THE CROWN ESTATE

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A synthesis of current knowledge on the genesis of the Great Yarmouth and Norfolk Bank Systems

A Synthesis of Current Knowledge on the Genesis of the Great Yarmouth and Norfolk Bank Systems

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Cooper, W.S. (ABPmer), Townend, I.H. (HR Wallingford) and Balson, P.S. (BGS).

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Glossary

ABPmer	ABP Marine Environmental Research Ltd. (formerly ABP Research & Consultancy Ltd.)
ADCMS	Anglian Coastal Defence Management Study.
ALSF	The Aggregate Levy Sustainability Fund.
Asymmetric	Not symmetrical.
BGS	British Geological Survey.
BP	Before Present.
Coriolis	The Coriolis effect results in a deflection of fluid flows (clockwise in the Northern Hemisphere and anti-clockwise in the Southern Hemisphere). This has profound effects on the flow of the oceans.
Devensian	Devensian (in the British Isles) and Weichselian (in northern central Europe) glaciations are the most recent glaciations of the Pleistocene epoch, which ended around 10,000 BCE (before the current era).
Eddies	A current at variance with the main current in a stream of especially one having a rotary motion.
Exceedence	The exceedence is the fraction of the time the wave height exceeds the given value. For example, if the 10% exceedence value for 'significant wave height', Hs, is 2.1m, this means that Hs is more than 2.1m for 10% of the time, i.e. a total of 36.5 days per year.
Flandrian	The Flandrian interglacial stage is the name given by geologists in the British Isles to the first, and so far only, stage of the Holocene, covering the period from around 10,000 years ago when the last ice age ended to the present day.
GIS	Geographical Information System.
Holocene	The Holocene epoch is the most recent of all subdivisions of geologic time, ranging from the present back to the time (c.11,000 years ago) of almost complete withdrawal of the glaciers of the preceding Pleistocene epoch.
Hydrodynamics	Fluid dynamics applied to liquids.
Intertidal	The intertidal zone, also known as the littoral zone, in marine aquatic environments is the area of the foreshore and sea bed that is exposed to the air at low tide and submerged at high tide.

LAT	Lowest Astronomical Tide.
Lacustrine	In ecology, is the environment of a lake; in geology, is the sedimentary environment of a lake.
LGM	Last Glacial Maximum. The maximum extent of northern hemisphere glaciation, generally believed to have occurred around 21,000 years ago.
Littoral	Littoral refers to the coast of an ocean or sea. The littoral zone is defined as the area between the high water and low water marks which is also known as the intertidal zone.
LOIS	Land Ocean Interaction Study (LOIS) was a Thematic Programme of the Natural Environment Research Council (NERC).
MCA	Maritime and Coastguard Agency.
NN	Normal Null. A German 'Metric' vertical datum reference which are measured with respect to Normal Null.
ODN	Ordnance Datum Newlyn.
Periglacial	Periglacial refers to places in the edges of glacial areas, normally those related to past ice ages rather than those in the modern era.
Pleistocene	The Pleistocene epoch on the geologic timescale is the period from 1,808,000 to 11,550 years BP.
Sand wave asymmetry	The morphological analysis of sand wave form to give an indication of the predominant direction of sediment transport.
Sigmoidal	A logistic function or logistic curve models the S-curve of growth of some set *P*. The initial stage of growth is approximately exponential; then, as competition arises, the growth slows, and at maturity, growth stops.
SNSSTS	Southern North Sea Sediment Transport Study. Completed in phases, with phases 1 and 2 complete at the time of reporting.
Transgression	A geologic event during which sea level rises relative to the land and the shoreline moves toward higher ground, resulting in flooding.
UKHO	United Kingdom Hydrographic Office.
Weichselian	Weichselian (in northern central Europe) and Devensian (in the British Isles) glaciations are the most recent glaciations of the Pleistocene epoch, which ended around 10,000 before the current era.

Executive Summary

ABP Marine Environmental Research Ltd (ABPmer) was commissioned by The Crown Estate to produce a report that synthesised the current knowledge on the genesis of the Great Yarmouth and North Norfolk Bank system of offshore banks. This study was carried out in partnership with HR Wallingford Ltd and British Geological Survey (BGS).

This report details the present scientific knowledge on the geological history and geomorphological process systems in this area. In particular, it is intended to update and clarify the conceptual model(s) that define the genesis of the bank systems.

A considerable body of work was drawn upon to produce this report including studies completed in relation to work on the Anglian Coastal Defence Management Study (ACDMS). Subsequent work for the ACDMS involved more detailed historical analysis of the Great Yarmouth Banks by Halcrow Group Ltd (Halcrow 1991).

This was followed by the first phase of the Southern North Sea Sediment Transport Study (SNSSTS), which comprised a further literature review and the establishment of a database of references and data (ABP Research & Consultancy 1996). This literature review was updated in a follow-up study prior to the letting of Phase 2 of the SNSSTS (ABP Research & Consultancy 2000).

Subsequently, BGS characterised the sea bed for much of the East coast, and HR Wallingford led the completion of SNSSTS Phase 2. These projects included net sand transport direction analysis based on an interpretation of the UKHO bottom texture sheets and inferred sand wave asymmetry.

In writing this report the project team sourced, reviewed and incorporated up-to-date data and information published since the studies mentioned above, including detailed work for aggregate sites and other publications relating to the study area.

The project deliverables include:

- An independent and authoritative report to assist The Crown Estate in stakeholder engagement;
- An updated database of literature and scientific; and
- A more technical version of the conceptual model in a peer reviewed journal so that the scope of the dissemination is maximised.

The key project conclusion is that the Outer Banks (Leman, Ower, Inner, Well, Broken, Swarte, etc.) lie in an area believed to be close to the limit of the last glacial ice advance. It therefore seems likely that their origin is at least in some way related to the antecedent sediment supply that would have existed prior to the marine transgression.

The mechanisms that best explain the genesis and evolution of the banks from the available evidence for the various groups of banks comprise:

- Reworking of sediments from outwash sediment of the last glaciation to form the Norfolk Offshore Banks;

- Headland tidal meander channels provide the mechanism for forming and maintaining the Inner Great Yarmouth Banks;

- A similar sequence of tidal meander channels provide a plausible mechanism for the formation of the Outer Great Yarmouth; and

- Headland shoals at nesses to explain the local circulation and formation of flood and ebb residual channels.

1 Introduction

The Norfolk Banks which lie off the East Anglian coast are one of the best known groups of offshore sandbanks in the world. They have been intensively studied over the last 40 years and have often been cited as 'classic' examples of this type of marine sedimentary bedform.

For the purposes of this report the 'Norfolk Banks' comprise the system of sandbanks that stretch northward from the shoreline-attached banks at Lowestoft Ness, on the Suffolk coast, to the outer banks such as Well Bank and Swarte Bank (Figure 1). In addition, this study includes other sandbanks further to the west including Sheringham Shoal and the banks that lie off the North Norfolk coast.

This report details the present scientific knowledge on the geological history and geomorphological process systems in this area. In particular, it is intended to update and clarify the conceptual model(s) that define the genesis of the bank systems. This study was carried out by ABP Marine Environmental Research Ltd (ABPmer) in conjunction with HR Wallingford Ltd and British Geological Survey (BGS).

The project objectives were to produce a report that synthesised the current knowledge on the genesis of the Great Yarmouth and North Norfolk Bank offshore bank systems, further to The Crown Estate highlighting the need for more ready access to previous studies for this area.

The key activities undertaken were:

- To produce an independent and authoritative report to assist The Crown Estate in stakeholder engagement; and

- To produce an updated database of literature and scientific data.

In addition to these activities a more technical version of the conceptual model will be published in a peer reviewed journal so that the scope of the dissemination is maximised.

A considerable body of work was drawn upon to produce this report which included studies completed in relation to work on the Anglian Coastal Defence Management Study (ACDMS). Subsequent work for the ACDMS involved more detailed historical analysis of the Great Yarmouth Banks by Halcrow Group Ltd (Halcrow 1991).

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Subsequently, BGS characterised the sea bed for much of the East coast, and HR Wallingford led the completion of SNSSTS Phase 2. These projects included net sand transport direction analysis based on an interpretation of the UKHO bottom texture sheets and inferred sand wave asymmetry.

In writing this report the project team sourced, reviewed and incorporated up-to-date data and information published since the studies mentioned above, including detailed work for aggregate sites and other publications relating to the study area.

The original literature database for the Southern North Sea was developed in 1997 and was provided as a project deliverable from the Phase 1 Southern North Sea Sediment Transport Study (ABP Research & Consultancy 1996). Updates were provided to the database in 2000, prior to the second phase of this project, and further development made as part of the Phase 2 scope. ABPmer host the database, which is managed with Reference Manager database software. Within this study a further update of relevant literature (with specific relevance to the project area) published post-2000 was added to the database.

This study also considered literature already collated for the Marine Aggregate Levy Sustainability Fund GIS (ALSF GIS website link), a project funded by the Marine Environmental Protection Fund (MEPF), and other sources known to the project team. The updated database will be translated into a format to enable easier integration to The Crown Estate managed software.

Various conceptual models to explain the evolution of the bank systems have been outlined in the earlier work, and this study has re-visited these models in the light of the more recent studies and data to consider whether they still provides an acceptable explanation of bank behaviour. Particular consideration has been given to other possible mechanisms that have been suggested in the light of the sedimentary and process evidence, as well as the understanding of the Quaternary Geology for the area.

On the 9th March 2007, conclusions of this study were presented to The Crown Estate, key regulating bodies, including CEFAS, Department for Environment, Food and Rural Affairs (DEFRA) and the aggregate industry. It was important to complete this wider involvement, as this report is designed to provide independent and authoritative information to assist The Crown Estate in future stakeholder engagement. In presenting the findings, care was taken to make clear what was well-established and what remained uncertain, and, where possible, trying to quantify or put some bounds on the uncertainty.

The study area was defined by combining the contributing author's understanding of the classifications of the bank systems in these areas with existing literature and input from The Crown Estate. Additional reference was also derived from the Joint Nature Conservation Committee (JNNC) 'Potential Sandbanks in UK Offshore Waters' (JNCC website link), which shows key offshore features in the study area. The inshore bank systems of Great Yarmouth exist within limits approximately defined by Benacre (Benacre Ness) in the south up to Winterton-on-Sea (Winterton Ness) in the north, extending from the shoreline to approximately 8km offshore.

By combining the inshore and offshore Norfolk Bank systems an encompassing study area was defined with approximate limits being 0° 34’ E to 2° 40’ E and 52° 20’ N to 53° 45’ N (Figure 1).

2 Literature and scientific data databases

The original literature database for the Southern North Sea was developed in 1996 for SNSSTS Phase 1 (ABP Research & Consultancy 1996). Updates were provided to the database in 2000 prior to the second phase of this project, and further development made as part of the Phase 2 scope in 2002.

At the time of writing, ABPmer manage the database with Reference Manager database software. This database can be translated into another application or format to enable easier integration to The Crown Estate's managed software.

2.1 Database update

The database detailed above was updated with relevant literature and scientific data of relevance to the project area published post-2002. This now contains 2,726 literature and 127 data references. A key source for both literature and scientific data was the Marine ALSF GIS database (ALSF GIS website). Some further information was also provided by the aggregate companies holding licences within the study area.

The Maritime and Coastguard Agency (MCA) routine resurvey programme for the east coast provided new data (MCA and UKHO websites) in areas of importance to navigation within the study area. Since 2005, the MCA have presented multibeam bathymetric data in their reports which provides near 100% high-resolution sea bed coverage, providing a new level of detail on sea bed features such as sand waves. Additionally, the repeat survey reports also include some sediment transport vector analysis derived from observed sand wave asymmetry. This new data demonstrates how recent advances in technology (post-2002) continue to reveal new data and understanding of sea bed dynamics.

Post-2002 Environmental Impact Assessments (EIA) studies relating to new applications were also reviewed to assess if any new data was collected which might contribute to an improved understanding of processes in the study area.

3 Geological setting, Holocene evolution and geomorphology

3.1 Overview

This section describes the current state of knowledge on the genesis and evolution of the Norfolk Bank system and some associated sandbanks in the southern North Sea. It examines the inheritance from the retreat of the ice sheets of the last glacial period and the contribution from long-term sedimentary processes as the result of sea level rise and coastal erosion. In providing this review, reference has been made to both published and unpublished information from a variety of sources.

3.2 Sandbank systems

The Norfolk Banks which lie off the East Anglian coast are one of the best known groups of offshore sandbanks in the world. They have been intensively studied over the last 40 years and have often been cited as 'classic' examples of this type of marine sedimentary bedform. For the purposes of this report the 'Norfolk Banks' comprise the system of sandbanks that stretches northward from the shoreline-attached banks at Benacre Ness on the Suffolk coast to the outer banks such as Well Bank and Swarte Bank (Figure 1). In addition, this study includes other sandbanks further to the west including Sheringham Shoal and the banks which lie off the North Norfolk coast. For convenience the 'Norfolk Banks' will here be considered in three main groups;

- 'Norfolk Offshore Banks' - comprise the large linear banks of Leman, Haddock, Ower, Inner, Well, Broken and Swarte Banks which lie between 40 and 80km from the north-east Norfolk coastline;

- 'Dudgeon-Dowsing Shoals' - comprise the smaller and more scattered banks to the north of Norfolk including Sheringham Shoal, Race Bank, Dudgeon Shoal, Cromer Knoll and Outer Dowsing Shoal; and

- 'Great Yarmouth Banks' - comprise the nearshore banks off Lowestoft and Great Yarmouth out to Smith's Knoll, which all lie within 40km of the present coastline. In this discussion, these are occasionally subdivided and the banks immediately off the coast are referred to as the 'Inner Great Yarmouth Banks', whereas Haisborough Sand, Hammond Knoll, Winterton Ridge, the Hewett Ridges and Smith's Knoll are denoted as the 'Outer Great Yarmouth Banks'.

Numerous earlier studies have attempted to address the question of how the Norfolk Banks were initiated and how they are maintained. These studies will be briefly reviewed here and recent data acquired by the BGS will be described to produce a conceptual model of the geological history of the bank system.

