AGGREGATE LEVY SUSTAINABILITY FUND
MARINE AGGREGATE AND THE HISTORIC ENVIRONMENT

SEABED PREHISTORY: GAUGING THE EFFECTS OF MARINE AGGREGATE DREDGING

ROUND 2
FINAL REPORT

VOLUME IV: GREAT YARMOUTH

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Ref. 57422.34

February 2008

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Summary

This study forms Volume IV of the 'Seabed Prehistory: Gauging the Effects of Marine Aggregate Dredging. Final Report' commissioned by English Heritage (EH) and undertaken by Wessex Archaeology (WA). It was funded through Round 2 of the Aggregate Levy Sustainability Fund (ALSF) distributed by the Department for Environment, Food and Rural Affairs (DEFRA). The 'Final Report' comprises of eight volumes based on previous reports accomplished by WA for either EH or the Mineral Industry Research Organisation (MIRO), as part of Round 1 or Round 2 of the ALSF project 'Seabed Prehistory'.

Great Yarmouth was selected for study as it represented an aggregate dredging area with a different geological setting, and as such archaeological potential, to the previously studied Arun palaeochannel (**Volumes II-III**). Surveying the dredging area off Great Yarmouth aided in developing the understanding of the varying archaeological contexts in which aggregates are found.

The study area for this study was chosen as a result of prospective survey lines and in conjunction with representatives from the marine aggregate industry. The study area comprised an approximate 800 x 800m grid situated in the south-western corner of dredging area 254, approximately 10km to the east of Great Yarmouth.

The geophysical survey involved the acquisition of single beam echosounder, sub-bottom profiler (surface-tow boomer and pinger sources) and sidescan sonar data. The results of these are summarized below:

- A digital elevation model of the bathymetry within the study area was produced using single beam echosounder data. This highlighted a southeast–northwest orientated mound.

- The sub-bottom profiler data indicated a coarse sand and gravel unit observed throughout the study area, overlain by an intermittent unit of fine-grained sediments which may contain peat. These units were in turn overlain by a thin layer (<1m thick) of recent gravely sands. This was confirmed on the sidescan sonar data.

Based on the geophysical data interpretation vibrocore locations were proposed within the area. Seventeen vibrocores were acquired at eight locations within the study area. The aims of the vibrocore survey were to calibrate the geophysical data with regards to stratigraphy; to

help provide a relative chronology for the area identifying the relationship between palaeogeographic features; to provide an absolute timescale of the depositional processes through appropriate dating techniques; and to provide evidence for the environmental reconstruction of the depositional environments. Four sedimentary units were identified within the vibrocores correlating to those identified within the geophysical survey. Samples were assessed and analysesd for their pollen, diatom, foraminiferal, ostracod, waterlogged plant and molluscan content. Radiocarbon (^{14}C) and optically stimulated luminescence (OSL) dating were carried out on selected samples. The results of the sedimentological, environmental and chronological data and their interpretation are summarised below:

- **Unit 1** comprising gravels and sands interpreted as part of the shallow marine Yarmouth Roads Formation probably deposited during the Cromerian Complex period (OIS 13 - 19);

- **Unit 2** comprising silts sands and gravels interpreted as forming fluvial environments with OSL dates suggesting deposition during the Wolstonian (OIS 8, 7 and 6) period. Charcoal from this unit is a possible indication of human habitation at this location;

- **Unit 3** comprising sands, silts and clays indicative of sea level rise, climate amelioration, freshwater and estuarine environments with OSL dates suggesting deposition during the Ipswichian (OIS 5e) period. Charcoal from this unit is a possible indication of human habitation at this location. Sub-aerial exposure of this unit is also a clear indication of the survival of terrestrial deposits in this area;

- **Unit 4** comprising gravel and sands is indicative of more recent (Holocene) seabed sediments.

In terms of archaeological significance, the charcoal recovered from the vibrocores may have been caused by natural forces e.g. lightning, or the result of deliberate anthropogenic burning. One piece from **Unit 3** was radiocarbon dated to 49,500±3,000 yrs BP. This is at the limit of radiocarbon dating and the position of this sample between two OSL samples dating to 175.7±22.6 ka and 116.7±11.2 ka would suggest the charcoal dates from the Ipswichian (OIS5e) period. This would also be the case for the charcoal found higher up the profile in the same unit. If these pieces are evidence of habitation from Ipswichian deposits this would be highly significant as this period is at present thought to be one of non-occupation of the British Isles.

The charcoal further down the sequence at **Unit 2** may date from an archaeological period which is significantly earlier. Its proximity to the OSL sample at 31.37m below OD dating to 577.2±65.4 ka may be suggestive of occupation of this area during the Cromerian Complex period (OIS 13 - 19) or later. This unit, comprising fluvial sands and gravels, may contain reworked Palaeolithic material as Pleistocene fluvial deposits onshore have been proven to be implementiferous.

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Acknowledgements

English Heritage (EH) commissioned this project supported by the Aggregates Levy Sustainability Fund (ALSF).

The geophysical fieldwork was undertaken by Titan Environmental Surveys Ltd. and was supervised for Wessex Archaeology (WA) by Stuart Leather. WA would like to thank the crew of the *Titan Explorer* and Titan Environmental Surveys for their assistance during this phase of the fieldwork.

The geotechnical survey was undertaken by Gardline Surveys Ltd. onboard the S/V *Flatholm* and was supervised by Jack Russell of WA. WA would like to thank the crew of the *Flatholm* and Gardline Surveys for their assistance during this phase of the fieldwork. Processing and interpretation of the cores was carried out by Jack Russell and Dr Dietlind Paddenberg.

Pollen analysis was undertaken by Dr Rob Scaife at Southampton University. Diatom analysis was undertaken by Dr Nigel Cameron at University College London. Ostracod and foraminifera analysis were undertaken by Jack Russell at WA. Waterlogged plant and molluscan analysis were undertaken by Dr Chris Stevens and Sarah Wyles at WA. Optically stimulated luminescence (OSL) dating was undertaken by Dr Richard Bailey and Dr Matthew Telfer at the University of Oxford. Radiocarbon dating was undertaken by the University of Oxford and the Scottish Universities Environmental Research Centre (SUERC), funded by EH, and at the Rafter Laboratories New Zealand, funded by Mineral Industry Research Orginisation (MIRO).

This project was managed for WA by Stuart Leather. Louise Tizzard and Jack Russell compiled this report and it was edited by Dr Dietlind Paddenberg. Figures were compiled by Kitty Brandon and Karen Nichols.

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1. INTRODUCTION

1.1. PROJECT BACKGROUND

1.1.1. In 2005, Wessex Archaeology (WA) was commissioned by English Heritage (EH) to compile the final synthesis of the research project 'Seabed Prehistory – Gauging the Effects of Marine Aggregate Dredging'. The project synthesis was funded through Round 2 of the Aggregate Levy Sustainability Fund (ALSF) distributed by the Department for Environment, Food and Rural Affairs (DEFRA) (see **Volume I**).

1.1.2. Round 1 of the 'Seabed Prehistory' project was undertaken between 2003 and 2004 as part of the Sustainable Land Won and Marine Dredged Aggregate Minerals Programme (SAMP), funded by Round 1 of the Aggregate Levy Sustainability Fund (ALSF) and administered by the Mineral Industry Research Organisation (MIRO) on behalf of the former Office of the Deputy Prime Minister (ODPM), now Department for Communities and Local Government (DCLG).

1.1.3. The project was extended to Round 2 in order to assess the application of the Round 1 methodologies to aggregate dredging zones with different geoarchaeological characteristics. Round 2 comprised different components, each component funded through either EH or MIRO, under the ALSF funding for Round 2. Each component was an independent stand alone project, resulting in the eight volumes of this report. **Table IV.1** provides an overview of all volumes of 'Seabed Prehistory: Gauging the Effects of Marine Aggregate Dredging - Final Report', **Volumes I-VIII** (Wessex Archaeology 2007).

Volume	Title
I	Introduction
II	Arun
III	Arun Additional Grabbing
IV	**Great Yarmouth**
V	Eastern English Channel
VI	Humber
VII	Happisburgh and Pakefield Exposures
VIII	Results and Conclusions

Table IV.1: Overview of the volume structure of this report.

1.1.4. This report is **Volume IV** in the series and sets out the Round 2 investigations into the Great Yarmouth area. It is an updated version of a previous geophysical 'Seabed Prehistory' project report for EH (Wessex Archaeology 2006), which has been supplemented by geotechnical analyses. The report provides details on the acquisition, processing and interpretation of geophysical and geotechnical data for a specific area of seabed off the coast of Great Yarmouth. Surveying the dredging area off Great Yarmouth aided in the understanding of the varying archaeological contexts in which aggregates are found.

1.2. STUDY AREA

1.2.1. The survey was conducted in the vicinity of the aggregate dredging area 254 (currently licensed to United Marine Aggregates Limited) approximately 10km off the coast of Great Yarmouth (**Figure IV.1**).

1.2.2. The study area for this study was chosen based on prospective data and consultation with representatives from the marine aggregate industry. Previous work in this area highlighted peat and clay deposits close to the seabed occurring as part of a fine-grained sediment unit closely associated with the aggregate deposits within dredging area 254. These sediments were considered to be infill deposits within the Yare Palaeovalley (Bellamy 1998; Wessex Archaeology 2002).

1.2.3. This area was targeted for the survey because of the potential survival of archaeological material within the peat deposits and potential reworked archaeological material in the gravels. It also provided the opportunity to assess the ability of shallow seismic equipment to locate an archaeologically important layer in the near surface sediments.

1.2.4. The coordinates of the Great Yarmouth study area (WGS 84, UTM zone 31) are given in **Table IV.2.**

Easting	Northing
424329	5827029
425224	5827037
424319	5826238
425219	5826240

Table IV.2: Coordinates of the Great Yarmouth study area (WGS 84, UTM zone 31).

1.3. GEOARCHAEOLOGICAL BACKGROUND

1.3.1. Previous archaeological assessment (Wessex Archaeology 2002) and geophysical survey (Bellamy 1998) identified the study area as potentially containing a sequence of sediments from the Cromerian Complex to recent date.

1.3.2. The earliest deposits of archaeological interest within the study area are likely to belong to the Yarmouth Roads Formation deposits (Cameron *et al.* 1992). These comprise sediments deposited as part of a complex delta-top sequence forming part of the Ur-Frisia delta plain, consisting of sands with pebbles (including chalk), abundant plant debris and peat clasts (Cameron *et al.* 1992). This formation is of Cromerian Complex age (790 to 480 ka). Recent work at Happisburgh and Pakefield (Parfitt *et al.* 2005) along the Norfolk coast has revealed *in situ* archaeology dating to *c.* 700 ka. This places the Yarmouth Roads Formation within the time period of the first known occupation of Britain, and it therefore is of archaeological interest. Fluctuating sea levels during the last 800,000 years would have exposed the study area as land and as such it may have been occupied by our ancestors during this time.

1.3.3. Gravel deposits identified by Bellamy (1998) within area 254 possibly relate to the Palaeo-Yare valley. The River Yare was cut prior to the most recent marine transgression and is known to have extended offshore during periods of lowered sea level (Bellamy 1998).

1.3.4. Gravels observed in the study area are possibly analogous to the terrestrial Yare Valley Formation (Bellamy 1998). No direct evidence for the age of this formation has been established (Arthurton *et al.* 1994). However, these sediments are tentatively thought to be Upper Pleistocene (possibly Devensian) in age although the base of these gravels may be as old as Late Anglian, deposited as the River Yare was cut (Bellamy 1998).

1.3.5. Gravel deposits within area 254 would possibly contain reworked archaeological material including flint tools. Five flint implements of Palaeolithic date are known to have been found along the coast near Great Yarmouth. These records (based on a SMR data search) relate to finds of single stone tools, none of which are specifically dated to the Lower or Middle Palaeolithic (Wessex Archaeology 2002).

1.3.6. Fine-grained sediments and peat possibly relating to the Yare palaeovalley were identified in area 254 by Bellamy (1998). These sediments may be analogous to the Breydon Formation identified onshore which has been interpreted as being deposited in a nearshore/tidal, flat/marshland environment during the Holocene (Arthurton *et al*. 1994). The basal peat of the Breydon Formation was recorded at a depth of *c.* 23m below OD and up to 2m thick in a borehole located between Great Yarmouth and Caister-on-Sea. The peat is recorded to have formed around 7,580±90 BP/ 6,600 – 6,240 cal. BC (Arthurton *et al*. 1994).

1.3.7. Terrestrial archaeological finds have been documented along the course of the Palaeo-Yare (Wymer 1997). These refer to single, isolated finds along the valley and are predominantly hand-axes and stone flakes. These finds are considered to be Lower Palaeolithic and are predominantly found in re-worked fluvial or glacial sediments, rather than in an *in situ* context (Wymer 1997).

1.3.8. Sea level curves (Jelgersma 1979; Shennan and Andrews 2000) suggest that the study area was inundated for the last time *c.* 8,000 BP (*c.* 6,800 cal. BC). The formation of peat and fine-grained sediments possibly relating to the Palaeo-Yare probably relate to around this period.

1.3.9. Coles (1998) hypothesised that areas of the North Sea were populated during the Mesolithic period. In 1931 a Mesolithic bone harpoon point dating to 11,740±150 BP (11,950 – 11,340 cal. BC) was trawled from a peat deposit from the Leman and Owers Bank area at a depth of around 36m (Koojimans 1970; Verhart 1995). Further examples of worked flint and bone artefacts were trawled up around Brown Ridge and Dogger Bank in the southern North Sea (Louwe Koojimans 1970; Verhart 1995; Flemming 2002). A perforated mace head of Mesolithic date was also recovered from the coast near Great Yarmouth (Wymer 1977). These examples indicate the potential of preserved Mesolithic archaeology within deposits in the study area.

1.3.10. Surface deposits of sands and gravely sands (Cook 1991) may originate from fluvioglacial or fluvial deposits which were deposited before the area was inundated by the sea during the last transgression. These sediments might contain reworked archaeological material.

2. SURVEY METHODOLOGIES

2.1. OVERVIEW

2.1.1. The survey work undertaken included the acquisition of sub-bottom profiler data, sidescan sonar data, single beam echosounder and vibrocores.

2.1.2. Sidescan sonar data were not acquired in Round 1 of the 'Seabed Prehistory' project (**Volume II)**. However, they were acquired in Round 2 (**Volumes IV-VI**) in order to enhance and facilitate the interpretation of the sub-bottom profiler data by identifying the character of the seabed deposits. Echosounder data provided the actual seabed topography, and shallow seismic data allowed to identify individual geophysical sub-seabed horizons.

2.1.3. Thereupon a judgement-led vibrocoring programme based on the results of the geophysical data was conducted. The cores allowed calibration of the identified geophysical horizons and provided samples for environmental analysis and dating.

2.2. GEOPHYSICAL SURVEY

Introduction

2.2.1. WA commissioned Titan Environmental Surveys Limited to undertake the geophysical survey. The survey was conducted aboard the *Titan Explorer* between the 30th August and 19th October 2005. The data acquisition was conducted under the supervision of WA staff.

2.2.2. Initially, data was acquired along five regional prospective lines (totalling 65km) using a surface-tow boomer (**Figure IV.2**). The aim of acquiring data along these lines was to establish the extent of the alluvial plain of the river valley. However, this feature was not resolved by the geophysics data. This was probably due to the indistinct nature of the unconsolidated sediments marking the river valley edges which were not discernible by the seismic data.

2.2.3. Subsequently, a study area comprising an 800 x 800m area situated in the south-western corner of dredging area 254 was chosen for detailed study, after consultation with Dr. Andrew Bellamy (United Marine Aggregates Limited). East-west orientated lines of approximately 1km and north-south orientated lines of 1.7km were collected about this core study area, totalling approximately 340km of survey data, and are shown in **Figure IV.2**. Sidescan sonar, single beam echosounder and sub-bottom profiler data were acquired ensuring 100% coverage of the study area. The line spacings used for this survey were based on the findings of the Round 1 project (**Volume II**) and the prevailing survey conditions.

2.2.4. The seismic data set acquired was of variable quality due to the marginal weather and sea states during the survey period. The data quality and positioning of the towed equipment, particularly the sidescan sonar data, were also affected by the strong tidal currents occurring in this area of the southern North Sea.

Navigation

2.2.5. Throughout the survey all coordinates were expressed in WGS84, UTM zone 31N.

2.2.6. Onboard the *Titan Explorer* a Trimble DSM Pro GPS receiver was used as the primary navigation system. Secondary positioning was provided by a Trimble 4400 GPS receiver.

2.2.7. The navigation data for this survey were recorded digitally as part of the files containing the sub-bottom data. Position fix data were logged at 30-second intervals and the position logged every five metres. Corrected navigation files could then be calculated during processing to interpolate between these known positions. This corrected navigation file would then provide a position for every shot point in the seismic data.

Bathymetry

2.2.8. Bathymetric data was recorded throughout all stages of surveying and was acquired using an Odom Hydrotrac single beam echosounder. Erroneous points were removed from the dataset using a graphical editor and then provided to WA as an ASCII text file to be processed at a later stage.

2.2.9. All depth references have been reduced to Ordnance Datum (OD) using observed tides from post-processed kinematic GPS observations recorded by Titan Surveys Limited onboard the survey vessel. Chart Datum (Gorelston) relative to Ordnance Datum (Newlyn) is -1.56m.

Sub-bottom Profiler Survey

2.2.10. Initially, data were collected using an Applied Acoustics surface-tow boomer system at 50m line spacing. However, due to the relatively low frequency signal (500 – 3000 Hz) and consequent low signal resolution, the data did not characterize the peat layer to the degree anticipated in the near surface sediments. As such, only east – west orientated lines were run with this seismic source.

2.2.11. Based on previous data the peat layer was expected less than two metres below the seabed (Wessex Archaeology 2002) and as such, on the basis of discussions with Dr. Andrew Bellamy (UMA Ltd.), the pinger profiler was considered a more appropriate tool for this project. Pinger data were collected at 50m line spacing on east-west orientated lines and 100m line spacing on north-south orientated lines. A full survey grid was completed with a Probe 5000 pinger profiler mounted on a surface-tow catamaran. The pinger profiler seismic source has a higher frequency (3.5 kHz) than the boomer source; although it provides less penetration sub-seabed, the data has a higher vertical resolution in the upper layers.

