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Dudgeon Offshore Wind Farm

Stage 4 Palaeoenvironmental Analysis, Borehole BH06

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August 2016

geoservices

Dudgeon Offshore Wind Farm

Stage 4 Palaeoenvironmental Analysis, Borehole BH06

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Summary

Wessex Archaeology was commissioned by Royal HaskoningDHV to undertake a Stage 4 palaeoenvironmental analysis of borehole BH06 from the site of the proposed Dudgeon Offshore Windfarm. The Stage 4 work comprised analysis of pollen, foraminifera, ostracod, waterlogged plant and molluscan remains from borehole BH06, supported by additional AMS radiocarbon dates. The analysis of borehole BH06 is the first integrated geoarchaeological and palaeoenvironmental analysis of late Glacial and early Holocene sediments from the southern North Sea Basin. The sediments in borehole BH06 include a complex sequence of late quaternary sediments infilling a linear northwest – southeast feature, probably similar to scaphiform glacial valleys recorded in other areas of the southern North Sea basin. The sediments analysed from borehole BH06 cover a period of as much as ca. 4800 years over the transition between the last (Devensian) Ice Age and current (Holocene) warm period (ca. 12700–7900 cal BP). This represents a period of significant climate change, with the abrupt cooling of the Younger Dryas (from ca. 12.9–12.7 ka BP) followed by rapid warming associated with the onset of the Holocene (ca. 11.7 ka BP). The southern North Sea basin saw major transformations, with climate and sea-level rise radically altering the physical and vegetation environments and culminating in the final marine inundation of this landscape by ca. 7900 cal BP. Included in borehole BH06 is 7.5 m of mixed gravelly shelly sand (10.22–2.35 mbSB), bracketed by two radiocarbon dates (8996–8760 and 8105–7931 cal BP) that suggest this deposit may relate to the tsunami event linked with the Storegga submarine landslide ca. 8100 BP.

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Wessex Archaeology is grateful to Royal HaskoningDHV for commissioning the Stage 4 analysis and in particular to Helen Craven and Victoria Cooper (Royal Haskoning DHV) and Michael Corney (Statkraft) for their assistance.The Stage 4 palaeoenvironmental analysis, and processing of samples was undertaken by Rob Scaife (pollen), John Whittaker (foraminifera and ostracods) and Sarah Wyles (plant macrofossils and molluscs). The radiocarbon dating was undertaken at the Scottish Universities Environmental Research Centre (SUERC), East Kilbride under the supervision of Gordon Cook and Chrono centre and the 14C CHRONO Centre at Queens University Belfast. This report was written by Alex Brown and figures were prepared by Kitty Foster. The project was managed for Wessex Archaeology by Jack Russell.

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Stage 4 Palaeoenvironmental Analysis, Borehole BH06

1 INTRODUCTION

1.1 Project background

1.1.1 Wessex Archaeology was commissioned by Royal HaskoningDHV to undertake a Stage 4 palaeoenvironmental analysis of Borehole BH06 on the site of the proposed Dudgeon Offshore Wind Farm – hereafter known as 'the site'. The site is located within the southern North Sea Basin, approximately 32 km north-east off the Cromer coast of North Norfolk (**Figure 1**).

1.1.2 The analysis presented here represents the first integrated geoarchaeological and palaeoenvironmental analysis of late Glacial and early Holocene sediments from the southern North Sea Basin. It forms part of an ongoing program of geoarchaeological works for the proposed Dudgeon Offshore Wind Farm, as detailed in two written schemes of investigation (WSI) (WA 2013, 2014a) and a Stage 1–3 geoarchaeological and palaeoenvironmental assessment (WA 2014b).

1.1.3 The Stage 1–3 assessment of geotechnical logs and boreholes, recovered from the site by GEO (2014), comprised geoarchaeological recording and sub-sampling (Stage 1 and 2) supported by palaeoenvironmental assessment and radiocarbon dating (Stage 3). The sediments at the site include a sequence of Pleistocene glacial and shallow marine deposits of Wolstonian (Marine Isotope Stage 'MIS' 10–8; ca. 350–250 ka BP) and Late Devensian date (18 –12 ka BP), overlain by terrestrial sediments of early Holocene date deposited prior to final marine inundation of Doggerland.

1.1.4 The assessment focused on late Glacial and early Holocene sediments contained within two boreholes (BH06 and BH21), with BH06 showing by far the most potential. Recommendations were made for further targeted analysis of BH06 (WA 2014b), the results of which are the subject of this Stage 4 report.

1.1.5 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.

Stage 1: Review	Initial archaeological assessment of the logs generated by geotechnical contractors to establish the presence and location of sediment units with likely archaeological, palaeo-environmental and/or dating potential. Typically units of interest would be fine-grained sediments deposited in fluvial or estuarine environments, and sediments containing organic remains such as peat or other plant material.

Stage 2: Geoarchaeological recording	Each core containing sedimentary units identified as having geoarchaeological, palaeoenvironmental or dating potential will be split and recorded in detail. A sedimentary description for each of the units will be made, and those units of particular archaeological/palaeoenvironmental interest will be highlighted and a simple deposit model produced from the core logs. The Stage 2 and Stage 3 assessment can be conducted concurrently, whilst ensuring that the samples collected are treated in the appropriate way for archaeological study.
Stage 3: Assessment	Assessment of sub-samples taken from units of archaeological and/or palaeoenvironmental interest. The assessment of microfossil environmental indicators (pollen, diatoms, ostracods and/or foraminifera) will be taken, with the core retained should further sub-sampling be required. Assessment will comprise identification and quality of preservation of a series of subsamples to enable the value of the palaeoenvironmental material surviving within the cores to be identified. Subsamples may also be taken and submitted for scientific dating if required at this stage.
Stage 4: Analysis and Dating	Full analysis of pollen, diatoms and/or foraminifera assessed during Stage 3. Typically, Stage 4 will be supported by radiocarbon dating of suitable sub-samples. Should the Stage 3 assessment indicate that there is no further analytical work required on the microfossil assemblages, consideration will still be given for a programme of radiocarbon analyses to provide a chronological framework for the deposits encountered unless no suitable samples could be procured. The Stage 4 report will provide an account of the palaeoenvironment(s) at each relevant coring location within a chronological framework (absolute or relative) and an outline of the archaeological implications of the analysis.
Final Reporting and Publication	If the archaeological results are sufficiently significant as to warrant it, a Stage 5 report covering all aspects of palaeotopography and prehistory of the area affected by projects will be compiled after the last phase of analysis, and could be prepared as a publication, possibly in conjunction with BGS. If the archaeological results are less significant then the relevant Stage reports will constitute the final documents on the geotechnical work. If required, a Stage 5 report will include relevant data generated by other archaeological investigations on the site. It will, if warranted include a full assessment of the available seismic data, undertaken in order to place the results of the core recording and analysis within the context of the broad pattern of deposits within the area. The report will comprise as detailed a Quaternary deposit model for the area as possible, and address the implications of that model in terms of archaeological potential.

1.2 Aims and Objectives

1.2.1 The aim of the investigation is to maximise the geoarchaeological value of borehole BH06, with the following objectives:

- To build upon the Stage 1–3 assessment of geotechnical logs with further analysis on boreholes with high palaeoenvironmental potential;
- To generate data on the physical and vegetation environments of the southern North Sea basin and their development over the course of the late Glacial and early Holocene;
- To mitigate the potential negative impacts of the construction of the scheme on archaeology and cultural heritage.

2 GEOARCHAEOLOGICAL BACKGROUND

2.1 Solid and superficial geology

2.1.1 The following background summarises the geological formations known to exist at the site, focusing primarily on superficial sediments of Quaternary age and providing a broader context for the Late Devensian and early Holocene sediments in BH06. Where age estimates are available these are expressed in millions of years ago (MA), thousands of years ago (Ka), and as years before present (BP) within the Holocene epoch. These dates are supplemented, where known, with the comparable Marine Isotope Stage (MIS) where odd numbers indicate an interglacial period and even numbers a glacial period.

2.1.2 The solid and superficial geology in the area has been mapped by the British Geological Survey (BGS), comprising Upper Cretaceous Chalk bedrock overlain by Pleistocene and Holocene deposits. The geology has been interpreted largely from seismic surveys of the North Sea undertaken between 1968 and 1981, supplemented in some areas by coring where microfossil analyses and stratigraphic relationships have been used to determine the ages of the formations (Hopson *et al*. 1991).

2.1.3 Three major Pleistocene formations have been identified by the BGS in the area (Cook 1991, Brown 1986); the Swarte Bank, the Egmond Ground formation and the Bolders Bank formation.

2.1.4 The Swarte Bank Formation comprises the infill of sub glacial valley systems originally cut during the Anglian glaciation and infilled during the early part of the Wolstonian period (MIS 10 to 9; ca. 350 to 280ka). The basal sediments of the Swarte Bank formation comprise gravels, sands and stiff grey diamictons overlain by glaciolacustrine and glaciomarine sands and muds.

2.1.5 The Egmond Ground Formation is up to 16m in thickness and comprises sands and gravels thought to be marine in origin. The formation is thought to be Wolstonian age (MIS 8; ca. 280 to 250Ka).

2.1.6 The Bolders Bank Formation comprises extensive glacial till deposits that blanket the entire site, overlying earlier Pleistocene Formations and outcropping near the seabed surface. The Formation comprises stiff red brown gravelly, sandy clays containing erratics including chalk, red-brown sandstone, grey mudstone and other metamorphic and igneous rocks. The formation is similar to the Hunstanton till of East Anglia and the tills of Holderness north of Spurn point. The formation is thought to be of late Devensian age (MIS 2; ca. 18ka).

2.1.7 Whilst not mapped from the area by the BGS (Cook 1991, Brown 1986), incised into the Bolders Bank Formation are known scaphiform glacial valleys which are in places infilled with the Botney Cut Formation. These valleys are up to 60m in depth and 4km in width. The basal fill of the Botney Cut Formation comprises red brown gravelly, sandy clays which are lithologically indistinct from the Bolders Bank Formation (Cameron *et al*. 1992). The upper part of the Botney Cut Formation comprises laminated sands and clays thought to have formed in glaciolacustrine and occasionally glaciomarine environments. The Botney Cut Formation is thought to be of Devensian to possibly early Holocene age (ca. 18 to 12ka).

2.1.8 Following the retreat of the Devensian ice sheet, and under the influence of the post-glacial palaeodrainage and rising sea-levels, a series of terrestrial environments (fluvial, estuarine, lacustrine and coastal) developed in the area. These environments have been largely inferred from the relatively shallow bathymetry and finds made by fishermen of terrestrial sediments such as peat and bones of terrestrial mammals. Prehistoric archaeological finds made across the North Sea also imply that the areas was inhabited in the early Holocene prior to marine inundation (e.g. Reid 1913, Godwin and Godwin 1933 and Coles 1998).

2.1.9 Whilst the exact geomorphology of the areas in the early Holocene, particularly the location and elevation of areas of higher ground (which may have been subject to subsequent marine erosion) is unknown, it is possible to guess, based on current bathymetry and with reference to known sea level curves (Shennan *et al*. 2000, 2002; Ward *et al*. 2006) when the area would have become submerged for the last time. Weninger *et al.* (2008) place a date for the final inundation of Doggerland around 8000 cal BP, with Lambeck (1995) arguing that the southern North Sea was fully marine by 7840 cal BP.

2.1.10 Recent seabed sediments are known across the site. These comprise sands and gravels and which are generally less that 2m in thickness where they are associated with the Bolders Bank formation (Cook 1991, Brown 1986).

2.2 Previous investigations in the southern North Sea basin

2.2.1 The palaeoenvironmental analyses presented in this report represent an important contribution building upon previous research into the archaeology and palaeoenvironments of the North Sea basin.

2.2.2 The archaeological potential of the southern North Sea has long been known, highlighted at an early stage in Clement Reid's (1913) book on the submerged forests of the United Kingdom and later through Graham Clarke's seminal work on the Mesolithic settlement of Europe (1936). At the same time, the Cambridge botanist Harry Godwin was able to demonstrate the palaeoenvironmental potential of former terrestrial deposits from Doggerland (Godwin and Godwin, 1933), and the later work of Coles (1998) was instrumental in demonstrating that the submerged landscapes of the North Sea represented a significant habitable landscape, rather than merely a land-bridge between Britain and the rest of Europe.

2.2.3 Coles (1998) review of Doggerland resulted in an increasing academic interest in the archaeology of North Sea (e.g. Flemming 2004), and highlighted how little was known about the palaeogeography of the former landsurfaces of the North Sea basin.

2.2.4 More recently, however, the North Sea Palaeolandscapes Project used seismic data originally collected for petroleum, oil and service companies to map the submerged palaeolandscapes of the southern North Sea, covering an area totalling 23,000 km^2 (Gaffney *et al.* 2007). Existing borehole data was also utilised to assess the palaeoenvironmental potential of former terrestrial deposits, though in most cases the boreholes were poorly preserved.

2.2.5 The North Sea Palaeolandscapes Project was an important step forward in our understanding of the palaeogeography of the North Sea, forming the basis of the current European Research Council (ERC) funded 'Europe's Last Frontiers' Project. The project will combine a range of seismic, environmental and modelling techniques to investigate climate change, settlement and colonisation of the submerged landscapes of the North Sea basin.

2.2.6 In addition to academic interest, an increasing number of developer-funded projects have been undertaken, typically in advance of windfarm projects, including the Dogger Bank offshore windfarm (WA 2012) where deposits of early Mesolithic date were investigated.

3 METHODOLOGY

3.1 Stage 4 analysis

3.1.1 The Late Devensian and early Holocene sediments in borehole BH06 showed the most potential at Stage 3 (WA 2014b) for closer interval analysis of pollen, foraminifera, ostracod, waterlogged plant and molluscan remains. Processing methods are outlined below with the type, quantity and depth of each sub-sample analysed listed in **Appendix 1** and sample location shown on the borehole log (**Figure 2**). All depths are quoted as metres below seabed (mbSB) unless otherwise stated.