The Norfolk Banks have long been regarded as typical examples of modern tidal sand ridges found on the world's continental shelves. Their asymmetric cross-sectional profile and internal structure indicate migration perpendicular to their long axes, and in an offshore direction. It is, however, difficult to demonstrate whether or not such migration occurs at the present time and at what rate.

Recent observations of water movement, sand wave asymmetry and sand tracers support an offshore sand transport component (Collins, *et al* 1995). Data obtained as part of the UK's Land Ocean Interaction Study (LOIS) has allowed the internal geometry of some of the Norfolk Banks to be determined more clearly than ever before. The new data confirms the unidirectional nature of the dipping internal reflectors first noted by Houbolt (1968) which contrasts with the structure observed within sandbanks elsewhere in the North Sea (e.g. Davis and Balson, 1992; Berné *et al,* 1994). The new data has allowed the relationship between the sandbank and the underlying topography to be reconstructed and the sediment volume within the banks to be estimated. These volumes help to relate the banks to the long-term sediment budget for the area and inform the subsequent discussion of conceptual models that seek to explain the evolution of the Norfolk Bank system.

3.3 Geological setting

The North Sea shelf in this area is shallow, mostly less than 30m water depth and consists of a relatively flat plateau of Late Pleistocene (Weichselian) glacigenic deposits. The plateau is approximately 150km from east to west, 90km from north to south with an area of over 13,000km². The plateau, termed the 'Humber Spur' by Houbolt (1968), is bounded to the north by the deeper water (up to 100m) of the Outer Silver Pit, a broad submarine valley which separates the plateau from the shallow waters of the Dogger Bank to the northeast and the open shelf waters beyond.

During the most recent Devensian, glaciation ice covered much of Scotland and northern England. The maximum extent of northern hemisphere glaciation is generally believed to have occurred around 21,000 years ago, the so-called Last Glacial Maximum (LGM), but locally the ice may still not have reached its maximum geographical extent. A lobe of glacial ice is believed to have streamed south and southeastwards along the east coast of England and into the area of the modern southern North Sea since the LGM. The timing of this glacial ice advance is controversial but must post-date the deposition of the Dimlington silts which contain plant remains radiocarbon dated to 18500-18240 BP (Penny *et al,* 1969). The ice lobe which deposited the Skipsea and Withernsea till sheets may have extended southwards immediately after that date or at some time subsequently. Boulton and Hagdorn (2006) suggest that the ice reached its maximum extent around 17000 BP whereas authors such as Peacock (1997) and McCabe *et al* (1998) suggest that it may have been several thousand years before the ice reached its maximum extent and began to retreat. Evans *et al* (2001) believed that the Skipsea and Withernsea tills of the Holderness coast indicate that two ice streams were involved with one from the Tees valley overriding one from Northumberland and southern Scotland to produce the two overlying till units.

Evidence of the offshore extent of this glacial ice sheet comes from the distribution of a glacial lodgement till, the Bolders Bank Formation, which was deposited beneath the ice. Its present-day distribution, therefore, indicates the *minimum* extent of the ice-sheet as thin glacial till at the ice margin may have been subsequently removed by erosion. The mapped distribution of these glacial till deposits is shown in Figure 2 and an interpretation of the palaeogeography and

environments based on mapped Pleistocene formations is shown in Figure 3. In a study of the offshore glacial deposits in the southern North Sea, Carr (1999) suggested that there had not been significant post-depositional erosion of the till formations and that the thin gravel lag deposits which are found on the sea floor overlying the tills was evidence that less than 1m of thickness had been eroded during the Holocene marine transgression. He therefore believed that the mapped limit of the till deposits was a good indicator of the maximum ice extent in the southern North Sea.

The majority of the Norfolk Banks lie to the south of the mapped till limit with the larger more offshore banks within a belt which runs parallel to the orientation of the limit of the till outcrop. Of the banks considered here, only the banks of the Dudgeon-Dowsing Shoals lie entirely within the limit and therefore overlie this till. To the south of the Devensian till outcrop, older Pleistocene deposits formed during previous glacial, interglacial and preglacial periods are exposed on the seafloor and are directly overlain by the Norfolk Offshore Banks.

Shallow seismic reflection profiling and vibrocore sampling have proved the presence of sediments which were deposited prior to, and during the early-mid Holocene transgression. These deposits consist of a basal peat layer overlain by a sequence of silts and clayey silts up to 14m thick. The basal peat is thin, often only a few centimetres thick, and yields the alga *Pediastrum* indicative of freshwater environments. In cores, the peat is often found to be sharply truncated by modern marine sediments with frequent burrows from the plane of unconformity. Occasionally cores have recovered sections which show a gradual upward transition through saltmarsh peat and intertidal muds. The deposits, therefore, record the flooding, by the rapidly advancing sea, of a land surface with freshwater ponds and marshes lying in shallow depressions. Radiocarbon dates show that this flooding occurred between around 9000 and 7500BP and indicate a rate of relative sea level rise of approximately 12mm/year.

The peats and overlying muds are found as discontinuous erosional remnants of a presumably formerly more continuous sheet. Examination of surface grab samples of the sea bed sediments has revealed the frequent presence of valves of the Common Cockle *Cerastoderma edule*, a species common in modern intertidal sediments around the North Sea but not found inhabiting subtidal environments. The valves are found on the modern seafloor at water depths in excess of 30m and must therefore either have been transported there from modern intertidal areas or must reflect an earlier site of intertidal deposition. The samples where *C. edule* valves have been found are shown in Figure 4 which shows a close correlation with core sites where the basal peat and intertidal sediments have been preserved on the shelf. This suggests that the shells have been winnowed from intertidal deposits on the shelf with relatively little subsequent transport (Balson, *et al* 1997).

A similar conclusion was reached by Eisma *et al* (1981) who were able to show the relationship between sea level history and the depth at which *C. edule* shells were found on the floor of the Southern Bight of the North Sea to the south of the area considered here. A contrary situation was recently described by Flessa (1998) in the German Bight of the North Sea to the east where *C. edule* shells are believed

to have been transported both landwards and seawards from their original life position.

3.3.1 Norfolk Offshore Banks

The two outermost banks in this group, Swarte and Broken Banks mostly overlie the Eem Formation but their north western ends lie on the Devensian till of the Bolders Bank Formation. Well, Inner, Ower and Leman Banks overlie Anglian glacial deposits of the Swarte Bank Formation in the west and the Eem Formation in the east. At its south eastern end, Well Bank overlies a formation of well-sorted, fine-grained, windblown coversands which are associated with the Devensian glacial period. These sands may once have been more extensive and were deposited in the periglacial environment to the south of the glacial ice limit.

3.3.2 Dudgeon-Dowsing Shoals

This group of banks lie off the coast of North Norfolk to the north and east of Burnham Flats. Water depths in this area are relatively shallow and are mostly less than 20m. In contrast to the Great Yarmouth and Norfolk Offshore Banks, this group of banks lies almost entirely on the glacial till of the Bolders Bank Formation. This surface appears to have a greater surface topography than the surface on which the Norfolk Offshore Banks lie with a number of channel-like features and hollows. Consequently, the basal surface beneath a bank may be concave with some of the ‘bank’ sediment infilling a pre-existing hollow.

3.3.3 Great Yarmouth Banks

The nearshore banks off Lowestoft and Great Yarmouth such as Scroby Sands and the Newarp Banks mostly overlie pre-glacial Pleistocene formations comprising the mud-rich Westkapelle Ground Formation and the sandy Yarmouth Roads Formation. The more offshore banks in this group such as Winterton Ridge, Hewett Ridge and Smiths Knoll mostly overlie shelly fine to medium sands of the Eem Formation.

3.4 Holocene transgression

In the following section reference is made to age dates before present (BP). It should be noted that dates obtained by radiocarbon (^{14}C) dating are given in radiocarbon years before present where the ‘present’ is defined as the year 1950. Calibration of the radiocarbon time scale allows a conversion to be made to calendar years before present. The discrepancy between radiocarbon years and calendar years generally increases with time such that 18,000 ^{14}C years BP is approximately equivalent to 21,000 calendar years BP. Similarly the base of the Holocene period is defined as 10,000 radiocarbon years BP which is approximately equivalent to 11,500 calendar years BP. In the literature both time scales are used which may cause confusion when comparing dates between different authors.

The Devensian glaciation reached its peak around 21,000 calendar years ago. At this time it is generally accepted that global sea level may have been around 120m lower than the present time (Fairbanks, 1989) although more recent studies

suggest that sea level may have reached as much as 130-135m below present (Peltier & Fairbanks 2006). Sea levels began to rise after this time which is known as the LGM. In eastern England, however, the glacial ice had still not reached its maximum geographical extent. Evidence from lodgement till deposits attributed to the Devensian glacial period show that the ice sheet reached as far south as the present day north Norfolk coast (Figure 3). Most of the area presently occupied by the North Sea was either beneath the ice or was exposed as a land surface at this time. As the ice began to melt the glacial margin retreated rapidly northwards leaving behind moraines of gravel and boulders and large quantities of finer sand and mud. It is expected that deposits of outwash sands and gravels were typical of the area. Strong periglacial winds formed deposits of windblown coversands.

The uneven topography on the surface of the till deposits would have allowed the formation of lakes which subsequently may have become bogs as vegetation increased and the climate ameliorated. These bogs subsequently produced peat deposits which have been found in numerous locations in the vicinity of the Norfolk Offshore Banks, in particular. In 1931 an antler harpoon was trawled from a peat deposit between Leman and Ower Banks (Godwin & Godwin, 1933). The peats from the area at the southern end of Well Bank have been dated to around 9000-9200 ^{14}C BP and all lie in water depths between 37 and 39m below sea level. Some small rivers flowed across the plateau at this time.

The flooding of the plateau commenced around 8500BP and was probably complete by 7000BP. The transgression of the plateau was, therefore, extremely rapid due to its low gradient and the relatively rapid rise in sea levels at this time. A new sea level curve for the North Sea indicates that between 9700 and 8000 calendar years BP the rate of sea level rise may have exceeded 20mm/year, Figure 5 (Behre, 2007).

The very low topography meant that the plain was very rapidly transgressed with a coastline translation rate probably exceeding 100m/year. Extensive intertidal flats were formed depositing muddy sediments. The preservation of the freshwater peat deposits indicates that if coastal cliffs were present in the area they must lie landward of the location of these peat deposits, unless the peat deposits were formed within valleys incised within more elevated upland areas. There is no evidence for former upland areas around the location of the peat deposits and, therefore, it is assumed that coastal cliffs were not formed until later in the transgression and that they must have lain closer to the present day coastline.

This assumption will have a dramatic effect on any calculations of potential sediment supply from coastal cliff erosion in the Holocene and also has important implications to the formation of the Norfolk Offshore Banks as coast parallel banks. The implied morphology means that the coastline was low-lying and the transgression passed rapidly over the site of the Norfolk Offshore Banks before encountering higher ground and forming possible coastal cliffs somewhere landward of the present location of Leman Bank. By this time the location of Swarte Bank would have been already nearly 40km offshore, precluding a genesis as a coast-parallel nearshore bank for Swarte Bank and probably most of the Norfolk Offshore Banks, as will be discussed later.

The rate of sea level rise probably began to outstrip the ability of the tidal flat accretion to keep pace and the tidal flats were drowned. The tidal currents increased when the growing North Sea finally overtopped the low ridge which joined Britain to the Netherlands and united with the tongue of sea which had been progressing northwards through the Dover Straits and into the area of the modern Southern Bight. Marine sea floor erosion then reworked the tidal flat and glacial deposits. Some of this reworked sediment may have formed the initial bank deposits. The transgression reached more upland areas at its margin by the mid-Holocene and began to erode the landscape and produce the first coastal cliffs. This erosion released further sediment to feed the developing bank system.

Off northeast Norfolk this new coastline may have been between 10 and 40km seaward of the modern coastline. Sandbanks which are presently to the landward of this former coastline could not, therefore, form until the coastline had retreated closer to its present position. If typical present day retreat rates of around 1m/year are representative of retreat rates in the past, some of the Great Yarmouth Banks, which lie within 4km of the coastline could not have formed until relatively recently. They have, therefore, had a relatively shorter period of evolution compared to the more offshore banks.

3.5 Geomorphology of the Norfolk Banks

3.5.1 Norfolk Offshore Banks

The most notable sandbanks in this area are the Norfolk Offshore Banks which lie towards the eastern end of the plateau. The banks are elongated roughly parallel to the modern coast and the tidal currents. They are asymmetric in profile with their steeper slope (up to 7°) facing away from the coast and towards the northeast. Well Bank is over 50km long, 1.7km wide and is in places over 38m high compared to the adjacent sea floor. The shallowest waters on Swatre Bank are 9.6m (the deepest of the Outer Banks) and on Ower Bank 2.1m (the shallowest of the Outer Banks) at Lowest Astronomical Tide (LAT). Houbolt (1968) first recognised dipping internal reflectors within these banks which imply migration to the northeast. It remains to be proven whether migration is presently occurring and at what rate, although recent work has shown the potential for northeastward sand transport (Collins, *et al* 1995). Seismic profiles obtained by BGS, particularly over Leman and Well Banks show them to occasionally overlie the early Holocene intertidal deposits already described (Figure 6). These banks together represent a very large sand accumulation which must have been formed some time after the flooding of the plateau was largely completed, and after open marine conditions became fully established around 6000BP. The sediment either arose from the ‘cannibalisation’ of late Pleistocene or early Holocene deposits already lying on the plateau or from inputs from coastal erosion once the coast reached the antecedent higher topography to the south (i.e. north east Norfolk).

From an analysis of historic bathymetric charts, Caston (1972) found that some of the more offshore Norfolk Banks had elongated towards the north west, the direction of net regional sand transport. The evidence for bank migration perpendicular to their long axis is, however, more equivocal (see discussion in Balson, 1992, p124). Whilst, the internal structure within some of the banks

(Houbolt, 1968; Balson, 1999) provides evidence of north eastward migration it does not necessarily imply that this is a contemporary process. However, many of the Norfolk Banks are covered in active sand waves, which reflect the pattern of modern sand transport around these banks. Over the lower part of the banks the sand waves have their crests aligned more or less at right angles to the bank crest with their steep faces in opposing directions on either side of the sandbank reflecting the dominance of a clockwise circulation of sand around the bank (Collins, *et al* 1995). Where visible, the sand waves on the upper part of the flatter slope are seen to be directed more towards the crest, suggesting that the process that gave rise to the internal structure is ongoing and evidence that such features remain as sinks for sand.