2.2.12. The surface-tow boomer profiler data was of fair quality throughout the survey and reflections were regularly observed to a depth in excess of 10m (**Figure IV.3**).

2.2.13. The pinger profiler data was generally of poorer quality, partly due to poor weather and sea state conditions and partly due to the pinger source being attached to the surface-tow catamaran where the data is likely to be more affected by the sea state than if it was towed at depth. Unfortunately, towing at depth was not possible for this survey because of logistic reasons.

2.2.14. On the pinger data it is difficult to discern any sediment structure in the first metre immediately below the seabed as it was obscured by the strength of the seabed return signal. Seismic reflections were observed to a maximum depth below seabed of 6m (**Figure IV.3**).

2.2.15. Due to the differences in resolution each dataset highlighted specific features. The fine-grained sediment unit was clearly observed on the pinger data as areas with no reflections; this was more difficult to discern on the boomer data. However, the boomer data highlighted the stratigraphy with more resolution than the pinger data. **Figure IV.3** illustrates the difference in vertical resolution and quality of the two sources.

2.2.16. As such, and taking into account the quality of each dataset, the mapping of the seismic layers was based on the boomer dataset using the pinger dataset to aid interpretation and provide interpretation for the tie-in line data.

2.2.17. Chirp seismic source was not considered to be an appropriate survey method because it would not have been able to achieve the same data quality as the boomer seismic source due to its poor penetration generally achieved in gravelly sediments.

Sidescan Sonar Survey

2.2.18. A sidescan sonar system consists of transducers on either side of a towfish which emit pulses of acoustic energy in the direction perpendicular to travel. The acoustic energy is reflected from the seafloor to the transducers and the strength of the pulses recorded via a workstation onboard the vessel. The strength of the reflections is dependent on the properties of the seafloor material; different sediment types produce different strength signals. This results in an acoustic image of the seabed relief and indicates the character of the seabed sediments.

2.2.19. For this survey a Klein 3000 dual frequency digital sidescan sonar was used. This system collects data at 125 kHz and 445 kHz simultaneously. The Klein 3000 was chosen as it is widely used in the marine aggregate industry for both prospecting and seabed sediment mapping. In addition, because the Klein collects data at both high and low frequencies it produces high quality images suitable for archaeological purposes. The sidescan sonar towfish was towed directly behind the survey vessel. The data quality was optimised by adjusting the height of the fish by changing the length of cable paid out (between 10 and 40m) to account for changes in water depth and vessel speed.

2.2.20. East-west orientated survey lines were run at 50m; north-south orientated lines were collected at 100m line spacing. The sidescan sonar range of 75m was used throughout the survey and full coverage of the study area was obtained.

2.2.21. The data was collected digitally on a workstation using Klein SonarPro software in *.xtf format and stored on hard disk as date/time referenced files for post-processing and the production of sonar mosaics.

2.2.22. The sidescan sonar data acquired during this survey was of variable quality. The north-south orientated lines were generally of good quality. However, due to the prevailing wind direction and currents in this area, on the east-west orientated lines the towfish was not towed directly behind the survey vessel causing the fish to fly skewed; this adversely affected the data. As such, when constructing a mosaic of the data north-south orientated lines were given higher priority, and east-west lines were used to ensure 100% coverage of the study area.

Data Processing

2.2.23. The single beam echosounder data was processed by Titan Environmental Surveys Limited and corrected for tides. This processed data was presented to WA as an x, y, z text file for interpretation.

2.2.24. The processing of the digital seismic data was undertaken by WA using Coda Geosurvey software, which is a standard package for processing and interpreting single channel seismic data.

Seismic Interpretation using Coda Geosurvey Software

2.2.25. A digital copy of all the sub-bottom profile data was retained by WA for processing using the Coda Geosurvey software.

2.2.26. Coda Geosurvey is a software package designed for the acquisition and processing of sub-bottom profile and sidescan sonar data. This software allows the data to be replayed as one line at a time with user selected filters and gain settings in order to optimise the appearance of the data for interpretation. Coda Geosurvey then allows an interpretation to be applied to a line of data by identifying and selecting boundaries between layers.

2.2.27. Coda Geosurvey software, however, does not show the position of any boundary already identified on any intersecting lines. This is because Coda Geosurvey treats every survey line as an individual data file; therefore, care needs to be taken when interpreting the data in order to ensure consistency between lines of data.

2.2.28. The seismic data is collected and interpreted with two-way travel time (TWTT) along the z-axis, not depth. Therefore, to convert the TWTT to the interpreted boundaries into depths the velocity of seismic waves through the geology must be known or estimated. For this project the velocity of the seismic waves was estimated to be 1600 m/s which is a standard estimate for shallow, unconsolidated sediments of the type being studied in this survey (Sheriff and Geldart 1983; Telford *et al.* 1990).

2.2.29. Once the seismic data had been interpreted the position of the boundaries could be exported in the form of x, y, z text files where z was now the calculated depth, not the TWTT.

2.2.30. The x, y, z text files were output from the Coda Geosurvey software and isopachytes of specific layers were produced.

2.2.31. The sidescan sonar data (*.xtf) collected using the Klein SonarPro software were post-processed using Coda Geosurvey and a sonar mosaic of the seafloor was produced.

Bathymetry Data

2.2.32. The processed single beam echosounder data was input into Fledermaus software and a surface was created.

2.2.33. Fledermaus is a 3D-visualisation and analysis software package. This software can create 3D solid surfaces for any set of data containing points with an x, y and z value. These surfaces are made by gridding the data and interpolating between the data points before shading the surface with a user selected colour file so that the colours represent the relative heights over the surface. This 3D surface can then be explored and visualised in conjunction with other relevant geo-referenced data sets.

2.2.34. A cell size and weighting must be selected when gridding a data set. The chosen cell-size is the minimum value that can be used to ensure that data can be assigned to each cell. This value will vary depending on the line spacing used and the distance between data points. The resulting surface will be made up of rectangles corresponding to the cell size. The heights between neighbouring cells will be averaged over the number of adjacent cells corresponding to the weighting value. The weighting value affects the smoothing of the data. The higher the weighting value used, the smoother the data will appear. If there is a large number of closely spaced x, y, z points then small cell sizes can be used and a surface containing a high resolution of horizontal spatial detail can be produced.

2.2.35. In data sets with relatively large gaps between the data points, such as the single beam bathymetry dataset, a large cell size must be used to prevent holes appearing in the surface.

2.2.36. For the single beam bathymetry dataset a cell size of 20m and a weighting of three was used. This choice of gridding parameters has left holes in the data from the larger study area where the line spacing was 100m. These holes could have been covered by using a higher weighting value but this would adversely smooth the central area where the line spacing was 50m. As such, a cell size of 20m with a weighting of 3 was deemed appropriate for this dataset.

2.3. Geotechnical Survey

2.3.1. Based on geophysical data interpretation of the study area, ten potential vibrocore locations were proposed. From these locations eight were specified for acquisition. The vibrocoring was undertaken by Gardline Surveys on the 23rd and 24th July 2006, from the S/V *Flatholm*.

2.3.2. A high powered vibrocore unit was used for the survey. A 5m core barrel was used in order to obtain optimum depths indicated by the geophysical data. Date, time, position and water depth at each site were recorded.

2.3.3. A total of 17 vibrocores were acquired at the eight specified locations, because at each location one additional core specifically for optically stimulated luminescence (OSL) dating was collected (**VC1-8** and **VC1a-8a**). A third core was acquired at one location (**VC7i**) because of the lack of penetration of the original core (**VC7**).

2.3.4. Once the fieldwork was complete the cores were transported to WA's environmental processing laboratory, where the cores were archaeologically recorded. One core from each site was split longitudinally, photographed and logged. The core logs (**Appendix I**) provided details of the depth to each sediment horizon, the character and form of the sediment. Sedimentary characteristics recorded included texture, colour and depositional structure.

2.3.5. The logs were then compared in terms of their vertical distribution throughout the study area. This was achieved by adjusting the water depths for tides and plotting the cores in section referenced to OD heights.

2.3.6. The depositional and sedimentary boundaries identified in the core logs were then compared with the geophysical data interpretation in order to characterise the geophysical units identified at the core locations and to extrapolate the units throughout the site.

2.3.7. Environmental samples were taken from relevant deposits in order to provide chronological and environmental information relating to their formation, in accordance with the sampling strategy oulined in the Project Design (WA 2005). The selections were made on the basis of the sediment identified from the archaeological recording of the vibrocores and analysis of the geophysical data.

3. RESULTS

3.1. GEOPHYSICAL DATA

3.1.1. **Figure IV.4** illustrates that the bathymetric surface of the study area varies between a maximum water depth of 35.7m below OD in the north-east to a minimum of 26.5m below OD in the centre of the study area. The water depth generally increases to the north-east and extreme south-west of the area.

3.1.2. The shallowest part of the study area occurs along a discontinuous north-west to south-east orientated mound which is up to three metres higher than the surrounding seabed. The width of this feature varies: to the south, the feature is up to 400m wide; to the north it is less than 100m wide. The extension of the north-south orientated survey lines indicates that the southern limit of this feature is situated less than 100m south of the 800 x 800 m study area. The feature extends beyond the limits of the study area to the north and as such, the true extents of this feature are unknown (**Figure IV.4**).

3.1.3. A typical section of the survey data is shown in **Figure IV.5**. The deepest unit is seismically structureless in its upper part with weak, sub-parallel reflectors below (**Figure IV.5**). This unit is observed throughout the study area and the surface of the unit is generally in excess of 6m below seabed. However, to the north-east of the study area where the seabed deepens the top of this unit is recorded within 4m of the seabed.

3.1.4. This unit has been interpreted as the Yarmouth Roads Formation which is known to be seismically structureless (Cook 1991). The observed sub-parallel reflectors may indicate deposition of the Westkapelle Ground Formation, a series of laminated clays and sands deposited in an open marine shelf environment during the Lower Pleistocene. However, no distinct boundary was observed between these two formations on the geophysical data.

3.1.5. Throughout the study area the Yarmouth Roads Formation is overlain by a unit distinguished on the seismic data as high acoustic amplitude, irregular and chaotic reflections which have been interpreted as coarse sands and gravels and are best observed on the surface-tow boomer data (**Figure IV.5**). This structure reflects a high energy depositional environment; a large amount of energy would be required to transport particles of this size.

3.1.6. The sand and gravel unit is observed throughout the study area and the unit is generally up to 5m thick.

3.1.7. On the geophysical data no distinct boundary was observed between the top of the Yarmouth Roads Formation and the overlying sand and gravel unit due to the gradual increase in the coarseness of the sediments.

3.1.8. Throughout the majority of the study area a unit of lower amplitude reflections was observed on the boomer data (**Figure IV.5**), and it was observed on the pinger data as a unit with no reflections (**Figure IV.6**). This has been interpreted as a fine-grained sediment unit that is likely to have been deposited in a low energy environment.

3.1.9. The fine-grained sediment unit is observed either overlying the coarse sediment unit as a relatively uniform layer, forming mound structures (**Figure IV.5**), or infilling channels cut into the underlying gravels (**Figure IV.7**).

3.1.10. The extent of the fine-grained sediment unit has been mapped across the study area (**Figure IV.8**) and is generally associated with the mound and its flanks. Predominantly the thickness of this layer is less than 2m, thickening to 4m associated with channel infill to the south-east of the study area, and with a mound feature to the north.

3.1.11. Study of the seismic data in conjunction with the bathymetric surface reveals that the mound predominantly comprises a thickness of gravels periodically overlain by fine-grained sediments.

3.1.12. Based on the surface-tow boomer data and the sidescan sonar data a thin layer (<1m) of sediments overlying the coarse sand and gravel unit and/or the fine-grained sediment unit has been identified throughout the study area.

3.1.13. The sidescan sonar data shows that to the east of the mound there are mobile sediments, which are indicated by sand ripples (**Figure IV.9**). On the mound feature no ripples are observed, however this is likely to be due to hydrographical processes rather than a distinct change in sediment type. These sediments are likely to comprise sandy gravels (Cook 1991) and may originate from fluvioglacial or fluvial deposits which were deposited before the area was inundated by the sea during the last transgression.

3.1.14. It has been hypothesised that these coarse sediments were deposited by rivers derived either from periglacial weathering or glacial sources. The study area has been provisionally interpreted as being situated in the extension of the River Yare, cut prior to the most recent marine transgression (Bellamy 1998).

3.1.15. The fine-grained sediments are likely to have been deposited in a low energy environment with sedimentation occurring in single channel rivers or estuaries that developed during climate warming and associated marine transgression.

3.1.16. No distinct blanking of reflectors associated with methane production from peat layers was observed on the seismic data. However, this does not necessarily mean that peat is not present within this fine-grained sediment unit. The presence of peat was suggested by Bellamy (1998).

3.2. GEOTECHNICAL DATA

Vibrocores

3.2.1. Seventeen successful vibrocores were recovered from eight locations (**Figure IV.10**). At each location two cores were taken, one for Optically Stimulated Luminescence (OSL) dating and the other for geoarchaeological description, environmental subsampling and radiocarbon (^{14}C) dating. The full results of the geoarchaeological descriptions are given in **Appendix I**.

3.2.2. The geoarchaeological descriptions have been compared to depth in metres below OD and with the geophysical horizons and boundaries at which they were targeted. The four major geophysical horizons 'sand' (**Unit 1**), 'coarse sand and gravels' (**Unit 2**), 'fine-grained sediment' (**Unit 3**) and 'veneer of sand and gravel' (**Unit 4**) were identified and an example of the correlation between the geotechnical and geophysical results is illustrated in **Figure IV.11**.

3.2.3. These units can be stratigraphically linked between the vibrocores. Two examples of correlation between the vibrocores are shown as profiles in **Figures IV.12-13**. There are subtle variations between the cores and in particular within **Unit 3** which has been subdivided into subunits (**Figures IV.12-14**). These subunits are best represented in **VC1** (**Figures IV.14-15**). A description of each of the sedimentary units is given below:

Unit 1. Sandy gravel. 31.92 to 32.78m below OD

3.2.4. This unit was brown poorly sorted sand and gravel (subangular/subrounded) including frequent shell fragments. The unit was recorded in vibrocore **VC8** only and is interpreted as possible shallow marine sands and gravels (**Figures IV.12** and **IV.15**).

Unit 2. Gravelly sand. 27.65 to 36.68m below OD

3.2.5. This unit was grey, occasionally silty, gravely sand. The unit was observed in every vibrocore. Very few inclusions were recorded except for occasional finely crushed shell and occasional small organic flecks. One well preserved 12mm diameter piece of waterlogged wood was recovered from vibrocore **VC6**. In some cores (**VC7** and **VC8**) the sediment was brown and orange indicating iron oxide. This appeared to be reworking of oxidised sediment. The sediment was tentatively interpreted as a fluvial deposit.

Unit 3i Clayey silt. 29.56 to 30.75m below OD

3.2.6. This unit was black/dark grey organic clayey silt. The unit was only observed in vibrocore **VC1**. Organic content including plant stems was high. Gastropods were frequent at the top of the unit. Fine sandy bands were apparent at the base of the deposit. The deposit was also notably dry and friable. This deposit was interpreted as having been deposited in a slow moving or still, probably freshwater, environment.

Unit 3ii. Sandy clayey silt. 28.00 to 32.16m below OD

3.2.7. This unit was grey silty sand and clayey silt. The unit was observed in vibrocores **VC1**, **VC2** and **VC7**. In **VC1** the unit was generally dark with a high organic content and contained many molluscs including *Ostrea edulis*, *Cerastoderma edule* and hydrobiids especially towards the base. The deposit was interpreted as estuarine alluvium.

Unit 3iii. Silty clay. 27.31 to 28.82m below OD

3.2.8. This unit was brown compact gleyed clay and silty clay. The unit was observed in vibrocores **VC1** and **VC7** (**Figure IV.15**). In **VC1** the unit was 0.15m thick with probably intrusive gravel inclusions at the top. A sample of this unit was obtained from the top of OSL core **VC7a,** which when split showed an *in situ* root. The unit in this core (**VC7a**) was 0.04m thick. In vibrocore **VC7** the unit was 0.03m thick. This unit was interpreted as gleyed clay.

Unit 4. Sandy gravel. 27.61 to 32.69m below OD

3.2.9. This unit was yellow and brown sandy gravel. The unit occurred in vibrocores **VC1**, **VC2**, **VC3**, **VC6**, **VC8** and **VC9**. The unit comprised poorly sorted coarse sand and gravel with occasional broken marine shell. This deposit was interpreted as a seabed lag deposit.

3.3. ENVIRONMENTAL DATA

3.3.1. Environmental samples have been assessed and analysed for pollen (**Appendix II**), diatoms (**Appendix III**), foraminifera (**Appendix IV**), ostracods (**Appendix V**), waterlogged plants (**Appendix VI**) and molluscs (**Appendix VI**). The environmental zones and indicative species recovered from samples within **VC1** are shown in **Figure IV.14**.

Pollen

3.3.2. The pollen sequence recovered from vibrocore **VC1** is of interest. It is indicative of post-glacial warming with successive colonisation of various woodland types. Pollen is not regarded as a reliable dating method in the Pleistocene. The five pollen zones (**Appendix II**) are indicative of a Pleistocene post-glacial sequence. The sequence could be interpreted as a Holocene sequence although the absence of hazel (*Corylus avellana*) in the sequence makes this interpretation suspect. This highlights the limitations of dating sediments by pollen analysis.

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3.3.3. The environmental succession represented by the pollen zones is of greater interest. Pollen zone 1 is within sedimentary **Unit 2** (**Figure IV.14**) and contains grass dominated pollen spectra indicative of permafrost/soliflucted soils. Temperature amelioration is indicated by pioneer trees and shrubs including birch (*Betula*) into a landscape including areas of marsh and freshwater as demonstrated by the presence of freshwater algal *Pediatsrum* (**Appendix II**).

3.3.4. Pollen zone 2 straddles the sedimentary unit boundary between **Unit 2** and **Unit 3ii** (**Figure IV.14**) and shows the colonisation of pioneer birch (*Betula*) woodland, with pine (*Pinus*) also present (**Appendix II**). Aquatic environments are inferred with increasing numbers of aquatic plants including *Myriophyllum verticillatum* and occasional *Nuphar*. The presence of some Chenopodiaceae in this zone might indicate some brackish and/or saline conditions. Pollen zone 3 corresponds to **Unit 3i** (**Figure IV.14**) and is characterised by a rapidly expanding pine (*Pinus*) forest with marsh and aquatic taxa present (**Appendix II)**. Pollen zone 4 corresponds to the upper part of **Unit 3i** (**Figure IV.14**) and is characterised by the dominance of pine (*Pinus*) and oak (*Quercus*) beginning to expand, with elm (*Ulmus*) also present. Increasing numbers of freshwater, marsh and aquatic taxa are recorded (**Appendix II)**.

