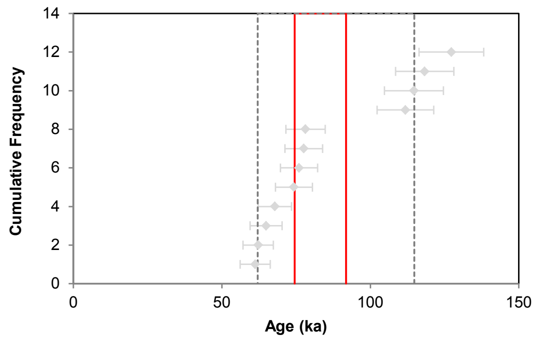

Fig. 1 Signal Calibration Natural blue and laboratory-induced infrared (IR) OSL signals. Detectable IR signal decays are diagnostic of feldspar contamination. Inset, the natural blue OSL signal (open triangle) of each aliquot is calibrated against known laboratory doses to yield equivalent dose (D_e) values. Repeats of low and high doses (open diamonds) illustrate the success of sensitivity correction.

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Fig. 3 Inter-aliquot D_e distribution Abanico plot of inter-aliquot statistical concordance in D_e values derived from **natural** irradiation. Discordant data (those points lying beyond **±2 standardised ln D_e**) reflect heterogeneous dose absorption and/or inaccuracies in calibration.

Fig. 4 Signal Analysis Statistically significant increase in **natural** D_e value with signal stimulation period is indicative of a partially-bleached signal, provided a significant increase in D_e results from **simulated partial bleaching** followed by insignificant adjustment in D_e for simulated **zero** and **full bleach** conditions. Ages from such samples are considered maximum estimates. In the absence of a significant rise in D_e with stimulation time, simulated partial bleaching and zero/full bleach tests are not assessed.