3.5.2 Dudgeon-Dowsing Shoals

This group includes Race Bank, Dudgeon Shoal, Triton Knoll, Outer Dowsing Shoal and Cromer Knoll. In general these banks are between 15 and 20km long, 1.5 and 3 km wide and between 7 and 12m high. They are, therefore, much lower than the Norfolk Offshore Banks and their crests may lie less than 5m below LAT. Sea bed sampling has shown that the banks consist of fine to medium sand.

Race Bank and Dudgeon Shoal both have a conspicuous asymmetric cross-sectional profile with a steeper south west flank slope of 3°. Internal dipping reflectors appear to confirm a south westward migration for these two banks. The implied long-term landward migration is therefore the opposite of the pattern of offshore migration observed in the Norfolk Offshore Banks. A seismic record across the Outer Dowsing Shoal has revealed a more complex internal structure with possible movements to both the south west and north east.

3.5.3 Great Yarmouth Banks

The Great Yarmouth Banks lie sub-parallel to the modern Norfolk coast. The most nearshore of these banks appear to be attached to the shoreface at the location of small headlands, known locally as nesses. Thus, Caister Shoal extends northwards from Caister Ness, and Holm Sand is attached to Lowestoft Ness. The nearshore banks are smaller, much more closely spaced and are generally set much higher in the tidal frame (and are in places inter-tidal) than the more offshore banks. Banks are between 4 and 15km long, 1.5 to 3km wide and are mostly between 10 and 20m high above the surrounding sea floor. Sandbanks such as Holm Sand and Scroby Sands may have much shallower depths on their landward margins than on their seaward sides which are prone to breaking waves. The nearshore banks such as Scroby Sands are within 2 to 3.5km of the modern coastline.

3.6 Sediment sources and sinks

The Great Yarmouth and Norfolk Offshore Banks systems represent a very significant sink for sand-sized sediment in the Southern North Sea. It is difficult to accurately estimate the total amount of sediment involved. The estimates given below are based on dimensions summarised by Caston (1972) and information abstracted from Admiralty Charts of the area. The volume calculation assumes a

simple prism (1/3xLxWxH) for the linear banks and the volume to 10m below ODN given by Reeve *et al* (2001) for the Inner Great Yarmouth Banks.

Table 1 Sandbank volumes

Bank	Distance offshore	Spacing	Length	Average width	Height above bed	Volume
	(km)	(km)	(km)	(km)	(m)	($10^6 m^3$)
Norfolk Offshore Banks						
Indefatigable 3	97	-	31.0	3.0	10.0	310
Indefatigable 2	86	10.3	13.8	1.5	10.0	69
Indefatigable 1	83	3.4	29.3	1.0	10.0	98
Swarte	76	6.9	37.1	1.3	27.4	440
Broken	67	8.6	32.5	1.1	30.5	360
Well	59	8.6	51.9	1.7	38.4	1100
Inner	53	5.2	12.6	1.1	24.4	110
Ower	48	5.2	39.0	1.7	32.9	730
Leman	41	6.9	40.8	1.5	41.2	840
Total	-	-	-	-	-	4100
Outer Great Yarmouth Banks						
Smiths Knoll	38	3.4	30.6	0.9	42.7	390
Hewett Ridge	35	3.4	18.2	1.3	24.4	190
Hearty Knoll	30	4.1	12.2	0.9	32.9	120
Winterton Ridge	24	6.2	17.6	0.9	29.3	105
Hammond Knoll	22	1.7	13.9	0.7	30.5	99
Haisborough Sand	16	6.9	21.5	2.2	33.5	530
Total	-	-	-	-	-	1500
Inner Great Yarmouth Banks						
Great Yarmouth Banks	-	-	-	-	-	620
Overall Total	-	-	-	-	-	6200

For the area as a whole, the volumes in the Dudgeon-Dowsing Shoals need to be added. As some of the shoals are less well defined this is more difficult to quantify. They are however comparable to the Norfolk Offshore Banks and so a volume of the order of 3800×10^6 m^3 is assumed, giving a total estimated volume of 1×10^{10} m^3.

At the present time, the major sediment sources in the area are the eroding cliffs of the Holderness coast and the north east Norfolk coast. The eroding cliffs of Suffolk may also make a contribution, particularly to the sand supply to the Great Yarmouth Banks. The modern rivers along this coast input relatively little sediment, around 0.1×10^6 m^3/year (McCave, 1987), and this is dominated by suspended fine-grained material. Estimates for the inputs from cliff erosion vary widely; for the Holderness coast which consists largely of Pleistocene mud-rich glacial tills retreating at a rate of up to 2 m/year, a figure of between 3 and 4×10^6 m^3/year is generally accepted (Balson, *et al* 1998). This figure includes the yield from the subtidal shoreface which makes an important contribution to the total (Balson and Tragheim, 1999). Of this total volume, approximately 60% is mud, 30% sand and 10% gravel. The northeast Norfolk cliffs are also formed of glacigenic deposits but are less muddy than those of Holderness. These cliffs are presently retreating at up to 1 m/year and are estimated to yield a total of approximately 0.5 to 0.6×10^6 m^3/year consisting of approximately 66% sand and gravel and 33% mud (Clayton,

1989). From these approximate figures it would appear that the recession of the Holderness cliffs yields around 12 times the mud and 4 times the sand and gravel, compared to the northeast Norfolk cliffs. Thus, the Holderness cliffs are by far the dominant local sediment source into the offshore region at the present time.

Even with these very approximate figures it can be seen that at the present annual rate of sand supply from coastal erosion it would take around 6-8,000 years to supply the necessary sand to form all the banks and shoals. If the Holderness cliff source is removed on the assumption that its sand supply does not contribute, then the estimate becomes 25-30,000 years.

In the past, other sources of sediment may have been important. It is very likely that the retreating glacial ice sheet left behind an extensive outwash plain of sands and gravels beyond the ice margin. As the ice retreated more sediments may have melted out of the ice and been deposited on top of the lodgement tills. In the periglacial environment in front of the ice, fine sands and silts may have been blown by winds to form coversands such as those represented by the Twente Formation. As already mentioned, Carr (1999) has suggested that the tills themselves have suffered only minimal erosion but the outwash and coversands may have been readily reworked as the Holocene transgression proceeded. The relative contributions from reworking of glacial sediments on the sea floor and the input from coastal erosion in the past is impossible to judge and it should be remembered that even the estimates above are based on the assumption that modern erosion rates and sediment yields today are typical of the Holocene period.

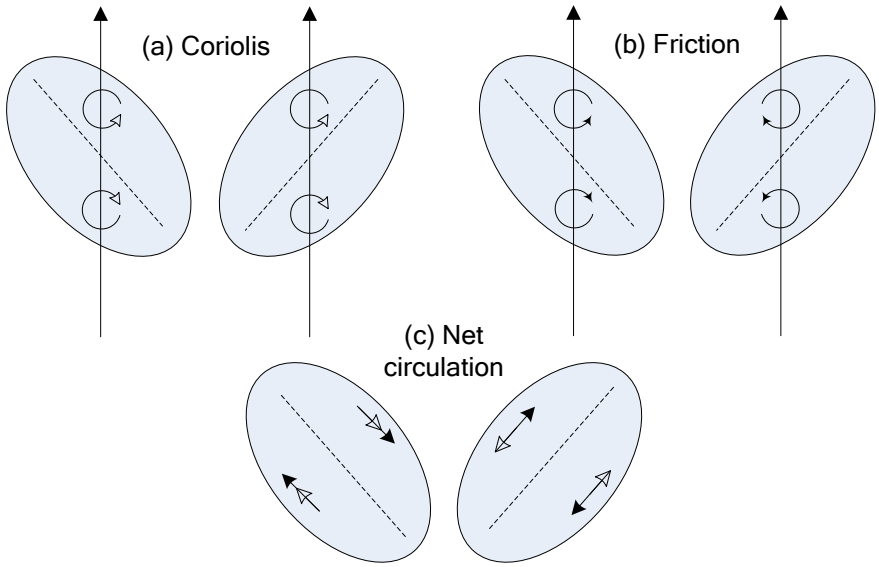
3.7 Norfolk Offshore Banks formation

3.7.1 Formation of linear banks

A mechanism for the formation and maintenance of submerged sandbanks, based on the generation of vorticity, was proposed by Zimmermann (1981). For flows that are highly rectilinear, the bank crest forms at an angle to the flow and is accelerated going up the slope and decelerated going down the slope. For a bank rotated anticlockwise to the flow this results in Coriolis and friction both producing torques in the same direction so that the net circulation is reinforced, Figure 7. In contrast, a clockwise rotated bank tends to generate friction with the opposite sense to the Coriolis torque and so the net circulation is reduced. This concept has subsequently been further substantiated using theoretical analysis and numerical models (Huthnance, 1982a, b; Hulscher & van den Brink, 2001; Besio *et al* 2005). It should also be noted that the case described applies to the Northern Hemisphere and Coriolis would have the opposite sense in the Southern Hemisphere.

Field work by a number of researchers (Houbolt, 1968; Caston & Stride, 1970; Caston, 1972; Huthnance, 1973; Stride, 1974; Stride, 1988; Collins *et al* 1995) confirm that the flows, sediment transport, bed geology, internal bank structure, bank morphology (length, side slopes, bank separation and angle of the bank crests to the tidal flow) and long-term movement of the banks all conform to his model. The vertical growth of banks is limited by wave action, which tends to plane off the crest (Houbolt, 1968; Caston, 1972; Kenyon *et al*, 1981; McCave & Langhorne, 1982; Huthnance, 1982a).

Figure 7 Residual circulation over a sandbank



Huthnance (1982) suggested that sandbanks can form due to a pre-existing bedform instability and that they then can grow rapidly to reach a size and spacing that is in equilibrium with the sea level, tidal and sedimentological conditions. He believed that evolution might typically be measured in centuries and that the relatively rapid evolution implied that the overall size and profile are in equilibrium under present conditions. He concluded that 'the composition of the bulk of a bank should reflect some of the changes in conditions since its formation'.

There is no sedimentological evidence that the sandbanks formed as the result of earlier perturbations of the seafloor. Elsewhere sandbanks have been observed to preserve evidence in their internal structure of earlier sediment bodies which may have formed the 'nucleus' for subsequent sandbank growth. However, the internal structure of the Norfolk Offshore Banks shows only a progressive migration of the bank which exceeds the width (wavelength) of the present bank form and therefore any evidence of an initial form or bedform anomaly is not preserved. Collins *et al* (1995) suggested that the absence of any irregularity seen in a seismic profile across Broken Bank argued against the Huthnance model of origin but they failed to appreciate that the location of the initial bank formation would lie landward (i.e. to the southwest) of the present bank location and that erosion in the swales between the banks, or simply reworking of the sediments as the bank migrates, could have subsequently destroyed any initial perturbation of the sea bed.

The existence of prograding reflectors across the full width of the bank profile, as is typical for the Norfolk Offshore Banks, can also indicate a minimum rate for the advance of the bank in a north eastward direction. Thus, the steep lee face must have advanced by at least the width of the bank during its evolution to account for the observed internal structure. The example shown in Figure 8 for Ower Bank indicates a migration of at least 2000m. If it is assumed that the maximum age for the banks is around 5000 years this indicates a minimum rate of 0.4m/yr over that

period. A profile across the widest part of Well Bank (5000m) shows prograding reflectors across its width which implies a migration rate of at least 1 m/year. The rate could have been higher because the starting location for the migrating bank is unknown and because the bank may have originated more recently than 5000BP. It is also unknown whether the rate of migration has been constant or has had periods of slower migration, or even pauses and reversals, before resuming in the dominant north-eastwards migration.

3.7.2 Headland shoreline retreat banks

Swift (1975) believed that the Great Yarmouth and Norfolk Offshore Banks originated as the result of shoreline retreat during the Holocene. The most inshore of the Great Yarmouth Banks are connected at their landward ends to the shoreline and Swift believed that coastal retreat had resulted in the observed sequence of detached tidal sandbanks on the adjacent inner shelf. He also noted the different character of the banks further offshore with a change at the Hewett Ridges between a more closely spaced sigmoidal form landward and more widely spaced linear sandbanks offshore. He believed that the inner sigmoidal banks would be subject to the cyclic evolution proposed by Caston (1970).

The Swift model requires that banks are formed by sediment supply and accumulation within the nearshore zone and that subsequently shoreline retreat means that the banks become ever more distant from the shoreline. The more offshore the bank, therefore, the more ‘relict’ it has become. This model seems inconsistent with the sedimentological evidence. The internal bank structure shows consistent and presumably active migration of the bank in a north-easterly direction over long time scales. Collins *et al* (1995), in a study using current meters and fluorescent tracers, showed that there is a net offshore residual sand transport to the northeast at the present time supporting the hypothesis of Stride (1988) that sediment transport is still maintaining the outer banks. It is not, however, proven that *new* sediment from erosion of the Norfolk coast is responsible, or that the banks act as ‘stepping stones’ in the sand transport path. It is also possible that the banks represent more self-contained bodies of sediment without the requirement for an external sediment supply. Thus, the sandbank migrates north-eastwards by sediment derived from the stoss side being moved to the steeper lee side whilst maintaining the overall bank volume and form. This movement is most likely to be evidenced in clockwise sand wave migration.

Further evidence against the Swift model for the origin of the Norfolk Offshore Banks comes from the nature of the floor of the North Sea before the banks were formed. An outwash plain of sands and gravels was initially left behind by the retreating glacial ice. Coversands formed by aeolian transport of the finer sand fractions. Lacustrine environments eventually became marshes and formed freshwater peat deposits. The Holocene transgression flooded this plain rapidly and extensive tidal flats of fine grained muds were formed which gradually became drowned by the speed of the transgression. Subsequent marine erosion must have removed much of these tidal flat deposits and also eroded extensive areas of the outwash sands and gravels. There is no evidence of any marked coastline to form the source of sediment to ‘feed’ the offshore bank system until the majority of the

area had already been transgressed. The distribution of the preserved peats might be used as evidence of the maximum extent of any former upland area which existed in this area prior to the Holocene inundation. On the barrier coastline of North Norfolk, between Blakeney and Hunstanton, early Holocene peat deposits are found beneath Holocene marine deposits the length of the coastal lowland. This would appear to indicate a lack of higher ground or potential cliffs seaward of the modern coastline in the past. Coastal peat deposits at Sea Palling and elsewhere are associated with former valleys and therefore do not preclude the possibility of flanking higher ground and cliffs in the same manner that they exist today. Offshore records of peat deposits are very fragmentary and a summary of known locations is shown in Figure 4.