3.3.5. Pollen zone 5 corresponds to **Unit 3ii** and **Unit 3iii** (**Figure IV.14**) and is characterised by a sharp increase in oak (*Quercus*). Aquatic spores and palynomorphs including dinoflagellates are also present in this zone. These include Chenopodiaceae and occurrence of beaked tasselweed (*Ruppia ?maritima*) and sea lavender (*Armeria*) which strongly indicate brackish/saline conditions in zone 5 (**Appendix II)**.

Diatoms

3.3.6. Eight samples from vibrocore **VC1** were analysed for their diatom content (**Appendix III**). Diatoms were absent from the basal (30.31m below OD) and uppermost (28.74m below OD) samples. At 30.13m below OD very few (three) diatoms were preserved and all three were brackish/marine forms including *Paralia sulcata* indicating a possible tidal connection within **Unit 3i** (**Figure IV.14**). At 29.65 and 29.59m below OD a low concentration of freshwater diatoms was recovered including *Epithemia adnata* corresponding to **Unit 3i** (**Figure IV.14**).

3.3.7. At 29.47, 29.41 and 29.11m below OD, within **Unit 3ii** (**Figure IV.14**), greater numbers of diatoms were recovered. These samples included *Paralia sulcata* and species of the genus *Dimeregramma.* Freshwater species were more common in the lower sample (at 29.47m below OD) of this group indicating a transition from freshwater to estuarine environments. Species associated with sandy shores (*Rhopalodia musculus* and *Diploneis didyma*) and those associated with seaweeds (*Cocconeis scutellum*) indicate the marine and coastal connection at these levels.

Foraminifera

3.3.8. Foraminifera were recovered from vibrocore **VC1** but not from samples in **VC3 Appendix IV).** The foraminifera were divided into zones. A few reworked fossil taxa were recovered from 31.33 to 29.59m below OD at the top of **Unit 2** and at the base of **Unit 3i** (**Figure IV.14**). In foraminiferal zone 1 (29.53 to 29.47m below OD) corresponding to the base of **Unit 3ii** (**Figure IV.14**) a brackish water assemblage dominated by *Ammonia beccarii* is probably indicative of sediments deposited between mean high water neap tides (MHWNT) and mean high water spring tides (MHWST).

3.3.9. Foraminiferal zone 2 from 29.41m to 28.81m below OD corresponding to **Unit 3ii** (**Figure IV.14**) comprises of brackish and shallow marine taxa including *Haynesina germanica* and indicates deposition below the level of mean high water neap tides (MHWNT). The marine influence is seen to increase up the profile with shallow marine forms such as Miliolids becoming more dominant indicative of sea level rise (**Appendix IV**).

Ostracods

3.3.10. Ostracods were assessed and analysed from vibrocore **VC1**. No ostracods were recovered from vibrocore **VC3**. The ostracods were divided into two broad environmental zones with subzones marking more subtle environmentally faunal changes (**Appendix V**). No ostracods were recovered from 31.33 to 30.67m below OD. Ostracods appeared in small numbers at 30.76 and 30.73m below OD (zone 1a) corresponding to the top of **Unit 2** and the base of **Unit 3ii** (**Figure IV.14**) and are indicative of probably fluvial reworked freshwater environments. At 30.55 to 3.25m below OD (zone 1b) corresponding to the base of **Unit 3i** (**Figure IV.14**) the ostracod fauna is dominated by *Darwinula stevensoni* indicative of a shallow, slow-moving or still freshwater body. At 30.13 to 29.65m below OD (zone 1c) corresponding to the upper part of **Unit 3i** (**Figure IV.14**) the ostracod fauna is dominated by *Pseudocandona sarsi* and *Candona candida* indicative of a small shallow freshwater body which in the broader context of a river valley may in this case be an oxbow lake (**Appendix V**). Within this zone (from 30.01 to 29.65m below OD) there are some occasional indications of brackish conditions including the species *Cyprideis torosa*.

3.3.11. Zone 2a from 29.59 to 29.35m below OD marks the inception of fully brackish/estuarine conditions with a clear marine connection established. This zone corresponds to the upper part of **Unit 3i** and the lower part of **Unit 3ii** (**Figure IV.14**) This zone is dominated by *Cyprideis torosa*, indicative of tidal creek and mudflat environments. This marine influence is seen further in Zone 2b (from 29.23 to 28.99m below OD) within **Unit 3ii** (**Figure IV.14**) with shallow marine species becoming more prominent. Zone 2c (28.87m below OD) corresponding to the upper part of **Unit 3ii** (**Figure IV.14**) is dominated by shallow marine taxa including *Palmoconcha guttata* and *Aurila woutersi*. Very few ostracods were recovered from the oxidised sediment (**Unit 3iii**) at 27.87 and 28.81m below OD and this is probably due to preservation conditions.

3.3.12. The ostracod faunas are clearly indicative of freshwater and then estuarine environments with increasing marine influence up the profile commensurate with sea level rise. The presence of the taxon *Semicytherura sella* within **Units 3i** and **3ii** indicates that these sediments units probably date to a post-Cromerian (OIS 13) interglacial period (**Appendix V**).

Waterlogged Material

3.3.13. Six 0.5 litre samples were retrieved from vibrocore **VC1** and examined for waterlogged material in conjunction with material recovered from foraminifera and ostracod samples to give an indication of on-site vegetation. From 30.89 to 30.73m below OD within **Unit 2** and **Unit 3i** (**Figure IV.14**) an open birch woodland is indicated and birch bark charcoal recovered which is a possible indication of human activity in the area (**Appendix VI**). Mare's tail (*Hippurus vulgaris*) is indicative of ponds, lakes and slow streams at this level. Above this from 30.24 to 30.01m below OD birch (*Betula*) and pine (*Pinus*) woodland was recorded. These levels also contain still and slow flowing water indicators such as horntwort (*Ceratophyllum demersum*).

3.3.14. From 29.56 to 29.41m below OD within **Unit 3i** (**Figure IV.14**) tassel-weed (*Ruppia maritima*) and horned pondweed (*Zannichellia palustris*) are indicative of shallow lagoons of brackish water. From 29.36 to 28.81m below OD within **Unit 3ii** (**Figure IV.14**) some poorly preserved wood and a single occurrence of probably reworked hornwort (*Ceratophyllum demersum*) occurred (**Appendix VI**).

Molluscs

3.3.15. Molluscs were identified from the same six 0.5 litre samples as the waterlogged material and from the foraminifera and ostracod samples (**Appendix VI**). From 30.79 to 30.30m below OD corresponding to the top of **Unit 2** and the base of **Unit 3i** (**Figure IV.14**) molluscs indicative of freshwater floodplain environments were recovered including *Pisidium*, *Lymnaea*, *Bithynia* and Planorbids. From 30.29 to 30.01m below OD within **Unit 3i** (**Figure IV.14**) similar species were recovered with the notable additions of *Hydrobia ventrosa* and *Valvata* sp. indicative of some brackish and marsh conditions respectively. Above this level at the top of **Unit 3i** (**Figure IV.14**) a return to freshwater floodplain environments is represented from 29.65 to 29.89m below OD by *Lymnaea*, *Pisidium* and *Bithynia* (including frequent operculae).

3.3.16. From 29.59 to 29.48m below OD corresponding to the top of **Unit 3i** and **Unit 3ii** (**Figure IV.14**) a mix of marine, brackish and freshwater molluscs were recovered. From 29.47 to 28.99m below OD corresponding to the top of **Unit 3ii** and **Unit 3iii** (**Figure IV.14**) brackish and estuarine conditions are inferred from the molluscs including *Hydrobia ulvae* with some more marine species including oysters and cockles. Above this level from 28.94 to 28.81m below OD more marine species including oysters (*Ostrea edulis*), cockles (*Cerastoderma edule*), sea urchin spines and herring type fish bones were recovered.

Animal Bone

3.3.17. Two small mammal bones were retrieved from the foraminifera/ostracod samples (**Figure IV.14**). At 29.44m below OD (**Unit 3i**) a small mammal molar was recovered. At 30.91m below OD (**Unit 2**) a small mammal bone was found. Small herring type fish vertebrae were also recovered from the top of **Unit 3i** and **Unit 3ii** and **Unit 3iii** (**Appendix VI**, **Figure IV.14**).

3.4. CHRONOLOGY

Radiocarbon Dating (^{14}C)

3.4.1. Seven radiocarbon (^{14}C) samples from vibrocore **VC1** were sent to three different laboratories. All results are given in **Appendix VII** and summarised in **Table IV.3** and in **Figure IV.14**.

Depth below OD (m)	Material	Result no.	Result BP
29.47	*Carex*	NZA-27096	23,760±300
29.53	*Nassarius reticulatus*	SUERC-11983	43,800±400
29.53	*Nassarius reticulatus*	OxA-16466	39,820±390
29.77	Bullrush seeds	NZA-27099	47,800±2,400
29.86	Herbaceous stem	SUERC-11979	>50,000
30.01	*Schoneoplectus* sp (Bullrush seeds)	NZA-27100	>47,000
30.73	*Betula* charred bark	NZA-27095	49,500±3,000
30.79	*Betula* cone scales	OxA-	Too small sample

Table IV.3: Radiocarbon (^{14}C) dating results (**VC1**).

3.4.2. Two samples each consisting of a single shell (*Nassarius reticulatus*) at 29.53m below OD were dated to test whether the shells were deposited in a single event. Statistical tests indicate that the two samples are not of the same radiocarbon age.

3.4.3. These results are, with the exception of the date at 29.47m below OD (23,760±300 BP), at the limits or beyond the range of radiocarbon dating. The sample (*Carex*) at 29.47m below OD was dated to 23,760±300 BP which is within the range of radiocarbon dating, however, is beyond the limits of calibration.

Optically Stimulated Luminescence (OSL) Dating

3.4.4. Optically stimulated luminescence (OSL) dating was carried out on samples from vibrocores **VC1a** and **VC3a.** Eight samples were submitted for dating and the methodology is provided in **Appendix VIII.** The results are summarised in **Table IV.4** and shown in **Figures IV.12-14**.

Vibrocore	Unit	Depth below OD (m)	Age (ka)	Comment
VC1a	3iii	28.81	16.6±2.3	
VC1a	3ii/3iii	29.59	116.7±11.2	
VC1a	-	30.19	-	No dateable material extractable
VC1a	2	30.97	175.7±22.6	
VC1a	2	31.37	577.2±65.4	
VC3a	2	33.81	309.5±29.1	
VC3a	2	34.87	226.0±26.5	
VC3a	2	35.95		Not dateable, older than Holocene

Table IV.4: Optically stimulated luminescence (OSL) dating results.

3.4.5. Five samples were taken from **Unit 2**: three from VC3a and two from VC1 (**Table IV.4**). The OSL dates indicate that **Unit 2** sediments are older than 175 ka. In **VC3a** two dates (226.0±26.5 ka and 309.5±29.1 ka at 34.87m below OD and 33.81m below OD, respectively) appear reversed (**Figure IV.13**). However, these dates still fall within the date range for **Unit 2** as indicated in **VC1a**. The cause of this reversal is uncertain; it is possible that the sediments have been re-worked due to sediment dynamics or that this is a result of the OSL methodology.

3.4.6. In **VC1a**, one sample (29.59m below OD) was acquired at the boundary of **Unit 3ii** and **Unit 3iii**. OSL dating indicated an age of 116±11.2 ka. At 28.81m below OD the sample was OSL dated to 16.6±2.3 ka at the base of **Unit 3i** (an oxidized sediment). Based on these dates the disparity between the ages either indicates slow or interrupted deposition of sediments over 80,000 years, or that the younger date refers to the oxidation episode rather than the age of deposition. The chronology of the deposits is discussed fully in **Section 4.2**.

4. DISCUSSION AND CONCLUSIONS

4.1. GEOTECHNICAL AND GEOPHYSICAL DATA INTERPRETATION

4.1.1. The dominant features observed on the geophysical data were the large mound to the south of the study area and the smaller mounds to the northwest (**Figure IV.8**), which, based on their seismic nature and background geological knowledge, were interpreted as comprising a layer of fine-grained sediments. This was confirmed in **VC1** and **VC7**, situated on the large mound (**Figure IV.10**), where fine-grained silts and clays deposited in an estuarine/freshwater environment were observed. The thickness of the estuarine sediment varies between the cores. In **VC1** the core was taken in an area where a small channel cuts into the underlying sands and gravels (**Figure IV.11**). The channel has been infilled by the fine-grained sediments and is therefore a thicker sequence than in **VC7**. **VC2** was acquired at the location of the smaller mound to the north-west of the study area (**Figure IV.10**). Fine-grained sediments were also observed within this vibrocore corresponding to the geophysics data (**Figure IV.11**).

4.1.2. **VC9** is situated on the western edge of the main mound (**Figure IV.10**) and a small layer (0.55m) of fine-grained sediments is observed indicating that the fine-grained sediments drape over the mound and its edges.

4.1.3. **VC6** and **VC8** are situated away from the mounds (**Figure IV.10**). At the location of these cores the geophysics data indicated a layer of fine-grained sediments similar in seismic nature to those on the mound. However, the vibrocores indicate that there are no fine-grained estuarine sediments at these locations, but fine-grained sands with some gravel.

4.1.4. Although the fine-grained sediment layer can be traced on the geophysical data across the central study area both on and between the mounds, the geotechnical data indicate that there is a lateral sediment change across the area, with the fine-grained estuarine sediments confined to the mounds.

4.1.5. In the vibrocores where the fine-grained sediments were observed, there was no evidence of any peat. However, in **VC1** an organic silt layer was observed at 30.01m below OD. This corresponded with a strong reflector on the geophysics data (**Figure IV.11**).

4.1.6. **VC3** and **VC5** were acquired in an area to the north-east of the study area (**Figure IV.10**) where the geophysics data indicated that modern sediments directly overlie marine sands (Yarmouth Roads Formation). This was confirmed in the vibrocores.

4.2. CHRONOLOGICAL AND ENVIRONMENTAL INTERPRETATION

4.2.1. Based on the geophysical data **Unit 1** is considered likely to comprise sediments of the Yarmouth Roads Formation. The earliest data attained by OSL dating was 577.2±65.4 ka at the base of **VC1** at a depth of 31.37m below OD, indicating a Cromerian Complex date (**Figure IV.14**). This would agree chronologically with the interpretation as described by Cameron *et al.* (1992). Sedimentologically there is little difference between **Unit 1** and **Unit 2**. Both units comprise sands and gravels; although a marked increase in molluscan inclusions was observed in VC8, differentiating the units. Although the depth at which the OSL sample was taken indicates a **Unit 2** sample in **VC1**, it is at the bottom of the core and it is possible that in **VC1a** (OSL core) this date refers to **Unit 1**. Given that three further samples successfully OSL dated in **Unit 2** (309.5±29.1 ka; 226.0±26.5 ka; 175.7±22.6 ka) are indicative of a Wolstonian (OIS 8,7 or 6) age for formation, it is considered more likelt that the OSL date of 577.2±65.4 ka is likely indicative of **Unit 1** rather than **Unit 2**.

4.2.2. Sedimentological interpretation of Unit 2 as fluvial would be in accordance with the interpretations given by Bellamy (1998) and Arthurton *et al.* (1994). Pollen samples taken from this unit in **VC3** are indicative of post-glacial climatic amelioration. This has probably occurred at the end of the Wolstonian (OIS 6) and beginning of the Ipswichian (OIS 5e) period.

4.2.3. **Unit 3**, the fine grained sediment unit identified by geophysical survey, has been split into three separate sedimentary units on the basis of the geotechnical results: **Unit 3i**, **Unit 3ii** and **Unit 3iii**. The unit had previously been tentatively interpreted as analogous to the onshore Holocene Breydon formation (Bellamy 1998) however the dating indicates the sediments pre-date the Holocene.

4.2.4. The successive environments interpreted from the environmental remains recovered from the samples broadly confirmed the sedimentological observations and interpretations of freshwater (**Unit 3i**) to estuarine (**Unit 3ii**) environments. The summary of environmental data is shown in **Figure IV.14**. Some indications of increasing salinity were however noted amongst the predominantly freshwater faunas indicative of a freshwater pool, lake or oxbow lake surrounded by a birch and pine woodland. Brackish tolerant species of molluscs, diatoms and ostracods in **Unit 3i** suggest sporadic slight increases in salinity. The underlying deposits in this area are predominantly sands and gravels (**Unit 1** and **Unit 2**) and therefore in order for a freshwater lake, pool or oxbow lake to develop in this area a high water table is needed to prevent drainage. This high water table may have been caused by sea level rise which would explain the arrival of mollusc and ostracod species tolerant of slight increases in salinity at the top of the **Unit 3i**, the predominantly freshwater unit.

4.2.5. **Unit 3i** was only recorded in **VC1** and was interpreted as a freshwater deposit with occasional brackish indicators. The OSL date towards the top of this sub-unit at 29.59m below OD and dated to 116.7±11.2 ka suggests an Ipswichian date (OIS 5e). Radiocarbon dates at 29.86m below OD (>50,000 BP, SUERC-19979) and 30.01m below OD (>47,000 BP, NZA-27100) are beyond the range of radiocarbon dating, therefore not necessarily contradicting the OSL result. However, two radiocarbon dates at 30.73m below OD (49,500±3,00 BP, NZA-27095) and at 27.77m below OD (47,800±2,400 BP, NZA-27099) are stratigraphically below the OSL sample but indicate a younger age (although they are towards the limits of radiocarbon dating). Further dating is required to resolve these inconsistencies (see **Section 4.5**). However, environmental indicators support an Ipswichian date.

4.2.6. Seeds of the brittle water-nymph (*Najas Minor*) observed within **Unit 3i** also indicate Ipswichian or earlier deposition (**Appendix VI**). *Najas Minor* is no longer native in Britain and generally the species is not recovered in deposits later than the Ipswichian interglacial (Godwin 1975). Also, the pollen sequence observed in **VC1** is similar to East Anglian Ipswichian sites where pine (*Pinus*) and birch (*Betula*) woodland is succeeded by oak (*Quercus*) before the occurrence of hazel (*Corylus*) (Godwin 1975). This expansion of oak corresponds to **Unit 3ii**.