3.2 Radiocarbon dating

3.2.1 Four sub-samples were taken for AMS Radiocarbon dating (**Table 1**). Material for radiocarbon dating were selected from sub-samples analysed for foraminifera, ostracod, waterlogged plant and molluscan analysis. Suitable material was identified under microscope and stored in glass tubes. Two samples were sent for dating at the Scottish Universities Environmental Research Centre (SUERC), East Kilbride, Glasgow, with a further two samples sent for dating to the ^{14}CHRONO Centre at Queens University Belfast. Due to the failure of one sample from borehole BH06 at 14 mbSB a second sample from 2.35 mbSB was submitted. Calibrated age ranges were calculated with OxCal 4.1 (Bronk-Ramsey 2009) using the IntCal13 curve (Reimer *et al*. 2013).

3.3 Pollen

3.3.1 Twenty sub-samples of 1.5 ml were processed using standard pollen extraction methods (Moore *et al.* 1991). Micromesh sieving was used to aid removal of the clay fraction from largely minerogenic samples. Pollen was identified and counted using an Olympus biological research microscope fitted with Leitz optics. A total of 400 pollen grains was counted for each sample, thus increasing the statistical validity, taxonomic diversity and stratigraphic detail of the Stage 3 assessment (WA 2014b). Marsh taxa, fern spores and miscellaneous elements (largely pre-Quaternary palynomorphs and algal *Pediastrum*) were also counted. Pollen percentages were based on total dry land pollen (tdlp) with marsh/aquatic, spores and miscellaneous calculated as a percentage of tdlp plus the sum of the respective category. Taxonomy in general follows Moore and Webb (1978), modified according to Bennett *et al.* (1994) for pollen types. The pollen diagram (**Figure 4**) was plotted using Tilia version 1.7.16 (Grimm 2011), with pollen zones based on observed changes in the palynological assemblages.

3.4 Foraminifera and Ostracod

3.4.1 Twenty-five sub-samples of approximately 25cm^3 were processed for foraminifera and ostracod analysis. The sub-samples were broken into small pieces by hand, placed in ceramic bowls and oven dried. The samples were then immersed in boiling hot water with sodium carbonate added to help disaggregate the clay fraction, and left overnight to soak before being washed through a 75 µm sieve. The remaining sediment was returned to ceramic bowls for final oven drying. The silty peat sub-samples (especially those from 10.45–11.72 mbSB) required processing several times, although disaggregation remained quite poor. The residues were stored in labelled plastic bags. For examination, each sample was processed through a nest of sieves (>50, >150, >250 µm and base pan). Each grade was then sprinkled onto a picking tray and viewed under a binocular microscope. Organic remains were logged on a presence/absence basis. Identification follows Murray (2006) for foraminifera and Athersuch, Horne and Whittaker (1989) and Meisch (2000) for brackish/marine and freshwater ostracods respectively. The abundance of each foraminifera and ostracod species was estimated semi-quantitatively (one species, several species, common and abundant/superabundant) by experience and eye. The results are presented in tabular form (**Tables 3–5**).

3.5 Plant macrofossils

3.5.1 Six sub-samples were processed for analysis of plant remains. The samples were soaked in hot water to aid the disaggregation of sediment and then washed through a nest of sieves (1mm, 500µm and 300µm mesh diameter). The processed residues were examined under a low-power (x8–x56) stereomicroscope and all plant remains removed and identified using a modern plant reference collection and Cappers *et al.* (2006). The plant nomenclature follows Stace (2010). The results are shown in **Table 6**.

3.6 Molluscs

3.6.1 Five sub-samples were processed for molluscan analysis. Sediment was processed either to 250µm or 500µm, with material sorted by size (>2mm, 1–2mm and 500µm–1mm) with whole, nearly whole and diagnostic elements retaining for identification using a Kyowa SDZ PL microscope. Shells were identified to species level where feasible and where not possible to family level. The results are presented in **Table 7**.

4 RESULTS

4.1 Sediments and Chronology

4.1.1 Borehole BH06 is situated within a linear NW-SE oriented feature, and from which a total of 25 samples were retrieved between 2.35 and 19.35 mbSB (WA 2014b, **Appendix 3**). The detailed borehole descriptions for BH06 are reproduced here as **Figure 2** and **Appendix 2**, but broadly comprise fine grained organic sediments (19.35–12.82 mbSB), peat (12.82–10.22 mbSB), a thick layer of mixed gravelly, shelly sand (10.22–2.35 mbSB), with a thin silty peat at 2.35 mbSB. AMS dates UBA-30873 and 30872 (**Table 1, Figure 3**) derive from the base of the sequence of peat deposits (**Figure 2, Appendix 2**) and suggest that peat formation is closely connected with the shift from the warmer Bølling-Allerød interstadial to colder Younger Dryas stadial ca. 12.9–12.7k BP, and continued accumulating throughout the early Holocene. Two further radiocarbon dates bracket the thick 7.5 m layer of mixed gravelly shelly sand (GU-33574 and GU-34111, **Table 1, Figure 3**), and suggest this deposit may relate to the tsunami event following the 'Storegga slide' (**See 5.3.12**), a huge submarine landslide that is thought to have occurred around c 8100 BP (Bondevik *et al.* 1997; Weninger *et al.* 2008). Dates for the final marine inundation of Doggerland around 8000 cal BP (Weninger *et al.* 2008), and of the southern North Sea by 7840 cal BP (Lambeck 1995) correspond closely with GU-34111 (8105-7931 cal BC) (**Table 1**). However, some minor truncation of the upper peat in borehole BH06 may have occurred through erosion of the peat surface during the initial marine inundation.

Table 1: AMS radiocarbon dates, borehole BH06

Laboratory No	Material dated	Depth (mbSB)	Age B.P	δ13 C (‰)	Age range cal BP	Age range cal BC
GU-34111	Marine shell: *Cerastoderma*	2.35	7549 ± 31	0.0 ‰	8105–7931	6155–5981
GU-33574	Marine shell: *Littorina*	10.29	8324 ± 32	-3.9 ‰	8996–8760	7046–6810
UBA-30873	*Betula* seeds (x11)	12.35 – 12.40	10629 ± 89	corrected	12730–12392	10780–10442
UBA-30872	*Betula nana* seeds (x22)	12.40 – 12.45	10655 ± 65	corrected	12722–12528 12463–12438	10772–10578 (92.9%) 10513–10488 (2.5%)

4.2 Pollen

4.2.1 The pollen profile from borehole BH06 spans 2.25m of sediment (12.4–10.25 mbSB), providing information on the vegetation development of this region of the southern North Sea Basin during the Late-Devensian (Younger Dryas) and early Holocene prior to marine inundation, covering a period of roughly 4000 years from ca. 12700–8760 cal BP. Four local pollen assemblage zones (LPAZ) have been recognised in the BH06 profile. These are defined and characterised in **Table 2** and illustrated in **Figure 4**. Pollen was absent in a basal sample at 13.25 mbSB.

Table 2: Palynological description of Local Pollen Assemblage Zones (LPAZ), borehole BH06

LPAZ (depth mbSB)	*Palynological character*
LPAZ DUDG 1 12.40–11.87 *Betula*- Poaceae-*Pediastrum*	*Betula* is the dominant tree peaking to 65% at the base of the zone. There are low levels of *Pinus*, *Juniperus* and *Salix* throughout. Herbs are important with greater diversity and higher numbers/percentages. Poaceae are dominant (to 70%) peaking in the middle of the zone. Taxa of note include *Polemonium caeruleum, Plantago maritima* and *Artemisia* (2–3%). Marsh and aquatic taxa comprise high levels of *Pediastrum* (50% sum + misc.) and Cyperaceae (16%) with aquatic macrophytes (*Nymphaea, Myriophyllum* spp., *Potamogeton* type) and marginal aquatic/fen taxa (*Menyanthes trifoliate*, *Alisma plantago-aquatica.* There are greater numbers of pre-Quaternary palynomorphs than in subsequent zones with highest values at *c*. 12.00mbSB (30% sum + misc.)
LPAZ DUDG 2 11.87–11.45 *Betula*	Samples were not obtained between *c*.12 and 11.70mbSB. Above a gap in the stratigraphy, this zone is delimited by reduced numbers of herbs and the absence of *Pediastrum* after its importance in the preceding zone. *Betula* is the dominant tree pollen peaking to 80%. As with LPAZ DUDG 1 below, there are low levels of *Pinus* (minor peak to 4%), *Juniperus* and *Salix.* Poaceae declines from *c.* 50% at the base of the zone to low levels at the top. There is a minor peak of monolete Pteropsida spores (*Dryopteris* type).
LPAZ DUDG 3 11.45–10.90 *Corylus avellana* type	The lower zone boundary is delimited by a sharp change at 11.45mbSB with *Betula*, *Pinus*, Poaceae, *Pediastrum* and aquatic/fen taxa declining to low levels. In contrast, *Corylus avellana* type is incoming and becomes dominant (to 90%). *Quercus* and *Ulmus* are also incoming. *Salix* is present throughout. Herbs comprise low levels of Poaceae and *Typha angustifolia*/*Sparganium*. Spores comprise monolete *Dryopteris* type and occasional *Polypodium*.
LPAZ DUDG 4 10.90–10.25 *Corylus avellana* type-*Quercus*-*Ulmus*	This upper zone is characterised by a further expansion of trees and shrubs comprising *Ulmus* (to 6%), *Quercus* (to 20%) with incoming *Alnus* and *Tilia* occurring in small numbers. *Betula* and *Pinus* also remain at low levels. There is some increase of herb pollen from LPAZ DUDG 2 with an expansion of Poaceae in the upper levels (10%). Chenopodiaceae (1–2%) is incoming. There are small numbers of marginal aquatic/fen taxa (*Typha angustifolia/Sparganium* type) and *Typha latifolia.*

4.3 Foraminifera and Ostracod

4.3.1 Overall, 11.65 m of sediment was examined for microfauna along with any accompanying organic remains. **Table 3** outlines the presence/absence of foraminifera, ostracod and other organic remains from Borehole BH06. The two lowest samples (13.25 and 14 mbSB) were barren of organic remains save for Cretaceous microfossils derived from the underlying bedrock, suggesting significant reworking of the Late Devensian sediments at these depths.

Table 3: Organic remains recorded in foraminifera and ostracod samples, borehole BH06. (recorded on a presence (x)/absence basis only; f = fragments only)

	SAMPLE												
Depth below seabed (mbSB)	**2.35**	**3.1**	**3.8**	**9.1**	**9.7**	**10.2**	**10.29**	**10.45**	**10.66**	**11.4**	**11.52**	**11.62**	**11.72**
Plant debris + seeds + megaspores	x	-	-	-	-	-	x	x	x	x	x	x	x
Charcoal	x	-	-	-	-	-	-	-	-	-	-	-	-
Molluscs	x	x	x	x	x	x	x	x	-	-	-	-	f
Brackish foraminifera	x	x	x	x	x	x	x	x	-	-	-	-	x
Brackish ostracods	x	-	x	x	-	-	x	x	-	-	-	-	-
Outer estuarine/marine foraminifera	x	x	x	x	x	x	x	-	-	-	-	-	x
Outer estuarine/marine ostracods	x	x	x	-	-	x	x	-	-	-	-	-	-
Cretaceous microfossils (reworked)	-	x	x	x	x	x	-	-	-	-	-	-	-
Insect	-	-	-	-	-	-	x	x	x	x	x	x	-
Fish	-	-	-	-	-	-	x	x	-	-	-	-	x
Freshwater ostracods	-	-	-	-	-	-	-	-	-	-	-	-	-
Ccharophyte oogonia	-	-	-	-	-	-	-	-	-	-	-	-	-
Bithynia opercula	-	-	-	-	-	-	-	-	-	-	-	-	-

	SAMPLE											
Depth below seabed (mbSB)	**12**	**12.05**	**12.1**	**12.15**	**12.25**	**12.39**	**12.53**	**12.71-12.76**	**12.76**	**12.76-12.82**	**13.25**	**14**
Plant debris + seeds + megaspores	x	x	x	x	x	x	x	x	x	x	x	x
Charcoal	-	-	-	-	-	-	-	-	-	-	-	-
Molluscs	x	x	x	x	-	f	x	x	x	x	-	-
Brackish foraminifera	x	-	-	x	-	-	-	x	x	x	-	-
Brackish ostracods	x	-	-	x	-	-	-	x	x	x	-	-
Outer estuarine/marine foraminifera	x	-	-	x	-	-	-	x	x	x	-	-
Outer estuarine/marine ostracods	-	-	-	-	-	-	-	x	-	x	-	-
Cretaceous microfossils (reworked)	-	-	-	-	-	-	-	x	-	x	x	x
Insect	-	x	x	x	x	x	x	x	x	x	-	-
Fish	x	-	-	x	-	x	-	x	-	x	-	-
Freshwater ostracods	x	x	x	x	x	x	x	x	x	x	-	-
Charophyte oogonia	-	x	-	-	-	x	-	x	-	x	-	-
***Bithynia* opercula**	-	-	-	-	-	-	-	x	-	-	-	-

4.3.2 The results of foraminifera and ostracod analysis are presented in **Tables 4–5** respectively, excluding those depths absent of microfossils (**see Table 3**). Foraminifera and ostracods are grouped on the basis of either brackish, outer estuarine/marine and freshwater ecological preference.

4.3.3 Samples between 12–12.8 mbSB contain a rich freshwater ostracod fauna of nine species in total (**Table 5**), by far the most common being *Cytherissa lacustris*, most of them preserved as carapaces and *in-situ*. This species prefers cool/deep water in rivers and lakes (Meisch 2000). The other species suggest a weedy spring-fed freshwater body indicative more of shallows. The lowest sample and the top two also contain an estuarine component. Interspersed within this undoubted freshwater environment is evidence of pulses, especially initially and latterly, of estuarine/outer estuarine components.

4.3.4 At 11.72 mbSB freshwater ostracod disappear and instead the sample contains an estuarine signal; the sediment changes at 12.00 mbSB from a soft sandy-silt peat to compact peat with only a minor sand component (**Appendix 2**). The next four samples (10.66–11.62 mbSB) contain no foraminifera or ostracod (**Table 4–5**)

4.3.5 The sample at 10.45 mbSB contains a rich brackish microfauna with very large populations (albeit of low diversity) of calcareous foraminifera of mid–low saltmarsh and tidal flats, accompanied by equally large populations of ostracods of tidal flats and creeks. The sample above this (10.29 mbSB), dated between 8996–8760 cal BP (**Table 1**), is even more diverse, but with an added outer estuarine/marine component of both foraminifera and ostracod, much of it clinging on sea-grass or phytal (ostracod) on marine algae.