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Sample: GL17154

Fig. 1 Signal Calibration

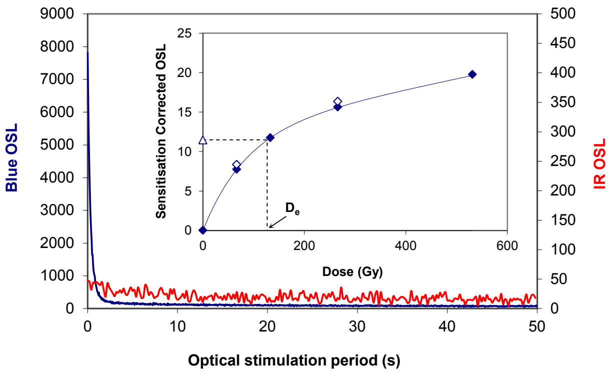

Fig. 2 Dose Recovery

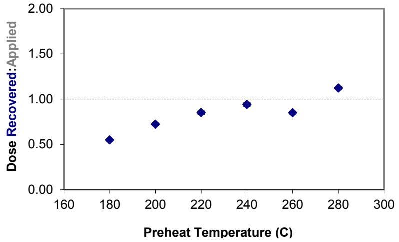

Fig. 4 Signal Analysis

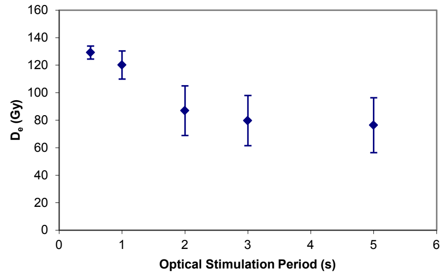

Fig. 3 Inter-aliquot D_e distribution

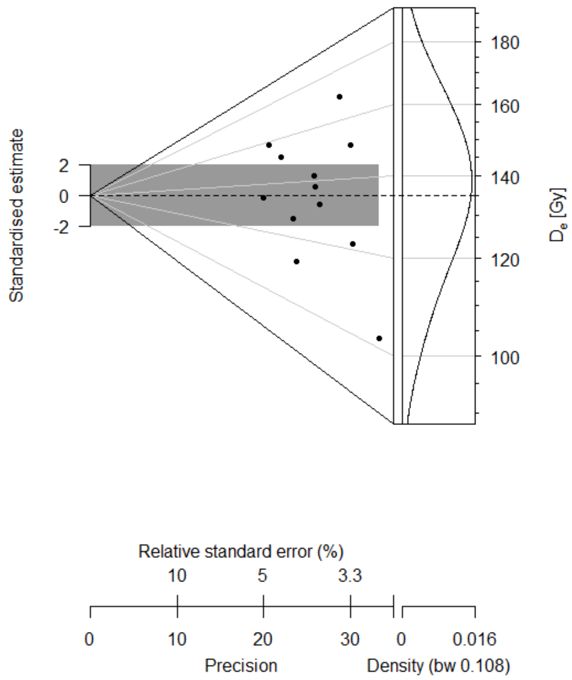

Fig. 5 U Decay Activity

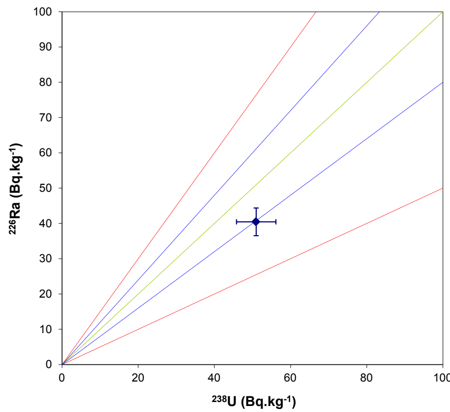

Fig. 6 Age Range

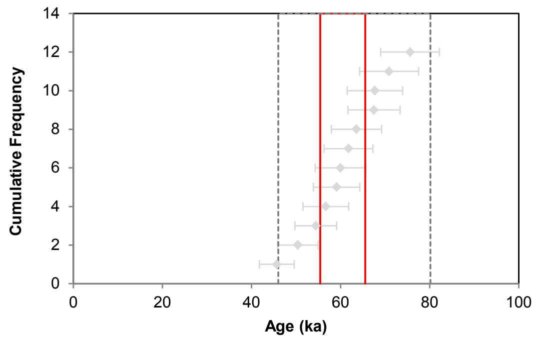

Fig. 1 Signal Calibration Natural blue and laboratory-induced infrared (IR) OSL signals. Detectable IR signal decays are diagnostic of feldspar contamination. Inset, the natural blue OSL signal (open triangle) of each aliquot is calibrated against known laboratory doses to yield equivalent dose (D_e) values. Repeats of low and high doses (open diamonds) illustrate the success of sensitivity correction.

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Fig. 3 Inter-aliquot D_e distribution Abanico plot of inter-aliquot statistical concordance in D_e values derived from **natural** irradiation. Discordant data (those points lying beyond **±2 standardised ln D_e**) reflect heterogeneous dose absorption and/or inaccuracies in calibration.

Fig. 4 Signal Analysis Statistically significant increase in **natural** D_e value with signal stimulation period is indicative of a partially-bleached signal, provided a significant increase in D_e results from **simulated partial bleaching** followed by insignificant adjustment in D_e for simulated **zero** and **full bleach** conditions. Ages from such samples are considered maximum estimates. In the absence of a significant rise in D_e with stimulation time, simulated partial bleaching and zero/full bleach tests are not assessed.

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Fig. 6 Age Range The Cumulative frequency plot indicates the inter-aliquot variability in age. It also shows the **mean age range**; an estimate of sediment burial period based on mean D_e and D_r values with associated analytical uncertainties. The **maximum influence** of temporal variations in D_r forced by minima-maxima variation in moisture content and overburden thickness is outlined and may prove instructive where there is uncertainty in these parameters. However the combined extremes represented should not be construed as preferred age estimates.