4.2.7. The environmental remains from **Unit 3ii** all indicate a marine influence and sea level rise with salt marsh and estuarine foraminifera, ostracods, molluscs, plants and diatoms. At the top of **Unit 3ii** more shallow marine taxa show an increasing marine influence in an alluvial estuarine environment with salt marsh and proximal deciduous forest. This description and a potential Ipswichian date would suggest that **Unit 3ii** is analogous to the brackish silty clays of the Brown Bank Formation as described further east by Cameron *et al.* (1992).

4.2.8. **Unit 3ii** was observed more widely across the survey area in the vibrocores **VC1**, **VC2** and **VC7**. Of the two radiocarbon dates from this unit in **VC1** (**Figure IV.14**), one (43,800±400 BP, SUERC-11983) is at the limit of radiocarbon dating, and the other at a depth of 29.47m below OD (23,760±300 BP, NZA-27096) is unusual: given the environmental data which indicate that this deposit is a brackish silty clay, relative sea level must have been less than *c.* 30m below OD at this time. Known relative sea levels suggest that at 23,760±300 BP relative sea level would have probably been greater than 100m below OD (Siddall *et al.* 2003). The result is therefore enigmatic. Also, sea levels were at or around 30m below OD twice during OIS 5e (Siddall *et al.* 2003), further suggesting a possible Ipswichian age.

4.2.9. **Unit 3iii** shows evidence of sub-aerial exposure of **Unit 3ii**. An OSL date of 16.0±2.3 ka might be indicative of a period (Devensian OIS2) when this occurred, rather than the date of sediment deposition.

4.2.10. **Unit 4** has not been scientifically dated although geophysical and sedimentological interpretation would suggest that it is seabed sediment or Holocene lag deposited during rising sea levels. Comparison with sea level curves (Jelgersma 1979; Streif 2004) would suggest that this unit was probably deposited *c.* 8,000 BP/6,800 cal. BC. Seabed sediment in this area is not thought presently to be mobile (Cameron *et al.* 1992).

4.3. ARCHAEOLOGICAL SIGNIFICANCE

4.3.1. Charcoal was recovered from vibrocore **VC1** (**Figure IV.14**). This charcoal may have been caused by natural forces e.g. lightning, or the result of deliberate anthropogenic burning. One piece (charred birch bark) from **Unit 3i** at 30.73m below OD was radiocarbon dated to 49,500±3,000 BP (NZA-27095). This is at the limit of radiocarbon dating and is inconsistent with the OSL dates acquired stratigraphically earlier and later than this sample (175.7±22.6 ka at 30.97m below OD and 116.7±11.2 ka at 29.59m below OD). Although the radiocarbon dates indicate a younger date the OSL samples and environmental indicators (pollen sequence and the presence of *Najas minor*) would suggest the charcoal dates from the Ipswichian (OIS 5e) period, in agreement with the OSL dating. This would also be the case for the charcoal found higher up the profile at 29.77m below OD. If these pieces are evidence of habitation from Ipswichian deposits this would be highly significant as this period is at present thought to be one of non-occupation of the British Isles (Wymer 1999).

4.3.2. The charcoal further down the sequence at 31.33m below OD (**Unit 2**) may date from an archaeological period which is significantly earlier. Its proximity to the OSL sample at 31.37m below OD dating to 577.2±65.4 ka may be suggestive of occupation of this area during the Cromerian Complex period (OIS 13) or later. This unit, comprising fluvial sands and gravels (**Unit 2**), may contain reworked Palaeolithic material as Pleistocene fluvial deposits onshore have been proven to be implementiferous (Wymer 1999).

4.4. CONCLUSIONS

4.4.1. Both pinger and surface-tow boomer data were used in conjunction to interpret sub-surface geology within the study area. For this survey acquiring data with two seismic sources (pinger and surface-tow boomer) allowed a more detailed interpretation than one source alone. However, the choice of source used during geophysical surveys should be based on the geological environment and will differ from survey to survey.

4.4.2. Sidescan sonar data has aided the geophysical data interpretation with regard to seabed sediment type and seabed morphology (in combination with bathymetric data). In this case, the sidescan sonar data indicated that no peat was exposed on the seabed. Furthermore, the sidescan sonar data indicated any features on the seabed which might have hindered the vibrocoring operations. Therefore, sidescan sonar data, as part of a complete geophysical data suite, facilitated the design of the vibrocore survey.

4.4.3. This project has highlighted the difficulties in trying to delineate stratigraphic changes in the near surface sediments, particularly with data acquired in marginal weather conditions in an area that is also affected by strong sea-surface currents.

4.4.4. The geophysical data demonstrated the post-transgressive survival of fine-grained sediments, which could potentially contain archaeological deposits in offshore locations.

4.4.5. Geophysical data is a useful tool for conducting the initial palaeogeographic evaluation of an area. However, this study highlights the importance of a combined geophysical and geotechnical survey. Although important palaeosurfaces can be identified on the geophysical data, in order to fully reconstruct the palaeogeographic sequence of the area it is important to groundtruth this data with vibrocoring, grab sampling and subsequent analyses of these data.

4.4.6. Based on the geophysical data alone it is difficult to relate offshore stratigraphy to terrestrial analogues and there is a consequent need for further research and the development of new geomorphological models.

4.4.7. Based on the geotechnical, environmental and chronological data the sedimentary units are thought to comprise shallow marine, freshwater and estuarine environments dating from the Cromerian Complex period to recent. **Unit 1** comprising gravels and sands was interpreted as part of the shallow marine Yarmouth Roads Formation, probably deposited during the Cromerian Complex period (OIS 13). **Unit 2** comprising silts sands and gravels was interpreted as fluvial sediments with OSL dates suggesting deposition during the Wolstonian (OIS 8, 7 and 6) period. **Unit 3** comprising sands, silts and clays was indicative of sea level rise, climate amelioration, freshwater and estuarine environments with OSL dates suggesting deposition during the Ipswichian (OIS 5e) period. **Unit 4** comprising gravel and sands was indicative of more recent (Holocene) seabed sediments.

4.5. RECOMMENDATIONS FOR FURTHER WORK

4.5.1. There are clearly some inconsistencies in the dating of the deposits within the Great Yarmouth study area. Both the OSL and radiocarbon dates indicate that the fine grained deposits (**Unit 3**) originally thought to be Holocene are clearly older. Discrepancies between the OSL and radiocarbon results are apparent, particularly in **Unit 3,** and although the environmental evidence suggests that the OSL dates are more reliable further work is clearly required to resolve these date issues. To confirm these dates it is suggested that amino acid racemisation be undertaken on operculae which were found within **Unit 3.** Within Pleistocene interglacial deposits beetles can be of some biostratigraphic value and may also be present within **Unit 3**.

4.5.2. Further environmental samples from **Unit 3ii** within vibrocores **VC2** and **VC7** should be undertaken. Within these vibrocores **Unit 3ii** is elevated slightly higher and could therefore provide a more complete sedimentary sequence and provide detail on lateral changes in environment across the study area. Within Pleistocene interglacial deposits beetles can be of some biostratigraphic value (Coope 2001) and may also be present within **Unit 3i (VC1)**.

4.5.3. Molluscan material within **Unit 1** (**VC8**) should be assessed for its potential biostratigraphic and environmental significance.

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APPENDIX I: VIBROCORE LOGS

VC1

Depth below seabed (m)	Depth below OD (m)	Description	Unit
0.00-0.41	27.61-28.02	2.5Y 5/4 Light olive brown sandy (c) gravel. Gravel is angular to subrounded (<80mm) Poorly sorted. Clear boundary. Lag	4
0.41-0.81	28.02-28.42	2.5Y 5/4 Light olive brown sand (mc). occasional subangular gravel inclusions (<25mm). Moderately sorted. Clear boundary.	4
0.81-1.06	28.42-28.67	2.5Y 5/4 Light olive brown sandy (c) gravel. Gravel is subangular to subrounded (<50mm). Poorly sorted. Sharp boundary.	4
1.06-1.21	28.67-28.82	5Y 4/2 Olive grey gleyed clay. Reddish (oxidised?) patches. Very occasional subangular gravel inclusions (<30mm) in the upper 1.06-1.10. Very well sorted. Sharp boundary.	3iii
1.21-1.83	28.82-29.44	5Y 3/1 Very dark grey silty clay. Occasional shell fragments, very well sorted. *Ostrea edulis* at 1.28-1.32, 1.36-1.41, plant remains at 1.27. Diffuse boundary.	3ii
1.83-1.89	29.44-29.50	5Y 2.5/1 Black clayey silt. Very organic. Frequent shell fragments, very well sorted. Sharp boundary.	3ii
1.89-1.95	29.50-29.56	Dense shell (bivalves – including *Cerastoderma edule* and hydrobiids. Sediment matrix same as above and below. Sharp boundary.	3ii
1.95-2.15	29.56-29.76	5Y 2.5/1 Black clayey silt. Very organic content. Frequent shell fragments. Very well sorted. Gradual boundary.	3i
2.15-2.40	29.76-30.01	2.5Y 2.5/1 Black clayey silt. Very organic. Friable and dry. Frequent shell inclusions and brighter bands at 2.19, 2.21, 2.22, 2.24. Plant remains (including degraded herbaceous stem) at 2.25. Well sorted. Diffuse boundary.	3i
2.40-2.64	30.01-30.25	5Y 3/1 Very dark grey clayey sandy silt. Black irregular and broken (organic?) bands at 2.47, 2.51, 2.55. Occasional shell fragments especially around the laminae/lenses. Mottled black. Very well sorted. Abrupt boundary.	3i
2.64-3.14	30.25-30.75	5Y 2.5/1 Black clayey silt. Very organic. Moderate slightly sandy bands (5-10mm) at 2.64, 2.66, 2.71, 2.76, 2.90, 2.94, 3.04, 3.06, 3.09, 3.11. Occasional shell fragments throughout especially within the sandy bands. Dark (organic?) lamination at 2.66 (2mm), dark flecks at 2.74, 2.76. Brighter bands (2mm) at 2.69, 3.07. Slight black mottling. Well sorted. Abrupt boundary.	3i
3.14-3.21	30.75-30.82	5Y 2.5/1 Black clayey silt. Very organic. Moderate slightly sandy bands (5-10mm) at 3.15 and 3.20 containing subangular to subrounded gravel inclusions (<24mm). Occasional shell fragments. Slightly black mottling. Well sorted. Clear boundary.	2
3.21-3.38	30.82-30.99	5Y 5/1 Grey sand (m). Irregular bands (5-10mm) of brownish silty clay at 3.24, 3.27, 3.29, 3.30, 3.33, 3.34, especially at 3.24 bounded by fine dark (organic?) bands. Clear boundary.	2
3.38-3.66	30.99-31.27	5Y 3/1 Very dark grey sand (mc). Silty lenses and frequent subrounded to subangular gravel inclusions (<60mm). Poorly sorted. Abrupt boundary.	2
3.66-3.75	31.27-31.36	5Y 4/1 Dark grey sand (m), very slightly silty, no visible inclusions. Very well sorted. Abrupt boundary.	2
3.75-3.76	31.36-31.37	No recovery; according to visible remains probably same as 3.38-3.66.	-

VC2

Depth below seabed (m)	Depth below OD (m)	Description	Unit
0.00-0.20	27.80-28.00	10YR 5/6 Yellowish brown slightly silty gravelly sand (mc). Soft. Poorly sorted. Frequent rounded – angular (<15mm) flint. Occasional broken shell (including *Ostrea edulis*). Clear boundary.	4
0.20-2.01	28.00-29.81	2.5Y 4/2 Dark greyish brown silty sand (fm). Moderate-frequent broken shell (very shelly/dark 0.50-0.52 including *Ensis* sp., echinoid spines and ?organics). Infilled burrow at 0.69. *Cerastoderma edule* at 1.61. Some horizontal laminae of lighter (2.5Y 5/2 Greyish brown) /darker material (as above) (<40mm). Moderate unidentifiable organics. Fining upwards. Increasing shell fragments and sand (m) from 1.80-2.01. Gradual boundary.	3ii
2.01-2.44	29.81-30.24	2.5Y 3/1 Very dark grey very silty sand (f). Very occasional rounded (black) flint (<12mm). Burrow filled with black ?organic sandy silt/shell fragments at 2.08 to 2.15. Frequent broken shell becoming very frequent 2.25-2.44. *Littorina ?litoralis* at 2.25. Coarsening up. Silt content increases 2.25-2.44. Abrupt boundary.	3ii
2.44-3.23	30.24-31.03	2.5Y3/1 Very dark grey very silty sand (f). Occasional small subrounded to subangular flint (<15mm). Occasional to moderate organics including wood (2.55). 2.55-2.61 frequent *Cerastoderma edule,* occasional *Littorina* sp., *Ostrea edulis* and serpulid worm tubes. 2.64 broken sea urchin, frequent spines. 2.67-2.70 *Nassarius reticulatus*. 2.75-2.82 frequent spines/ occasional Hydrobiids. 2.80-3.10 darker 2.5Y very dark grey silt bands (<15mm) including ?Hydrobiids, urchins and *Nassarius reticulatus*. 3.10-3.20 frequent shell including *Cerastoderma edule* and occasional *Ostrea edulis*. Abrupt boundary.	3ii
3.23-3.35	31.03-31.15	2.5Y 3/1 Very dark grey clayey silt. Comact/firm. Laminae of darker/lighter bands (2.5Y 4/1 dark grey silty sand). ?Flood couplets (<5mm). Darker bands look organic. Lighter bands include moderate broken shell. Abrupt boundary.	3ii
3.35-3.45	31.15-31.25	2.5Y 4/2 Dark greyish brown silt. Very soft/wet. ?Disturbed during coring or degraded soft organic (?mollusc?echinoid). Large *Ostrea edulis* at 3.35. Abrupt boundary.	3ii
3.45-3.65	31.25-31.45	2.5Y 5/1 Grey slightly silty sand (m). Soft. Very frequent *Ostrea edulis* 3.45-3.55. Sand band at 3.56-3.58. Moderate *Cerastoderma edule* 3.59-3.62. Abrupt boundary.	3ii
3.65-4.36	31.45-32.16	2.5Y 4/1 Dark grey slightly silty sand (fmc). Soft. Moderately sorted. Moderate small-medium rounded to subangular poorly sorted flint. Frequent shell including *Cerastoderma edule*, hydrobids. Leaf at 3.91. Occasional ?organics. 4.06-4.11, 4.19-4.22 gravelly, frequent subrounded to subangular black flint (<20mm). 3.80-4.36 frequent crushed shell. Abrupt boundary.	3ii
4.36-4.71	32.16-32.51	2.5Y 5/3 Light olive brown compact slightly silty (?intrusive in wet core) sandy (mc) gravel (<40mm). Flint (80%), mudstone, quartz, chalk rounded-subrounded. 4.58-4.71 occasional broken shell.	2

VC3

Depth below seabed (m)	Depth below OD (m)	Description	Unit
0.00-0 53	31.81-32.34	10YR 4/2 Dark greyish brown silty sandy (mc) gravel. Very frequent flint (<30mm) rounded – angular. Poorly sorted. Occasional broken shell (bivalves). Lumps of grey silt. Sand is flint/quartz. Soft. Abrupt boundary.	4
0.53-0.61	32.34-32.42	10YR 4/2 Dark greyish brown sand (m). Well sorted. Occasional broken shell (bivalve). Soft. Abrupt boundary.	4

Depth below seabed (m)	Depth below OD (m)	Description	Unit
0.61-0.88	32.42-32.69	10YR 4/1 Dark grey silty gravelly sand (mc). Very frequent flint rounded – angular (<15mm). Very occasional lumps of silt (c.30x8mm). Frequent broken bivalve shell. Sorted. Abrupt boundary.	4
0.88-1.00	32.69-32.81	10YR 4/1 Dark grey sand (fm). Soft. Occasional large flint at 0.92m, (<80mm) subrounded – rounded. Clayey silt laminae (0.94-0.95, 0.98-1.00) 10YR 4/1 dark grey. Occasional darker bands within. Well sorted. Boundary missing.	2
1.00-1.06	32.81-32.87	Gap	
1.06-1.71	32.87-33.52	10YR 5/1 Grey slightly silty sand (fm). Moderate – occasional lumps (20x10mm) of grey clayey silt. Coarsening upwards. Very occasional organics at 1.27. Well sorted. Gradual boundary.	2
1.71-2.58	33.52-34.39	10YR 5/1 Grey slightly silty sand (fm). Soft. Frequent convoluted clayey silt laminae (1-3mm width). Thicker clayey silt laminae from 2.03-2.06, 2.18-2.21 (<15mm) horizontally bedded. More convoluted bedding from 2.45 to 2.55m. Well sorted. Clear boundary.	2
2.58-2.62	34.39-34.43	10YR 5/1 grey gravelly sand (mc). Soft. Moderate clay/mudstone subrounded – subangular. Poorly sorted. Abrupt boundary.	2
2.62-2.69	34.43-34.50	10YR 5/1 sand (mc). Soft. Well sorted. No inclusions. Abrupt boundary.	2
2.69-2.76	34.50-34.57	10YR 5/1 grey gravelly sand (mc). Soft. Frequent subrounded – subangular mudstone (light brownish grey <60mm). Poorly sorted. Abrupt boundary.	2
2.76-3.38	34.57-35.19	10YR 4/1 Dark grey slightly silty sand (fm). Moderate clayey silt laminae (2.81-2.85, 2.91-2.96, 3.00-3.04, 3.12-3.18) <15mm with occasional black “organic” laminae <1mm within. ?charcoal at 3.28. Well sorted. Clear boundary.	2
3.38-3.53	35.19-35.37	10YR 4/2 Dark greyish brown gravelly sand (fm). Occasional rounded (<15mm) flint. Occasional-moderate subangular mudstone (light brownish grey). Poorly Sorted. Abrupt boundary.	2
3.53-4.74	35.37-36.55	10YR 4/2 Dark greyish brown sand (fm). Very well sorted. No bedding/inclusions. Sand becoming coarser from 4.50 onwards and occasional (<10mm) subrounded – rounded flint. Abrupt boundary.	2
4.74-4.87	36.55-36.68	10YR 3/1 Very dark grey sand (fm). Occasional coarse sand. Soft. Well sorted. No bedding (as above except slightly darker).	2

VC5

Depth below seabed (m)	Depth below OD (m)	Description	Unit
0.00-0.09	32.37-32.46	2.5Y 6/2 Light brownish grey sand (m). Loose. Well sorted. Occasional subangular gravel inclusions (<9mm). Occasional shell fragments. Clear boundary.	2
0.09-0.21	32.46-32.58	2.5Y 6/4 Light yellowish brown sand (m). Very loose with occasional subangular gravel inclusions (<10mm). Occasional shell fragments. Moderately sorted. Clear boundary.	2
0.21-0.41	32.58-32.78	2.5Y 6/1 Grey sand (m). Very loose. Occasional subangular gravel inclusions (<12mm). Occasional shell fragments. Moderately sorted. Gradual boundary.	2
0.41-0.48	32.78-32.85	2.5Y 4/2 Dark greyish brown sand (c). Frequent subrounded gravel inclusions (<12mm). Occasional shell fragments. Moderately sorted. Clear boundary.	2
0.48-0.60	32.85-32.97	2.5Y 6/1 Grey sand (m). Very loose. Occasional subangular gravel inclusions (<12mm). Occasional shell fragments, moderately sorted. Gradual boundary.	2
0.60-0.97	32.97-33.34	2.5Y 4/3 Olive brown sandy gravel. Gravel is subangular to subrounded (<50mm). Occasional shell fragments. Poorly sorted. Gradual boundary.	2

Depth below seabed (m)	Depth below OD (m)	Description	Unit
0.97-1.18	33.34-33.55	2.5Y 6/2 Light brownish grey gravelly sand (c). Gravel is subangular to subrounded (<15mm). Frequent shell fragments. Moderately sorted. Gradual boundary.	2
1.18-1.27	33.55-33.64	2.5Y 6/4 Light yellowish brown sand (c). Occasional large gravel (<25mm). Occasional shell fragments. Moderately sorted. Gradual boundary.	2
1.27-1.42	33.64-33.79	2.5Y 6/4 Light yellowish brown sand (c). Frequent small gravel (<10mm). Occasional shell fragments. Moderately sorted. Gradual boundary.	2
1.42-2.13	33.79-34.50	2.5Y 5/4 Light olive brown sand (c). Occasional gravel (<14mm). Occasional shell fragments. Moderately sorted. Gradual boundary.	2
2.13-2.53	34.50-34.90	2.5Y 4/2 Dark grey slightly silty sand (fm). One rounded gravel inclusion (12mm). Well sorted. Clear boundary.	1
2.53-2.60	34.90-34.97	2.5Y 4/2 Dark greyish brown sand (m). No visible inclusions. Well sorted.	1
Cutting shoe sample VC5a (i) (nearly 5m)		Same sediment as in 2.53-2.60.	