Table 4: Results of foraminiferal analysis, borehole BH06: o - one specimen; x - several specimens; xx - common; xxx - abundant/superabundant

Depth (mbSB)	**2.35**	**3.1**	**3.8**	**9.1**	**9.7**	**10.2**	**10.29**	**10.45**	**11.72**	**12**	**12.15**	**12.71-12.76**	**12.76**	**12.76-12.82**
BRACKISH FORAMINIFERA														
***Ammonia* sp.**	xxx	x	xx	xx	xx	xx	xxx	xxx	o	x	x	x	-	x
Elphidum williamsoni	xx	-	o	-	-	-	x	xxx	x	-	o	o	o	o
Haynesina germanica	xx	-	x	o	-	-	x	xx	-	-	-	x	-	-
Elphidium waddense	-	-	-	-	-	-	-	x	-	-	-	-	-	-
OUTER ESTUARINE/MARINE FORAMINIFERA														
miliolids	xx	xx	x	xx	x	x	xxx	-	x	x	x	x	-	o
Ammonia batavus	xx	xx	xx	xx	xx	xx	x	-	x	xxx	o	xxx	xx	x
Elphidium macellum	x	o	-	-	-	-	xx	-	-	-	-	-	x	-

4.3.6 The microfauna from samples at 2.35 mbSB, and especially those from 3.10–10.20 mbSB within the gravelly sands and sandy gravels, is surprising poor. The foraminifera comprise mainly large *Ammonia batavus* and some miliolids in the 250µ fraction, and a small, more brackish *Ammonia* in the 150µ fraction; ostracods, on the other hand, are very rare. The previous open estuary environment appears to be replaced by high energy deposition.

4.3.7 The top sample (2.35 mbSB), dated between 8105–7931 cal BP, is also poor in remains of microfauna, but contains foraminifera (particularly *Ammonia* sp) and ostracod suggestive of a shift back to outer open estuarine environments (**Table 4**).

Table 5: Results of ostracods analysis, borehole BH06: o - one specimen; x - several specimens; xx - common; xxx - abundant/superabundant

Depth (mbSB)	2.35	3.1	3.8	9.1	10.2	10.29	10.45	12	12.05	12.1	12.15	12.25	12.39	12.53	12.71-12.76	12.76	12.76-12.82
BRACKISH																	
***Cyprideis torosa* (smooth)**	xx	-	x	-	-	x	xxx	o	-	-	-	-	-	-	x	o	-
Loxoconcha elliptica	x	-	-	-	-	xx	xx	-	-	-	o	-	-	-	o	x	o
Leptocythere castanea	x	-	-	-	-	x	-	-	-	-	-	-	-	-	-	-	-
Xestoleberis nitida	o	-	-	-	-	xx	x	-	-	-	-	-	-	-	x	-	-
Leptocythere lacertosa	-	-	-	o	-	-	-	-	-	-	-	-	-	-	-	-	-
Cytherois fischeri	-	-	-	-	-	x	-	-	-	-	-	-	-	-	-	-	-
Cytherura gibba	-	-	-	-	-	o	x	-	-	-	-	-	-	-	-	-	-
OUTER ESTUARINE/MARINE																	
Hirschmannia viridis	xx	-	o	-	-	xx	-	-	-	-	-	-	-	-	o	-	-
Hemicythere villosa	xx	o	x	-	o	xx	-	-	-	-	-	-	-	-	o	-	o
Leptocythere pellucida	xx	-	o	-	-	x	-	-	-	-	-	-	-	-	-	-	-
Semicytherura nigrescens	x	-	-	-	-	xx	-	-	-	-	-	-	-	-	-	-	-
Loxoconcha rhomboidea	x	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Heterocythereis albomaculata	x	-	o	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Cythere lutea	o	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Semicytherura sella	-	-	-	-	-	o	-	-	-	-	-	-	-	-	-	-	-
FRESHWATER																	
Cytherissa lacustris	-	-	-	-	-	-	-	x	xxx	xx	xx	x	x	xxx	xx	xx	x
Candona neglecta	-	-	-	-	-	-	-	o	xx	x	x	x	x	xxx	x	o	x
Cyclocypris ovum	-	-	-	-	-	-	-	-	x	-	xx	x	o	x	o	-	-
***Ilyocypris* sp.**	-	-	-	-	-	-	-	-	x	-	-	-	-	xx	-	-	-
Candona candida	-	-	-	-	-	-	-	-	o	-	x	-	-	-	-	-	-
Herpetocypris reptans	-	-	-	-	-	-	-	-	o	-	-	-	-	xx	-	-	-
Cyclocypris globosa	-	-	-	-	-	-	-	-	-	-	-	o	-	-	-	-	-
Limnocythere inopinata	-	-	-	-	-	-	-	-	-	-	-	o	-	-	-	-	-
Potamocypris zschokkei	-	-	-	-	-	-	-	-	-	-	-	-	-	x	-	-	-

4.3.8 Fish remains, comprising teeth, scales and more rarely vertebrae, were found in several samples in Borehole 06, especially in samples 12.71–12.82 mbSB. They were all identified as freshwater fish of the carp family tolerant of low salinities in estuaries (Parfitt, S, NHM pers. comm.).

4.4 Plant macrofossils

4.4.1 Plant and other biological remains were present in five of the six samples (**Table 6**) with the sample from 10.66–10.72 mbSB producing no remains at all. Plant remains were preserved by waterlogging and in the majority of cases so well preserved to allow identification to subspecies level. Remains of wood were not recorded from any of the samples although very small fragments of charcoal were recorded from the lowermost samples.

4.4.2 **BH06 12.50–12.55 mbSB:** The plant remains from this sample were not common and consisted of aquatic species such as white water-lily (Nymphaea alba), and wetland taxa including celery-leaved buttercup (*Ranunculus sceleratus*) and sedges (*Carex* sp). The presence of a fragment of an eelgrass (*Zostera marina*) leaf may be intrusive. Grass caryopses were present and are most likely to be of wetland taxa. Other indicators of an aquatic environment included the occasional presence of Cladoceran (water flea) egg pouches, the moss animal *Cristatella* sp and fish bones and scales; insect and moss remains were rare.

4.4.3 **BH06 12.40–12.45 mbSB:** The plant remains from this sample were more numerable and diverse than the previous sample and consisted of aquatic species such as crowfoot (*Ranunculus* subgenus *Batrachium*), pondweed (*Potamogeton* sp) including possible small pondweed (*Potamogeton berchtoldii*) and bur-reed (*Sparganium* sp). Wet ground species included marsh-marigold (*Caltha palustris*), celery-leaved buttercup, marsh yellow-cress (*Rorippa palustris*), gypsywort (*Lycopus europaeus*), bulrush (*Typha* sp), and sedges. The grass fruits present are most likely of wetland taxa. Other indicators of an aquatic/wetland environment included stonewort (Characeae oogonia), *Cristatella* sp, and occasional fish bones and scales. Dryland species consisted of the tree birch (*Betula* sp) and the shrub dwarf birch (*Betula nana*).

4.4.4 **BH06 12.35–12.40 mbSB:** The plant taxa and other remains from this sample were very similar to those of the previous one and consisted of the aquatic species rigid hornwort (*Ceratophyllum demersum*), crowfoot and pondweed. Wetland species included celery-leaved buttercup, marsh yellow-cress, water mint (*Mentha aquatica*), and sedges. Stonewort remains were also present as were occasional mosses, *Cristatella* sp, molluscs and fish bones and scales. Insect remains were common. Tree and shrub species were represented by seeds and cone scales of silver birch (*Betula pendula*) and dwarf birch. Docks (*Rumex* sp) may be indicative of either dryland or wetland environments.

4.4.5 **BH06 11.52–11.62 mbSB:** This sample contained very little in the way of plant remains and consisted of white water-lily, birch and very occasional mosses.

4.4.6 **BH06 10.66–10.72 mbSB:** No biological remains were recovered from this sample.

4.4.7 **BH06 10.35–10.45 mbSB:** This sample proved to be the richest sample in terms of number of seeds, diversity of taxa and variety of habitat types. An aquatic habitat was indicated by the presence of rigid hornwort, fool's-water-cress (*Apium nodiflorum*), duckweed (*Lemna* sp), water-plantain (*Alisma* sp), pondweeds including fen pondweed (*Potamogeton coloratus*), horned pondweed (*Zannichellia palustris* ssp *pedicellata*) and bur-reed. A wetland/fen environment is indicated by the presence of the following taxa; celery-leaved buttercup, meadowsweet (*Filipendula ulmaria*), common nettle (*Urtica dioica*), purple-loosestrife (*Lythrum salicaria*), great willowherb (*Epilobium hirsutum*), bittersweet (*Solanum dulcamara*), gypsywort, water mint, bogbean (*Menyanthes trifoliata*), hemp-agrimony (*Eupatorium cannabinum*), bulrush, rushes (*Juncus* spp) and sedges. Grass remains in the form of culm nodes and bases as well as fruits may well be of wetland species. A salt-marsh habitat was indicated and the taxa include; thrift (*Armeria maritima*), common glasswort (*Salicornia europaea*), annual sea-blite (*Suaeda maritima*), holly-leaved naiad (Najas marina), sea arrowgrass (*Triglochin maritima*). Eelgrass (*Zostera maritima*) spiral tasselweed (*Ruppia cirrhosa*) indicate a marine element. Other remains include stonewort oogonia, *Sphagnum* sp moss leaves, rare other mosses, budscales, leaf fragments, the moss animal *Cristatella* sp as well as occasional water flea egg pouches and insects.

Table 6: Results of plant macrofossils analysis, borehole BH06. Habitat A – cultivated ground, B – disturbed ground, C – woodlands, hedgerows, scrub, D – grasslands, meadows and heathland, E – aquatic/wet habitats, F – cultivar, G – marine/saltmarsh, H – uplands, moor, bog

Depth (mbSB)			**10.35-10.45**	**11.52-11.62**	**12.35-12.40**	**12.40-12.45**	**12.50-12.55**
Volume of sample (l)			0.4	0.1	0.1	0.2	0.2
Species	**Common name**	**Habitat**					
		WATERLOGGED					
Nymphaea alba	white water-lily	E	-	1f	-	-	1f
Ceratophyllum demersum	rigid hornwort	E	1	-	1	-	-
Caltha palustris	marsh-marigold	E	-	-	-	1	-
Ranunculus sceleratus	celery-leaved buttercup	E	1	-	35	9	2
Ranunculus subgenus Batrachium	crowfoot	E	-	-	1	1	-
Filipendula ulmaria	meadowsweet	E	1	-	-	-	-
Urtica dioica	common nettle	ABDE	43	-	-	-	-
Betula sp seeds	birch	C	29	2	11	5	-
Betula pendula cone scales	silver birch	C	4	-	2	-	-
Betula nana seeds	dwarf birch	H	-	-	2	22	3
Betula nana cone scales	dwarf birch	H	-	-	2	4	2
Lythrum salicaria	purple-loosestrife	E	6	-	-	-	-
Epilobium hirsutum	great willowherb	E	5	-	-	-	-
Rorippa palustris	marsh yellow-cress	E	-	-	48	22	-
cf *Armeria maritima*	thrift	G	4	-	-	-	-
Armeria maritima calyx fragments	thrift	G	2	-	-	-	-
Rumex sp fruit	docks	ABCDGH	-	-	1	-	-
Salicornia europaea	common glasswort	G	2	-	-	-	-
Suaeda maritima	annual sea-blite	G	2+5f	-	-	-	-
Solanum dulcamara	Bittersweet	CEG	2+5f	-	-	-	-
Lycopus europaeus	gypsywort	E	2	-	-	2	-
Mentha aquatica	water mint	E	81	-	2	-	-
Menyanthes trifoliata	bogbean	E	1	-	-	-	-
Eupatorium cannabinum	hemp-agrimony	E	8+132f	-	-	-	-
Apium nodiflorum	fool's-water-cress	E	3	-	-	-	-
Lemna sp	duckweeds	E	1	-	-	-	-
Alisma sp seed	water-plantain	E	1	-	-	-	-
Najas marina	holly-leaved naiad	G	1	-	-	-	-
Triglochin maritima	sea arrowgrass	G	6	-	-	-	-
Zostera marina	eelgrass	G	12+8f	-	-	-	-
Zostera sp leaf fragment	eelgrass	G	-	-	-	-	1
Potamogeton sp lids	pondweed	E	5	-	1	3	-
Potamogeton coloratus	fen pondweed	E	3	-	-	-	-
Potamogeton cf *berchtoldii*	small pondweed	E	-	-	-	1	-

Zannichellia palustris ssp *pedicellata*	horned pondweed	EG	30	-	-	-	-
Ruppia cirrhosa	spiral tasselweed	G	11	-	-	-	-
Sparganium sp embryos	bur-reed	E	5	-	-	1	-
Typha sp	bulrush	E	27	-	-	2	-
Juncus sp	rushes	E	35	-	-	-	-
Carex sp (biconvex)	sedges	E	11	-	1	1	1
Carex sp (trigonous)	sedges	E	2	-	1	-	-
Poaceae caryopses	grasses	ABCDEGH	4	-	1	1	2
Poaceae culm nodes		ABCDEGH	8	-	-	-	-
Poaceae culm base		ABCDEGH	1	-	-	-	-
OTHER REMAINS							
Characeae oogonia	stoneworts	E	1	-	7	3	-
Sphagnum sp leaf fragments	sphagnum moss	E	9	-	-	-	-
Musci	mosses	E	rare	rare	occasional	-	Rare
Buds		-	-	-	1	3	-
Budscales		-	14	-	-	-	-
Leaf fragments		-	4	-	-	-	-
Charcoal fragments		-	-	-	-	1	1
Ignota		-	5	-	-	-	-
Cenococcum geophilum sclerotia		-	-	-	-	3	1
Cristatella sp	moss animal	E	11	-	14	4	1
Molluscs (marine)		-	abundant	-	occasional	moderate	occasional
Cladoceran egg pouches	water fleas	E	occasional	-	occasional	-	occasional
Insecta		-	occasional	-	common	occasional	rare
Fish bone and scale		-	-	-	occasional	occasional	occasional

4.5 Molluscs

4.5.1 The results of molluscan analysis are presented below in Table 7, distinguishing between gastropods and bivalves.

4.5.2 **12.40–12.45 mbSB:** This sample contained only single species of gastropod and bivalve, comprising small numbers of *Peringia ulvae* and *Cerastoderma edule*, typically found within low energy, low to high shore infra-littoral environments on mixed sediment.