Sample: GL17155

Fig. 1 Signal Calibration

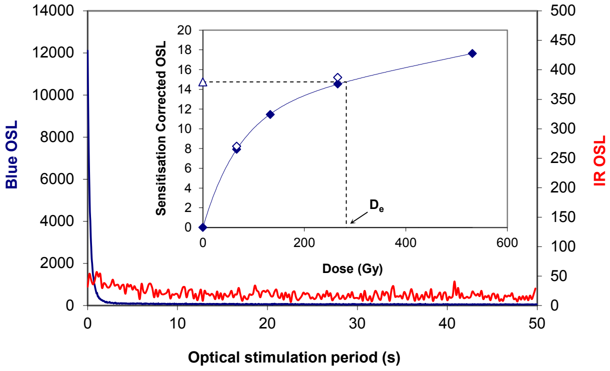

Fig. 2 Dose Recovery

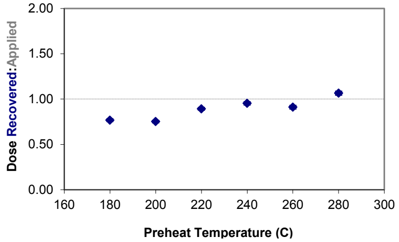

Fig. 4 Signal Analysis

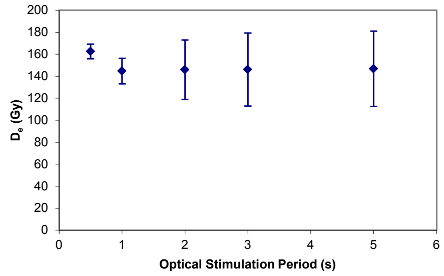

Fig. 3 Inter-aliquot D_e distribution

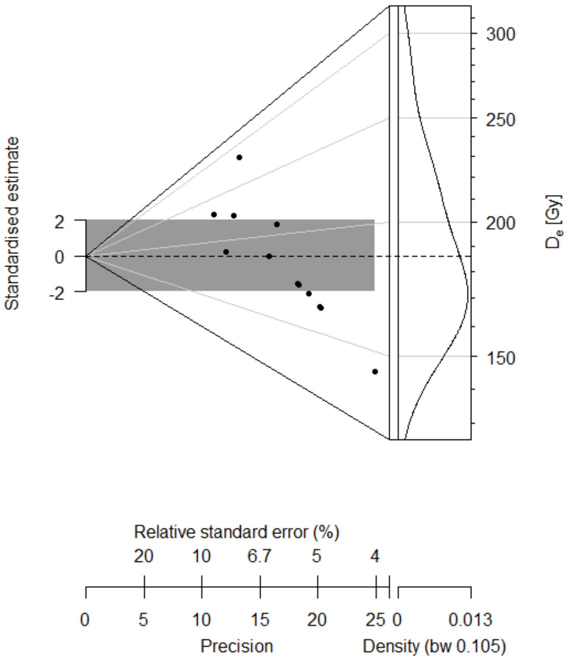

Fig. 5 U Decay Activity

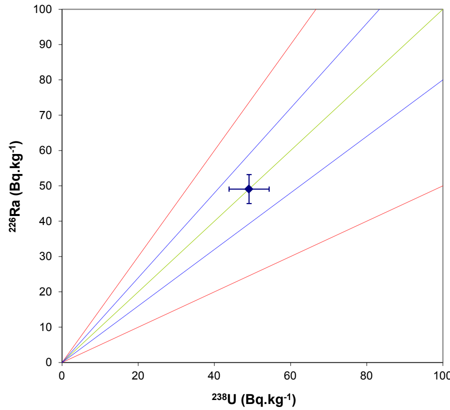

Fig. 6 Age Range

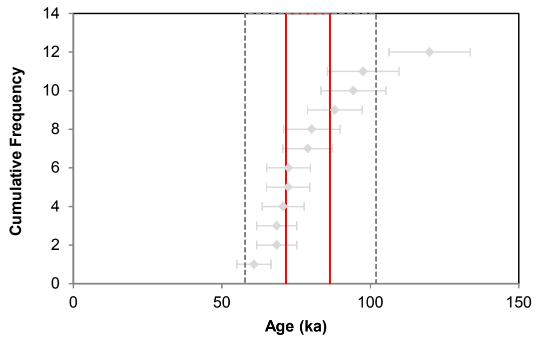

Fig. 1 Signal Calibration Natural blue and laboratory-induced infrared (IR) OSL signals. Detectable IR signal decays are diagnostic of feldspar contamination. Inset, the natural blue OSL signal (open triangle) of each aliquot is calibrated against known laboratory doses to yield equivalent dose (D_e) values. Repeats of low and high doses (open diamonds) illustrate the success of sensitivity correction.

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Fig. 4 Signal Analysis Statistically significant increase in **natural** D_e value with signal stimulation period is indicative of a partially-bleached signal, provided a significant increase in D_e results from **simulated partial bleaching** followed by insignificant adjustment in D_e for simulated **zero** and **full bleach** conditions. Ages from such samples are considered maximum estimates. In the absence of a significant rise in D_e with stimulation time, simulated partial bleaching and zero/full bleach tests are not assessed.

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Fig. 6 Age Range The Cumulative frequency plot indicates the inter-aliquot variability in age. It also shows the **mean age range**; an estimate of sediment burial period based on mean D_e and D_r values with associated analytical uncertainties. The **maximum influence** of temporal variations in D_r forced by minima-maxima variation in moisture content and overburden thickness is outlined and may prove instructive where there is uncertainty in these parameters. However the combined extremes represented should not be construed as preferred age estimates.

Sample: GL17156

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APPENDIX 4

Core	**VC032**						**VC039**	
Depth (mbsf)	**3.50**	**3.58**	**3.40**	**3.30**	**3.69**	**3.77**	**2.75**	**2.90**
Sample id	**D4**	**D5**	**D6**	**D7**	**D8**	**D9**	**D14**	**D15**
Polyhalobous								
Auliscus sculptus								1
Biddulphia sp.				1				
Coscinodiscus sp.								1
Dimeregramma minor				1				
Grammatophora sp.	1	1	2	1	1	2		1
Paralia sulcata	2	1	2	2		1	1	2
Podosira stelligera	1	1	2	2				
Rhabdonema sp.			1					
Rhaphoneis surirella			1	1				
Trachyneis aspera	1			1				
Polyhalobous to Mesohalobous								
Actinoptychus undulatus	1		1	1				
Ardissonia crystallina		1	1	1	1			
Cocconeis scutellum	3	3	3	1	3	3		
Hyalodiscus scoticus	2		1					
Nitzschia constricta					1	2		
Synedra gaillonii	1		1				1	
Mesohalobous								
Achnanthes brevipes		1				1		
Achnanthes delicatula					1	1		
Campylodiscus echeneis	1							
Diploneis aestuari			1					
Diploneis didyma	1	2	1	1	1	1	1	1
Nitzschia granulata		1						
Nitzschia navicularis			1	1		1	2	1
Nitzschia punctata			1		1			
Rhopalodia musculus	2	2	1			1		
Synedra tabulata		2	1	1		1		
Mesohalobous to Halophilous								
Actinocyclus normanii	1							
Halophilous to Oligohalobous Indifferent								
Rhoicosphaenia curvata						1		
Oligohalobous Indifferent								
Amphora pediculus				1				
Aulacoseira sp.	2		1	1				
Cocconeis disculus				1				
Cocconeis placentula	1	2			2	3		
Fragilaria brevistriata		1						
Fragilaria construens var.binodis						1		
Fragilaria pinnata		1	1					
Navicula scutelloides	1							