VC6

Depth below seabed (m)	Depth below OD (m)	Description	Unit
0.00-0.12	30.18-30.30	2.5Y 5/4 Light olive brown gravelly sand (mc). Gravel is subrounded to subangular (<25mm). Frequent shell fragments. Poorly sorted. Abrupt boundary.	4
0.12-0.22	30.30-30.40	2.5Y 5/3 Light olive brown sand (m). Frequent shell fragments. Well sorted. Abrupt boundary.	4
0.22-0.69	30.40-30.87	2.5Y 4/2 Dark greyish brown gravely sand (mc). Gravel is subangular (<55mm). Frequent shell fragments. Poorly sorted. Sharp boundary.	4
0.69-0.86	30.87-31.04	5Y 4/1 Dark grey slightly silty sand (f). No visible inclusions. Very well sorted. Gradual boundary.	2
0.86-0.96	31.04-31.14	5Y 4/2 Olive grey slightly silty sand (fm). Occasional subangular gravel (<15mm). Well sorted. Clear boundary.	2
0.96-1.01	31.14-31.19	2.5Y 4/3 Olive brown sand (c). Occasional subrounded to subangular gravel (<20mm). Sorted. Clear boundary.	2
1.01-1.21	31.19-31.39	5Y 5/2 Olive grey slightly silty sand (f). Occasional subrounded to rounded large gravel (<105mm), well sorted. Gradual boundary.	2
1.21-1.35	31.39-31.53	5Y 5/2 Olive grey slightly silty sand (f). No visible inclusions. Very well sorted. Abrupt boundary.	2
1.35-1.59	31.53-31.77	2.5Y 4/3 Olive brown gravely sand (m). Gravel is large subangular (<100mm). Moderately sorted. Gradual boundary.	2
1.59-2.11	31.77-32.39	2.5Y 3/2 Very dark greyish brown sand (fm). Occasional small subrounded to subangular gravel (<15mm). Diffuse boundary.	2
2.11-2.91	32.29-33.09	5Y 4/1 Dark grey slightly silty sand (fm). Very well sorted. One wooden stick (12mm wide) running vertically from 2.11 to 2.21, one stone (5mm) at 2.16, two black (organic?) inclusions at 2.18 and 2.47. Abrupt boundary.	2
2.91-2.97	33.09-33.45	5Y 4/1 Dark grey slightly silty sand (fm). Laminated with 5-6 arched, irregular, broken clay bands (3mm) and a dark (organic/silty?) band at 2.90. No visible inclusions apart from a tiny black (organic?) spot at 2.91. Very well sorted. Abrupt boundary.	2

Depth below seabed (m)	Depth below OD (m)	Description	Unit
2.97-3.27	33.15-33.45	5Y 4/1 Dark grey slightly silty sand (fm). Very well sorted. One black (organic?) spot at 3.00. Traces of strongly washed out flood couplets(?): slightly darker (more organic?) laminations (5mm, every 5-50mm) in the brighter sandy sediment. Diffuse boundary.	2
3.27-3.60	33.45-33.78	5Y 4/1 Dark grey slightly silty sand (fm), with clearly visible flood couplets (*c.* 5mm wide, every 5-50mm) and two clayey laminations (2-3mm) at 3.56 and 3.58, especially at 3.56 directly overlain by a clearly defined dark (organic?) band. One tiny black (organic?) spot at 3.37. Very well sorted. Gradual boundary.	2
3.60-4.37	33.78-34.55	5Y 5/2 Olive grey slightly silt sand (fm). Very well sorted. Two mudstone inclusions (15mm) at 4.21-4.24, tiny black (organic?) spot at 4.25 and a clay patch (10mm) at 3.73-3.74.	2

VC7

Depth below seabed (m)	Depth below OD (m)	Description	Unit
0.00-0.04	27.27-27.31	No recovery (remains of sandy gravel (<50mm), subangular, poorly sorted).	4
0.04-0.07	27.31-27.34	7.5YR 4/3 Brown (oxidised?) gleyed slightly silty clay. Occasional subangular gravel inclusions (<40mm). Well sorted. Abrupt boundary.	3iii
0.07-0.16	27.34-27.43	10YR 4/2 Dark greyish brown slightly silty clay. Well sorted. Occasional subrounded to subangular gravel inclusions (<12mm) and brownish sand spots. Abrupt boundary.	3iii
0.16-0.38	27.43-27.65	2.5Y 4/1 Dark grey silty clay. Very frequent large shell inclusions (*Ostrea edulis*). Occasional subangular gravel inclusions (<5mm). Poorly sorted. Abrupt boundary.	3ii
0.38-0.46	27.65-27.73	10YR 4/4 Dark yellowish brown silty sand. Frequent shell fragments. Occasional subrounded gravel (<9mm). Sorted. Clear boundary.	2
0.46-0.80	27.73-28.07	2.5Y 3/2 Very dark greyish brown silty gravelly sand (m). Gravel is subrounded (<50mm). Poorly sorted. Gradual boundary.	2
0.80-1.26	28.07-28.53	10 YR 5/6 Yellowish brown gravelly sand (mc). Gravel is subrounded to subangular (<30mm). Occasional shell fragments. Loose. Moderately sorted. Sharp boundary.	2
1.26-1.30	28.53-28.57	2.5Y 5/3 Light olive brown sand (fm) becoming more olive towards the base. No visible inclusions. Well sorted. Sharp boundary.	2
1.30-1.38	28.57-28.65	10YR 4/4 Dark yellowish brown gravelly sand (c). Gravel is subrounded (<14mm). Poorly sorted. Diffuse boundary.	2
1.38-1.68	28.65-28.95	10YR 4/4 Dark yellowish brown gravelly sand (mc). Gravel is subrounded to subangular (<20mm). Moderately sorted. Occasional shell fragments. Diffuse boundary.	2
1.68-1.89	28.95-29.16	2.5Y 6/3 Light yellowish brown sand (mc). Occasional subrounded gravel inclusions (<25mm). Occasional shell fragments. Moderately sorted. Clear boundary.	2
1.89-2.24	29.16-29.51	2.5Y 6/3 Light yellowish brown sand (mc). Frequent subrounded to subangular gravel inclusions (<10mm). Frequent shell fragments. Poorly sorted. Sand band at 2.00-2.01.	2

VC7a - top of OSL-sample

Depth below seabed (m)	Depth below OD (m)	Description	Unit
0.00-0.02	27.35-27.37	10YR 4/6 Dark yellowish brown gravelly sand. Gravel is subangular to subrounded (<12mm). Poorly sorted. Abrupt boundary.	4
0.02-0.13	27.37-27.48	2.5Y 3/2 Very dark greyish brown clay. Organic inclusion at 0.06-0.07. Organic inclusion at 0.08. Well sorted.	3iii

VC7i

Depth below seabed (m)	Depth below OD (m)	Description	Unit
0.00-0.20	27.36-27.56	10 YR 5/4 Yellowish brown sand (c). Occasional subrounded to subangular gravel inclusions (<12mm). Occasional shell fragments. Very loose. Sorted. Gradual boundary.	4
0.20-0.28	27.56-27.64	10YR 5/6 Yellowish brown sand (c). Frequent subrounded to subangular gravel inclusions (<54mm). Occasional shell fragments. Very loose. Poorly sorted. Clear boundary.	4
0.28-0.36	27.64-27.72	10YR 3/6 Dark yellowish brown slightly silty sand (mc). Frequent subrounded to subangular gravel inclusions (<15mm). Poorly sorted. Gradual boundary.	2
0.36-0.47	27.72-27.83	2.5Y 3/2 Very dark greyish brown slightly silty sand (m). Occasional subrounded to subangular gravel inclusions (<40mm). Sorted. Clear boundary.	2
0.47-0.83	27.83-28.19	2.5Y 4/3 Olive brown gravely sand (mc). Gravel is subrounded to subangular (<60mm). Occasional shell fragments. Poorly sorted. Abrupt boundary.	2
0.83-0.86	28.19-28.22	2.5Y 4/3 Olive brown band of subrounded gravel (<10mm). Abrupt boundary.	2
0.86-0.92	28.22-28.28	2.5Y 4/3 Olive brown gravelly sand (m). Gravel is subrounded to subangular (<60mm). Occasional shell fragments. Poorly sorted. Abrupt boundary.	2
0.92-0.99	28.28-28.35	2.5Y 4/3 Olive brown sand (mc). Occasional subrounded to subangular gravel inclusions (<10mm). Sorted. Abrupt boundary.	2
0.99-1.03	28.35-28.39	2.5Y 4/2 Dark greyish brown sand (mc). No visible inclusions. Very well sorted. Abrupt boundary.	2
1.03-1.07	28.39-28.43	2.5Y 4/4 Olive brown sand (mc). No visible inclusions. Very well sorted. Abrupt boundary.	2
1.07-1.13	28.43-28.49	2.5Y 4/4 Olive sand (mc). Frequent subrounded gravel inclusions (<35mm). Occasional shell fragments. Poorly sorted. Abrupt boundary.	2
1.13-1.20	28.49-28.56	10YR 4/6 Dark yellowish brown slightly clayey gravelly sand (mc). Gravel is subrounded to subangular (<13mm). Occasional shell fragments.	2

VC8

Depth below seabed (m)	Depth below OD (m)	Description	Unit
0.00-0.89	29.00-29.89	10YR 4/3 Brown gravelly sand (mc). Gravel is subangular to subrounded (<50mm). Occasional shell fragments. Poorly sorted. Clear boundary.	4
0.89-1.27	29.89-30.27	10YR 5/8 Yellowish brown gravely sand (mc). ?Oxidised. Gravel is subrounded to subangular (<35mm). Poorly sorted. Gradual boundary.	2
1.27-1.56	30.27-30.56	10YR 4/4 Dark yellowish brown gravelly sand (mc). Oxidised. Gravel is subrounded to subangular (<55mm). Poorly sorted. Gradual boundary.	2

Depth below seabed (m)	Depth below OD (m)	Description	Unit
1.56-1.72	30.56-30.72	7.5YR 4/6 Strong brown gravelly sand (mc). Oxidised. Gravel is subrounded to subangular (<50mm) Sorted. Abrupt boundary.	2
1.72-1.87	30.72-30.87	10YR 4/6 Dark yellowish brown sand (fm). Oxidised. Occasional large subrounded gravel inclusions (<100mm). Well sorted. Sharp boundary.	2
1.87-2.39	30.87-31.39	10YR 5/8 Yellowish brown gravelly sand (mc). Gravel is subrounded to subangular (<80mm). Poorly sorted. Gradual boundary.	2
2.39-2.51	31.39-31.51	10YR 5/8 Yellowish brown sand (mc). Oxidised. Well sorted. Gradual boundary.	2
2.51-2.67	31.51-31.67	10YR 5/8 Yellowish brown gravelly sand (mc). Oxidised. Gravel is subangular to subrounded (<40mm). Sorted. Gradual boundary.	2
2.67-2.88	31.67-31.88	10YR 5/6 Yellowish brown gravely sand (mc). Oxidised. Gravel is subrounded to subangular (<40mm). Poorly sorted. Clear boundary.	2
2.88-2.92	31.88-31.92	10YR 5/8 Yellowish brown gravelly sand (c). Oxidised. Gravel is small and subrounded (<10mm). Sorted. Abrupt boundary.	2
2.92-3.67	31.92-32.67	2.5Y 4/4 Olive brown gravelly sand (mc). Oxidised. Gravel is subangular (<60mm). Frequent shell fragments. Poorly sorted. Clear boundary.	1
3.67-3.78	32.67-32.78	10YR 5/8 Yellowish brown very gravelly sand (mc). Oxidised. Gravel is subrounded to subangular (<20mm). Frequent shell fragments. Poorly sorted.	1
Cutting shoe sample		Same as above, but with two large subangular flints (<70-80mm).	1

VC9

Depth below seabed (m)	Depth below OD (m)	Description	Unit
0.00-0.05	28.09-28.14	2.5Y 3/2 Very dark greyish brown gravelly sand (fmc). One large rounded flint at top (50mm). Occasional broken shell. Soft/Loose. ?FeO staining. Abrupt boundary.	3ii
0.05-0.35	28.14-28.44	2.5Y 3/2 Very dark grey greyish brown clayey silty sand (fmc). Loose-firm. Very frequent *Ostrea edulis* whole/broken. Grey silty clayey bands ?FeO staining. Abrupt boundary.	3ii
0.35-0.55	28.44-28.64	2.5Y 4/1 Dark grey silty clay/2.5Y 3/3 Dark olive brown silty sand (fm). Firm. Occasional broken *Ostrea edulis*. Occasional small (<15mm) subangular flint becoming more frequent (gravelly sand) 0.50-0.55. Clear boundary.	3ii
0.55-2.50	28.64-30.59	2.5Y 6/4 Light yellowish brown gravelly sand (mc). Frequent flint subangular to rounded (<30mm) poorly sorted. Moderate broken bivalve shell (larger fragments from 1.10 onwards). 0.55-1.00 slightly darker/siltier, less shell. Fining upwards. Diffuse boundary.	2
2.50-3.97	30.59-32.06	2.5Y 6/2 Light brownish grey gravelly sand (mc). Frequent flint (200mm) rounded-angular. Moderate broken shell. 2.70-4.00 increasing fine sand. 2.80-3.97 less gravel (<15mm) predominantly 5mm. Fairly compact.	2

APPENDIX II: POLLEN ANALYSIS

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I.) Introduction

This sediment sequence lies off-shore from Great Yarmouth and was thought to be part of the palaeo-Yare river system. Initially, samples from two core profiles were examined (Scaife 2006). Vibrocore **VC1** proved to be a more complete sequence containing fine grained, humic silts and clays which are occasionally laminated. The palynological data demonstrate a sequence of vegetational changes comprising successional colonisation of the region by various woodland types following the close of a cold stage.

II.) Pollen Method

Pollen sub-samples of 1-2ml volume taken from the core (**VC1**) were processed using standard techniques for the extraction of the sub-fossil pollen and spores (Moore and Webb 1978; Moore *et al.* 1992). Micromesh sieving (10u) was also used to aid with removal of the clay fraction present in these sediments. Absolute pollen frequencies were calculated using added exotics to known volumes of sample (Stockmarr 1971). The concentrated sub-fossil pollen and spores were identified and counted using an Olympus biological research microscope fitted with Leitz optics at x400 and x1000. A pollen (assessment) sum of 400 or more grains of dry land taxa per level was counted where preservation was more satisfactory. Marsh taxa and aquatic taxa, spores of ferns and derived geological microfossils were also counted outside of the standard pollen sum. A pollen diagram (figures 1a and 1b) has been plotted using Tilia and Tilia Graph in which percentages have been calculated as follows.

Sum =	% total dry land pollen (tdlp).
Marsh/aquatic =	% tdlp+sum of marsh/aquatics.
Spores =	% tdlp+sum of spores.
Misc. =	% tdlp+sum of misc. taxa.

Taxonomy, in general, follows that of Moore and Webb (1978) modified according to Bennett *et al.* (1994) for pollen types and Stace (1992) for plant descriptions. These procedures were carried out in the Palaeoecology Laboratory of the School of Geography, University of Southampton.

III.) The Pollen Data

Absolute pollen frequencies and preservation were substantially better in the principal sequence (**VC1**) which was thus chosen for more detailed analysis. Five local pollen assemblage zones have been recognised and are described as follows from the base of the profile upwards.

Zone 1: 354cm to 324cm: Betula-Juniperus-Artemisia-Poaceae.
Herbs are dominant with higher values than in any subsequent zone. Poaceae are dominant (to 49%) with important numbers of *Artemisia* (to 8%) and Cyperaceae (peak to 19% sum + marsh). There is a moderately diverse range of other herbs which occur sporadically. Trees and shrubs are dominated by *Betula* (30%) with *Juniperus communis* (5%) and small numbers of 'small' *Betula* (possibly *Betula nana*). Algal *Pediastrum* is important in this basal zone with some derived pre-Quaternary palynomorphs.