4.5.3 **12.35–12.40 mbSB:** Only a small number of molluscan remains were recovered from this sample, comprising single shells of *Littorina littorea*, *Peringia ulvae* and *Corbula gibba* typically found in low energy marine/brackish environments similar to the previous zone. In addition, the sample contained body whorls of an unidentified gastropod, possibly *Nassarius reticulatus*.

4.5.4 **10.35–10.45 mbSB:** This sample contains a greater quantity of molluscan remains than previous samples, with two gastropod (*Peringia ulvae* and *Littorina littorea*) and one bivalves species (*Cerastoderma edule*), again reflecting a low energy infra-littoral marine/brackish environment.

4.5.5 **9.20–9.30 mbSB:** This sample contains a significant number of molluscan remains, largely gastropods dominated by *Peringia ulvae* with a smaller quantity of *Littorina littorea*, *Nassarius reticulatus* and occasional *Ventrosia ventrosa* and *Retusa obtusa*. Two Planorbidae are likely to represent *Skeneopsis planorbis*, whilst two shells of Rissoidae are likely *R. parva*. Bivalves are represented by smaller numbers of species and shells of *Corbula gibba*, *Cerastoderma edule*, *Parvidcardium exiguum*, *Scrobicularia plana* and a single *Abra alva*. The assemblage reflects a mix of environments including marine to brackish infra-littoral, estuarine and intertidal settings.

4.5.6 **3.35–3.45 mbSB:** The sample is dominated by gastropod molluscs, particularly *Littorina littorea* and *Peringia ulvae*, with far smaller quantities of *Nassarius reticulatus*, *Buccinum undatum*, *Ventrosia ventrosa* and single shells of *Littorina mariae* and *Skeneopsis planorbis*. Bivalves by comparison occur in very small quantities, but together suggest a mixed marine environment with nearby brackish conditions comprising organically rich muds, sands and gravels.

Table 7: Results of molluscan analysis, borehole BH06

Taxon		Sample (depth mbSB)				
Latin name	**Common name**	**3.35 - 3.45**	**9.20 - 9.30**	**10.35 - 10.45**	**12.35-12.40**	**12.40-12.45**
Gastropods						
Littorina littorea	Common periwinkle	128	49	20	1	-
Peringia ulvae	Laver spire shell	106	137	48	1	3
Nassarius reticulatus	Netted dog whelk	18	10	-	-	-
Buccinum undatum	Common whelk	3		-	-	-
Ventrosia ventrosa	Spire snail	2	4	-	-	-
Littorina mariae	Flat periwinkle	1	1	-	-	-
Planorbidae (cf *Skeneopsis planorbis*)	Flat skenea	1	2	-	-	-
Retusa obtusa	Arctic barrel-bubble	-	1	-	-	-
Rissoidae (cf *Rissoa parva*)	Common spire shell	-	2	-	-	-
Bivalves						
Corbula gibba	Basket shell	9	17	-	1	-
Cerastoderma edule	Common cockle	2	5	24	-	3
Anomiidae (cf *ephippium*)	Saddle oyster	2	-	-	-	-
Parvidcardium exiguum	Little cockle	1	5	-	-	-
Abra alva		-	1	-	-	-
Scrobicularia (cf *plana*)	Peppery furrow shell	-	5	-	-	-
Unidentified		-	3	-	3	-

5 DISCUSSION

5.1 Introduction

5.1.1 Discussion of the palaeoenvironmental evidence from borehole BH06 represents a consideration of the combined results of several individual analytical techniques. However, for the sake of completeness, the separate discussions provided with each of the specialist reports are provided at the end of this report as **Appendices 3–6**.

5.1.2 The results of palaeoenvironmental analysis of borehole BH06 provide important new information on the development of the prehistoric sub-marine landscapes of the southern North Sea basin.

5.1.3 The sediments analysed from borehole BH06 cover a period of as much as ca. 4800 years over the transition between the last (Devensian) Ice Age and current (Holocene) warm period (ca. 12700–7900 cal BP).

5.1.4 This represents a period of significant climate change, with the abrupt cooling of the Younger Dryas (from ca. 12.9–12.7 ka BP) followed by rapid warming associated with the onset of the Holocene (ca. 11.7 ka BP). The southern North Sea basin saw major transformations, with climate and sea-level rise radically altering the physical and vegetation environments and culminating in the final marine inundation of this landscape by ca. 7900 cal BP.

5.1.5 On the basis of the pollen data, the transition between the late Glacial and early Holocene (ca. 11.7 ka BP) has been suggested at ca. 11.87 mbSB. Coarse age-depth modelling using the Bacon age-depth modelling program (Blaauw and Christen 2011), although based on a comparatively small number of radiocarbon dates (**Figure 5**), suggests a transition at around 11.85 mbSB (mean data of 11,706 cal BP). The strong agreement between the pollen data and age-depth modelling suggests a high degree of chronological robustness and integrity in the borehole BH06 sediments.

5.2 Late Glacial palaeoenvironments

5.2.1 Palaeoenvironmental analyses below ca. 11.85 mbSB provide a consistent picture of the local and surrounding environment during the late Glacial. The pollen spectra and microfauna show a strong freshwater influence at the base of the sediment profile. Freshwater ostracods (**Table 5**) and cysts of freshwater *Pediastrum* are especially frequent along with a range of aquatic macrophytes and plant taxa of marginal aquatic fen environments (**Table 2** and **Figure 4**, LPAZ DUDG 1). Plant macrofossils from the lowest three samples (**Table 6**), although not especially numerous, likewise derive from freshwater aquatic habitats and fringing fen vegetation. Molluscan remains from the basal two samples are too infrequent to interpret (**Table 7**).

5.2.2 The frequency and diversity of herbaceous pollen taxa in LPAZ DUDG 1 (**Figure 4**) is diagnostic of the late Glacial (Younger Dryas) and entirely consistent with the radiocarbon dates and age-depth modelling. Plants include Jacobs ladder (*Polemonium caeruleum*), rock rose (*Heliantemum*), Saxifragaceae, sea plantain (*Plantago maritima*) and mugwort (*Artemisia*), along with meadow rue (*Thalictum*), meadowsweet (*Filipendula*) and valerian (*Valeriana officinalis*) suggest the presence of both tall and shorter herb grassland of a sub-alpine character.

5.2.3 The pollen and macrofossil data also show the contribution of open birch woodland on areas of better drained soils. Although differentiation of tree and dwarf shrub pollen is not possible, macrofossils of birch are largely represented by seeds and cones of dwarf birch but with very occasional cone scales of silver birch at 12.35–12.40 mbSB (**Table 6**).

5.2.4 The sediments, including those within borehole BH06, have been shown to infill a northwest to southeast channel-like feature, cut during the late Devensian and within which a freshwater lake is thought to have developed (WA 2104b). Freshwater habitats are likely to have formed both in response to drainage of seasonal meltwaters and deglaciation of the ice sheet located to the north as well as through seasonal thawing of the local permafrost.

5.2.5 However, the progressive reduction in pollen of fen plant up through LPAZ DUDG 1 (**Figure 4**) suggests some reduction in the local importance of aquatic habitats towards the end of the late Glacial. Some estuarine influence is also suggested by the presence of both foraminifera and ostracod of marine/outer estuarine environments (**Table 4 and 5**), perhaps a result of periodic storm surges.

5.3 Early Holocene palaeoenvironments

5.3.1 The changing local to regional environment during the early stages of the Holocene is best reflected in the pollen data. Plant macrofossils are largely absent from the sample at 11.52–11.62 mbSB, there is no molluscan data between 12.40 and 10.45 mbSB, whilst foraminifera and ostracod are absent between 11.72–10.45 mbSB.

5.3.2 The increase in arboreal pollen, particularly of birch, reflects the migration and expansion of trees from their glacial refugia as a result of the ameliorating climate conditions occurring with the onset of the Holocene. Birch, present along within Juniper during the late Glacial, expands to become the dominant woodland component at the beginning of the early Holocene (**Figure 4**, LPAZ DUDG 2).

5.3.3 The increase in birch is typically followed by an increase in pine and hazel in southern England. Pine expanded in southern and central Britain between 9000–8500 cal BP, and although present in the southern North Sea basin (Godwin 1975, Birks 1989) does not appear to be dominant. Pollen from Star Carr in the Vale of Pickering shows similarly low quantities of pine pollen, with birch dominant but giving way to a significant expansion in hazel from 9000 yrs BP (Day 1995, Dark and Mellars 1998).

5.3.4 Hazel expands in borehole BH06 to become the dominant woodland component (**Figure 4**, LPAZ DUDG 3), followed by increases in oak and elm that would have formed an important element of the woodland canopy. The small quantities of herbaceous pollen emphasise that open grassland formed only a minor component of the surrounding vegetation, with freshwater aquatic habitats similarly much reduced compared to the late Glacial.

5.3.5 Foraminifera, ostracod, plant macrofossil and molluscan remains are better preserved in the top of the organic deposits from 10.45–10.22 mbSB, closely associated with the radiocarbon date at 10.29 mbSB of 8996–8760 cal BP (**Table 1**).

5.3.6 The microfauna include no freshwater ostracods, but instead include large quantities of foraminifera and ostracods characteristic of low-mid saltmarsh, tidal flats and creeks with an outer estuarine/marine component at 10.29 mbSB.

5.3.7 Pollen in the upper parts of LPAZ DUDG-3 and 4 (**Figure 4**) include Chenopodiaceae (goosefoots, oraches and samphire) which is likely to derive from halophytic plant communities, likewise suggesting the development of saltmarsh. Molluscan remains at 10.35–10.45 mbSB (Table 7) also suggest similar habitats to the pollen and microfauna, with remains of shells indicative of intertidal and near-shore environments (e.g. saltmarsh and tidal flats).

5.3.8 However, the plant macrofossils from 10.35–10.45 mbSB (**Table 6**) present a more complex picture. Several habitats are represented, including aquatic and fringing freshwater communities along with fen and dry woodland, although the dominant environment is that of saltmarsh and estuarine habitats. The presence of species such as thrift, sea arrowgrass, common glasswort and annual sea-blite show that there is a clear saline influence at this time.

5.3.9 Marine species are also present, including eelgrass which can be found from half-tide to approximately 4–9 m below low water mark (Stace 2010). Spiral tasselweed grows in brackish water, tidal inlets and in coastal lakes and lagoons connected to the sea, as well as ponds and pools on saltmarshes and shingle beaches (Preston and Croft 1997).

5.3.10 The picture from all the palaeoenvironmental proxies within the top of the organic deposits (10.45–10.22 mbSB) is of a shift in habitats from freshwater aquatic to saltmarsh, tidal creek and mudflats; a change that can be linked to marine transgression in the area as a result of progressive post-glacial sea-level rise.

5.3.11 The organic deposits are overlain by 7.5 m of mixed gravelly shelly sand (10.22–2.35 mbSB), bracketed by two radiocarbon dates (8996–8760 and 8105–7931 cal BP; **Table 1**) that suggest this deposit may relate to the tsunami event linked with the Storegga submarine landslide ca. 8100 BP (Bondevik *et al.* 1997; Weninger *et al.* 2008).

5.3.12 The radiocarbon date below the gravelly shelly sand significantly pre-dates the 'Storegga' event (by as much as 900 years), the age-difference potentially representing sediment lost to erosion as a consequence of the tsunami. The Tsunami waters were so powerful that they stripped away part of the underlying peat, deposited a layer of coarse sediment transported by the tsunami waters, followed by renewed organic deposition after the tsunami waters receded. The radiocarbon date from the thin silt peat immediately overlying the gravelly shelly sand (8105–7931 cal BP, **Table 1**) very closely post-dates the 'Storegga' event and is strong supporting evidence that the underlying sediments may be connected to the tsunami.

5.3.13 The microfauna from the gravelly shelly sands are very poor and were mixed amongst large quantities of fragmented and worn molluscan remains. The two molluscan samples (9.20–9.30 mbSB and 3.35–3.45 mbSB; Table 7) contain a similar variety of species, largely gastropods species indicative of shallow marine and brackish environments and with a preference for muds, sands and gravels. The basket shell bivalve, along with the common periwinkle and laver spire shell are together suggestive of mixed mud and gravels with high organic content and low exposure. The saddle oysters, however, can occur from the intertidal zone to depths of 150 m (National Museum of Wales, 2014). A single valve of the little cockle was also present at 3.35–3.45 mbSB. This species is common only at depths of more than 30 m (Petersen, 2004), suggesting that it may have been washed into the area.

5.3.14 The molluscan data does not lend definite support for the gravelly shelly sands representing a tsunami event, despite the associated sedimentary and radiocarbon evidence to the contrary. There is no clear evidence of a major wave event causing greater fragmentation of shells. Hydrobidae shells, which are associated with low energy habitats, were present within the horizon where this event may have occurred, as were other species associated with lower energy environments.

5.4 Borehole BH06 is the broader context

5.4.1 The analysis of borehole BH06 is the first integrated geoarchaeological and palaeoenvironmental analysis of late Glacial and early Holocene sediments from the southern North Sea Basin. The results represent an important contribution towards understanding the palaeogeographic development of the submerged former land surfaces of an area for which the archaeological potential has long been appreciated but not given appropriate attention until more recently.

5.4.2 This work is particularly timely in view of recent research into the palaeogeography of the North Sea (Flemming *et al.* 2004; Gaffney *et al.* 2007), and particularly the ERC funded (2015-2020) 'Europe's Last Frontiers Project'.

5.4.3 Although no archaeological finds were recovered from the Dudgeon site, the terrestrial environments identified during the course of geophysical, geoarchaeology and palaeoenvironmental works, could contain Mesolithic archaeological remains.