Core	VC032						VC039	
Depth (mbsf)	**3.50**	**3.58**	**3.40**	**3.30**	**3.69**	**3.77**	**2.75**	**2.90**
Sample id	**D4**	**D5**	**D6**	**D7**	**D8**	**D9**	**D14**	**D15**
Unknown Salinity Group								
Amphora sp.		1				1		
Cocconeis sp.		1		1	1			
Diploneis sp.	1					1		1
Fallacia/Lyrella sp.			1		1			
Fragilaria sp.	1			1	1	1		
Inderminate centric sp.		1		1		1	1	2
Inderminate pennate sp.			1	1				1
Mastogloia sp.	1							
Navicula sp.		1			1			
Pleurosigma sp.							1	
Unknown diatom fragments							3	3
Unknown naviculaceae			1				1	

APPENDIX 5

VC016

Lithostratigraphic Unit	***Unit 5***	***Undifferentiated***					***Unit 3***							
DEPTH IN CORE/BSF	**0.22m**	**0.47m**	**0.72m**	**0.97m**	**1.17m**	**1.42m**	**1.67m**	**2.20m**	**2.40m**	**2.60m**	**3.37m**	**3.87m**	**4.38m**	**4.85m**
OUTER ESTUARINE/MARINE FORAMINIFERA														
miliolids	x	x	x	x	xx	x	x	x	x	o	xx	x	x	x
Elphidium bartletti	x	x	xx	xx	xx	xx	xx	xx	xx	x	x	o	o	x
Nonion orbicularis	x	x		x	x	o	o	x	x		o			
Elphidium excavatum/clavatum	x	x	x	x	x	x	o	x	o	x	x	x	x	x
Ammonia batavus (large)	x				o	o								
Elphidium williamsoni	x		x	o	x	x			o	o				
Pseudopolymorphina novangliae	o	o	x		x	xx	x	x		x	o	x	o	o
Elphidium albiumbilicatum	o		o	x		x	x		x			x		
lagenids		o		o	o	x						x	x	
Elphidium margaritaceum			x			x		x		o		o	o	
OUTER ESTUARINE/MARINE OSTRACODS														
Hemicythere villosa	x	o		o	x				o	x	o	x		
Hemicytherura clathrata	x	o	x	x	x	x	x	x	x	o		x		
Cythere lutea	o	x	x	o	x	x	x	x	x	x	o			
Leptocythere pellucida/psammophila	o		o	x		x	o	x	x	o	x	x		
Sarsicytheridea punctillata	o	o						o						
Cytheropteron spp.	o			x	x	x	x	x	x	o	o	x	o	
Finmarchinella finmarchica		x	o	o	x	x	o	x						
Robertsonites tuberculatus		o	o		x			o	o		o			o
Sarsicytheridea bradii			x	x	o	o	o	x	x	x	o			
Callistocythere curryi			o		o									
Roundstonia globulifera				o	o	x	o			x	x	o		
Sclerochilus sp.					o								o	
Hirschmannia viridis					o	o		o	o	o	x	x		
Semicytherura undata					o									
Finmarchinella angulata						x		o	o	o	x		o	
Loxoconcha rhomboidea									o	o				o

Contained material is recorded on a presence (x)/absence basis; f – fragments only
Foraminifera and ostracods are recorded: o – one specimen; x - several specimens; xx – common; xxx – abundant/superabundant
Cold indicator ostracod, extinct in Britain since MIS 3
Not part of the British fauna but living today further north in Europe
Species restricted to northern Britain today and further north
Extinct; latest record in MIS 5e, but with southern affinities
Cold indicator foraminifera

VC032	*Lithostratigraphic Unit*	*Unit 5*			*Unit 4c*			*Unit 4a*			
	DEPTH IN CORE/BSF	3.30m	3.40m	3.50m	3.58m	3.69m	3.77m	4.17m	4.32m	4.44m	4.56m
	BRACKISH FORAMINIFERA										
	Ammoniasp. (brackish)	x	xxx	xxx	x	x	x				
	Haynesina germanica	o	x	x	x	x	x				
	Elphidium williamsoni		x	x							
	Elphidium waddense				o	x					
	BRACKISH OSTRACODS										
	Cyprideis torosa		x	xx	x	xx	xxx				
	Loxoconcha elliptica		x	xx	xx	xx	x				
	Xestoleberis nitida			x		x					
	Cytherois fischeri			x							
	Leptocythere castanea			x							
	Cytherura gibba					x					
	OUTER ESTUARINE/MARINE FORAMINIFERA										
	miliolids	x									
	Ammonia batavus	o									
	OUTER ESTUARINE/MARINE OSTRACODS										
	Hemicythere villosa		x								
	Hirschmannia viridis		x	x							
	Semicytherura nigrescens		x	x	x						