Zone 2: 324cm to 308cm. Betula.
Herb values decline sharply in response to rapidly expanding *Betula* (peak to 68%) also with some increase of *Pinus* (15%). *Juniperus, Artemisia* and *Pediastrum* of the preceding zone die out. Herbs remain dominated by Poaceae but with reducing values (to *ca.* 20%). Chenopodiaceae is incoming in small numbers. Aquatic plants become more important with *Myriophyllum verticillatum* and occasional *Nuphar.* Monolete spores of *Dryopteris* type (37%) and *Thelypteris palustris* (<5%) become significant.

Zone 3: 308cm to 244cm. Betula-Pinus-Ulmus.
This zone is characterised by rapidly expanding Pinus (70%). Betula remains important throughout but with progressively declining percentages (to ca. 20%). Ulmus is incoming (to 7%) along with sporadic occurrences of Quercus, Populus and Salix. Corylus avellana type is incoming but with only occasional/sporadic occurrences. Herbs remain dominated by Poaceae (but with smaller values) with a range of other herbs which occur infrequently. These also include occasional Plantaginaceae. Chenopodiaceae are consistent, increasing slightly after their arrival in the preceding pollen zone (2-3%). Marsh and aquatic taxa are present throughout with Cyperaceae, Myriophyllum spp., Typha latifolia, Typha angustifolia type and occasional Nuphar. Spores (monolete Dryopteris type including Thelypteris palustris) remain important from Zone 2.

Zone 4: 244cm to 196cm: Pinus-Dryopteris type.
Betula declines progressively as *Pinus* (to 85%) become dominant. There are smaller numbers of *Ulmus* which remain while the incoming *Quercus* continues to expand (<1%). There are small numbers of shrubs (*Corylus avellana* type, *Rhamnus cathartica, Salix)*. There are fewer herbs with Poaceae continuos at low levels (<10%) and sporadic occurrences of other taxa including *Filipendula ulmaria* (meadow sweet) and Fabaceae (medicks and clover). Of note is the increasing numbers of freshwater aquatic and fen taxa in this zone. These include *Nuphar luteum* (yellow water lily), *Myriophyllum spicatum* (water millfoil), *Typha* (reed mace) and/or *Sparganium* (bur-reed) and Cyperaceae (sedges). Spores become markedly important and attain their highest values at 240cm (80% sum+spores) with *Dryopteris* type (typical ferns) and specifically *Thelypteris palustris* (marsh fern).

Zone 5: 196cm to 112cm: Pinus-Quercus-Ulmus.
This upper zone is delimited by the sharp increase in *Quercus* (oak; to 49%) from previous, sporadic occurrences. *Pinus* remains important with some decline in response to the expanding *Quercus* (to 20% at the top of the profile. There are also sporadic and incoming

occurrences of *Alnus* and *Ligustrum vulgare* and Ericales (*Erica, Calluna* and *Empetrum*). Herbs remain largely in preceding zone 4 with the exception of Chenopodiaceae which become more important. Spores have diminished numbers with a sharp reduction in monolete forms (to <5%). There is, however, a peak of *Pteridium aquilinum*. There are also few of the aquatic and fen taxa seen in zone 2 although freshwater algal *Pediastrum* returns in small numbers along with geological palynomorphs and dinoflagellates the latter which may be Quaternary or pre-Quaternary.

IV.) The Vegetational History

The basal pollen zone 1 contains substantially more herbs than subsequent zones. These are dominated by Poaceae (grasses) and with *Artemisia* (mugwort) and a range of other herbs. These suggest a more open landscape with the latter taxon being indicative of the disturbed habitat of permafrost/soliflucted soils. Areas of marsh and freshwater on the site are demonstrated by sedges and cysts of freshwater, algal, *Pediastrum*. Although the basal zone 1 shows elements of an open herbaceous landscape, there is also clear evidence that this habitat was changing in response to temperature amelioration which prompted migration and expansion initially of pioneer tree and shrub elements. These comprised essentially birch but with some juniper.

Subsequently, pollen Zone 2 shows the colonisation of pioneer (birch) woodland. Pine pollen is, evident in relatively small numbers and, given its anemophily and high pollen productivity, it seems likely that this elements is extra-local from long distance transport. This situation, however, rapidly changed as pine migrated into the region and became dominant in zone 3, progressively ousting the earlier colonising and dominant birch evidenced in zone 2. Birch however, remained important throughout but decline consistently over a long period. While pine was dominant (zone 3), the slower migrating, but more competitive trees were also making ingress into the environment.

Ulmus (elm) shows an early importance at this site becoming an important local woodland constituent at a time when pine was dominant (in zone 3). At this time *Quercus* (oak) is only represented by occasional grains of long distance/extra-local transported pollen. Because of its competitive ability, in spite of its slow migration rate oak, however, becomes dominant on site after its arrival (in pollen zone 5). This marked the establishment of oak and elm woodland with remaining pine although the latter continued to be suppressed.
In summary, this expansion of woodland types is a classic seral succession of migration from refugia, establishment, dominance and subsequently, ousting by competition from more competitive forms. Thus, the juniper and birch of zones 1 and 2 superseded by colonisation by pine woodland which became dominant in zones 3 and 4. This succession of woodland types was responsible for the demise of the heliophilous herb taxa which represent vestiges of open permafrost/tundra habitats. Subsequently the more competitive deciduous elements of oak and elm (zones 3 onwards for elm and zone 5 for oak) became established.

V.) The Archaeological Significance

It is only in the upland, ecotonal zones (at the tree line) that the effects of Human communities on the habitat are seen in the ‘fragile’ ecosystems described by Simmons on for example, Dartmoor (e.g. Simmons 1975a, 1975b) where soil/sediment inwash to small basins has been observed. Microscopic charcoal may, however, reflect use of fires and examination for this is often carried out. Here, subjective estimations have been made for each of the levels. This has, however, proved problematic in that the small black isotropic particles appear similar (identical?) to Iron Sulphide (pyritise) which may form in anaerobic conditions. Thus, at present this use of 'black microscopic particles' at this site is not conclusive.

VI.) Eustatic Change

The autochthonous pollen reflects the changing depositional habitat of the site both in its sedimentological characteristic and the pollen record. Zone 1 has *Pediastrum* indicating an initial freshwater habitat. Subsequently, throughout pollen zones 1 to 4 there are predominantly freshwater and marsh elements with sedges, bur reed and/or reed mace and marsh fern. Chenopodiaceae (goosefoots, oraches and glassworts) are incoming in pollen zone 2 and is most probably an indication of either occasional saline ingress (tidal movement up the channel) or the presence of salt marsh in the local region. By zone 5, Chenopodiaceae become more important and along with sedimentological changes which also saw the input of reworked geological palynomorphs and hystrichospheres reflecting changes in sediment input, indicate strongly saline/brackish conditions. The data obtained is further enhanced by the fact that this site lies in deep off-shore waters and has obviously been subject to Flandrian marine transgression. It is possible that ponding back of the freshwater system or deposition of sediments behind a barrier bar prior to total submergence was caused by increasing relative sea level. *Ruppia* (? *maritima;* beaked tasselweed) is noted at the base of zone 5 (albeit a single occurrence) which indicates brackish water conditions and *Armeria* (thrift or sea lavender) is also present at the top of the profile adding evidence to expansion of saline habitats.

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Pollen diagram Figure 1(a+b)

APPENDIX III: DIATOM ANALYSIS

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Background

A sequence of eight samples from vibrocore **VC1** has been chosen for diatom analysis. These samples have been selected to examine the transition from freshwater (1.95-3.38 m), a possible storm/inwash event (1.83-1.95 m no sample), estuarine (1.21-1.83 m) and gleyed, possibly estuarine material towards the surface (1.06-1.21 m). It is hypothesised that the sequence contains freshwater deposits overlain by a layer of marine deposits that are likely to be the result of the breach of an offshore bar, a storm event or rapidly rising sea-level. Following the marine phase, clay deposits seem to represent an estuarine environment. One aim of employing diatom analysis here is to investigate whether salinity increases gradually toward the top of the freshwater phase or if there is a complete and immediate change.

Methods

Diatom preparation followed standard techniques: the oxidation of organic sediment, removal of carbonate and clay, concentration of diatom valves and washing with distilled water. Two coverslips, each of a different concentration of the cleaned solution, were prepared from each sample and fixed in Naphrax, a mounting medium of a suitable refractive index for diatom microscopy. Slides were scanned at magnifications of x400 and x1000 under phase contrast illumination and diatom counting was carried out at a magnification of x1000. Where possible a total of approximately 300 diatom valves was counted per slide.

Diatom floras and taxonomic publications were consulted to assist with diatom identification, including Hendey (1964), Hartley *et al.* (1996) and Krammer & Lange-Bertalot (1986-1991). Diatom species' salinity preferences are discussed using the classification data in Denys (1992) and the halobian groups of Hustedt (1953, 1957: 199), these salinity groups are summarised as follows:

1. Polyhalobian: >30 g l^{-1}

2. Mesohalobian: 0.2-30 g l^{-1}

3. Oligohalobian - Halophilous: optimum in slightly brackish water

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

5. Halophobous: exclusively freshwater

6. Unknown: taxa of unknown salinity preference.

Results
The results of diatom analysis for each sample in the sequence from **VC1** are as follows. The sample depths are in metres below the sea bed.

2.70 m
Diatoms are completely absent from the slide prepared from 2.70 m depth. This may reflect unfavourable conditions for diatom silica preservation (Flower 1993, Ryves *et al.* 2001). It is not therefore possible to comment on the salinity or other aspects of the aquatic environment.

2.52 m
An extremely low concentration of diatoms is present in the sample from 2.52 m depth. As a result of the very low number of diatoms it is not possible to make a percentage diatom count for the sample. However, the three diatoms identified are all marine, marine-brackish or brackish water species (Table 1). The marine-brackish and marine diatoms present are: a fragment of *Actinoptychus undulate* and a whole valve of *Paralia sulcata*. These species represent marine-brackish and coastal marine plankton respectively. In addition a single cyst resembling the cyst of the brackish or marine diatom genus *Chaetoceros* was identified. On the basis of other evidence the banded clay/sand sediments from which this sample was taken have been interpreted as freshwater (M.J. Allen pers. comm.). Given the extremely low concentration of diatoms here and the robust nature of the types present it is possible that these diatoms have been differentially preserved and a local non-planktonic flora has been lost as a result of taphonomic processes. In addition because of the small number of diatoms involved an interpretation based on the diatom flora alone unreliable. Nevertheless at this (early) stage of a post-glacial period it is significant that marine diatoms are present at the site, albeit in very low numbers.

2.04 m
At 2.04 m depth diatoms are present, however the diatom assemblage is at a very low concentration and all the valves are much dissolved. It has not therefore been possible to carry out percentage counting on the degraded assemblage. The taxa that it was possible to record are listed in Table 1. Here the diatom assemblage is consistent with the lithological interpretation from the black clay, organic silt with shell remains. The diatoms identifiable to species level are all from freshwater habitats. Further the species are non-planktonic, shallow water taxa some of which are epiphytes (*Cocconeis placentula, Epithemia adnata*). Others such as *Ellerbeckia arenaria* are found on sandy sediments. *Melosira varians* is a halophilous species that it is not usually found in full estuarine or marine conditions but inhabits freshwater with moderately high concentrations of dissolved salts.

Table 1. **VC1** Diatom species in samples from 2.52 m, 2.04 m and 1.98 m Great Yarmouth Offshore Seabed in Prehistory (57422).

+ indicates species is present; ++ indicates that several valves or fragments were seen on the slide.

Species and halobian group	2.52 m	2.04 m	1.98 m
Polyhalobous			
Paralia sulcata	+		
Polyhalobous to Mesohalobous			
Actinoptychus undulatus	+		
Polyhalobous to Halophilous			
Chaetoceros cyst	+		
Halophilous			
Melosira varians		+	
Oligohalobous Indifferent			
Amphora libyca			+
Aulacoseira sp.		+	
Cocconeis placentula & var *.euglypta*		+	
Cymbella cf. *affinis*			+
Ellerbeckia arenaria		+	
Epithemia adnata		++	++
Epithemia sp.		+	+
Indeterminate centric sp.		+	
Pinnularia cf. *major*		+	
Rhopalodia gibba		+	
Synedra ulna			+
Unknown Salinity Group			
Cocconeis sp.		+	
Indet. pennate diatom spp.		++	
Indeterminate diatom sp.			+
Navicula sp.		+	
Navicula sp.		+	
Nitzschia sp.		++	
Unknown naviculaceae		+	

1.98 m

Diatoms are present at only very low concentrations at 1.98 m depth. It is not therefore possible to make a percentage diatom count for this sample. However, as at 2.04 m depth, those species present are consistently from freshwater and are associated with shallow water depths(Table 1). These species include *Amphora libyca, Cymbella* cf. *affinis, Epithemia adnata* and *Synedra ulna*. The idea that the habitat is one of freshwater is consistent with the lithostratigraphic interpretation. Again the diatoms here are non-planktonic types that grow in shallow water both attached to submerged surfaces (e.g. epiphytes) and on the surface of mud (benthic).

1.86 m, 1.80 m, 1.50 m

The diatom assemblages of the three samples from 1.86, 1.80 and 1.50 m are of good quality and diatom percentage counts have been made for these levels in the sequence. The results of species counts are presented in Figure 1 and the halobian groups are summarised in Figure 2. The results for these three samples are discussed together here.

The proportion of polyhalobous (marine) diatoms is high in all three samples and is consistently between 70-80% of the total diatom sum. The most common polyhalobous diatoms are the planktonic species *Paralia sulcata* and *Podosira stelligera* along with the littoral species *Dimeregramma minor* and *Dimeregramma minor* var. *nanum*. The latter species are epipsammic (growing on sand grains) and are also epiphytic on seaweed. *Dimeregramma minor* (and var.*nanum*) is most common at 1.80 m depth where the species reaches over 30% of the total. Although the total proportions of marine, marine-brackish, brackish and freshwater diatoms is fairly consistent it can be seen in the plot of species percentages (Figure 1) that at 1.86 m and to a lesser degree at 1.80 m depth there are more occurrences of oligohalobous indifferent (freshwater) diatoms (rare species indicated by the cross symbol). The idea that salinity was lower (and in transition from a freshwater phase) is also supported by the maximum of mesohalobous diatoms at 1.86 m depth. These brackish water diatoms include *Rhopalodia musculus* and *Diploneis didyma*, both littoral diatoms that are sometimes associated with sandy shores. The benthic brackish water species *Nitzschia compressa* is common at 1.50 m depth and a marine-brackish littoral (e.g. epipsammic and epiphytic on large seaweeds) diatom *Cocconeis scutellum* is present at between about 2-4% in all three samples.

1.14 m

Diatoms are completely absent from the slide prepared from 1.14 m depth (see comments on the basal sample at 2.70 m).

Discussion

Diatoms are absent from the basal and uppermost samples of the sequence at 2.70 m and 1.50 m depth. The poorly preserved diatoms at 2.52 m depth are marine or brackish taxa and appear inconsistent with the lithostratigraphic interpretation of freshwater sediments. Given the very small number of diatoms present in the sample from 2.52 m depth and the predicted early age of these sediments an interpretation of a marine transgressive phase based on diatom evidence alone must be viewed cautiously. It would be valuable here to have supporting evidence from other aquatic fossil groups and confirmation of the sediment age from radiocarbon dating. The overlying samples from 2.04 m and 1.98 m depth have low diatom numbers, however, the diatom assemblages from both are consistent with the interpretation of freshwater sediments. The freshwater diatoms at 2.04 m and 1.98 m depth are non-planktonic, shallow water species that live either attached to underwater surfaces or are motile within surface mud.

The results of diatom analysis from samples at 1.86 m, 1.80 m and 1.50 m depth are plotted in Figure 1 and Figure 2. The interpretation of estuarine alluvium (Mike Allen pers. comm.) is supported by high numbers of marine planktonic diatoms, along with significant numbers of marine-brackish benthic and planktonic species, and brackish water diatoms.

Allochthonous, marine plankton tends to be over-represented in estuarine conditions, but does reflect the full tidal nature of the environment. A question that was to be addressed by the diatoms concerns the rate at which the salinity changed towards the top of the freshwater phase (2.04 m and 1.98 m). Although the diatoms are poorly preserved here they show a consistent picture of shallow, freshwater conditions with no appearance of mesohalobous diatom species for example. Neither are halophilous diatoms evident in any numbers at this stage. Moving to the sediments immediately overlying these at 1.86 m depth there has been a clear shift to a marine and brackish water diatom flora. The only evidence here for gradual change is that freshwater (oligohalobous indifferent) diatoms persist in the lower two samples (1.86 m and 1.80 m), particularly in the basal sample (1.86 m depth) shown on Figure 1 and Figure 2. Mesohalobous diatoms are also at their maximum at the base of the diatom diagram. However, in terms of rate of change this may be deceiving. Although remnants of the freshwater flora remain, their ecology is inconsistent with growth in estuarine or marine conditions. The mixed diatom assemblage is more likely the result of time-averaging processes. Conversely the environmental conditions that might have caused the mixing of freshwater and brackish-marine sediments may also have resulted in the erosion and loss of any intermediate phase sediments (halophilous and brackish water dominated). As discussed there is some evidence of higher numbers of mesohalobous species at 1.86 m depth. In conclusion it appears from diatom analysis that the marine transgression was a rapid event but again dating (or pollen analysis) across the contact with the freshwater sediments may reveal that has been distorted by erosion of sediments at the contact.

Conclusions

Diatoms are present in six of the eight samples prepared from the **VC1** sequence. Diatoms are absent from the bottom sample at 2.70 m depth and from the top sample at 1.14 m depth. The basal diatomaceous sample from 2.52 m depth has evidence for tidal water but diatom numbers are very low. Sediments from 2.04 m and 1.98 m depth have low numbers of shallow, freshwater diatoms. Marine and brackish water diatoms are absent from these samples. Three samples analysed from 1.86 m , 1.80 m and 1.50 m depth are dominated by marine and brackish water diatoms. This is consistent with the lithological interpretation of estuarine alluvium. The samples from 1.86 m and 1.80 m depth have moderately high numbers of brackish water diatoms and only low numbers of freshwater diatoms. The diatom assemblages therefore appear to show a rapid transition from freshwater to marine conditions, but there is a likelihood of sediment erosion causing the loss of sediments containing intermediate brackish water diatom assemblages.