5.4.4 Early Mesolithic sites with organic preservation are rare from eastern England, apart from the well-known sites at Star Carr (Clark 1956, Mellars and Dark 1998) and Howick (Waddington 2007).

5.4.5 The value of this work rests not only in extending terrestrial research into the former pre-inundation landsurfaces of the North Sea, but in seeing this as an actively settled landscape that can contribute towards broader research questions regarding Palaeolithic and Mesolithic occupation and exploitation of the North European continental shelf during periods of significant climate and environmental change.

6 SUMMARY

6.1.1 The palaeoenvironmental analysis of borehole BH06 has revealed a sequence of organic deposits dating over a period of as much as ca. 4800 years over the transition from the late Glacial to early Holocene (ca. 12700–7900 cal BP).

6.1.2 Pollen, ostracod, foraminiferal, waterlogged plant and molluscan remains demonstrate that the late glacial landscape of the site was dominated by freshwater aquatic and sub-alpine environments with strands of dwarf birch.

6.1.3 With the transition to the Holocene, arboreal species expanded, dominated initially by birch and then hazel. There was a reduction in aquatic habitats and an increasing influence of estuarine and saltmarsh habitats, reflecting the impact of post-glacial sea-level rise.

6.1.4 The 7.5 m of mixed gravelly shelly sands are considered to be closely related in date to the Storegga submarine landslide and subsequent tsunami ca. 8100 BP.

6.1.5 This is followed by a brief return to semi-terrestrial fen and saltmarsh environments prior to the final marine inundation of the site by ca. 7900 cal BP.

7 RECOMMENDATIONS

7.1.1 The results of analysis are significant in representing one of the first detailed multi-proxy geoarchaeological and palaeoenvironmental studies of late Glacial and Holocene sediments from the southern North Sea basin. As such, the results will be of wider academic and public interest and it is recommended that the results are prepared for publication in an appropriate journal.

7.1.2 Three additional samples for radiocarbon dates are recommended on borehole BH06 at 12.0, 11.7 and 11.4 m. The three samples will date key early Holocene biostratrigraphic changes in the pollen sequence and are considered necessary to provide the minimum appropriate degree of chronological precision required to publish the results in a journal appropriate to the importance of the results. The cumulative dates for borehole BH06 will be modelled in the Bacon computer program (Blaauw and Christen 2011) to provide an age-depth model for the pollen sequence. This will provide a chronologically robust sequence – the most detailed thus far for the southern North Sea Basin – allowing for direct and meaningful comparison with contemporary early Holocene terrestrial-based pollen sequences.

12.0 m

7.1.3 This sample is required to date the decline in aquatic pollen (representing a decline in freshwater environments) and provide increased chronological control on the Pleistocene-Holocene transition through age-depth modelling using Bacon.

11.7 m

7.1.4 This sample is required to date the rise in birch, representing a key change in vegetation from sub-arctic to open woodland environment at the beginning of the present Holocene warm period. This is a key biostratrigraphic marker in early Holocene pollen diagrams and will allow for direct comparison with terrestrial based pollen sequences.

11.4 m

7.1.5 This sample is required to date the rise in hazel - a key biostratrigraphic marker in early Holocene pollen diagrams representing a major shift in the composition of the vegetation from a more open to closed woodland environment. The hazel rise is a key component of early Holocene pollen sequences across NW Europe and will allow for direct chronological comparison between the Dudgeon pollen sequences and contemporary terrestrial-based pollen sequences on both sides of the North Sea basin (e.g. Day 1995).

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9 APPENDICES

9.1 Appendix 1: Sub-samples processed for palaeoenvironmental analysis from borehole BH06

Depth (mbSB)	Palaeoenvironmental Proxy			
	Pollen	Foram / Ostracod	Waterlogged plants	Molluscs
2.35	X	X		
3.1		X		
3.35-3.45				X
3.8		X		
9.1		X		
9.2-9.3				X
9.7		X		
10.2		X		
10.26	X			
10.29		X		
10.3	X			
10.36	X			
10.35-10.45			X	X
10.44	X			
10.45		X		
10.66	X	X		
10.66-10.72			X	
11.1	X			
11.4	X	X		
11.5	X			
11.52		X		
11.52-11.62			X	
11.55	X			
11.6	X			
11.62		X		
11.65	X			
11.7	X			
11.72		X		
12		X		
12.05	X	X		
12.1	X	X		
12.15		X		
12.25	X	X		
12.35	X			
12.35-12.40			X	X
12.39		X		
12.40-12.45			X	X
12.45	X			
12.5	X			
12.5-12.55			X	
12.53		X		
12.71-12.76		X		
12.76		X		
12.76-12.82	X	X		
13.25		X		
14		X		

9.2 Appendix 2: Geoarchaeological recording, borehole BH06

Depth mbSB		Description
from	to	
2.35		(b) 10YR 3/2 grey/brown on outside. 2.5Y 2.5/1 dark grey/nearly black in middle. Very silty very fine sand. Quite wet. Frequent granular inclusions
3.00	4.00	(c) 2.5Y 5/2 greyish brown. Gravelly sand (medium to coarse grain). Gravel is mostly flint sub-rounded to angular up to 15mm in diameter. Very frequent marine molluscs (broken and whole). Particularly from 3.2 to 3.46. Includes oyster, cockle and winkle. Slightly sorted with horizontal beds of broken shell. Whole netted dogwhelk at 3.30m. at 3.48 slightly silty below shell bed. Uniform to the end and a darker greyer shade - possibly due to drying.
9.00	10.00	(c) 2.5Y 4/1 dark grey. Uniform sand. Medium to very coarse grained. Includes occasional small flint rounded to angular up to 8mm in diameter. Frequent broken shell. Occasionally whole including a cockle at 9.14 and a bivalve at 9.54. Band of broken shell from 9.23 to 9.25. Sorted. Shallow marine deposits.
10.00	10.47	(c) 10.00-10.22 2.5Y 4/1 Dark Grey. Slightly silty gravelly sand. Wet. Sand fine to coarse with frequent granules to pebbles of chalk and flint up to 4mm visible. Gravels predominantly shell fragments which are larger and more frequent between 10.20 and 10.22. Marine molluscs. 10.22 - 10.47 - Layers of horizontally bedded gravelley sandy peaty silty clay and sandy silty clay. 10.22 - 10.29 2.5Y 3/2 Very dark greyish brown. Peaty gravelley sandy silty clay/ clay sand. Gravels are granules and shell fragments. Cockles and whole *Hydrobia* 4mm brown at 10.27m. 10.29 - 10.36 2.5Y 4/2 Dark greyish brown. Layers of sandy silty clay with peaty inclusions. Also layers of more sandy deposit. 10.36 - 10.47 2.5Y 3/2 Very dark grey brown. Visibly darker than above layer. Layers of sandy silty clay. Occasional whole marine molluscs - possible burrows from marine deposit? 10.33-10.36, 10.36-10.37, 10.39 - 10.40 and 10.42 - 10.43.
10.52	10.61	(b) 10YR 2/2 very dark brown/black peat. Occasional fine sand. Occasional broken cockle fragments up to 12mm in diameter. Broken fragments in a bag - compacted.
10.61	10.66	(b) 10YR 2/2 Very dark brown. Fragmented peat? Stiff/compacted. Occasional fine to medium sand, possible tiny shell fragments.
10.66	10.72	(b) 10YR 2/2 Very dark brown/ almost black. Very stiff peat. Compacted but slightly broken core sample. Seems horizontally bedded. Occasional fine sand. Small areas of mould growth indicate organic matter.
11.10		(b) 10YR 2/2 Very dark brown with 10YR 3/3 more brown edges. Silty sand/wet peat? With fine sand. Outer coating of 2.5Y 4/1 dark grey sand medium on the outside. Broken up lump.
11.40		(b) 10YR 2/2 Very dark brown/ almost black. Fragmented core sample of sandy silt? Peat? Occasional fine to medium sand. Seems horizontally bedded.
11.50	11.70	(c) 10YR 2/2 Very dark brown. Seems to get darker at 11.69, possibly due to storage. Stiff peat with very occasional fine sand. Some plant remains. Very dry/crumbly. Seems horizontally bedded.
12.00	12.56	(c) 2.5Y 3/2 Dark greyish brown. 12.00 - 12.04 Soft sandy silty peat. Sand fine to medium. 12.04 - 12.08 2.5Y 4/1 Dark grey. Wet silty sand. 12.08 - 12.16 2.5Y 3/2 Dark greyish brown sandy silty peat - sand fine to medium. Occasional shell inclusions with darker patches of organic material. 12.16 - 12.38 2.5Y 3/2 Very dark grey brown. Stiff. Horizontal layers of peat and sandy peaty silty clay with 2.5Y 2.5/1 Black peat. Burning smell present. Occasional shell fragments. 12.38 - 12.56 2.5Y 4/2 Dark grey brown. Sandy peaty silty clay layered with 2.5Y 2.5/1 Black peat. Occasional shell fragments and burning smell.

12.60	12.71	(b) 10YR 2/2 Very dark brown. Wet intact core sample. Surrounded by dark greyish brown sandy clay. Wet sandy silt. Maybe peat? Possibly banded in bedding? Occasional fine sand. Broken shell fragment visible (cockle) 9mm in diameter.
12.71	12.76	(b) 10YR 2/2 Very dark brown/ almost black. Wet. Sandy silt? Maybe peat. Very fine sand with some medium inclusions. Occasional large granular inclusions - possibly shell?
12.76	12.82	(b) 10YR 2/2 Very dark brown/ almost black. Wet sandy silt/silty sand? Sand very fine. Slightly darker on the inside. Frequent shell fragments up to 9mm, possibly oyster? And cockle. Whole small spiral shell 4mm long.
13.10	13.15	(b) 2.5Y 4/2 dark greensih grey brown may be more 5Y 3/2. Fragmented sample. Soft very sandy silt (can be moulded - clay present?) Sand predominately fine. Possible inclusions of organic matter/ very dark brown. Impossible to determine structure from this sample.
13.15	13.25	(b) 2.5Y 4/2 Very dark greenish grey brown - possibly 5Y 3/2? Fragmented sample so no clear structure. Soft sitly sand /sandy silt. Very crumbly but can be moulded so clay may be present. Sand predominately fine. Occasional small pebble inclusions up to 11mm in diameter. Possible flint and chalk?
13.25	13.30	(b) 2.5Y 4/3 Very dark greenish grey brown. 2.5Y 4/1 dark grey in centre, possibly dried on the outside. Darker patches possibly organic? Intact core sample. Silty clay sand/ very sandy clay - clay in bands. Sand predominantly fine. Some small pebble inclusions. Flint 8mm - white 14mm.
13.30		(b) 2.5Y 4/1 dark grey - brown on outside - possibly on gley scale? Seems layered though impossible to tell if vertical or horizontal. Layers of darker possibly organic material. Layers of clay. Soft silty clay sand - it's mouldable.
13.65	13.68	(b) 7.5YR 4/3 or 10YR 4/3 brown. Possibly aerated? Sample completely fragmented. Sandy silty clay or silty clay sand. Sand predominantly fine. Some larger grains to granule inclusions. Infrequent small pebbles 4mm.
14.00	14.??	(b) 2.5Y 4/1 dark grey - brown on outside - possibly dried? Very soft sandy silt on inside - some darker organic inclusions. More sandy on outside. Sand predominantly fine but occasional medium to coarse. Infrequent granule to small pebble inclusions up to 10mm visible. Possibly flint. No determinable structure but may alternate in brown sand and grey silt. Broken up core into 3 separate lumps.
14.39	14.44	(b) 10YR 4/3 Brown. Wet, soft, silty sand. Predominantly fine grains. Occasional larger grains. Frequent black flecks - organic matter? Small granules - flint? 3mm.
14.44	14.79	(b) 10YR 4/3 Brown. Wet and seems layered (one long sample broken into lumps - only fully checked one). Silty sand/Sandy silt (grey) with darker patches. Layer of medium to coarse sand thought impossible to tell depth structure. Possible granule/shell inclusions up to 4mm. Occasional organic fragments?
14.79	14.85	(b) 10YR 4/3 Brown with 2.5Y 4/1 dark grey at centre. Possibly oxidised or layered can't tell from this sample. Sandy silty clay or silty clay sand. Sand predominantly fine. Possible some fragments of flint/shell.
15.30		(b) 10YR 4/3 outside 2.5Y 4/1 Dark grey at centre. Possibly due to oxidation. Wet gravelley silty clay sand. Sand predominantly fine. Gravel is very coarse sand to small pebbles of different origins. Chalk and flint up to 9mm. Possible shell fragments.
19.20	19.23	(b) 10YR 4/3 Brown. Loose wet silty gravelly sand as a whole core sample. Sand medium to very coarse. Granules and pebbles up to 17mm flints/chalks. Some red/purple and black. Very dark flecks of organic material.

9.3 Appendix 3: Discussion of borehole BH06 pollen results (By Rob Scaife)

The vegetation and environment

The Late-Devensian (Zone III; Younger Dryas) is present in l.p.a.z. DUDG:1 which has been radiocarbon dated at 10655+/-65BP (UBA-30872) at 10.45-10.40 metres and 69685 +/-89BP (UB-30873) at 12.40-12.35m metres. Overlying sediment from which pollen has been obtained, extends to 8324+/-32BP AT 10.29m (SUERC-51293). Interpretation of the pollen spectra can be considered in terms of the contribution of the on-site and off-site vegetation.

Here, the former shows a strong freshwater habitat, especially at the base of the profile (l.p.a.z. DUDG; 1) where cysts of freshwater algal *Pediastrum* are especially important. This corresponds with the sedimentology which consists of laminated Gyttja. A range of aquatic macrophytes and marginal fen/aquatic plant taxa are present and include white water lily (*Nymphaea*), water milfoil (*Myriophyllum alterniflorum* and *M*. *spicatum*) and possibly pond weed (*Potamogeton*). The latter pollen taxon may also include arrow grass (*Triglochin*). This phase probably corresponds with increasing wetness during the late-Devensian (ZIII; Younger Dryas; Loch Lomond re-advance) and possibly into the early Holocene (Flandrian Ia; Pre-Boreal). De-glaciation of ice sheets to the north of this periglacial zone and the seasonal thawing of local permafrost may have been responsible for this aquatic habitat. Open fen and possibly aquatic conditions subsequently remained, although pollen numbers of macrophytes and marginal fen plants are much reduced from the basal zone (l.p.a.z. DUDG: 1) upward.