Contained material is recorded on a presence (x)/absence basis only

Foraminifera and ostracods are recorded: o – one specimen; x - several specimens; xx – common; xxx – abundant/superabundant

VC039

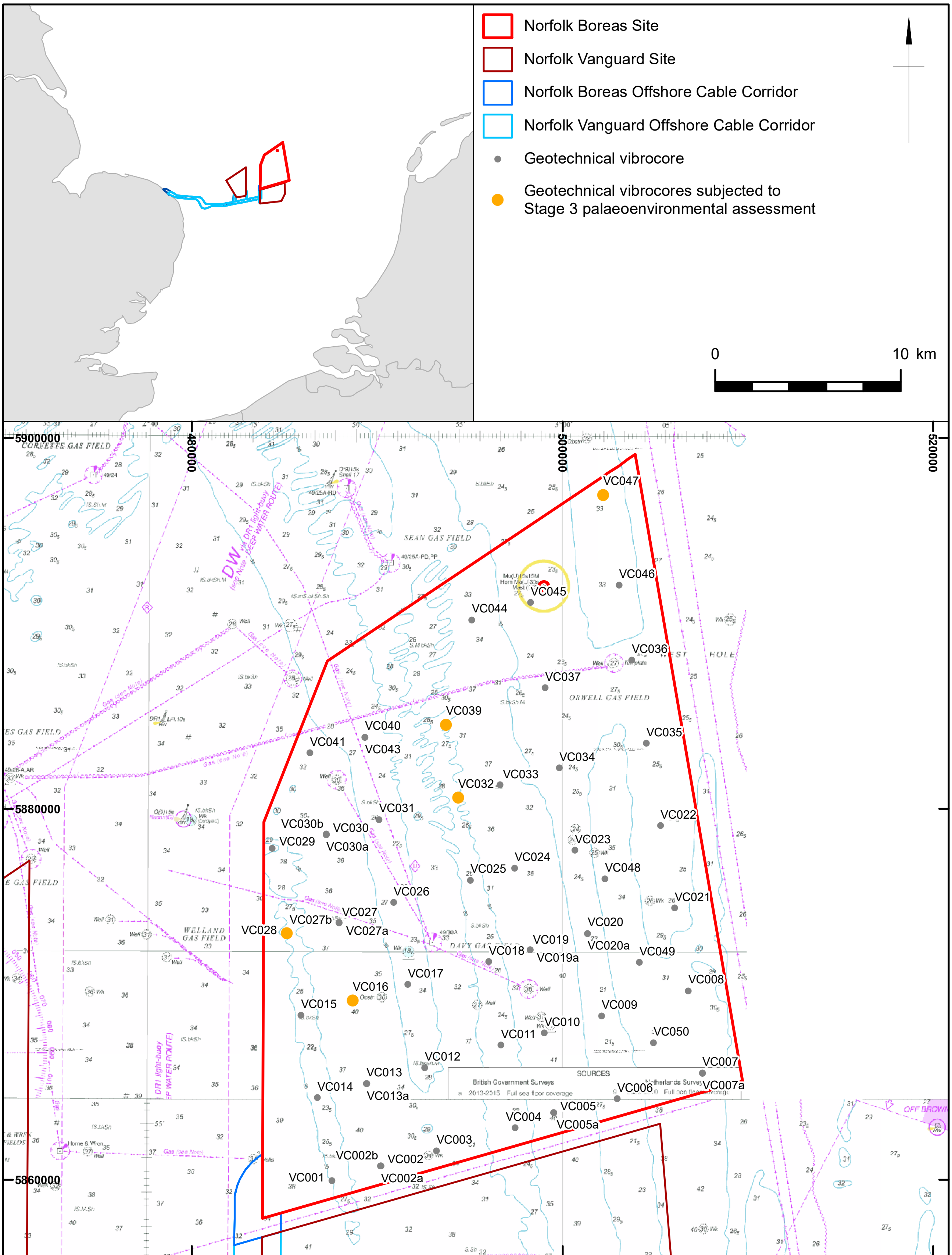
Lithostratigraphic Unit	*Unit 5*		*Unit 4a*		
DEPTH IN CORE/BSF	2.75m	2.90m	3.15m	3.31m	3.51m
BRACKISH FORAMINIFERA					
Ammoniasp. (brackish)	xxx	xxx			
Haynesina germanica	xx	xx			
Elphidium williamsoni	x	xx			
Elphidium waddense	o	x			
BRACKISH OSTRACODS					
Cyprideis torosa	x	xx			
Loxoconcha elliptica	x	x			
Xestoleberis nitida	x	o			
Leptocythere lacertosa	x				
Cytherois fischeri	x				
Cytherura gibba	o				
OUTER ESTUARINE/MARINE FORAMINIFERA					
miliolids	x	x			
Nonion depressulus	x	x			
lagenids	o				
OUTER ESTUARINE/MARINE OSTRACODS					
Hirschmannia viridis	x	x			
Semicytherura nigrescens	x	x			
Hemicythere villosa	x	x			
Leptocythere pellucida	x				
Leptocythere tenera	x				
FRESHWATER OSTRACODS					
Limnocythere inopinata	x		o		
Cyclocypris ovum			xxx	x	
Candona candida			xx		
Cypridopsis vidua			x		
Herpetocypris reptans			x		
Pseudocandona rostrata			x		
Ilyocypris gibba				o	
Limnocytherina sanctipatricii				o	