3.8 Great Yarmouth Banks formation

The main features of the Great Yarmouth Banks are indicated in Figure 9. The nearshore banks are distinct from the linear banks system further offshore in a number of respects. They are formed of fine to medium grained sand (Cloet, 1963) and on the steeper margins of the banks the sand is mixed with shell fragments and occasional patches of shingle (Robinson, 1966). The banks sit on the surface of the Pleistocene Crag which is relatively flat, sloping form about -15m to -20m at the outer (eastern) limit of the banks. Only the two main channels, Barley Picle and Yarmouth Roads, are cut into the Crag, extending down below 20m and 30m respectively. The banks are essentially shore parallel with shallow crests, some of which are dry at times. The side slopes are flatter than the linear banks, with a slope of about 2° on the western flank and 0.5° on the eastern flank (Arthurton *et al* 1994). They also exhibit an internal structure and seismic records from the north of South Cross Sand reveal internal northward dipping reflectors, indicating northerly bank movement. It is notable that although highly mobile in the north-south direction, there is no evidence of any lateral migration. Indeed, Arthurton *et al* note that there is no evidence of earlier channels having incised the underlying Crag, suggesting that the bank channel system may have formed in-situ, rather than migrating landwards as a response to the marine transgression.

The historic and geological records establish that, as recently as the 5th Century, the mouth of the Yare disgorged in an easterly direction, without turning parallel to the coast towards Gorleston. There is also evidence of a shoal in the mouth (Cerdic Sand) with channels to the north and south. Subsequent records show the development of a spit extending south almost as far as Lowestoft, before being trained to form the Seventh Haven at the location of the present mouth in 1613. This evidence led Arthurton *et al* (1994) to suggest that the banks off Great Yarmouth were a relatively recent feature beginning to form in about the 5th Century AD. If the supply of sediment due to coastal erosion were assumed to have been approximately constant (at around $5x10^5$ m^3/yr), this would have been sufficient to supply the present volume of the Inner Great Yarmouth Banks over the last 1,500 years. However, if they were recently formed, it follows that circulation around the Inner Great Yarmouth Banks and migration northwards cannot have been the basis for the formation of the Haisborough to Smiths Knoll sequence of banks (the Outer Great Yarmouth Banks).

Another notable feature of the Great Yarmouth Banks is that they are interlaced with flood and ebb channels, as identified by Robinson (1966). Two features are particularly notable. First, the main flow direction is west north west to west south east along the North Norfolk coast to the north of the Great Yarmouth Banks and north north east to south south west along the Suffolk coast to the south. Consequently, the location of the Great Yarmouth Banks is a turning point for the tidal flow. Secondly, the ebb and flood channels cut through the banks at relatively regular intervals, forming what appears to be a series of meandering channels that cross each other at each end of the bank. This pattern was also noted for some of the shoals in the Thames Estuary by Cloet (1972).

3.8.1 Flood-ebb meander channels

The pattern noted by Cloet (1972) is similar to the ebb and flood meander channels that are found in estuaries, as described by van Veen (van Veen, 1950; van Veen *et al* 2005). This effect has recently been reproduced using a morphological model (Hibma *et al* 2003; van der Wegen *et al* 2006) and found to be a function of positive feedback between the bottom topography and tidal currents. A small undulation in the bed will produce variations in the flow and transport fields due to the combined effects of bottom friction and advective processes. Stability analysis (Schuttelaars & de Swart, 1999) has shown that the growth rate is a function of the wave number (which depends on the tidal wavelength in this case) and the optimum growth rates give rise to preferred wavelengths for the channels and shoals. The advective transport converges over shoals and diverges in the channels. The dominant wavelength then depends on the width of the basin and the local maximum flow velocity. Transport is maximised where the flood and ebb channels meet and these fluxes enhance the tidally averaged circulation of the sediment around the shoals. Even after a stable overall pattern has established, the shoals remain highly dynamic because of this enhanced circulation around the shoal. In a similar manner to the growth of linear banks, the vertical growth of the banks is thought to be limited by wave activity (Huthnance, 1982; Hulscher & van den Brink, 2001; Hibma, 2004).

3.8.2 Inner Great Yarmouth Banks formation

We now consider how this mechanism might apply to the Great Yarmouth Banks. The main flow in deeper water essentially follows the somewhat smoothed curve of the coast as it moves from north to south on the flood and vice versa on the ebb. Flows nearer the coast will tend to be slower because of the influence of bed friction and so will not be capable of disrupting the main movement of water. As such, at some distance offshore the main flow acts like a wall to the flow nearer the shore and as a consequence the nearshore flow moves down a channel between the coast and this virtual wall. In addition, this channel has the form of a large meander bend because of the change in orientation of the coast and the tidal flows. The relatively flat nature of the sea bed off the Norfolk coast means that the flow does not slow significantly until very close to the shore. As the flow curves around the coast, the induced centrifugal forces are balanced by a lateral variation in water levels between the inner and outer sides of the bend. This difference in water levels induces tidally averaged residual circulations, both along and cross channel. The primary residual flow is along-channel and Hibma (2004) shows that the

channel shoal system can be reproduced by just considering the along-channel component in a depth-averaged model.

As a result, a channel pattern, not dissimilar to that shown for an estuary in Figure 10, is set up along the coast. The two main flood and ebb channels are identified on Figure 11 passing on opposite sides of the Scroby and Holm sandbanks. The wavelength of the meander is about 30km, which based on the modelling simulations carried out by Hibma (2004) would suggest that the “virtual” width of the channel is about 7.5km off the shore, which is just beyond the outer flanks of Holm and South Cross Sands. Whilst there are additional flood and ebb channels further offshore, these become progressively weaker as the water gets deeper and the influence of the main offshore flow begins to dominate. As discussed below, the more offshore flood and ebb channels may also be the result of earlier meander forms. The resultant flow patterns are broadly consistent with the circulation patterns identified both from a mapping of flood and ebb channels (Robinson, 1966) and from sand wave data, Figure 12. In addition, the dominance of the ebb tide for the frontage from Benacre to north of Great Yarmouth means that this mechanism is also consistent with the observed northward movement of the banks, as noted earlier.

3.8.3 Outer Great Yarmouth Banks formation

However, if the mechanism discussed in Section 3.8.2 is correct, then it has only a limited ability to generate new banks to the north because the flood and ebb channel pairs will tend to maintain circulation around individual banks. Some loss of sand is likely during storm events as material is put into suspension and moved off to the northeast (Stride, 1988), particularly from the more exposed northern end of the bank system. If the geological and historical evidence presented by Arthruton *et al* (1994) is also correct, banks off Great Yarmouth are a relatively recent feature (around 5th Century AD). This does not necessarily mean that they did not exist. Simply that if they did, they were not in their present position, or that some of the other banks formed the nearshore banks at an earlier stage of the Holocene transgression, at some other position along the coast.

The formation of these banks can be explored further by considering the possible alignment of the coast some 5,000 years BP. The coastlines in Figure 13 are based on the reconstruction of the Holocene transgression, undertaken as part of the LOIS study (Shennan *et al* 2000). Although the coastline some 5,000 years ago was not dissimilar in overall shape to the present day Anglian coast, the turning point where the Norfolk coast begins to turn south was somewhat further to the north. If one takes this coastline and moves the present day flood-ebb channel meanders north and east to be in a similar position relative to the change in coastal alignment, this quite remarkably coincides with the position of the Middle Cross and Haisborough Sands, Figure 14 (left hand plot). Over the last 5,000 years the coast is assumed to have retreated at a rate of about 1m/yr giving a movement of about 5km. If the banks have also moved laterally to the north east at a similar rate, they will have moved offshore by about 5km (see black arrows on Figure 14). It is therefore more likely that the channels formed a tighter meander than the present day meander, as shown in the right hand plot of Figure 14 (although recent historical data suggests that Haisborough Sands may not have moved very much

(McCave & Langhorne, 1982). Thus, the banks system would have initially formed between Caister at the southern end and Mundesley to the north. As is evident from Figure 14, it is possible that this bank system was the source for the formation of the entire sequence of the Outer Great Yarmouth Banks from Haisborough Sands out to Smiths Knoll.

On the basis of the foregoing arguments, the genesis of the Offshore Great Yarmouth Banks is an earlier sequence of nearshore banks, established when the position where the coast starts to change its orientation was located further to the north. For some 3,500 years the erosion of the Norfolk coast fed sediment to the bank system which progressively expanded to the east, intersected by a series of flood and ebb channels. As the coast eroded, so the change in alignment altered and at some point a new flood ebb channel meander sequence was able to establish itself inside the old one, causing the initiation of the present day Great Yarmouth Bank sequence further to the south. Based on their different alignment and form, it is possible that the Hewett and Smiths Knoll banks were formed by an even earlier sequence, some time after about 7000BP when water levels in the area began to be sufficient to support the development of banks and shoals.

3.9 Ness formation

Between Winterton and Orford, the coast turns from an east-west alignment to a northeast-southwest alignment. It makes this change in a series of steps at approximately uniform intervals around the coast, Table 2. Whilst river outfalls account for some of these control points, most are due to nesses, where on average the coast alters direction by some 24°, approximately every 9 to 10km.

Table 2 Ness alignments and spacing

Ness/promontory	North alignment	South alignment	Change in alignment	Distance between control points (km)	
Winterton	41-S	63-E	22-N	10.3	
Caister	63-E	90-S/E	27-N		8.6
Yarmouth (estuary)			0	8.6	
Lowestoft	72-E	110-E	38-N/P		9.3
Benacre	90-E	108-S	18-N	9.3	
Southwold (estuary)	108	138	30		8.6
Minsmere (sluice)			0	6.7	
Thorpeness	90-E	108-E	18-N		11.7
Orfordness					

Control points in italics are not nesses; S=straight coast current aligned, E=embayment, N=ness, P=promontory; Average spacing is 9.1km and average change of orientation is 24°; alignment numbers are degrees relative to north.

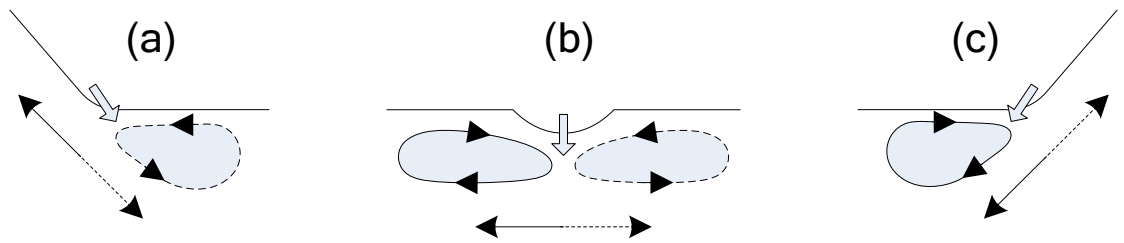
Robinson (1966) suggested that the nesses represent areas of excess shoreline sedimentation and are associated with converging flood and ebb channels. From a study of historic charts he found that the ebb-flood channel complex was highly dynamic and, as the dominance of the ebb or flood varies, so the nesses have migrated along the coast both north and south.

Sediment analyses identified the coarsening of the beach material away from cliff sources and led McCave (1978) to suggest that nesses were associated with the offshore movement of sediment. Robinson's (1966; 1980) view is diametrically opposed to McCave's in that he proposed nesses were sites of onshore sediment transfer, mainly as a result of residual currents. Carr (1981) examined both the views of McCave and Robinson in light of more recent data from between Aldeburgh and Southwold and came to the conclusion that nesses "seem more probably" sites of offshore sediment movement, although it was admitted that Robinson's argument could not be disproved.

To shed some further light on the possible formation of ness features, the circulation in the vicinity of a change in coastal alignment has been reviewed. Nesses might be thought of as promontories on an otherwise straight coast. Zimmerman (1981) describes how headland eddies drive the circulation patterns on either side of such promontories, Figure 15b. Frictional effects increase as the water gets shallower towards the coast and at the same time the flow is accelerated near the headland. As a result, vorticity is produced along the coast and is largest at the headland. This results in a residual circulation in the “lee” of the headland which switches to the other side of the headland when the tide reverses. When the coast is not straight the symmetry is broken and a single eddy is formed on the “lee” side of the headland relative to the direction of the flow, Figures 15a and 15c. This is the basis for the formation of banner banks (Dyer, 1986).

Hence, for this to be the controlling mechanism, there should be two shoals either side of a promontory, or a single shoal downstream of the headland in the direction of the dominant flow. However, this is not the case at the nesses on the Anglian coast where the shoal is to the north of the headland in all cases except Lowestoft. For the nesses to the north (Winterton and Caister) the flood flow is dominant, whereas to the south (Benacre and Thorpeness) the ebb flow dominant.