The late-Devensian environment (l.p.a.z. DUDG:1)

Here, the herb pollen numbers and taxonomic diversity are diagnostically much greater than l above zone/levels and represent the heliophilous flora of the late glacial (Younger *Dryas*; Zone III). Typically, a range of different plant communities is represented with diagnostic/indicator pollen/plant taxa present. These include notably, jacobs ladder (*Polemonium caeruleum*), rock rose (*Helianthemum*), Saxifragaceae, *Plantago maritima* and mugwort (*Artemisia*). Jacobs ladder is an uncommon pollen occurrence and, with Meadow Rue (*Thalictrum*), *Filipendula* (meadowsweet), valerian (*Valeriana officinalis*) suggest the presence of areas of tall herb grassland of sub-alpine character. Other herb pollen taxa indicate areas of short turf grassland (Poaceae, *Helianthemum* and possibly Saxifragaceae). Sea plantain (*Plantago maritima*) is probably associated with soil rich in salts due to evaporation of mineral soils rather than coming from a coastal salt marsh habitat. Such halophytes are also diagnostic of the diverse range of micro-habitats and vegetation communities which existed during the late Devensian and start of the Holocene. With the development of woodland, these largely heliophilous taxa were ousted from the environment.

Throughout l.p.a.z. DUDG:1, the pollen flora shows the importance of probably open birch (*Betula*) woodland on better drained soils. Along with juniper (*Juniperus*), this is diagnostic of the early Holocene (Flandrian Ia), Pre-Boreal period representing the expansion of these pioneer trees after temperature amelioration at *c*. 10,000BP, the close of the Devensian (Younger Dryas) cold stage. This is observed in l.p.a.z. DUDG:2 which is thought to represent the start of early Holocene seral woodland succession as trees and shrubs migrated from their glacial refugia. Here, unusually, birch woodland was clearly of some local importance during the earlier ZIII and it is probable that this remained from its expansion/colonisation during the Windermere interstadial (ZII; Allerod). Unfortunately sediment of this age is not present or does not contain pollen. *Betula nana* (Dwarf Birch) has also been identified from this basal sediment (Clapham this volume) and may also have contributed to the pollen record here. However, it is probable given its growth stature, that percentages were small. Unfortunately, differentiation of the tree and dwarf shrub birch pollen is not possible where rigorous chemical treatment, as here, is required

The early post glacial (Holocene)
The changing woodland elements, seen in this profile illustrate the dynamic biogeography of the pre-Boreal and early Boreal periods (Flandrian chronozones Ia-b) as trees migrated from their glacial refugia. Juniper (*Juniperus*) noted above (l.p.a.z. DUDG:l and 2) was typically followed by the expansion to dominance of birch (*Betula*) woodland and subsequently by pine (*Pinus*) and hazel (*Corylus*) and oak (*Quercus*) and elm (*Ulmus*) during the Boreal (here l.p.a.z. DUDG 3 & 4). Here, however, as noted, birch appears to have been important throughout the late-Devensian and increased its extent during the Early Holocene (l.p.a.z. DUDG:2).

The phase of pine-hazel woodland described by Godwin (1956, 1975) for southern England is not prominent here and this reflects the more northerly geographic position. It is probable that pine did not arrive and colonise this region prior to marine transgression. However, incoming of oak (*Quercus*) and elm (*Ulmus*) into the region is seen initially in l.p.a.z. DUDG:3 with their continuing expansion in l.p.a.z. DUDG:4 and along with hazel formed important woodland.

In the uppermost zone (DUDG:4), which has been C14 dated to 8324+\-32BP (SUERC-51293), there are traces if lime (*Tilia*) and alder (*Alnus*). These probably represent the first instances of these taxa which subsequently became important and dominant in suitable habitats during the middle Holocene (Flandrian II) from *c.* 7000 BP. These incipient records are from long distant transport especially in the case of *Alnus* rather than from any local growth. *Tilia* as a taxon which is poorly represented in pollen assemblages is enigmatic. It is probable that, along with *Alnus*, these pollen were fluvially transported from some distance (marine?).

The site was clearly, finally subject to the Flandrian marine transgression during the late-Boreal; or early Middle Holocene (Atlantic; Flandrian II). In the upper part of l.p.a.z. DUDG:3, there traces of Chenopodiaceae (goosefoot, oraches and samphire) which are likely to derive from salt marsh, halophytic communities. This likely represents developing salt marsh with brackish water conditions ahead of marine transgression in the basin.

The broad vegetation and environments identified are summarised below.

Period	**Habitat**
Boreal; Flandrian Ib *l.p.a.z. DUDG:3 & 4*. To *c.* 8324+/-32bp	*Hazel became dominant on, or adjacent to the site with oak and elm becoming progressively more important. There was some pine with occasional lime and alder pollen also present probably coming from more regional sources. Chenopodiaceae (halophytes incl. goosefoot and oraches), may indicate nearing brackish water and salt marsh habitats prior to full marine transgression.*
Hiatus ? between DUDG2 & DUDG: 3	*Hiatus through erosion or cessation of sedimentation*
Pre Boreal; Flandrian Ia *l.p.a.z. DUDG: 2* *c.* 10,000-9,400	*Early Holocene birch woodland was dominant on drier, developing soils. Heliophilous herbs were being ousted, as birch woodland became more important. The depositional habitat remained freshwater fen with aquatic macrophytes and marginal fen taxa but much reduced from the open Late-Devensian*
Late Devensian and Devensian/Holocene transition. *l.p.a.z. DUDG: 1* *c.* 11,000 to 10,000 BP	*Open birch and juniper pioneer woodland was present with light demanding (heliophilous) herb communities of typical late-Devensian affinity. Dwarf birch was present (see macrofossil record). There was an on site freshwater habitat with deposition of Gyttja. Possible glacial melt-water or permafrost thawing.*

Summary and conclusions

The following principal points have been made in this study.

- Pollen has been recovered which is attributed to the late Devensian (Younger Dryas/Loch Lomond re-advance) and the early Holocene (Pre-Boreal and Boreal) periods to *c*. 8,300 BP.
- Four local pollen assemblage zones have been recognised. These have been used to describe the changing vegetation represented by the pollen during the period of sediment deposition.
- Radiocarbon dating places the basal sediment of l.p.a.z DUDG:1 in the Younger Dryas and shows the dominance of herbs, including some indicator taxa (*Artemisia, Plantago maritima, Saxifragaceae* and *Polemonium*) with open *Betula* woodland and occasional *Juniperus*.
- The Devensian-Holocene transition is possibly present at the base of the profile and in previous studies of BH21 (Scaife 2015) but may have been lost in the core at *c.* 11.80m.
- The pollen assemblage data show the dynamic vegetation of the early Holocene.
- *Betula* as a pioneer tree became dominant in the Pre-Boreal (DUDG:2) and was followed by expansions of hazel and the incoming of oak and elm (DUDG:3).The latter became progressively more important accompanying the dominant hazel (DUDG:4).
- The depositional habitat as a freshwater and herb fen through the period represented by the pollen. This was clearly subject to marine transgression.
- In the upper sections of both this and BH06 profiles there are small numbers of possible halophytes which may indicate development (away from the site) of salt marsh prior to full marine incursion.

9.4 Appendix 4: Discussion of borehole BH06 foraminiferal and ostracod results (By John E Whittaker)

Results and discussion

As indicated in the previous Assessment Report (WA, 2014b), borehole BH06 is sited in a linear feature trending NW-SE (WA 2009; Figure 17) shown on the geophysics, and described as “cuts and fills”. From this a total of 25 samples have now been examined for their microfauna (11 from the original survey, 14 from the present one). This has given a much better appreciation of the sediments encountered and their faunas.

In **Tables 3, 4** and **5** the “organic remains” that can contribute to the overall environmental picture are listed, with several, especially the foraminifera and ostracods being colour coded. These latter form the main basis of the environmental reconstruction and are grouped into five further tables, namely brackish foraminifera and ostracods (colour-coded grey and lime-green, respectively), outer estuarine and marine foraminifera and ostracods (colour-coded in two shades of blue), and lastly freshwater ostracods (light blue). Their ecological preferences are derived to a large extent from Murray (2006) for the foraminifera, and Athersuch, Horne & Whittaker (1989) and Meisch (2000) for the brackish/marine and freshwater ostracods, respectively.

Overall, 11.65m of sediment was examined mainly for its microfauna. The lowest two samples - interval 13.25 down to 14.00 mbSB were barren, save for plant remains and much reworked Cretaceous microfossils, especially foraminifera (Cretaceous bedrock underlies the Holocene sediments), but from the sediment type (mature grains) it would appear to be alluvium from a quite high energy river (a pollen analysis will no doubt provide a more definitive ecology). The next 10 samples, although covering hardly one metre of sediment – interval 12.00-12.82 mbSB are certainly interesting. Their lithology consist of black organic silts (with some pebbles) below, and brown silt/sand above. They contain a rich freshwater ostracod fauna (colour-coded light blue) of 9 species in total, by far the most common being *Cytherissa lacustris*, most of them preserved as carapaces and thus *in situ.* This species likes/prefers cool/cold deep water in rivers and lakes (Meisch, 2000). The other species suggest a weedy spring-fed freshwater body, indicative more of shallows. The lowest sample in this particular interval and the top two also contain an estuarine component (see colour-coding in **Tables 3, 4** and **5**). Interspersed within this undoubted freshwater environment is evidence of pulses, especially initially and latterly, of estuarine/outer estuarine components (see colour-coding). From a series of sketch maps purporting to show the geography of the area between 18,000BP and the present day provided by Hamal & Michel (2009; Figure 4), the windfarm site is shown to be within a north flowing river in their two maps for 10,000 and *c.*7000BP. The results suggested by the microfaunas below 12.00 mbSB provided here, seem to support this, with a linear freshwater lake (possibly formed on the site of a deep Devensian tunnel valley) initially ponded back and as sea-level rose the site becoming occasionally, then fully estuarine. The occurrence of these curious estuarine occurrences seems to suggest a number of storm surges, the initial one providing the first marine transgression. Small pebbles and what appear to be (?rip-up) peat inclusions in the lower beds would seem to verify the catastrophic nature of at least the initial event. Previous attempts to date this interval using seeds and plant remains proved unsuccessful, but ought to be tried again using these peat fragments. Such a date might be older than that of the initial transgression, as they may have come from an earlier peat deposit eroded and caught up in this event, however, it will be useful, nevertheless, as a “maximum age” for this sequence.

At 11.72 mbSB the freshwater ostracods suddenly disappear. This sample, instead, contains an estuarine signature as in the previous sample, but the sediment type has now changed and is represented by hard compressed black, slightly silty peat. The next four samples of almost one metre (interval 10.66-11.62 mbSB) are totally barren save for plant debris and insect remains. The environment is freshwater - wetland or marsh (but NOT saltmarsh) and is a candidate for a more informed study by a palynologist. The samples may have once contained ostracods or even molluscs, but unlike in the previous sequence, they have been decalcified. Any one of these samples (perhaps both the top and bottom one of this interval) could be radiocarbon dated.

At 10.45 mbSB, in spite of the sediment still remaining peaty, a rich brackish microfauna appears with very large populations (albeit of low diversity) of calcareous foraminifera of mid-low saltmarsh and tidal mudflats (colour-coded grey), accompanied by equally large populations of ostracods of tidal flats and creeks (colour-coded lime green). The sample above this (10.29 mbSB) is even more diverse, this time with an added outer estuarine/marine component of both foraminifera and ostracods (colour-coded two shades of blue), much of it clinging (foraminifera) on sea-grass or phytal (ostracods) on marine-algae, as sea-level rose and a large open estuary/gulf developed. Moreover, this sample has been dated as 8324±32BP (8996-8760 cal BP).

This date is significant as the remaining interval of borehole BH06 was deposited at the time of or subsequent to the Storegga Slide and its subsequent tsunami(s), timed by Weninger *et al.* (2008) at 8100±100 cal BP. These sediments, comprising in excess of 10m of shelly gravelly sands, could indeed have been deposited by the tsunami(s), or they could just be typical outer estuarine sediments of an open gulf, containing both brackish and marine components. What is the evidence, one way or the other? The microfauna of the samples from 2.35 mbSB but especially those from the interval 3.10-10.20 mbSB is surprisingly quite poor. The foraminifera comprise mainly large *Ammonia batavus* and some miliolids in the 250μ fraction, and a small, more brackish *Ammonia* in the 150μ fraction. These are therefore of the size of the associated sand grains, and act as such, and being robust will withstand transport or high energy environments. Ostracods, on the other hand, are very rare, ones and twos at best. The residues are full of molluscs, but for the most part they are fragmentary and worn. A mollusc expert, will no doubt, be able to identify the main species and their provenance, and also for this reason the samples have been return to Wessex Archaeology for further analysis. The sediment therefore appears to be transported and worn, but does this necessarily mean it has been deposited by the tsunami (or tsunamis) originating from the Storegga Slide and which is (are) supposed to have invaded the North Sea. A tidal wave entering shallow water, as the northern fringes of Doggerland would still have provided, would surely just have redeposited any local outer estuarine/marine deposits in its way. The open estuary that seems to have been established 100 years of so before the timing of the tsunami (represented by the sediments at 10.29mbSB and containing much more diverse, *in situ* faunas, seems to be replaced by some sort of high energy deposition, it is true, the timing is in keeping with the Storegga tsunami. By 2.35mbSB things have “settled down” and what might be construed as a typical outer open estuarine environment is in place. This uppermost samples examined has been dated as 7549±31BP or 8105-7931 cal BP.

Fish remains were found in several samples in borehole BH06 (**Table 3**), as reported by Whittaker (WA 2014b). More were found in the present survey, especially from the interval 12.71-12.82m below sea-bed. Invariably they are from freshwater fish of the carp family and which can also tolerate low salinities in estuaries, reports Simon Parfitt (NHM; pers. comm.), who has examined them. Teeth, fish scales and more rarely, vertebrae occur in various samples (see **Table 3** for samples marked “fish remains” in the “Organic Remains” table).