Contained material is recorded on a presence (x)/absence basis only
Foraminifera & ostracods are recorded: o – one specimen; x - several specimens; xx – common; xxx – abundant/superabundant
cool/cold indicators

VC047

Lithostratigraphic Unit	*Undifferentiated*				*Unit 3*					
DEPTH IN CORE/BSF	1.70m	1.90m	2.15m	2.40m	2.65m	2.85m	3.40m	3.85m	4.40m	4.85m
OUTER ESTUARINE/MARINE FORAMINIFERA										
Ammonia batavus (large & ornate)	xxx	xx	xx	x	o	o				
Elphidium excavatum	xx	xx	xx	x	xx	x	x		x	
Elphidium williamsoni	x	xx	x			o				
Haynesina germanica	x	xx	x	x	xx	x				
miliolids	x	x	x	x	o	o	x	x	x	x
Pseudopolymorphina novangliae	x	x			x	x		xx	o	x
discorbids		x							o	
Cassidulina reniformis		x							o	
lagenids		o							x	x
Elphidium bartletti				x		x	xx	x	x	xx
Nonion orbicularis					x	x	x			x
Elphidium albiumbilicatum					x				x	
Elphidium clavatum								x	xx	x
OUTER ESTUARINE/MARINE OSTRACODS										
Pontocythere elongata	xxx	x		o				o		
Elofsonella concinna	x	xxx	xxx	x	o		x	o	o	
Hemicytherura clathrata	x	o			o				x	
Cypridels torosa	x	o								
Leptocythere baltica	o	o								
Cytheropteron spp.		o			o		o	o		o
Hemicythere villosa		x							x	o
Eucythere argus		x	x							
Finmarchinella finmarchica		x	o				o		x	x
Semicytherura undata		o								
Semicytherura spp.			o				x	o	x	o
Leptocythere psammophila/pellucida			o			o	o	o		o
Robertsonites tuberculatus				o	x				o	
Finmarchinella angulata					o		o			
Sarsicytheridea bradii					x	o	x	o	x	x
Hirschmannia viridis							o		o	
Roundstonia globulifera								x	x	x
Cythere lutea									x	x

Contained material is recorded on a presence (x)/absence basis; f – fragments only
Foraminifera and ostracods are recorded: o – one specimen; x - several specimens; xx – common; xxx – abundant/superabundant
Cold indicator ostracod, extinct in Britain since MIS 3
Species restricted to northern Britain today and further north
Not part of the British fauna; living today further north in Europe
Cold indicator foraminifera



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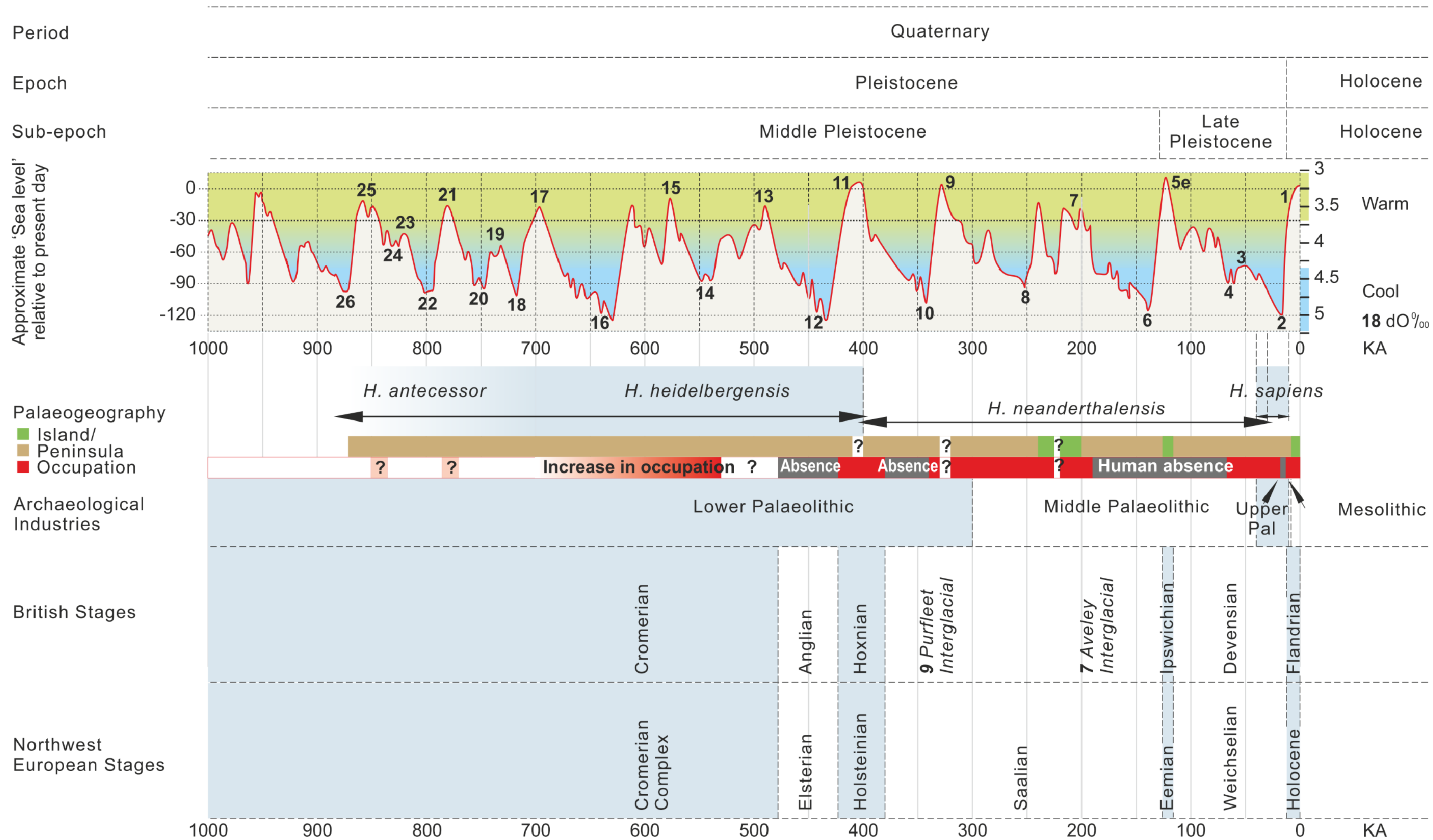
Coordinate system:
ETRS1989 UTM Z31N