Figure 15 Residual circulation adjacent to headlands



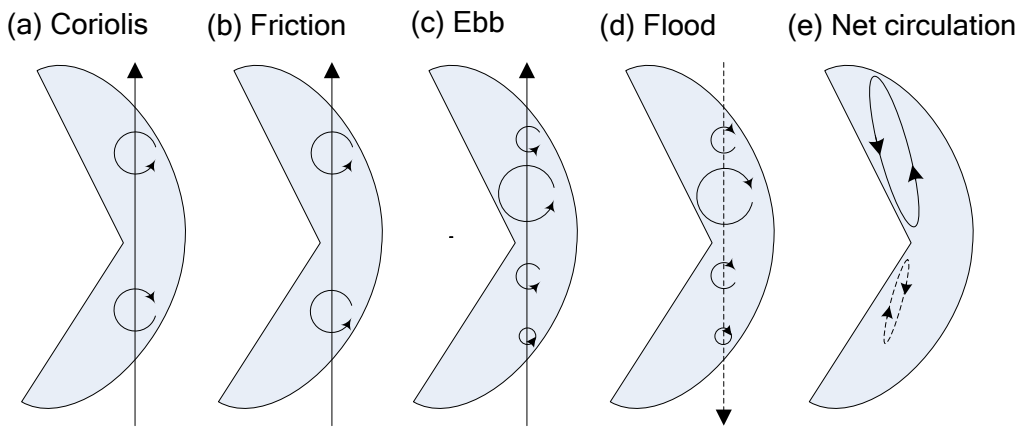
It is surmised that this is because the ness is not a fixed geological feature but a mobile sedimentary feature that adjusts its own form in response to the flow conditions. To the north there is a significant littoral transport that carries material from the Norfolk cliffs towards Winterton. Similarly, to the south there is a northerly drift transporting material from the cliffs at Covehithe and Easton towards Benacre (Vincent, 1979; Townend & McLaren, 1988; HR Wallingford, 2002). At each change in coastal alignment the drift towards Lowestoft reduces. As the rate of transport decelerates, so material will accumulate potentially creating wider, flatter beaches. When this occurs, where the coast changes alignment, the effect is to

create a form of shore-attached shoal. As well as considering eddies around headlands, Zimmermann (1981) also considered how vorticity provided a mechanism for the formation and maintenance of submerged sandbanks, as already outlined in Section 3.7.1.

If we now consider a ness as a shore attached shoal, we can represent this as two halves of a sandbank, each half having a different “crest” angle (in this case represented by the high water mark) to the mean flow direction, Figure 16. As the flow approaches the shoal, water is accelerated up the slope, so that a water column experiences a slightly higher Coriolis force on its shallower side. This is reversed as the water moves off the shoal, Figure 16a. When the flow direction is reversed so the sense of the torque is reversed on both sides of the shoal. Bottom friction also produces a torque with currents being slowed more in the shallower water, Figure 16b.

Consequently, as the flow approaches a shoal to the left of the flow, Coriolis and friction oppose each other on the upslope and reinforce each other on the downslope of the shoal, Figure 16c. When the flow direction reverses, such that the shoal is to the right of the flow, this effect is also reversed and the two sources of vorticity reinforce each other on the upslope and counteract each other on the downslope, Figure 16d. Considering the upper and lower halves of the shoal in Figure 16, the upper half has a net influx of anticlockwise vorticity giving rise to an anticlockwise net circulation. The lower half is a net importer of clockwise vorticity, but a much smaller amount, so that a smaller clockwise residual is generated in this area. The resultant circulation pattern bears some similarity to the promontory case, Figure 15b, but is now asymmetric. This asymmetry becomes even more marked when one considers the real flow directions rather than the mean direction, as used in Figure 16, and takes into account differences in flood and ebb dominance.

Figure 16 Residual circulation on a shore attached bank or ness



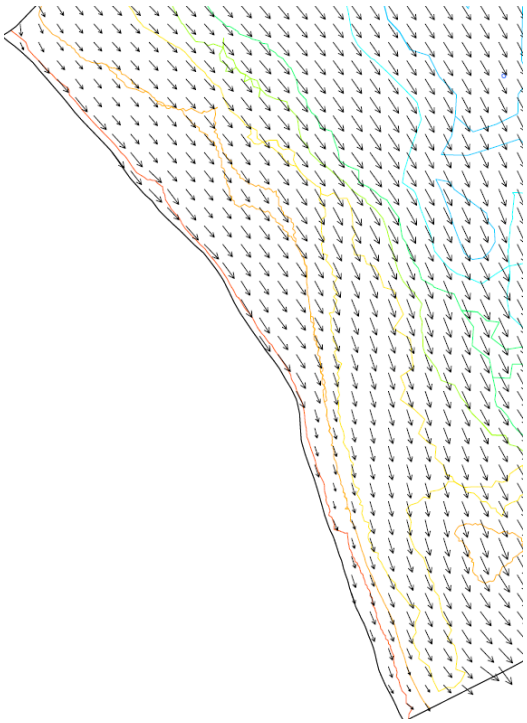
One of the key distinctions between a promontory or headland and a ness is that the change in coastal alignment at a ness is only just sufficient to generate the sort of recirculation described above. This means that the flow is almost capable of following the shore contours. When there are differences in the flood and ebb flows this can mean that the flow follows the coast in one direction but forms a recirculation in the other. Detailed modelling of the hydrodynamics undertaken for the Southern North Sea Sediment Transport Study (HR Wallingford, 2002) show this to be the case, Figure 17. On the flood, the peak flows are seen to follow the coastal contours, whereas on the ebb there are circulations on both sides of the ness but the stronger gyre is to the north of the ness. When waves from the north were added, the circulation pattern was similar. However, when waves from the southwest are applied, a small recirculation is generated to the south of the ness on the flood and both gyres are suppressed on the ebb. Based on the disposition of the shoals at Winterton, (Robinson, 1966) it would seem that, for this location, the ebb gyre is almost non-existent and the nearshore bathymetry is dominated by the movement of the gyre to the north of the ness.

On the basis of the mechanism described, nesses will form where there is a sufficient supply of sediment to create a shoal at a point where the coast alters its alignment by turning through a small angle (around15 to 25°). On the east coast, any shoals or banks associated with a ness are more likely to form to the north because of the asymmetry in the influence of Coriolis and bed friction. For the nesses between Winterton and Thorpness this is the case, with the exception of Lowestoft. However, here the coast turns through a much larger angle and it is also a point of sediment transport convergence. It might therefore be argued that this behaves more like a promontory, with the potential to form banks on either side. This is supported by the fact that a sediment exchange between the banks and coast was observed by Jolliffe (1963), which is interpreted as material leaving the coast at this point and tracking east to the offshore banks.

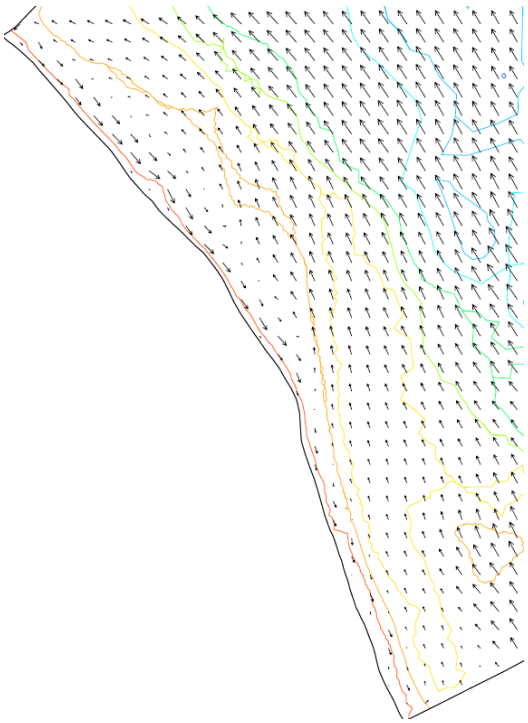
It would also appear that the nesses move along the coast in response to the prevalence of the ebb and flood flows. Thus, the tendency at Winterton and Caister is for the nesses to move south because the flows along this length of coast are flood dominant, whereas at Benacre the flows here tend to be ebb dominant and the ness has moved to the north, as reported by Robinson (1966).

Finally, it follows that if the mechanism described for forming the nesses is correct, whilst sediment may converge on a ness, transported by littoral drift, the recirculation will tend to move material offshore at the ness itself but return material to the shore at some distance to the north (and south if the change in alignment is large enough). Whether the ness accretes, migrates alongshore, or provides a pathway for sediment to be transported either alongshore, offshore to the banks, or both, will depend on the respective magnitude of the littoral drift and the recirculation cells. As noted by Robinson (1966), the resultant pattern and disposition of flood and ebb channels are also likely to be strongly influenced by storms and surge events.

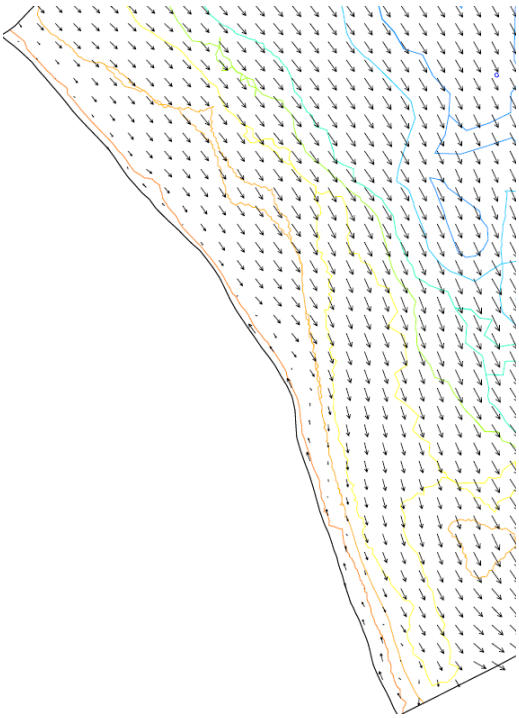
Figure 17 Flow patterns around Winterton Ness (HR Wallingford, 2002)



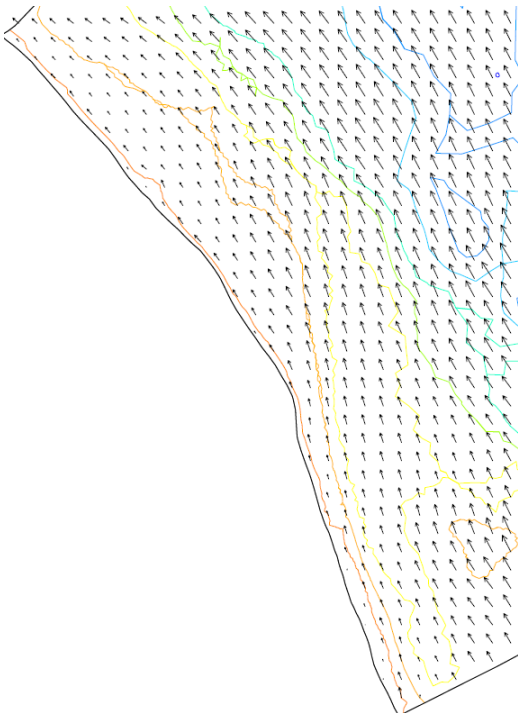
(a) Peak flood current on spring tide



(b) Peak ebb current on spring tide



(c) Peak flood current on spring tide with waves from southwest



(d) Peak ebb current on spring tide with waves from southwest

Consequently, nesses are similar to the offshore banks in that they constitute a dynamic component of the transport pathway, with self-organising properties that enable them to maintain their characteristic form over time.

4 Summary of existing understanding

As a backdrop to the discussion of possible conceptual models for the formation and subsequent evolution of the banks, this section provides a shorthand summary of what is presently known, drawing extensively on the material presented in Section 3. The key observations, findings from theoretical work and data or understanding that are relevant to the discussion that follows in Section 5 are provided as a series of bullet points. Reference to specific banks follows the definitions provided in Figures 1 and 9, whilst the grouping of banks retains the subdivision defined at the beginning of Section 3.2.

4.1 Norfolk Offshore Banks

(i) The banks are formed on top of a relatively flat bed, comprising Pleistocene sediments (Houbolt, 1968; Caston, 1972; Stride, 1988).

(ii) They are generally asymmetric with a steeper face of about 6° to the northeast and a flatter face of less than 1° on the opposite flank (Houbolt, 1968; Caston, 1972; Stride, 1988).

(iii) The internal structure has been clearly identified from seismic data and cores to reveal a layered formation of sands with thin interleaving clay layers (Stride, 1988).

(iv) The sediments have the same mineralogy as the Norfolk cliffs (Baak, 1936; Chang & Evans, 1992).

(v) If the banks are reworked glacial outflow deposits, they must have moved at least the width of the bank to establish the observed internal structure (Balson, 1999).

(vi) The observed layering of the banks, found in cores and seismic profiles, is explained as sand laid down by tidal currents, overlain by sand deposited immediately after storm events with a much higher content of fines. This leads to the observed thin mud layers (Stride, 1988).

(vii) Some the outer banks (Swarte and Indefatigable) may be moribund with their crests now in comparatively deep water (Kenyon *et al,* 1981).

(viii) The internal structure of the Norfolk Offshore Banks indicates that the banks are migrating to the northeast. Rates in the literature vary from 1-16m/yr (Houbolt, 1968; Caston, 1972; Stride, 1988), and, as noted in (v), to generate the observed structure they must have migrated the width of the bank (i.e. 2-5km which gives a rate of ~0.5-1m/yr).

(ix) A lateral rate of 1m/yr would indicate a 5km movement to the north east over the last 5,000 years. At this rate, the historical data available for the last 100 years, or so, would only reveal ~100m of movement, which is within the survey and charting error.

(x) Secondary helical circulations were originally suggested by Houbolt (1968) as a mechanism for bank formation, however, Huthnance (1982) reasoned that these would be too weak because of the size, spacing and relatively flat slopes of the linear banks. This was subsequently confirmed by field measurements (Collins *et al,* 1995).

(xi) Bank formation has been shown to be due to a combination of bed friction, vorticity and Coriolis (Zimmerman, 1981; Hulscher *et al,* 1993; 1996; 2001; Carbajal & Montaño, 2001; Besio *et al* 2005; 2006).

4.2 Outer Great Yarmouth Banks

(i) Similar in form to the Norfolk Offshore Banks, although some of the banks are more sinuous and this may reflect the subdivision of the bank into two or three smaller linear banks following the model suggested by Caston (1972).

(ii) These banks are also migrating to the north east (although this can vary locally due to the break up of the sinuous form) but their form is dominated by flood and ebb residual channels.

4.3 Inner Great Yarmouth Banks

(i) Formed on top of a flat Pleistocene bed (Arthurton *et al,* 1994).

(ii) The main channels do not appear to have migrated landwards as part of the marine transgression (Arthurton *et al,* 1994).

(iii) The banks show evidence of moving to the north but not laterally (Arthurton *et al,* 1994).

(iv) Sediment transport occurs in the opposite direction on either side of the banks leading to recirculation of sediment (typically south on the inner flank and north on the outer flank).

(v) Beach sediments coarsen in a southerly direction from Cromer to Lowestoft and northerly direction from Covehithe to Parkstone (McCave, 1978).