In summary the sequence in borehole BH06 indicates a complex and changing environment over time. Initially, the site was within a river and/or lake, occupying the immediate post-glacial landscape, perhaps occupying an old tunnel valley. This was subsequently invaded by several storm surges, including the original marine transgression, giving ephemeral brackish/marine environments. This was followed by another freshwater interval or a continuing freshwater interval, but this time of marsh or wetland behind a coastal barrier, which led to the deposition of peats. A further storm event and rising sea-levels broke the barrier and a brackish estuary with marine access was formed. Next, within the time-frame of the Storegga Slide and its tsunami(s) a great thickness of shelly gravelly sands were deposited, either in a series of great waves (the lower sands are grey, the upper brown, which might suggest different provenances), until a more stable outer estuarine or open gulf was established. Clearly, this part of time Doggerland at least had been witnessing rapidly changing geography, and with it, changes in both its internal and coastal types of deposition. By the time of the uppermost samples in borehole BH06 Doggerland had (almost) disappeared. It is also worth remembering that the English Channel re-opened at this time (9000-7700 cal BP; see Weninger *et al*., 2008), which must have been enormously significant in terms of tides, currents and general water circulation in the North Sea.

9.5 Appendix 5: Discussion of borehole BH06 waterlogged plant remains (By A J Clapham)

Discussion

The samples here can basically be divided into two zones (see Table and are similar in many ways to that of the local pollen assemblage zones described for BH06 by Scaife (WA 2014b). The lower four samples (12.50-12.55, 12.40-12.45, 12.35-12.40 and 11.52-11.62 mbSB) can be said to represent a freshwater aquatic environment with fringing vegetation including fen vegetation whilst on the drier land dwarf birch and silver birch are present. There appears to be no marine influence in these samples. Dwarf birch is a circumpolar arctic-alpine plant and in the British Isles is now restricted to the northern mountain areas of Scotland. According to Godwin (1975), the fossil record demonstrates that the distribution of this taxon has been restricted in the Holocene. This may be connected to the fact that the present day distribution of dwarf birch corresponds with the 22^{0}C maximum summer temperature summit isotherm (Conolly and Dahl, 1970) and therefore it may be that the species cannot tolerate any temperatures higher than this and therefore its presence here may suggest that temperatures were lower when these deposits were laid down. The presence of both birch species and the other taxa in these four samples correspond well with the pollen record for this part of the borehole.

The uppermost sample (10.35-10.45 mbSB) corresponds to local pollen assemblage zone 2 for BH06. The plant macrofossils indicate a more complicated picture than that shown by the four lowermost ones. Several habitats are represented here including aquatic freshwater, fringing vegetation, fenland and dry woodland, but the dominant environment in this sample is that of saltmarsh or estuarine conditions. The presence of species such as thrift, sea arrowgrass, common glasswort, annual sea-blite show that there is a definite saline influence at this time and when added to the presence of marine species such as eelgrass which can be found from half-tide to approximately 4-9 metres below low-water mark (Stace 2010). Spiral tasselweed, grows in brackish water in tidal inlets and in coastal lakes and lagoons connected to the sea and in other coastal lakes, ponds, pools on salt-marshes and shingle beaches and ditches (Preston and Croft 1997). It is often at found at depths of 0.5m or more. This taxon tolerates more saline conditions than other macrophytes in this area other than the marine species of *Zostera* (Preston and Croft 1997) which is also present in this sample.

Horned pondweed can be found in both freshwater and brackish conditions and in this case it is probably the latter condition in which the taxon was growing. The only tree species present at this level is that of silver birch which was probably growing on higher drier ground. Again, the taxa present here agree generally with the pollen record, whilst the pollen record provides a record of the vegetation over a greater region, the plant macrofossils provide a more detailed local picture of the habitats present at the site.

It can be seen that there is a gradual change in habitats represented in the samples and this is linked to the marine transgression during this period. In the lower samples, no real marine influence is demonstrated but cooler temperatures than those experienced today are indicated by the presence of dwarf birch. The plant macrofossils indicate an open freshwater and fenland environment with tree birch and dwarf birch growing on the drier land whilst in the upper sample a direct marine influence due to increasing sea-levels can be discerned by the presence of salt-marsh and marine species. In the areas that are less influenced by the marine conditions a gradual transition from marine to freshwater via brackish conditions can be seen with birch growing on the drier land.

9.6 Appendix 6: Discussion of borehole BH06 molluscan results (By

Habitat indications
In addition to species identification in core samples, a primary aim of this work was to provide information on the habitat preferences of the molluscan fauna from borehole BH06 at the five sampled depths (see **Table 7**).

3.35-3.45 mbSB
The 3.35-3.45 mbSB sample was dominated by the intertidal gastropod grazer *L. littorea* which shows a "*strong preference*" for gravels (Frid and James, 1988). This was followed by *P .ulvae* which requires a dominance of fine sediments which are organically rich (Frid and James, 1988). Also present and less abundant was *V. ventrosa*, which typically occurs in more brackish waters than *P. ulvae*, preferring isolated lagoons, creeks, and ditches to open coasts (Marine Species Identification Portal, 2012).

The presence of *C. gibba,* which was the dominant bivalve within this sample, is indicative of sediments comprised of muddy sand mixed with larger pieces of gravel and stone (Yonge, 1946); the species is rare in sediments with less than 10% mud content (Parry & Cohen, 2001). This appears to tie in with the habitat suggested by the presence of *L. littorea* and *P .ulvae* of mixed mud and gravels with high organic content and relatively low exposure. Two Anomiidae were recorded within this sample, these saddle oysters can be found from the intertidal to depths exceeding 150m attached by the byssus to hard substrates mostly in sheltered conditions (National Museum Wales, 2014b). *B. undatum* mainly occur in the subtidal on muddy sand, gravel and also rock, although they can occasionally be found in both the intertidal and brackish water environments (Ager, 2008). A single valve of the little cockle *P. exiguum* was also present. This species is common only at depths of more than 30m (Petersen, 2004) suggesting that it may have been washed into the area which is characterised by shallow-water intertidal species. Together these species suggest a mixed marine environment with nearby brackish conditions, with a heterogeneous habitat comprising organically rich muds, sand and gravels as well as some harder substrate.

9.20-9.30 mbSB
This was dominated by the marine to brackish water infauna *C. edule*, *C. gibbula,* and the epifaunal community of *L. littorea*, the hydrobids *P. ulvae* and *V. ventrosa* with a few fragments of *Mytilus edulis* also present. In this habitat, with brackish influence, a single specimen of *R. obtusa* was found. This species predates on Hydrobidae species (Tyrell Smith, 1967; Chambers, 2008) and foraminifera (Smith, 1967) amongst others. This community is suggestive of mixed sediments comprised of muds, sand and gravels (up to coarse gravels) with local brackish and saline influences. Two *S. planorbis* were recorded, this species is able to penetrate high up estuaries, presumably of a salt wedge type (where a river flows directly into the sea) (Barnes, 1994) indicating sea water incursion of more brackish waters. Also found in this sample was *L. mariae* which is predominantly associated with *Fucus serratus* on the lower shore (Watson and Norton, 1987). *Fucus serratus* is an intertidal species which can live in extremely sheltered to moderately exposed sites. In more sheltered sites it grows on substrata such as cobbles (Jackson, 2008). Whilst no cobbles were present within the BH06 sample, they may have been present on and in the muds and sandy sediments which likely predominated at the site. An alternative hypothesis for the record of *L. mariae* in the BH06 borehole is that it was translocated to the site via seaweed adrift in the North Sea or moved as part of the death assemblage through wave action (saltation).

10.35-10.45 mbSB
Again this comprised the marine to brackish water species, however species diversity of the sample was low with just three recorded; *C. edule*, *P. ulvae* and *L. littorea*. All these species are typically found within low energy, low to high shore infralittoral environments on mixed sediments.

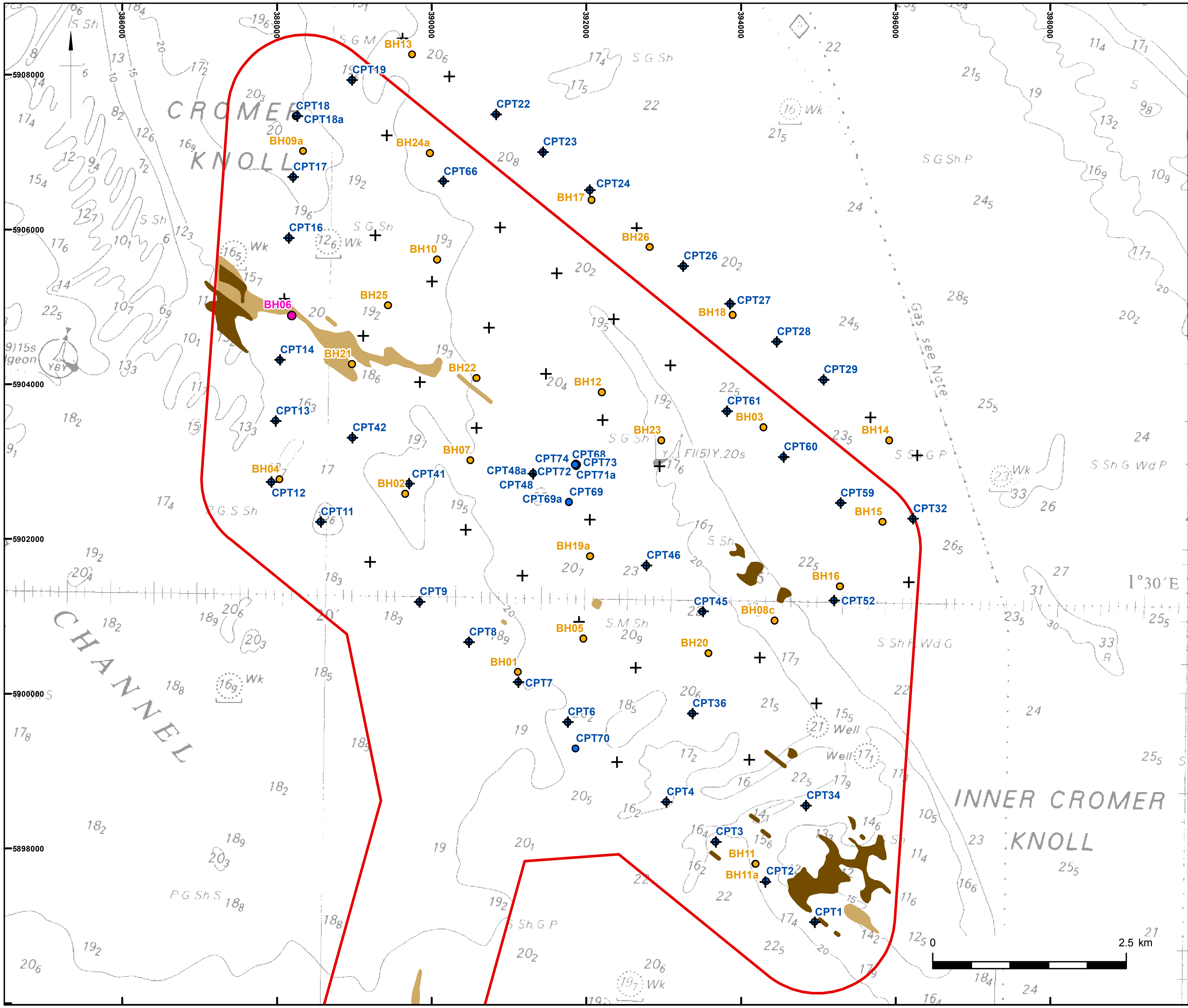
12.35-12.40 mbSB
This comprised the same marine/brackish water species as the 10.35-10.45m below seabed sample, but with the addition of fragments of a gastropod mollusc, thought to be *N. reticulatus* (lower shore whelk) that feeds on detritus or carrion and resides in fine sediment with coarser material in the matrix. Again, all these species are typically found within low energy, low to high shore infralittoral environments on mixed sediments.

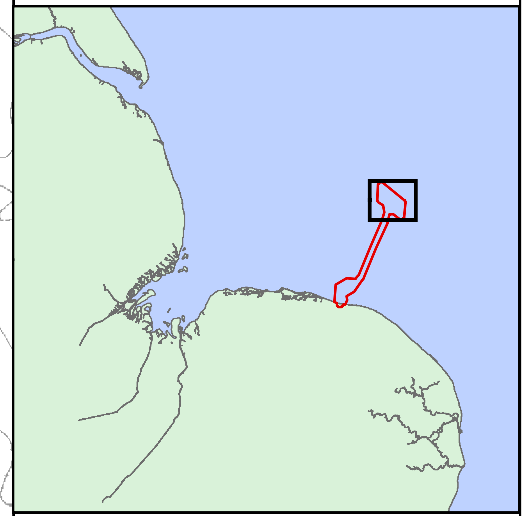
12.40-12.45 mbSB
In this sample just two species were positively identified *C. edule* and *P. ulvae* along with littorinid fragments. All these species are typically found within low energy, low to high shore infralittoral environments on mixed sediments. As above, all these species are typically found within low energy, low to high shore infralittoral environments on mixed sediments.

Summary
In terms of physical habitat indications, in general the faunal content of all samples was similar, though a trend of decreasing biodiversity with increasing depth was observed. The number of species identified decreased from a maximum of 11 in the 3.35-3.45 mbSB sample to just two within the 12.40-12.45 mbSB sample. Samples also tended to become increasingly coarse with depth, although the deepest three samples (10.35-10.40m, 12.35-12.40m and 12.40-12.45 mbSB) were similar. It should be noted that coarsening of sediment over time can occur through natural settling and may not be a clear indication of habitat change.

There is a possibility, although slight, that the habitat indications suggest deposition of fine material within a coarser matrix over time, thus a growing presence of species associated with brackish waters as coastal morphology grew to create creeks etc. However, the evidence is not clear enough to make this more than an interpretive suggestion.