Location of Norfolk Boreas project area

Figure 1



The figure presents information derived from several references: the global sea-level curve is from Lisiecki and Raymo (2005) and Jelgersma (1979). Details on the geology and archaeology were provided by Dix and Westley (2004); Funnel (1995); Gibbard and van Kolfschoten (2004); Kukla et al. (2002); Lee et al. (2006); Lowe and Walker (1997) and Wymer (1999).

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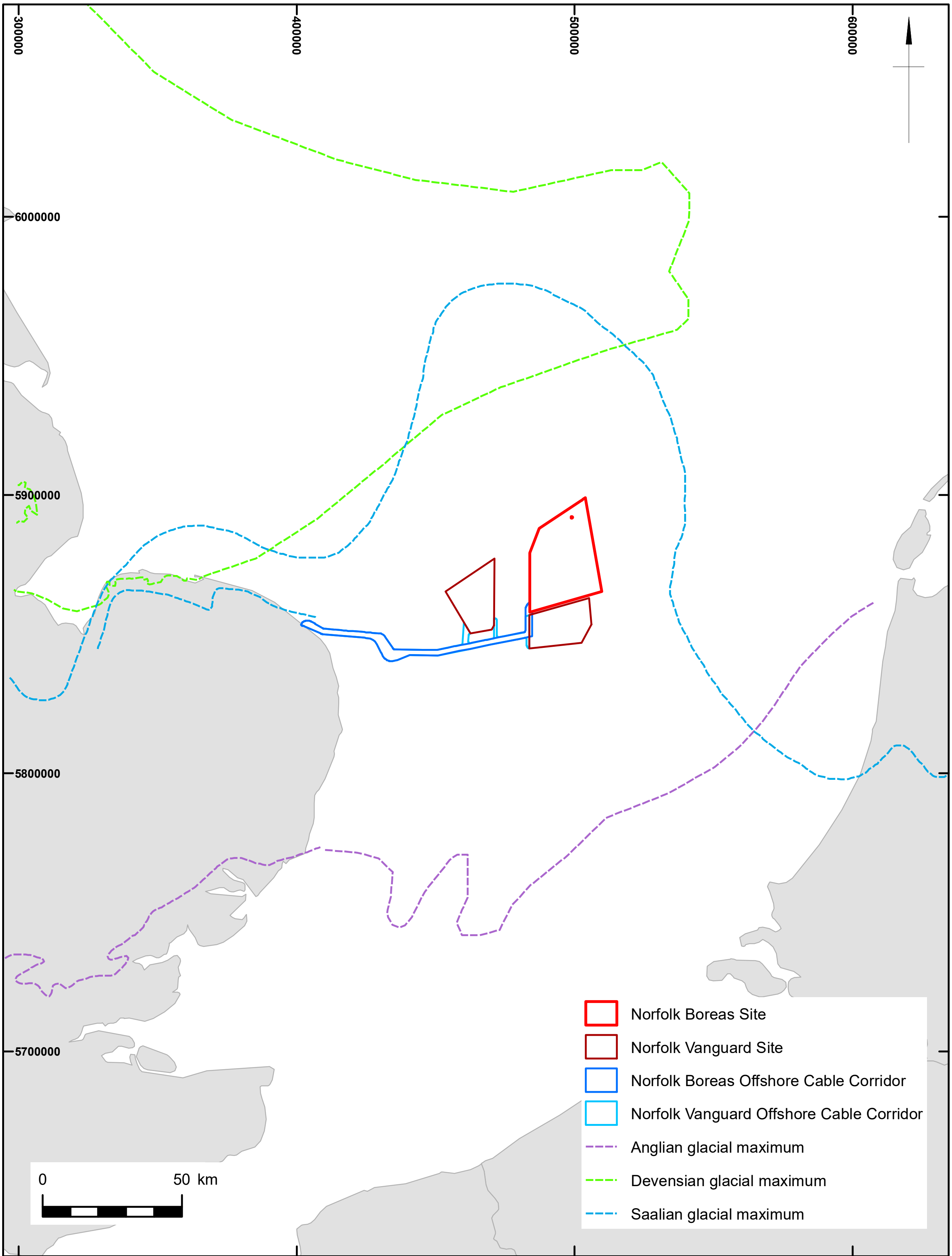
Chronostratigraphic timeline for the last 1 million years