(vi) Nesses are mobile sedimentary features that when considered in conjunction with the main estuaries are spaced along the coast at approximately 9km intervals (Robinson, 1966).

(vii) At each ness the coastal orientation changes on average by 24°.

(viii) Between Winterton and Benacre the coast turns through 72°, making the transition from the central North Sea alignment to that of the Southern Bight, so that the shore is aligned to the prevailing tidal regime in both sectors.

(ix) The banks are highly mobile, more or less shore parallel, with western slopes of about 2° and eastern slopes of about 0.5°, which is quite distinct from the Norfolk Offshore Banks which have angles of 6° and 1° respectively (Arthurton *et al,* 1994; Stride, 1988).

(x) The ridge off Lowestoft is a stable feature comprising a consolidated gravel bed (Cloet, 1963).

(xi) There is evidence of sediment exchange between the shore and the banks at Lowestoft (Jolliffe, 1963; Talbot *et al,* 1970) but not at several of the other nesses [Caister (Reid, 1958); Winterton (HR Wallingford, 2002)].

(xii) The volume of the Great Yarmouth Banks (between 0 and 10m below OD) is increasing at about $5x10^5 m^3/yr$ (Reeve *et al,* 2001).

(xiii) In the area to the east of South Cross Sands, the gravel beds lie beneath or in proximity to peat deposit layers (Arthurton *et al*, 1994, Bellamy, 1998) and are considered to be relict Pleistocene deposits (Harrison, 1988). As a consequence, this area is not considered to contribute, to any significant degree, to the highly mobile sediment transport that occurs in the vicinity of the inshore bank system (HR Wallingford, 2002). Calculations made by ABPmer and HR Wallingford for this study corroborate this statement (see Appendix A).

4.4 Tides and waves

(i) Tidal flows to the north are flood dominant in a south-east direction turning to the north-east further offshore to the east of the Anglian coast.

(ii) Flows to the south are ebb dominant in a north north-easterly direction.

(iii) Residual circulation around the Norfolk Offshore Banks is northerly on the landward flank trending towards the crest of the banks and southerly on the seaward flank of the banks.

(iv) The peak flows are to the north in the Southern Bight and to the east off Norfolk, converging in the area of Winterton Overfalls out to the Hewett Ridges and Smiths Knoll, extending south to Lowestoft under spring tide conditions (HR Wallingford, 2002).

(v) Averaged monthly winds fields are from the west and south west, except for April to June when they are from the north (Odd *et al,* 1995).

(vi) Waves limit the vertical growth of banks tending to plane off the crest (Houbolt, 1968; Caston, 1972; Kenyon *et al,* 1981; McCave & Langhorne, 1982; Huthnance, 1982).

(vii) Although several authors (Kennedy, 1969; Stride, 1974; Swift, 1975) have suggested that the tidal rotation is important for bank formation, this is not significant when the tides are highly rectilinear, as is the case in the area of the Norfolk Offshore Banks (Huthnance, 1982; Besio *et al,* 2005).

4.5 Sediment transport, sources and sinks

(i) A bed load parting exists between the nearshore and offshore and east-west from about Benacre (McCave, 1971; Kenyon *et al,* 1981).

(ii) Offshore and within the Norfolk Offshore Banks sediment transport is to the north north west (Stride, 1974; 1988; Collins *et al* 1995).

(iii) Nearshore the transport is to the south, although there are substantial variations around the Great Yarmouth Banks, as the dominance of ebb and flood varies (HR Wallingford, 2002, modelling and collated sand wave data).

(iv) For the Norfolk Offshore Banks the transport is to the north on the shoreward flank and to the south on the seaward flank. In both cases, there is evidence that the transport veers up the slope towards the bank crests (Houbolt, 1968; Caston, 1972; Stride, 1988; Collins *et al* 1995). The dominance of the northerly transport gives rise to the noted northeasterly migration of the banks.

(v) The influence of the ebb/flood residuals means that the transport pathways are more variable for the banks within the Great Yarmouth Bank system.

(vi) Storm surge activity suspends substantial quantities of sediment from the banks. On average, the suspended material tends to move in a north easterly direction, with the banks acting as a series of 'stepping stones'. This mechanism is thought to be capable of moving sediment up to 100km seawards (Stride, 1988).

(vii) Outwash from the last glaciation may have left a substantial quantity of sediment in the region of the Norfolk Offshore Banks (Balson, 1999; BGS, 2002).

(viii) Cliffs between Weybourne to Happisburgh supply about 400,000 m^3 of sand per year, with about 75% going to the east, and Covehithe to Easton supply about 30,000 m^3 per year (Cambers, 1976; Clayton, 1989).

(ix) These cliffs have been eroding since the sea level reached its current position about 5,000 years ago, with an average rate of retreat this century of about 1m/yr based on map data and a similar rate over the last 900 years based on historical records. This erosion has also formed the offshore ramp (1.5mm per 1m) and given the continuity of this ramp, such erosion is likely to have been a feature over the entire period since sea level rose to within a metre or two of its present position, i.e. the last 5,000 years (Clayton, 1989).

(x) The littoral supply is approximately equal to the current rate of growth of the Great Yarmouth Bank system (~$0.5 \times 10^6 m^3/yr$).

(xi) It has been suggested that there is a phase lag between sediment transport and the instantaneous current which can give rise to a difference in the net direction of sediment transport relative to the flow residual (Kennedy, 1969; Stride, 1974; Swift, 1975). However, Huthnance (1982) notes that such a lag is reduced near the sea floor and given the scale of the banks this effect is likely to be small. This effect also depends on the rotation of the tide, and is of secondary importance when the tides are highly rectilinear (Besio *et al,* 2005).

(xii) Northerly movement of sediment has been observed between Benacre and Lowestoft (Cloet, 1963).

(xiii) The littoral drift from the south and north converges towards Lowestoft, although the drift varies around the embayments and some lengths of coast experience significant inter-annual reversals in the net transport potential (Vincent, 1979; Townend & McLaren, 1988; HR Wallingford, 2002).

(xiv) The approximate volume of sediment stored in the banks, excluding the Dudgeon-Dowsing Shoals, is estimated as follows:

- Inner Great Yarmouth Banks = 620×10^6 m^3 (10%);
- Outer Great Yarmouth Banks = 1500×10^6 m^3 (24%); and
- Norfolk Offshore Banks = 4100×10^6 m^3 (66%).

5 Review of conceptual models

This section discusses the conceptual genesis and evolutionary models that have been proposed by the scientific community, and endeavours to identify the mechanisms that provide the best explanation of the available evidence.

5.1 Norfolk Offshore Banks

5.1.1 Model 1.1 – Shoal retreat massifs

(a) Estuarine banks survive transgression to become shelf banks;

- In the early Pleistocene the proto-Thames flowed to the northeast, with an outfall in the direction of the central North Sea basin (Arthurton *et al,* 1994);
- Given the potential size of this system, estuarine formed banks might be expected towards the mouth of such a system (Swift, 1975), roughly in the region of the contemporary Norfolk Bank system, which could have been left behind by subsequent marine transgression; and
- If left as relic forms during subsequent glaciations and associated falls in sea level, these would provide a source of material to be re-worked during the sea level transgression over the Holocene.

This model is unlikely because such relic features would have almost certainly been eroded during the Anglian glaciation.

(b) Shoreface connected banks become relic as coast migrates;

- Shoreline erosion forms shoreface connected banks of sigmoidal form;
- As the coast retreats under sea level rise the sigmoidal banks breakdown in to linear banks (following the sequence described by Caston, 1972);
- The linear banks are reworked by the prevailing tidal regime but are essentially located in the position of the original coast; and
- As a consequence the banks mark the retreat path of the coast over the Holocene.

This model is unlikely because it overstates the amount of erosion of an elevated shoreline that is required to generate the banks in their current positions. The relatively even spacing of the Norfolk Offshore Banks (~7km) would suggest an almost constant rate of retreat over a distance of 90km from the outer bank to the present day coastline. However, the very flat nature of the bed out to about 90km in the area of the Norfolk Offshore Banks and the rapid rise of sea levels from 20m below to within a few ms of present day level, which took place within a relatively short period of 500-1000 years some 7,000 years ago, means that this area would have been flooded rapidly giving rise to very rapid retreat of the coastline

(100-200m/year). In addition evidence from the bed sediments suggests that the outer banks sit on what was once wetland and the more elevated landscape only occurs much closer to the shore – possibly between Hewett and Lemen Banks (Balson, 1999).

5.1.2 Model 1.2 – Glacial outwash fan

- There is evidence to show that the limit of the last (Weichselian) glaciation ran approximately along the western end of the Norfolk Offshore Banks (Balson, 1999; BGS, 2002); and

- Outwash from the glaciation is thought to have deposited a substantial quantity of sediment in the area, which following the retreat of the ice and rise in sea levels over the Holocene, has been re-worked to form the present day banks (Houbolt, 1968; Robinson, 1968).

This model provides a possible explanation of the origin of the Norfolk Offshore Banks. For this to be the source of the sediment in the Great Yarmouth Banks requires sediment to have moved onshore, for which there is no evidence. Whilst the re-working argument accommodates the role of contemporary processes local to the Norfolk Offshore Banks, it does not account for changes along and close to the shoreline. Hence, this model provides a well supported explanation for the Norfolk Offshore Banks but this cannot be generalised to the system as a whole.

5.1.3 Model 1.3 – Coastal erosion and mobile bank system

- Contemporary process have been shown to be capable of forming and maintaining all of these bank systems and that both the Outer Great Yarmouth Banks and Norfolk Offshore Banks are migrating to the northeast;

- Coastal erosion from the Norfolk and Suffolk cliffs is transported along the coast to the Great Yarmouth Bank system;

- The circulation of sediment around the Inner Great Yarmouth Banks, with the northerly sediment migration on the outer bank sequence and southerly drift along the shore, provides a large-scale circulation that is fed by the littoral drift;

- Excess sediment is lost from the Great Yarmouth Banks at the northern end to form new banks. Winterton Overfalls and North Cross Sands are the most recent sequence of sinuous banks to form, with Haisborough Sand to Hearty Knoll and Hewett Ridges and Smiths Knoll the most mature of the transition sequence;

- The ebb and flood channels within the sinuous banks eventually break through to create two or three linear banks along the lines suggested by Caston (1972). This provides for the rapid initial migration away from the coast;

- Once formed as linear banks, these migrate to the northeast by the progressive transport of sediment over the bank crest (this may also be assisted by suspended transport under storms as discussed by Stride, 1988);

- This model assumes that coastal erosion has been similar to the present rates over the last 5,000 years so that the coast may have started some 5-10km seaward of its present position. This means the outer banks if initiated in a position similar to Haisborough Sand (~15km off the coast) would have had to travel 50-60km to reach their present position about 90km offshore, which implies a rate of about 10m/year; and

- The net result is that the banks represent a time history of the erosion that has taken place on the Anglian coast but do not indicate the history of the shoreline position (as implied by Model 1b) because of their movement to the northeast.

There are two problems with this model:

1) The rate of bank movement required is very high and, over the charted period of the last 100 years or so, implies the banks should have all moved about 1km. Reported rates vary between 1 and 16m/year (Houbolt, 1968; Caston, 1972; Stride, 1988) but the lower estimates (1-5m/year) seem more reasonable for the system as a whole.

2) The quantity of sediment required to form the banks is 3-4 times more than the current rate of coastal erosion would have provided over the last 5,000 years. This reduces to a factor of 1.5-2 if the shoreface is assumed to provide a similar volume as the coast erodes (as per the evidence of Wingfield and Evans (1998) in respect of the Holderness coast). It is possible that a different coastal alignment (e.g. a coastline that continued in a north west/south east alignment as far as the Lincoln coast) would have provided substantially more sediment. This would be about three times the length of coast and, if the supply increased proportionately, this would have been sufficient to supply the material for the Norfolk Offshore Banks and Great Yarmouth Banks.

It does however, introduce the area occupied by the Dudgeon-Dowsing Shoals and the genesis of these banks would need to be included in any model. Given that modelling of the palaeogeography of the North Sea (Shennan *et al,* 2000) suggests an embayment for a proto-Wash existed on the Lincoln coast at least 6,000 years ago, it seems unlikely that the coast from Winterton extended to the northeast as far as the Lincoln coast much after 7,000 BP, when the area of the Norfolk Offshore Banks would have been under about 5-10m of water. So, although with the upper rates of observed bank movement and an optimistic assumption about the amount of sediment supply, this model is feasible, on the available evidence it is considered to be less likely than Model 1.4.

5.1.4 Model 1.4 - Combination of coastal erosion, glacial outwash and mobile bank system (Models 1.2 + 1.3)

- The Norfolk Offshore Banks were formed from the glacial outwash sediments and re-worked by contemporary processes, as described for Model 1.2;

- The Great Yarmouth Banks are a sink for cliff erosion that is transported to the area by littoral drift and nearshore residual drift;

- As the Inner Great Yarmouth Banks grow over time (rate of ~$5x10^5 m^3$/yr) new banks are formed at the northern end and these are the genesis of the Outer Great Yarmouth Banks;

    - If the most recent sequence is the sinuous banks between Winterton Overfalls and North Cross Sands, this is forming some 10-20km off the coast. Assuming that 5,000 years ago the coast was about 5km seaward (retreat of about 1m/yr) then banks that formed early on and became relict would now be about 15-25km off the coast. This is almost the range of the Haisborough Sand to Hearty Knoll sequence (15-30km offshore) but the Hewett Ridges to Smith Knoll sequence are some 35-40km offshore;

    - If the banks are assumed to migrate to the north east at a rate of 1-3m/year (lower end of observations) the outer sequence would now be some 20-40km off the coast and an intermediate sequence might be expected to be 15-30km off; and

    - Thus although similar to the tidal shoal-retreat massif concept of Swift (1975), in this case the retreat of the coast is supplemented by the offshore migration of the banks themselves.

- This model therefore uses the mobile banks model to explain the evolution of the Great Yarmouth Banks (Model 1.3) and the glacial outwash model to explain the origin of the Norfolk Offshore Banks (Model 1.2) albeit with modern day processes reworking the banks and causing them to migrate to the northeast; and

- The annual coastal input is about 0.05-0.1% of the volume of mobile sediment in the Inner Great Yarmouth Banks. Assuming the banks maintain an approximately constant volume over geological time, this rate of input would generate a new bank approximately every 500 years. On this basis there would be about 10 banks in the system. Depending on what one counts as a bank there are 6-8 banks in the Outer Great Yarmouth Banks and ~9 banks in the Norfolk Offshore Banks. Allowing for some loss of sediment to the wider system, and some variation in the rate of supply, it therefore seems reasonable to suggest that the Outer Great Yarmouth Banks could have been generated by this mechanism.