Acknowledgements

Thanks to Mike Allen of Wessex Archaeology for the samples for diatom analysis, details of the sequence and the site.

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Diatoms Figure 1+2

APPENDIX IV: FORAMINIFERA ANALYSIS

Jack Russell
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Introduction
28 sub-samples taken from vibrocore **VC1** and four from vibrocore **VC3** have been assessed and analysed for the presence, preservation and environmental significance of their foraminiferal content. The samples were chosen on the basis of the ostracod (Russell 2006a) and foraminiferal assessment (Russell 2006b). The sediments are thought to comprise infill sediments of the palaeo-Yare river. Dr John Whittaker aided with the identification of this material.

Method
Sediment was wet sieved through a 63µm sieve to remove the silt fraction. The residue was dried and sieved through 500µm, 250µm, 125µm sieves. Foraminifera were picked out under 10-60x magnification under transmitted and incident light using a Meiji EMT microscope. Where possible 50 specimens per sample were picked out and kept in card slides. Identification follows Murray (1973) and interpretation of their ecology follows Murray (1991) and Haslett *et al.* (1997).

Results
VC1
3.72 to 1.98m
Very few foraminifera were recovered from these samples. The only samples to produce foraminifera were at 3.12, 2.94, 2.88 and 2.76m. These were all of the genus *Elphidium* and were taphonomically distinct from the taxa recovered from the upper part of the sequence. Fossilisation, abrasion and very low abundances of these taxa was noted. It is highly likely that these taxa are reworked from Neogene deposits.

1.92 and 1.86m
These samples were foraminiferally abundant and dominated by variants of the taxon *Ammonia becarrii*. One species of *Ammonia (Ammonia* sp. A), showing some similarities to the species *Haynesina germanica* although trochospirally coiled, was present from this part of the sequence onwards. *Haynesina germanica* and *Elphidium oceanis* were also present in significant numbers. *Elphidium williamsoni* was present in the sample at 1.86m. These taxa are all commonly found in brackish environments and together indicate estuarine conditions (Murray 1979). Occasional marine taxa (totalling 4-5% of relative abundance) including Miliolids and *Elphidium excavatum* indicate a marine contact.

1.80, 1.74, 1.62, 1.50, 1.38, 1.26 and 1.20m
These samples were foraminiferally abundant. They are dominated by *Haynesina germanica*. *Ammonia beccarii*. *Trochammina inflata* and *Ammonia* sp. A were also present in significant numbers. These brackish water taxa total 65-81% of the samples assemblage. Significant

numbers of marine taxa including Miliolids and species of the genus *Elphidium* were encountered indicating an increased marine influence further up the profile.

1.14m
No foraminifera were recovered in this sample which may be due to poor preservation potential within this oxidised sediment.

Small amounts of charcoal were recovered from the samples at 2.16, 3.12 and 3.72m.

VC3
0.98, 2.04 and 3.12m
No foraminifera were recovered from the samples in this core.

Discussion
The foraminifera recovered from vibrocore **VC1** indicate a slight relative sea level rise broadly defined by two foraminiferal zones:

Zone 1: 1.92 and 1.86m *Ammonia beccarii* zone
Ammonia aberdoveyensis, Ammonia beccari var *limnites* and *Ammonia beccarii* var *tepida* are the three variants of this species dominating the samples in this zone. These are known to prefer brackish conditions (Murray 1979). Haslett *et al.* (1997) report *Ammonia beccarii* dominating assemblages between MHWNT (Mean High Water Neap Tides) and MHWST (Mean High Water Spring Tides) from modern assemblages in the Severn Estuary.

Zone 2: 1.80, 1.74, 1.62, 1.50, 1.38, 1.26 and 1.20m *Haynesina germinica* zone
Haynesina germanica dominates these samples with significant numbers of *Ammonia beccarii* and *Trochammina inflata.* This zone is indicative of brackish conditions (Murray 1979). Increasing numbers of Miliolids indicate an increasing marine contact. Haslett *et al.* (1997) report *Haynesina germanica* dominating assemblages underneath the MHWNT (Mean High Water Neap Tide) area in the Severn Estuary.

This zonation indicates that inception of brackish environments suitable for deposition and preservation of foraminifera occurs in Zone 1, typically dominated by *Ammonia beccarii* around 1.92m which is indicative of marine influence and transgression. This sample also contained large numbers of molluscs including Hydrobiids. The environment indicated by the foraminifera at this level is estuarine mudflats. The occurrence of *Elphidium williamsoni* above this level at 1.86m indicates proximity to saltmarsh environments (Haslett *et al.* 1997).

Zone 2 the *Haynesina germanica* zone shows an increase in marine influence and brackish estuarine mudflat conditions which are elevated slightly lower in the tidal frame than Zone 1 concurrent with a relative rise in sea level up the profile from Zone 1 to Zone 2. The marine species including Miliolids (species of the genera *Quinqueloculina* and *Miliolinella*) and species of the genus *Elphidium* are relatively more abundant in Zone 2 confirming the increasing marine influence up the profile. This interpretation is confirmed by the fact that the sediment is oxidised and few marine foraminifera were recovered at this point.

No *in situ* foraminifera of biostratigraphic importance (i.e. that are restricted to certain periods within the Pleistocene) were recovered. Dating of these sediments would indicate the significance of this sequence of sea level rise in these samples. Comparison of this foraminiferal assemblage (at a known date) to known tidal ranges of extant forms (Haslett *et al.* 1997; Horton and Edwards 2006) could provide potential sea level index points (SLIPs) for the area. Charcoal recovered from samples at 2.16, 3.12 and 3.72m is a possible indication of occupation of the area.

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Table 1: Foraminifera presence/absence in vibrocore VC1

Sample (m)	1.20	1.26	1.38	1.50	1.62	1.74	1.80	1.86	1.92	2.76	2.88	2.94	3.12
Elphidium williamsoni		x			x		x	xx	xx				
Haynesina germanica	xx	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xx				
Milammina fusca		x		x									
Trochammina inflata	xx	x	xx	xx	x	x	x						
Ammonia beccarii sp. A	x	x	x	x	x	x	x	x	x				
Ammonia aberdoveyensis	x	x	x	x	x	x	x	xx	xx				
Ammonia batavus		x	x										
Ammonia limnites	x	x	x	x	xx	xx	x	x	xx				
Ammonia tepida	x			x	xx	xx	x	x	xxx				
Astergerinata mamilla		x											
Elphidium oceanis					x			x					
Elphidium sp.	xx		x	x		x		x					
Elphidium sp. fossil										x	x	x	x
Elphidium wadensia									x				
Brizalina pseudopunctata			x										
Cornuspira involvens			x										
Elphidium crispum		x		x	xx	x							
Elphidium cuvillieri					x	x							
Elphidium earlandi			x										
Elphidium excavatum		x		xx	x		x						
Elphidium gerthi	x			x	xx								
Elphidium incertum			x	x			x						
Elphidium macellum		x											
Elphidium magaritericum		x	x										
Massilina secans		x	x										
Miliolinella subrotundata			xx	x	x								
Nonion depressulus	X	x	x		xx	x	x						
Quinqueloculina bicornis		x		xx	xx	x	xx	x					
Quinqueloculina bicornis var. *angulata*		x		x				x					

Sample (m)	1.20	1.26	1.38	1.50	1.62	1.74	1.80	1.86	1.92	2.76	2.88	2.94	3.12
Quinqueloculina cliarensis			x				x						
Quinqueloculina dimidiata		x				x	x	x					
Quinqueloculina lata				xx	x	x							
Quinqueloculina oblonga				x									
Quinqueloculina seminulum			x										
Quinqueloculina sp.			xx	x	x	x							
Quinqueloculina subrotundata		x											

Key:

Abundance:
x – 1-9 specimens
xx – 9-50 specimens
xxx – greater than 50 specimens

Ecological preferences:
Brackish and marsh taxa
Brackish – marine taxa
Estuary mouth and nearshore areas of near to normal salinities taxa

APPENDIX V: OSTRACOD ANALYSIS

Jack Russell
Wessex Archaeology

Introduction
28 sub-samples taken from vibrocore **VC1** and four from vibrocore **VC3** have been assessed and analysed for the presence, preservation and environmental significance of their ostracod content. The samples were chosen on the basis of the ostracod (Russell 2006a) and foraminiferal assessment (Russell 2006b). The sediments are thought to comprise infill sediments of the palaeo-Yare river.

Method
Sediment was wet sieved through a 63µm sieve to remove the silt and clay fractions. The residue was then dried and sieved through 500µm, 250µm, 125µm sieves. Foraminifera were picked out under 10-60x magnification under transmitted and incident light using a Meiji EMT microscope. Where possible 50 specimens per sample were picked out and kept in card slides. Identification and interpretation of ecology of marine and brackish water taxa follows Athersuch *et al.* (1987). Identification and interpretation of ecology of freshwater taxa follows Meisch (2000).

Results
Abundance and species of ostracod recovered per sample is shown in **Figure 1**.

VC1
3.72, 3.30, 3.18 and 3.06m
These samples contained no ostracods. This correlates with the geotechnical descriptions of sands and increasing grain size down the profile as the potential preservation of (in particular non-marine) ostracod carapaces in my experience is often inversely proportional to grain size.

3.15 and 3.12cm - Zone 1a
One *Cypria exsculpta*, a freshwater form, was recovered from sample 3.15m. The sample at 3.12m contained a low abundance of ostracods dominated by *Candona candida*. Other taxa present included *Cyclocypris laevis*, *Darwinula stevensoni* and *Pseudocandona sarsi*. In both samples the assemblages were represented by adult forms, many of which were broken. Although indicative of freshwater environments the taphonomy, low abundance and dominance of adult forms point towards some reworking of these taxa.

2.94, 2.88, 2.82, 2.76, 2.70 and 2.64m - Zone 1b *Darwinula stevensoni*
These samples showed generally high abundances of ostracods except for sample 2.88m. The samples are dominated by *Darwinula stevensoni* a taxa known to prefer freshwater environments, particularly ponds, lakes and slow streams. It occurs at water depths between 0 and 12 metres although is often at greatest abundance around 6m water depth. The species can tolerate low to medium salinities (up to 15‰) and prefers a mud or sand substrate

(Meisch 2000). *Metacypris cordata,* a freshwater taxa, lives mainly in standing and slow moving waterbodies up to depths of 10m (Meisch 2000). *Cyclocypris ovum* was also present in these samples and prefers littoral zone of lakes, springs and occasionally slightly salty and swampy environments (Meisch 2000). *Candona candida* and *Pseudocandona sarsi* were also present.

2.52, 2.40, 2.28, 2.16 and 2.04m - Zone 1c *Pseudocandona sarsi/Candona candida*
These samples produced the greatest abundances of ostracods and are dominated by *Candona candida* and *Pseudocandona sarsi*. *Candona candida* is known to inhabit the littoral zone of lakes, ponds, ditches, swamps, acidic/peaty waters (pH<5), brooks, rivers, springs, wells and subterranean interstitial ground waters although prefers permanent waters. This taxa can tolerate low salinities (up to 5‰) (Meisch 2000). *Pseudocandona sarsi* prefers small water bodies including those that dry in the summer and is also known from the interstitial groundwater of streams (Meisch 2000). These ostracods would indicate a slow moving or still freshwater environment. At 2.04m a few adult *Cyprideis torosa* are noted (with singular occurrences at 2.16, 2.28 and 2.40m). These taxa are a brackish water indicator and adult forms would indicate reworking of these taxa from a nearby estuarine environment.

1.98, 1.92, 1.80 and 1.74m - Zone 2a *Cyprideis torosa*
These samples are dominated by the brackish water indicator *Cyprideis torosa*. At 1.98 and 1.74m the taxa comprises near 100% relative abundance. These taxa are tolerant of fluctuating salinities but usually most abundant between 2-15‰. It prefers a mud or sand substrate and is also found on algae (Athersuch *et al.* 1989). Only the unnoded form is recorded. The first occurrence of marine taxa is *Palmoconcha laevata* in sample 1.98m with numbers increasing up the profile. This taxon is common in marine waters at 10-90m depth in the sublittoral zone occasionally on littoral algae in rock pools (Athersuch *et al*. 1989). The relative abundance of this taxon is low in the samples and is indicative of marine input – probably tidal or storm surges redepositing small numbers of this taxon within a brackish creek/mudflat.

1.62, 1.50 and 1.38m - Zone 2b *Leptocythere lacertosa*
These samples contained lower abundances of ostracods dominated by *Leptocythere lacertosa.* This species is a common extant form found within estuarine environments in north-west Europe and prefers a mud/sand substrate (Athersuch *et al.* 1989). Greater numbers of marine taxa are noted up the profile with *Aurila woutersi* and *Palmoconcha guttata* becoming more prominent in samples at 1.50 and 1.38m.

1.26m - Zone 2c *Aurila woutersi* and *Palmoconcha guttata*
This sample contains *Aurila woutersi*. and *Palmoconcha guttata,* both phytal, sublittoral/shallow sublittoral marine taxa (Athersuch *et al*. 1989). This shows an increasingly marine environment up the profile. *Cyprideis torosa* and *Leptocythere lacertosa* are still present probably indicating estuary mouth type salinities at this sample.

1.26 and 1.14m
One *Cyprideis torosa* was recovered from the sample at 1.26m and none from the sample at 1.14m. It is possible that the oxidised nature of this sediment has caused differential preservation at these levels.

VC3
0.98, 2.04 and 3.12 and 4.08m
No ostracods were present in these samples.

Discussion
The ostracod assemblages can be divided into two clear environmental zones. Zone 1 contains a predominantly freshwater/non-marine fauna and Zone 2 a brackish to marine fauna. These zones have been further subdivided.

Zone 1a (3.15, 3.12m) is a freshwater deposit, however, the assemblages are too small to draw meaningful environmental conclusions from these samples. The first environmentally significant assemblages occur in Zone 1b 2.94-2.64m dominated by *Darwinula stevensoni* and indicate a shallow, slow moving or still freshwater body. This is superseded by Zone 1c dominated by *Pseudocandona sarsi* and *Candona candida* indicative of a small shallow and still freshwater body. Core **VC1** is within the paleo-Yare valley and as such it is seen as possible that the waterbody is an oxbow lake or billabong. Of interest is that all of the taxa recovered from Zone 1, although freshwater indicators, can tolerate slight increases in salinity. This may suggest sporadic and slight increases in salinity possibly from saline enriched groundwater.

Zone 2a marks the inception of brackish conditions with significant numbers of *Cyprideis torosa* indicating a tidal creek/mudflat environment in an area of fluctuating salinity. Zone 2b is indicative of estuarine conditions with an increased marine input. This input is more pronounced in Zone 2c where shallow marine, sublittoral taxa (*Aurila woutersi* and *Palmoconcha guttata*) dominate with brackish species (*Cyprideis torosa* and *Leptocythere lacertosa*) indicating an increased marine connection.

Semicythereura sella (in samples at 1.26, 1.36 and 2.40m) is of some biostratigraphic value in that it occurs in post-Cromerian (OIS 13) interglacial marine sediments (Whittaker 2007).

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Table 1: Ostracods per sample in vibrocore VC1

Sample (m)	1.20	1.26	1.38	1.50	1.62	1.74	1.80	1.86	1.92	1.98	2.04	2.16	2.28	2.40	2.52	2.64	2.70	2.76	2.82	2.88	2.94	3.06	3.12	3.15
Candona candida									xx	xx	x		xx	xx	x	xx	x	x	xx		x		xx	
Candona sp.																			x					
Cyclocypris laevis																				x			x	
Cyclocypris ovum												x	xx	xx	x	xx	xx	xx	xx	x	x			
Cyclocypris serena												xx												x
Cypria exsculpta													xx											
Darwinula stevensoni										x	x	x		x	xx	xx	x	xx	xx	x	xx		x	
Eucypris sp.												x												
Fabaeformiscandona sp.											x	xx												
Herpetocypris reptans											xx								xx	x	x			
Notodromas monacha									x	x		xx												
Pseudocandona sarsi											xx	xx	xx	xx	xx	xx	xx	xx	xx	x	xx		x	
Cypridopsis vidua									x	x	x	x	xx	x	x		x	x	x	x	xx			
Metacypris cordata														x	x	xx	xx	xx	x	x	x			
Pseudocandona albicans																								
Candona neglecta										x	x													
Candonopsis kingsleyi																								
Potamocypris sp.									x															
Pseudocandona sp.																								
Pseudocandona zchokeyi														x										
Eucythere sp.								x	x															
Heterocypris salina									x	x	x	x	x											
Sarsicypridopsis aculeata																			x					
Cytherois sp.		x			x																			
Hirschmannia viridis		x	x																					

Sample (m)	1.20	1.26	1.38	1.50	1.62	1.74	1.80	1.86	1.92	1.98	2.04	2.16	2.28	2.40	2.52	2.64	2.70	2.76	2.82	2.88	2.94	3.06	3.12	3.15
Paradoxostomata sp.		x																						
Eucythere sp.								x	x															
Heterocypris salina									x	x	x	x	x											
Semicytherura angulata		x																						
Semicytherura nigrescens			x																					
Semicytherura tela		x																						
Semcytherura sella		x	x											x										
Callistocythere littoralis			x																					
Cyprideis torosa	x	x	x	x	x	xx	xx	xxx	xxx	xxx	x	x	x	x				x						
Leptocythere lacertosa		x	xx	xx	xx		x																	
Leptocythre castanaea		x	x	x	xx		x																	
Loxoconcha elliptica		x			x																			
Xesteloberis nitida		x			x																			
Aurila convexa		xx	xx	x	x																			
Carinocythereis carinata		x																						
Eucythere ?declivis					x																			
Palmoconcha guttata		xx	x																					
Palmoconcha laevata							x	xx	x	x														
Leptocythere tenera		x																						

Non marine taxa — xxx – more than 50 specimens
Marine-brackish taxa — xx- 10 to 50 specimens
Brackish taxa — x- 1-9 specimens
Marine taxa

APPENDIX VI: WATERLOGGED MATERIAL AND MOLLUSCAN REMAINS

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Introduction
Six samples were examined from sections taken from core **VC1** and processed for the extraction of mollusc shells and waterlogged plant material. In addition plant material and molluscan material extracted from a further twenty-two smaller samples, taken for foraminifera and ostracods analysis, was also identified where possible and the results are included and presented with those from the other samples.