Figure 2



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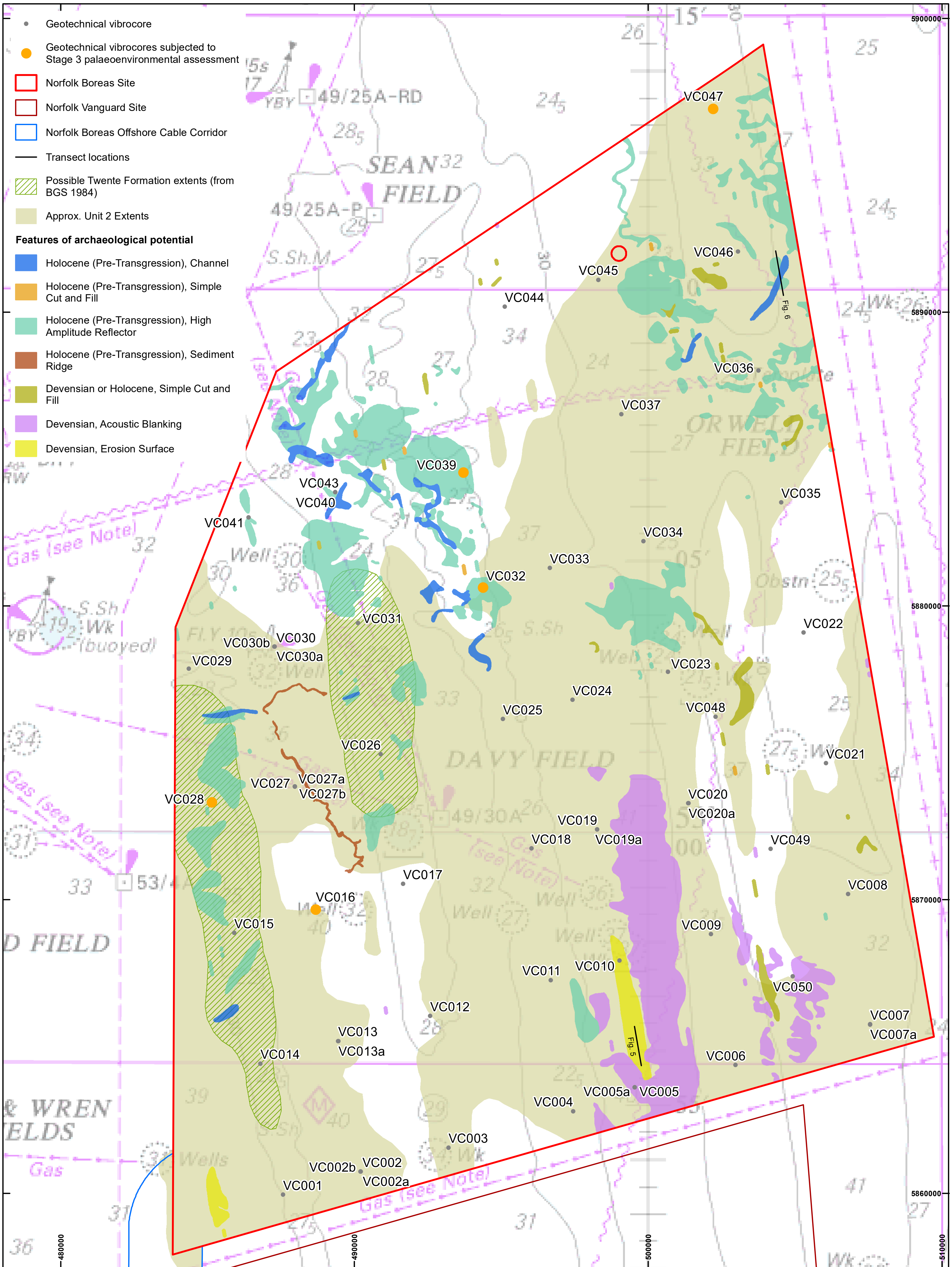
Pleistocene ice limits

Figure 3



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0 5 km

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Palaeolandscape features of archaeological potential interpreted from geophysical data

Figure 4

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