This model explains the dynamic nature of the banks and is consistent with but not explained by the prevailing hydrodynamic and sediment transport processes. The sediment supply from the eroding cliffs is approximately equal to the volume of mobile sediment within the Great Yarmouth Banks as a whole. If some supply from shoreface erosion is included, this readily provides for losses to the North Sea sediment transport system and a thin layer of sediment on the sea bed. The different origins of the Norfolk Offshore Banks and Outer Great Yarmouth Banks may also explain the slight difference in orientation and the offset between the Outer Great Yarmouth Banks and the Norfolk Offshore Banks (the latter being on a more northerly axis to the north east). This model assumes that the Inner system of banks has been present from the time that coastal erosion began to provide a significant source of sediment (~5,000 years ago). The available evidence suggests that the presence of the banks immediately seaward of the town of Great Yarmouth is a relatively recent development (last 1,500 years). This model does not readily explain any migration of the system along the coast, other than on the basis of the relative supply of sediment from the Norfolk and Suffolk cliffs.

5.1.5 Model 1.5 – Headland tidal meander channel and glacial outwash

- The Norfolk Offshore Banks were formed from the glacial outwash sediments and re-worked by contemporary processes, as described for Model 1.2;

- The Great Yarmouth Banks are a sink for cliff erosion that is transported to the area by littoral drift and nearshore residual drift;

- The present day Inner Great Yarmouth Banks system is a tidal meander system generated by the change in flow direction around the Anglian coast from Norfolk to Suffolk;

- One or more similar meander systems existed further to the north at earlier stages in the Holocene and were responsible for the formation of the Outer Great Yarmouth Banks, approximately in their existing positions (they may have moved north-eastwards by 2-5km since having formed, based on the elapsed time since formation); and

- As with Model 1.4 the bank volumes are consistent with the continuous supply of material from coastal erosion.

This model is consistent with the current geological understanding of the area and supported by the prevailing hydrodynamic and sediment transport processes, in the form of a flood-ebb tidal meander system. It also offers an explanation for the formation of the Outer Great Yarmouth Banks using the same mechanisms at an earlier stage of the Holocene. The mechanism for tidal meander formation has been extensively researched within estuaries and it is argued that similar physical conditions are present along this length of coast. However, a detailed quantification of this particular interpretation of the bank formation remains to be undertaken. This model therefore provides a qualitative explanation of the bank formation at this stage.

5.2 Great Yarmouth Banks

5.2.1 Model 2.1 – Relict coastline

- As sea levels have risen the coast has retreated westwards;
- At some point the beach sediments (supplemented by those being transported from the west and south along the shore) have rolled up against some more solid geology allowing beaches to form;
- Continued coastal erosion initially leaves extensive sand flats. River channels across these flats tend to be aligned shore-parallel because of the littoral transport; and
- With further shoreline migration and rising sea levels, the flats become banks.

There is some evidence of early Flandrian beach or spit deposits on the outer flank of the bank system. However, the underlying Crag formation, at a level of about 15-20m below OD, is relatively flat and extends well seaward of the banks. The current shore parallel channels are deeper than the level of the underlying Crag formation that the banks sit on. If these channels had migrated landwards with the shoreline, one might expect to see evidence of earlier channel alignments in the underlying bed to seawards, infilled by the overlying bank sediments but, as already noted, the Crag formation is fairly flat. In addition, historical chronicles and geological evidence indicate that the Great Yarmouth Banks are a relatively recent feature (last 1000-1500 years), making this model unlikely.

5.2.2 Model 2.2 – Circulation cell

- Littoral drift moves material from the Norfolk and Suffolk cliffs, with a convergence zone at Lowestoft;
- Sediment is moved offshore at Lowestoft and transported north in the offshore banks of Holm and Corton Sands;
- Material continues to track north some along the Cross Sands banks and some along the Scroby banks;
- The northern most bank on Cross Sands provides the genesis of sigmoidal bank which moves off to the northeast and breaks down into two or three linear banks; and
- Sediment on Scroby moves north to Cockle Shoal where it is moved shoreward to rejoin the south going transport at Caister Ness moving in the nearshore down to Lowestoft.

This model accounts for, but does not explain, the fact that the banks exhibit a very high degree of mobility but have maintained a relatively consistent overall form over the last two centuries. However, there is some doubt as to whether this circulation pattern does form a closed cell, or whether sediment from North Scroby goes north to Winterton Overfalls. There is also evidence to suggest that the Inner Great Yarmouth Banks have only been present off Great Yarmouth for about the last 1,500 years. As a consequence, they cannot have been a long-term mechanism for the genesis of the Outer Great Yarmouth Banks.

5.2.3 Model 2.3 – Headland tidal meander channel

- Littoral drift moves material from the Norfolk and Suffolk cliffs, with a convergence zone at Lowestoft;

- The flood and ebb residual channels are consistent with the dynamics of a flood-ebb tidal meander channel hugging the coast and generated by the change in coastal alignment; and

- This feature is unlikely to have been present off the Great Yarmouth coast for more than 1500-2000 years but the same mechanism could have existed further to the north generating a nearshore bank system which has now become the Outer Great Yarmouth Banks.

This explanation of the Great Yarmouth Banks has many similarities to the Shoal Retreat Massif mechanism of Swift (1975). Shore attached banks are progressively detached from the coast as it retreats leaving the earlier banks as relict features on the sea bed. In this case there may be some ongoing migration to the northeast but the magnitude is small in comparison to the magnitude (area covered) by the overall bank system. It is consistent with the available evidence and adequately explains the observed mobility of the banks using a known mechanism.

5.3 Nesses

5.3.1 Model 3.1 – Residual channels

- Converging flood and ebb channels transport sediment towards the ness (Robinson, 1966); and

- Sediment is moved onshore as a result of this tidal convergence.

Although the evidence of both bathymetry and sand wave movement are consistent with the plan form described there is significant disagreement as to whether nesses are locations where sediment is moved onshore. The tidal residual eddy mechanism identified by Zimmerman (1981) suggests that any residual circulation should be offshore at promontories. McCave (1978) and others have argued that sediment leaves the coast at nesses to feed the offshore banks and a review by Carr (1981) came to the conclusion that nesses "seem more probably" sites of offshore sediment movement.

5.3.2 Model 3.2 – Drift convergence zone

- Littoral drift along the coast on either side of the ness is typically towards the ness;
- The sediment leaves the coast at the ness to feed the offshore banks; and
- This transfer may occur during storms (McCave, 1978).

Whilst this model is consistent with the beach processes, it does not explain the formation of shoals on one or more sides of the ness. In addition clear evidence for the offshore migration of sediment is only provided from experiments carried out off the Lowestoft ness.

5.3.3 Model 3.3 – Headland shoal

- Littoral drift along the coast on either side of the ness is typically towards the ness;
- The change in coastal alignment is small such that flows are almost able to follow the shore contours;
- The convergence of sediment due to littoral drift creates a shore attached shoal;
- Residual tidal circulation over the shore attached shoal generates asymmetric circulation cells, with a stronger cell to the north and a weaker or non-existent cell to the south;
- Whether sediment is gained or lost by the ness will depend on the relative magnitude of the littoral drift, and the tidal eddies; and
- The shoals are also likely to be disrupted by storm and surge events.

This model is consistent with both beach and nearshore processes and explains why the shoals form to the north of the nesses on the east coast. The conceptual model is also consistent with the detailed flow modelling around Winterton Ness undertaken as part of SNSSTS Phase 2.

6 Conclusions

The geological and geomorphological evidence for the origins of the Great Yarmouth and Norfolk Banks systems has been reviewed. The Outer Banks (Leman, Ower, Inner, Well, Broken, Swarte, etc.) lie in an area believed to be close to the limit of the last glacial ice advance. It therefore seems likely that their origin is at least in some way related to the antecedent sediment supply that would have existed prior to the marine transgression. The low topography of the landscape ensured that the marine transgression flooded the area rapidly until it encountered higher ground some distance north east of the present day coastline. The rate of shoreline recession would then have slowed dramatically, with the switch from rapid inundation to a slower coastal erosion. This coastal erosion would then become the dominant source of sediment to the nearshore banks, whereas the dominant source of sediment for the offshore banks was from 'cannibalisation' of the sea floor.

The mechanisms that best explain the available evidence for the various groups of banks are therefore as summarised in Model 1.5 and comprise;

- Reworking of sediments from outwash sediment of the last glaciation to form the Norfolk Offshore Banks (model 1.2);

- Headland tidal meander channels provide the mechanism for forming and maintaining the Inner Great Yarmouth Banks (model 2.3);

- A similar sequence of tidal meander channels provide a plausible mechanism for the formation of the Outer Great Yarmouth Banks (extension of model 2.3); and

- Headland shoals at nesses to explain the local circulation and formation of flood and ebb residual channels (model 3.3).

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MCA Civil Hydrography Programme http://www.mcga.gov.uk/c4mca/mcga-safety_information/nav-com/mcga-dqs-hmp-hydrography.htm

UKHO Civil Hydrography Programme - Resurvey areas and reports http://www.ukho.gov.uk/amd/CivilHydrographyProgramme.asp.

7.2 Non-referenced Internet links

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DTI offshore strategic environmental assessment http://www.offshore-sea.org.uk/site/scripts/sea_archive.php.

Southern North Sea Sediment Transport Study Phase 2 http://www.sns2.org/.

The Anglian Coastal Authorities Group http://www.northnorfolk.org/acag/.

University of East Anglia, Coastal Processes Research Group, Blinks (**B**each **Link**s to **S**andbanks) http://www.uea.ac.uk/env/coastal/Blinks.htm.

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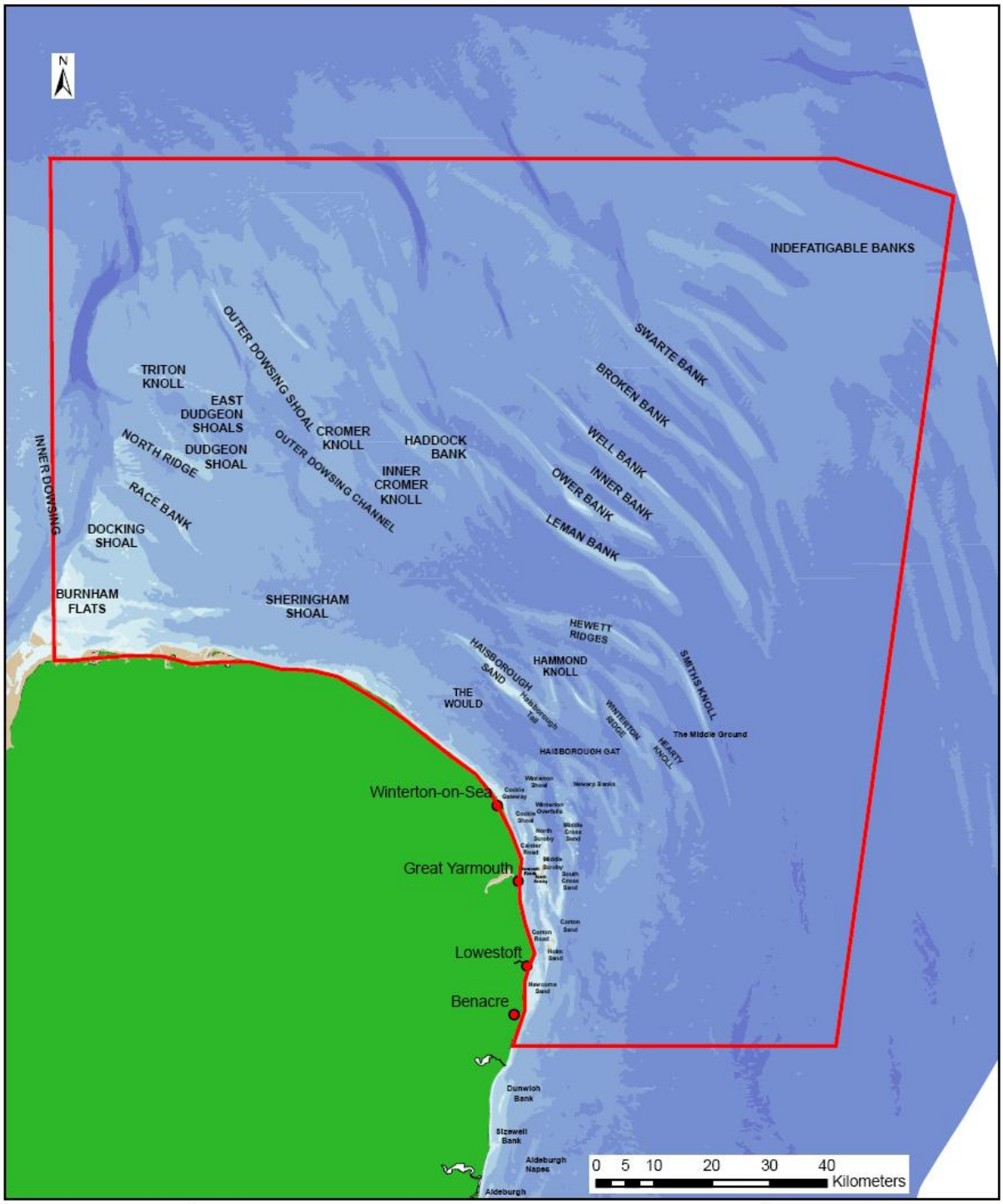
Figures