Methods
The samples were all approximately of 0.5 litres and were wet sieved using a 250µm mesh size. The samples were scanned while still wet and identifiable material was extracted, recorded and put into tubes with industrial methylated spirits. The material from the foraminifera and ostracod sub-samples was extracted and identified while dry. All the material is recorded in Table 1 following the nomenclature of Stace (1997).

The remainder of the sample was then dried and examined again for molluscan remains. These were recorded in Table 2 using presence absence and a broad abundance scale, + present (1-10) individuals, ++ 10 or more individuals, +++ 50 or more individuals. The material from the sub-samples is presented in the same table and was quantified in full.

Results

Waterlogged Plant Remains

While some of the waterlogged material was well preserved some was more fragmentary making identification problematic. Generally waterlogged material was scarce in the uppermost samples down to around 180mm. The remainder of the samples contained small amounts of material to the bottom of the core at 328mm.

There are some changes in species representation as we move down the core, and the sediments are discussed according to:

1.20-1.75m Marine sediments
There are almost no waterlogged remains for any of the samples from this section of the core. There are some pieces of poorly preserved wood and a single seed of hornwort (*Ceratophyllum demersum*) that looked highly reworked. Given the marine context of the material from this part of the core it is perhaps unsurprising that little plant material was preserved.

1.80-1.96m Estuarine, Lagoon, Brackish Water
While there was relatively little material from the samples at these depths, that between 1.87-1.96m did produce large numbers of oogonia of stonewort (*Chara* sp.), preserved through the

calcareous nature of the deposit. Stonewort is often found within freshwater, although several clear water brackish forms, *Chara canescens*, *Chara baltica Chara connivens*, are known around the British coast, and given the remainder of the deposit it would appear to be these species that are most likely to be present.

Of more significance were finds of tassel-weed (*Ruppia maritima*) and horned pondweed (*Zannichellia palustris*). Together these species indicate pools and shallow lagoons of brackish water. A few seeds of pond weed (*Potamogeton* sp.) were also recovered from this sample and whilst associated with both fresh and brackish water it might be suggested that the species present are of those associated with brackish water, most probably slender-leaved pondweed (*Potamogeton filiformis*) or small pondweed (*Potamogeton pusillus*). A seed of Chenopodiaceae from 180mm had a distinctive netted pattern is unlikely to be of Chenopodium or Atriplex, most probably of seablite (*Suaeda maritima*). In addition were small flat seeds of probable sedge (*Carex* sp.).

Other seeds included a those of common nettle (*Urtica dioica*), associated with waste ground and possible seeds of both aspen (*Populus tremula*) and birch (*Betula* sp.).

2.16-2.40m (2.63m) Open birch/pine woodlands/marsh

Five samples were examined from this part of the profile. The most dominant seeds were of bulrush/grey club rush (*Schoenoplectrus lacustris*/ *tabernaemontan*i). Bulrush is common in lakes, ponds and slow rivers, while grey club rush is found in these habitats along with marshes and can tolerate slightly saline conditions. Indicative of freshwater marshes in open woodland were seeds of water avens (*Geum* sp.) from 2.16-2.24m.

It is interesting to note that this species is also present in the pollen record between 2.16 and 2.00m. Stonewort is still present, but less common, although this may be a reflection of preservation conditions. Seeds of white water lily (*Nymphaea alba*) are relatively frequent in the samples from this part of the sequence and absent below. They are indicative of still ponds and lakes. A few seeds of hornwort (*Ceratophyllum demersum*) were also present and are also indicative of these habitats.

A further species of such environments and of some interest are seeds of brittle water-nymph (*Najas minor*), tentatively identified by their distinctive cell pattern. This species grows at the bottom of still pools of water, ponds and lakes at up to 4m depth. It is no longer native in Britain, but is found in central to south-eastern Europe, stretching from North-east France to the Black Sea. That it is found in post-glacial records from Finland and North Russia suggest that it's distribution has become increasingly restricted (Godwin 1975). Generally the species has not been recovered in deposits later than the Ipswichian interglacial, but is recovered from Denmark at the end of the last glaciations into the early post-glacial period (Wiberg-Larsen *et al*. 2001; Jensen *et al*. 2001; Bennike *et al*. 2004).

Also at this level and of some interest were a few fruits of probable bearberry (*Arctostaphylos uva-ursi*). Today this species is only found within moorland, but it is also found within late glacial and early post-glacial deposits (Godwin 1975). Within these deposits it is usually found within environments which are thought to be less wooded, although it was found in association with *Betula nana*, *B. pendula*, and from *Pinus* from south Devon (Godwin 1975, 294). However, in these deposits it might be noted that it is recovered at a time when pine forest appears dominant, although within the Americas certain sub-species are found within open pine forests. Hultén ascribes it to boreal-circum-polar plants. While today it is rarely found in locales with higher summer temperatures than 26˚C it is probable that it's present restriction is limited not by temperature but to areas of high altitudes. A couple of seeds of common nettle (*Urtica dioica*) and possible fat-hen (*Chenopodium album*) were also found indicative of slightly more open areas of disturbed soils. Representative of wet woodlands were whole utricles of probable smooth-stalked sedge (*Carex laevigata*), a few seeds of birch (*Betula* sp.) and a single bud scale of aspen (*Populus tremula*). While possible seeds of pine (*Pinus sylvestris*) may also indicate that even occasional trees were able to colonise close to these wet marshlands.

2.63/2.68-3.06m Open birch woodland/marsh
The flora, as seen within the samples from these levels, look very similar to the above deposit. Most noticeable is seeds of bulrush/grey club rush are largely absent and none are recovered below 2.82m. Open woodland adjacent to marshland is still indicated by the presence of birch and water avens, while oogonia of stonewort indicate shallow still or slowing flowing water, as do seeds of hornwort (*Ceratophyllum demersum*). Seed of hornwort are particularly common in the upper portion from 2.63-2.68m, the species is a sub-merged freshwater, aquatic and is tolerant of low-levels of shade. Several seeds of mint (*Mentha* sp.) are also present, the most likely candidate being water mint (*M. aquatica*) which is found in marshes, fens and wet woods. Brittle water-nymph (*Najas minor*) is still present.

Seeds and catkin scales of birch, with both dwarf birch (*Betula nana*) and downy birch (*Betula pubescens*) probably present. These are generally much more common indicating a probable birch carr growing close to the waters edge. A single seed of bearberry is also present from 2.69m.

3.12-3.18/3.28m Open birch woodland/pond/slow river
The final deposits are similar to those above, being dominated by remains of birch, in particular dwarf birch, and hornwort. The presence of kingcup/marsh marigold (*Caltha palustris*) indicates indicates wet open woodland, fens and marshes, while mare's tail (*Hippuris vulgaris*) is also found in ponds, lakes and slow streams. The pollen indicates for this period a more open grassland environment with birch forest. A single fragment of charred birch was also present at 3.12m and given the wetness of the environment might be taken to indicate human presence within the earlier stages of the sequence.

<u>Molluscan Remains</u>

As with the waterlogged plant remains molluscan remains were present through much of the sequence and similarly demonstrate a transition from freshwater through brackish to marine environments. Unlike waterlogged plant remains they were however more numerous in the uppermost samples becoming scarcer towards the base of the core.

1.20-1.22/1.33m Marine
All the molluscs from these upper deposits are of marine species, including oyster (*Ostrea edulis*) with polychoitic worm (*Polydora cilicata*) infestations, cockle (*Cardium* sp.), Tellin (*Tellina* sp.), and (*Nassarius incrassatus*). Small shells of Rissoidae species (resembling *Rissoa* spp. and *Pusillina* spp.) were also recovered. Spines of sea urchin as well as small fish bones resembling herring type were also recovered.

1.38-1.86m Marine/saltmarsh Brackish Water
The samples from these levels contain a mixture of marine species including oyster, small dogwelk, Rissoides and cockle, (occurring between 1.87-1.96m), but also several shells of lava spire snail (*Hydrobia ulvae*) indicating brackish water conditions, usually found within the silts of estuaries or saltmarshes, and occasionally lagoons. The presence of at least two shells of freshwater species Planorbids and *Pisidium* would indicate some proximity to estuarine conditions at 1.38m.

1.87-1.98m Estuarine/Marsh
The great mix of freshwater, marine and brackish water species at this level must indicate estuarine or proximity to an estuary with high inputs of both marine species and freshwater species, as well as those of brackish conditions. In the marine category we find shells of oyster, Rissoidae, Cerithiidae (resembling *Bittium* spp.), carpet shell (*Veneridae* sp.) and small dog-whelk. Along with *Hydrobia ulvae* are also probable shells of *Hydrobia ventrosa*. In contrast to the former this latter species can tolerate salinity as low as 6-10%, as well as sub-zero temperatures (Berger and Gobushin 2004). Freshwater species included shells of Planorbids, *Bithynia*, *Lymnaea* and *Pisidium*, as well as a vertebra of eel (*Anguila anguila*) assumingly all brought down nearby rivers. Shells of *Valvata* spp. were also recovered, the genus is usually associated with marshes and fens, but some species are also tolerant of saline conditions.

At 1.98m it is notable that there are no marine species are present and there are mainly shells of *Hydrobia ventrosa* rather than *H. ulvae*. It might be assumed at this depth we are dealing with a largely freshwater environment with a small amount of tidal influence or saltwater input.

2.04-2.28mm Fresh-water floodplain/near floodplain
Both marine and brackish water snails are entirely absent within these deposits with high numbers of *Bithynia* operculae and relatively few shells indicating a riverine or near riverine environment. Shells of Planorbids, *Lymnaea* and *Pisidium* are also all present along with those of river-limper (*Ancylus fluviatilis*).

2.40-2.63/2.68m Fresh-water, increased salinity
While on the whole these samples are similar to the above samples, although river-limpet shells are absent, it is notable that both *Hydrobia ventrosa* and *Valvata* spp. are again present at this earlier stage. The latter being indicative of marshland is less out of place, but the presence of the other suggests some salinity also present at this earlier stage. As above the remainder of the assemblage suggest a slow-river environment or at least proximity to such an environment.

2.69-3.18 Fresh-water floodplain/near floodplain
The remainder of the sequence produced only freshwater mollusca. From 2.69 - 2.76m this includes shells of *Pisidium*, *Lymnaea, Bithynia* and Planorbids. From 2.82m to 3.18m shells are much scarcer and only a few Planorbids and *Bithynia* operculae are recovered.

Discussion

Taking the lowest and earliest sedimentary deposits, we can see evidence for open birch woodland, comprising of dwarf and downy birch and some aspen. The presence of hornwort would indicate that rather than a river the deposit appears to be forming within small pools or oxbows close to a river and judging by the presence of *Bithynia* operculae within the floodplain. There is also indication of a wet grassland and marsh with areas of shade close to the water.

At 2.68 to 2.40m there is an indication of some saline input into this freshwater environment which is exploited by *Hydrobia ventrosa* and possibly *Valvata* sp. This is in contrast to the finds of numerous seeds of hornwort which are only associated with freshwater. Both shells and seeds could be potentially transported into the deposit, although the much higher proportion of both shells and seeds of freshwater species would suggest that at this time the deposit itself was freshwater. Unlike *Hydrobia ulvae*, *Hydrobia ventrosa* is found in non-tidal near coastal lagoons and it can only be assumed that shells were brought into the deposit from such areas through episodic flooding, of the area in general. It is quite probable that the oogonia of *Chara* also came into the deposits from such lagoons. During this period birch and aspen woodland appear to still predominate around the body of water, as seen in the pollen record.

After this event these indicators of salinity appear absent from at least 2.28-2.04m. During this period we see the extension of reed marsh throughout the area, although the body of water itself appears to be freshwater with brittle water-nymph and hornwort still present, along with white water-lily. It is notable that birch declines in the pollen diagram and fewer seeds of birch are also present. It may be that the area around the pool of water was becoming wetter and opening up to more marsh conditions. In the pollen record it might be noted Scaife records an increase in marsh taxa along with ferns (*Dryopteris* type) and particularly marsh fern (*Thelypteris palustris*). The period also sees the dominance of pine and the presence of possible seeds, might indicate that it was able to colonise closer to the edge of the marshland, and given the decline of birch and opening of the near water environment that the wing seeds could pass across this area to become deposited within the pool.

From around 2.00-1.62m we see a dramatic change in the general environment both around and within the pool itself. The coastal and marine influence changes the salinity of the pool and we see freshwater species such as white water lily and hornwort replaced by those of tolerant or associated with brackish water conditions, horned pondweed, tasselweed, and probably brackish water species of both stonewort and pondweed. Small amounts of birch and aspen still appear to be present, but the effect of rising-sea level probably means that such lagoons have become commonplace along with small amounts of saltmarsh. It might be noted that species of saltmarsh and marshland in general do not appear to increase in the pollen record, implying that vegetation was generally diminished, being quickly replaced by estuarine sands and silts and larger lagoonal pools in response to rising sealevels rather than the establishment of large tracts of brackish marshland or saltmarsh.

Acknowledgements

Thanks to Alan Clapham for help with the identification of some of the material within the samples.

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Table 1

Table 2

APPENDIX VII: RADIOCARBON DATING (^{14}C)

Eight samples were submitted for radiocarbon dating: two to the Scottish Universities Environmental Research Centre (SUERC); two to the Oxford Radiocarbon Accelerator Unit, University of Oxford; and four to the Rafter Radiocarbon Laboratory, Institute of geological and nuclear sciences, New Zealand. The samples dated at SUERC and Oxford Radiocarbon Accelerator Unit were funded by EH; the samples dated at the Rafter Radiocarbon Laboratory were funded by MIRO.

The Oxford samples were pre-treated following Hedges *et al* (1989) and dated by Accelerator Mass Spectrometry (AMS) according to Bronk Ramsey *et al* (2004). The SUERC samples were pre-treated following Slota *et al* (1987) and measured by AMS following Xu *et al* (2004). All the results are conventional radiocarbon ages (Stuiver and Polach 1977).

Due to the age of the samples the results cannot currently be calibrated (Table 1).

Depth (m)	*Depth (m below OD)*	*Material*	*Result no*	*δC^{13} ‰*	*Result BP*
1.86	29.47	*Carex*	NZA-27096	-25.0	23,760±300
1.92	29.53	*Nassarius reticulatus*	SUERC-11983	-6.8	43,800±400
1.92	29.53	*Nassarius reticulatus*	OxA-16466	-5.7	39,820±390
2.16	29.77	*Schoneoplectus* sp (Bullrush seeds)	NZA-27099	-28.4	47,800±2,400
2.25	29.86	Herbaceous stem –middle of freshwater	SUERC-11979	-27.9	>50,000
2.40	30.01	Bulrush seeds	NZA-27100	-27.9	>47,000
3.12	30.73	*Betula* Bark charred	NZA-27095	Estimate -15	49,500±3,000
3.18	30.79	*Betula* cone scales	OxA-	-	Too small sample

Table 1. Radiocarbon results of dates from the Great Yarmouth survey area.

It was not possible calculate a δC13 ‰ value for the charred *Betula* bark sample. As such, the value has been estimated. The sample containing the *Betula* cone scales at 30.79m below OD contained insufficient carbon (0.114mg) to produce a reliable date. These results are, with the exception of the date at 29.47m below OD (23,760±300 BP), at the limits or beyond the range of radiocarbon dating.

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APPENDIX VIII: OPTICALLY STIMULATED LUMINESCENCE (OSL) DATING

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Eight samples; **VC1** and **VC3** (**VC1a** 1.14m, **VC1a** 1.92m, **VC1a** 2.52m, **VC1a** 3.30m, **VC1a** 3.70m, **VC3a** 1.62m, **VC3a** 2.68m and **VC3a** 3.76m) were prepared for OSL dating.

All were subsampled from the cores provided, and only the middle of the core was used to reduce the likelihood of incorporating any light-contaminated edge material. Sample preparation was standard, and began with removal of carbonates and organics with HCl and H_2O_2. In two cases (**VC1a** 1.92m and **VC1a** 2.52m) the reaction with HCl was extremely vigorous and took an unusually long time to stop, suggesting extremely carbonate-rich sediments.

Subsequently samples were sieved to isolate the size fraction to be dated. In most cases this was 150-212 µm, but four samples (**VC1a** 1.14m, **VC1a** 1.92m, **VC1a** 2.52m and **VC1a** 3.70m) had very little quartz left, and a broader size fraction (90-212 µm) was selected to maximize available material. Heavy minerals were removed by flotation in sodium polytungstate, and samples were finally etched with HF for 45 minutes (to remove the outer alpha-irradiated rind and any remaining feldspars) and given a final sieving. No material from **VC1a** 2.52m survived this preparation procedure and it must be concluded that this sample was predominantly calcareous material.

Dosimetry was provided by ICP-MS and -AES at Royal Holloway, University of London, and saturated moisture contents were measured to calculate attenuation effects.

All samples were mounted on aluminium discs with Silkospray^{TM}, and were analyzed on a Riso TL-DA-15 with blue diode stimulation at 470nm, with luminescence measured with a 9235QA photomultiplier tube, shielded by two 3 mm thick Hoya U-340 filters. At least 10 aliquots were measured for each sample, using SAR protocols (Murray and Wintle, 2000, 2003; Wintle and Murray, 2006). All samples were preheated to 240°C for 10s prior to measurement An elevated test dose of 16.5 Gy was used to maximize signal-noise ratio, and a preheat of 220°C for 10s was used for the test dose measurements.

Most samples provided closely distributed Gaussian distributions of replicate equivalent dose (D_e) measurements, offering a high degree of confidence in the results. A skewed distribution for **VC1a** 1.14m resulted in the use of the Minimum Age Model of Galbraith et al (Galbraith *et al.*, 1999) for this sample. Sample **VC3a** 3.76m was at saturation, and thus cannot be dated. The implication of the signal, not least the stratigraphy, is that it is at least as old the overlying **VC3a** 1.62m and 2.68m. Using these methods the following results were achieved:

Core	Sample ID	Age (ka)	error (ka)	Comment
VC1a	1.14	16.6	2.3	
VC1a	1.92	116.7	11.2	
VC1a	2.52			No dateable material extractable
VC1a	3.30	175.7	22.6	
VC1a	3.70	577.2	65.4	
VC3a	1.62	309.5	29.1	
VC3a	2.68	226.0	26.5	
VC3a	3.76			Not dateable, but certainly older than Holocene

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