There is no clear evidence of a major wave event causing greater fragmentation of shells within the sample horizons. Hydrobidae shells, which are associated with low energy habitats, were present within the horizon where this event may have occurred, as were other species associated with lower energy environments. This is not dissimilar to the general impression from all samples, thus a clear indication of a high energy event was not obvious.





+ Proposed WTG location

2013 Borehole locations (Stage 1 to 4 assessed)

2013 Borehole locations (Stage 1 to 3 assessed)

2014 CPT and borehole locations (Stage 1 assessed)

Offshore Wind Farm and Cable Route study area (WA 2009)

SBP features - possible peat

SBP features - cuts and fills

Drawing projection: UTM WGS84 z31N
Admiralty Chart: 105 (dated 2008)

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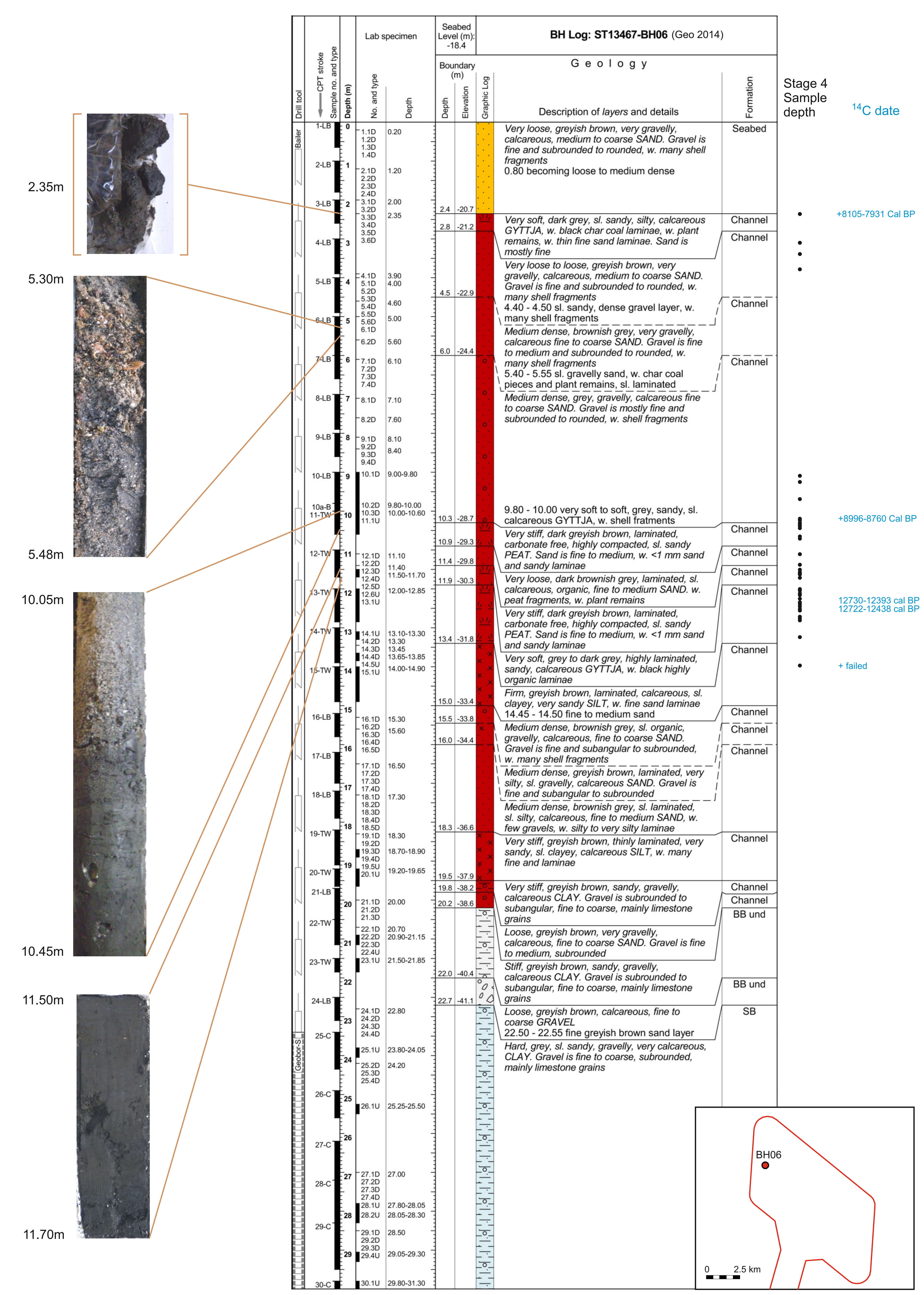
Site, boreholes (including borehole BH06) and CPT location

Figure 1



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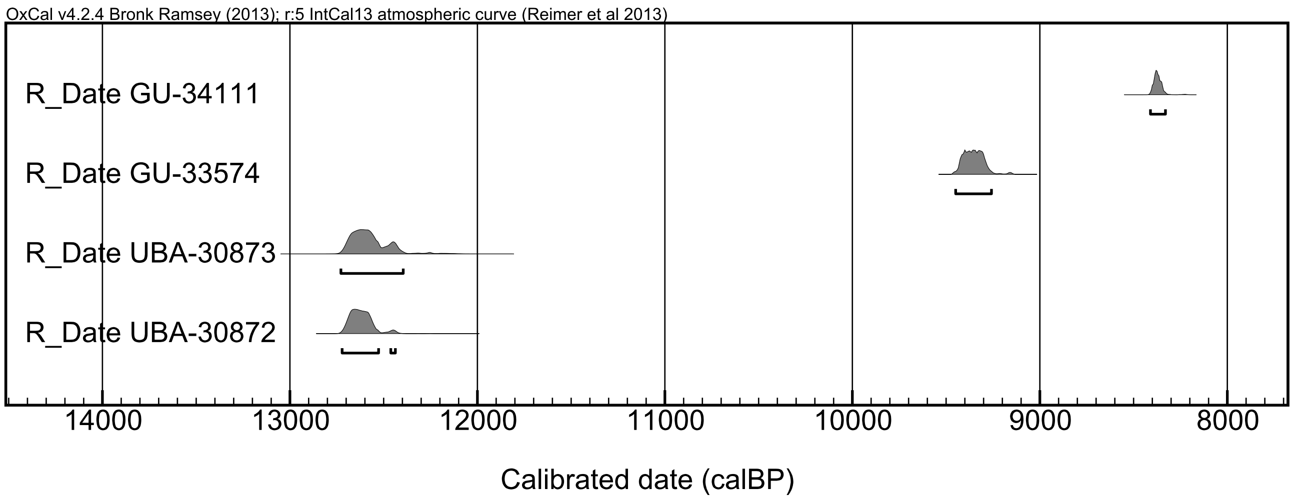
Borehole BH06, borehole log and stage 4 analysis sub-samples

Figure 2



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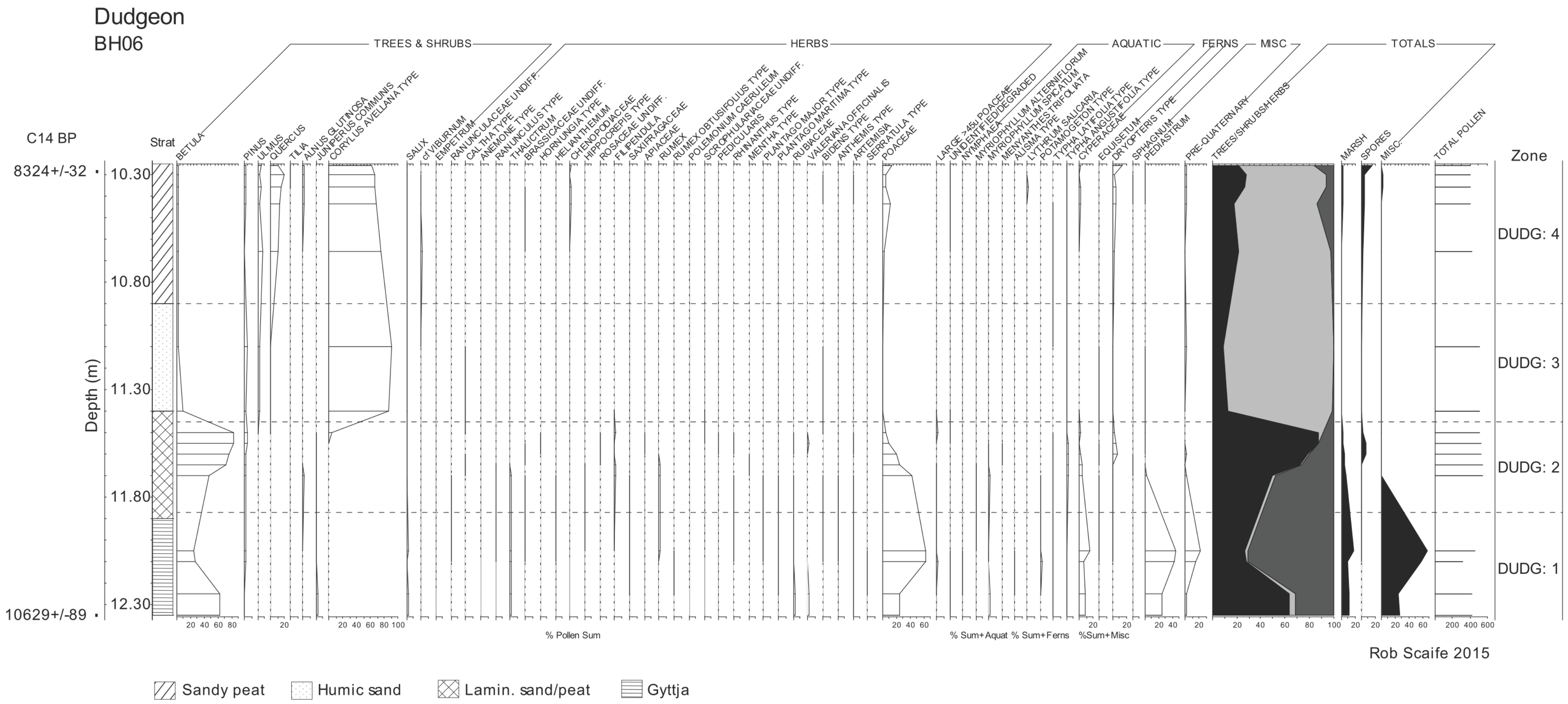
AMS 14C radiocarbon dates from borehole BH06 (see table 1 for details)

Figure 3



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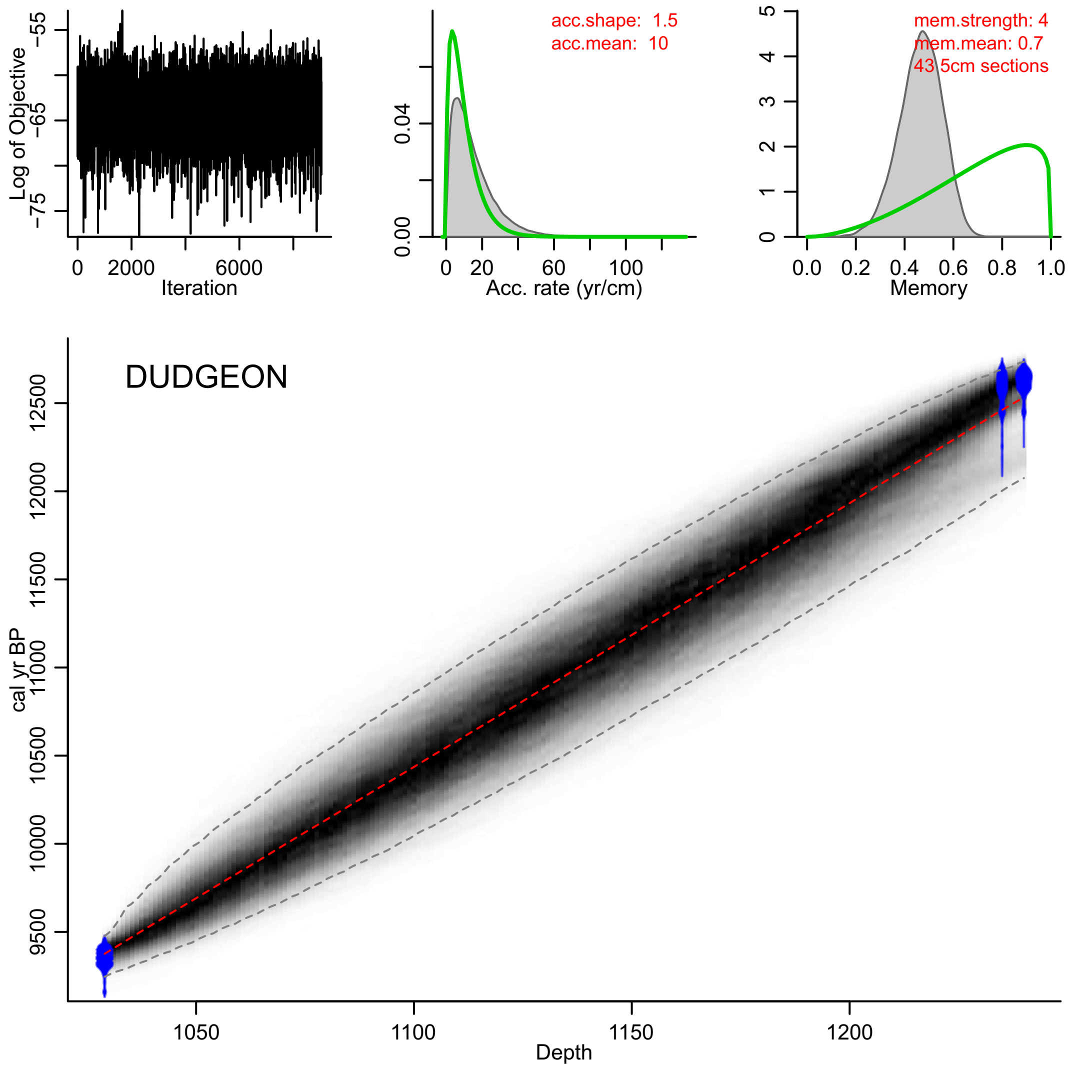
Results of pollen analysis, borehole BH06

Figure 4



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Age depth model for borehole BH06 (grey shaded area indicates 95% chronological uncertainty bands)

Figure 5

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