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Study area

Figure 1

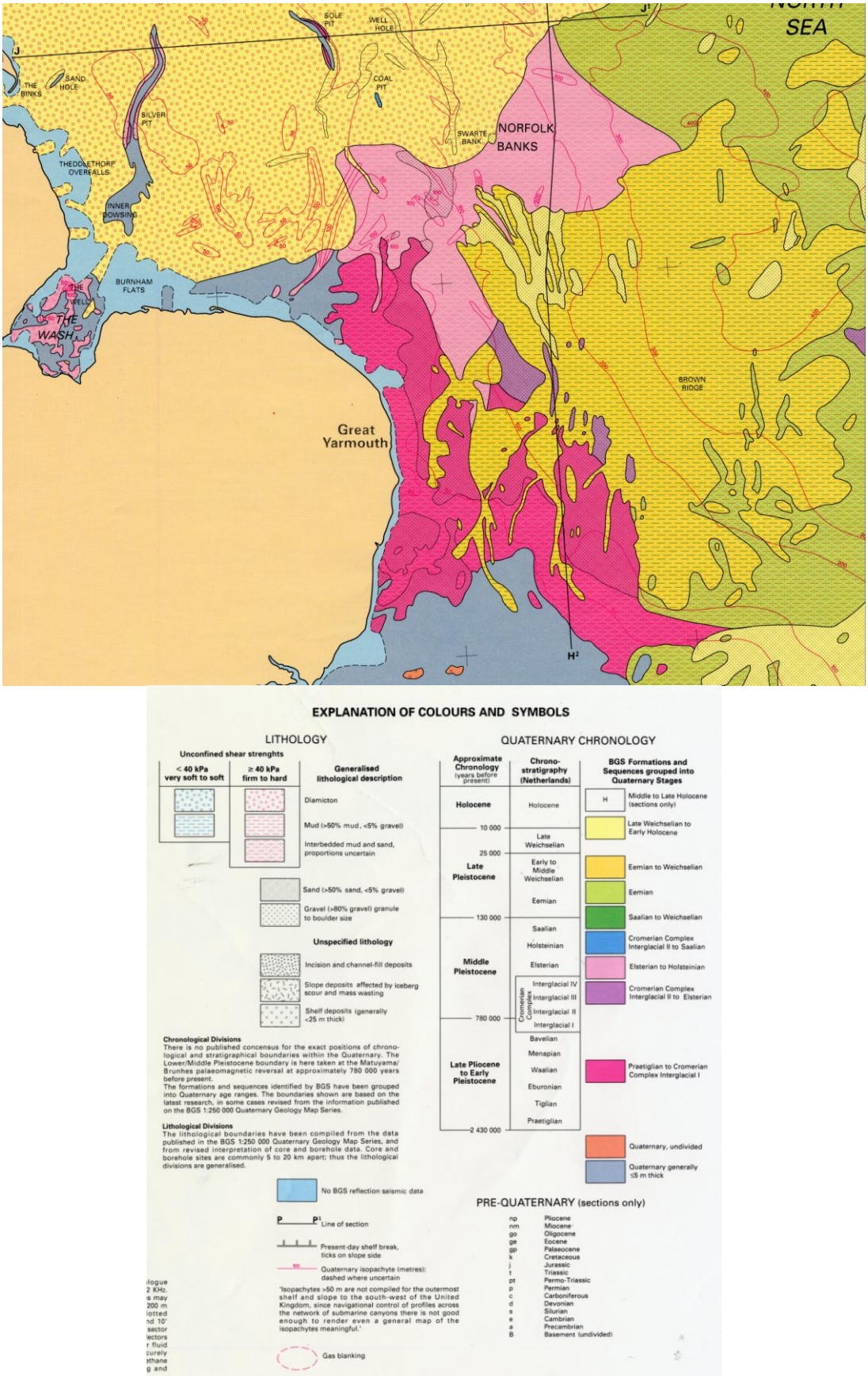


Figure 2 Quaternary geology of the study area (British Geological Survey, 1994).

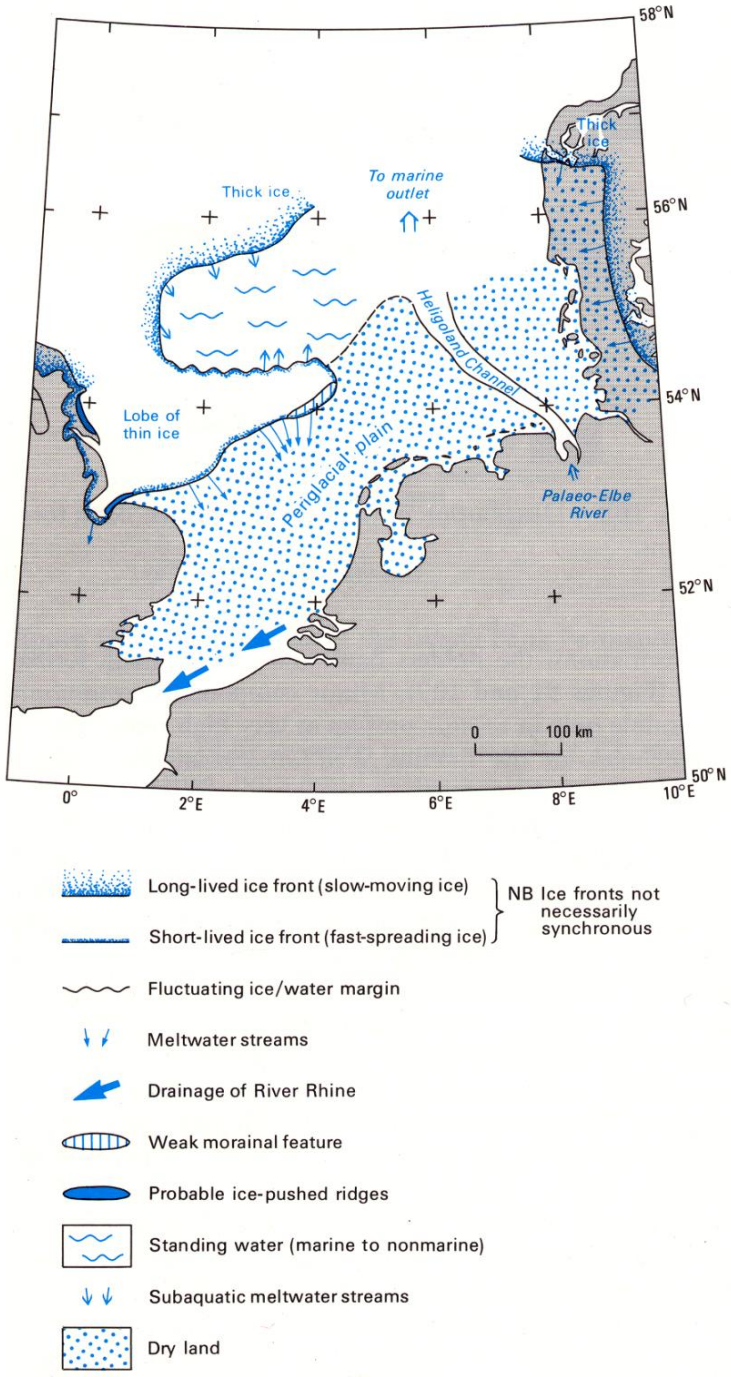


Figure 3 **Generalised palaeogeography of the southern North Sea at the time of the maximum extent of the Devensian ice (after Jeffery, 1992).**

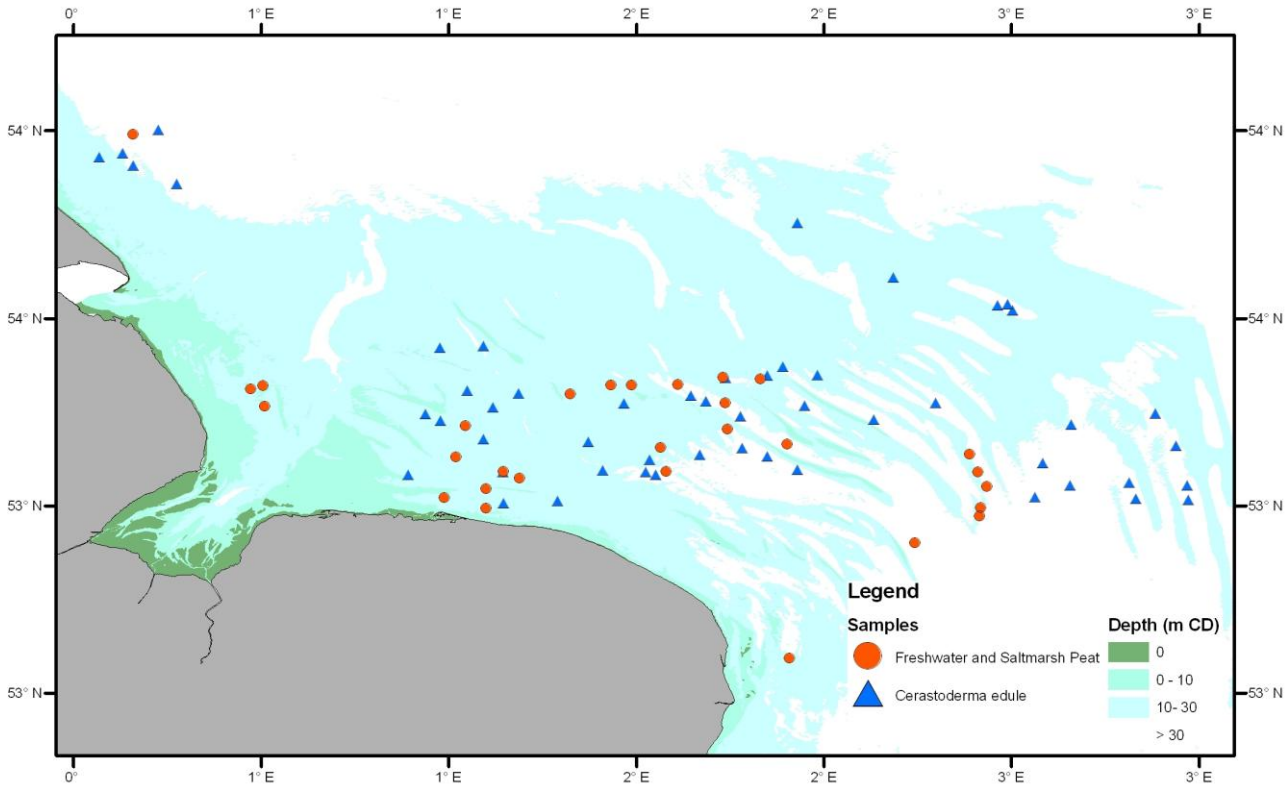


Figure 4 **Map showing location of sea bed samples with *Cerastoderma edule* and core locations with freshwater or saltmarsh peat, (after Balson, 1999).**

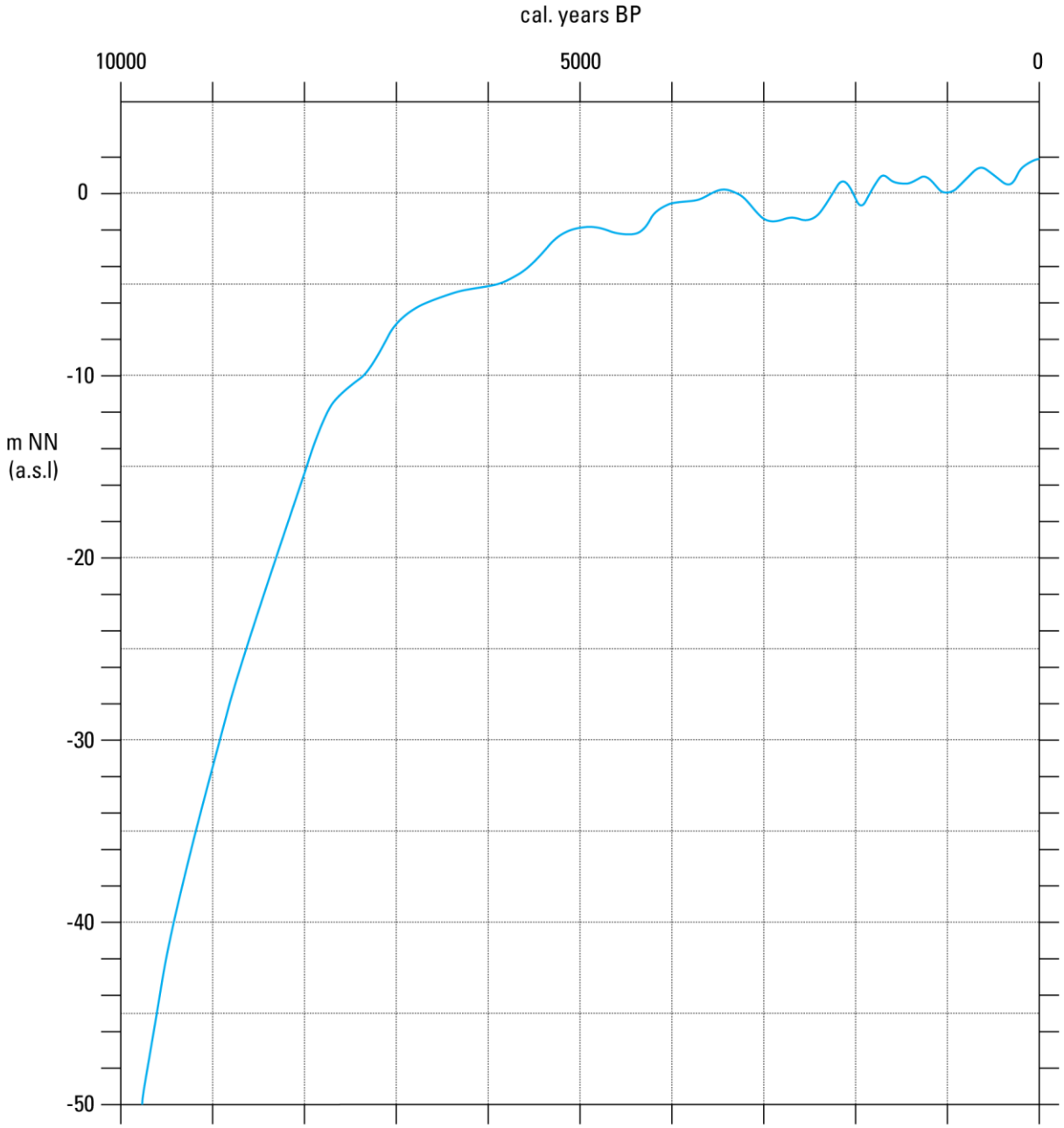


Figure 5 **Sea level changes (MHW) in the southern North Sea (after Behre, 2007) (NN = Normal Null, a.s.l. = above sea level).**

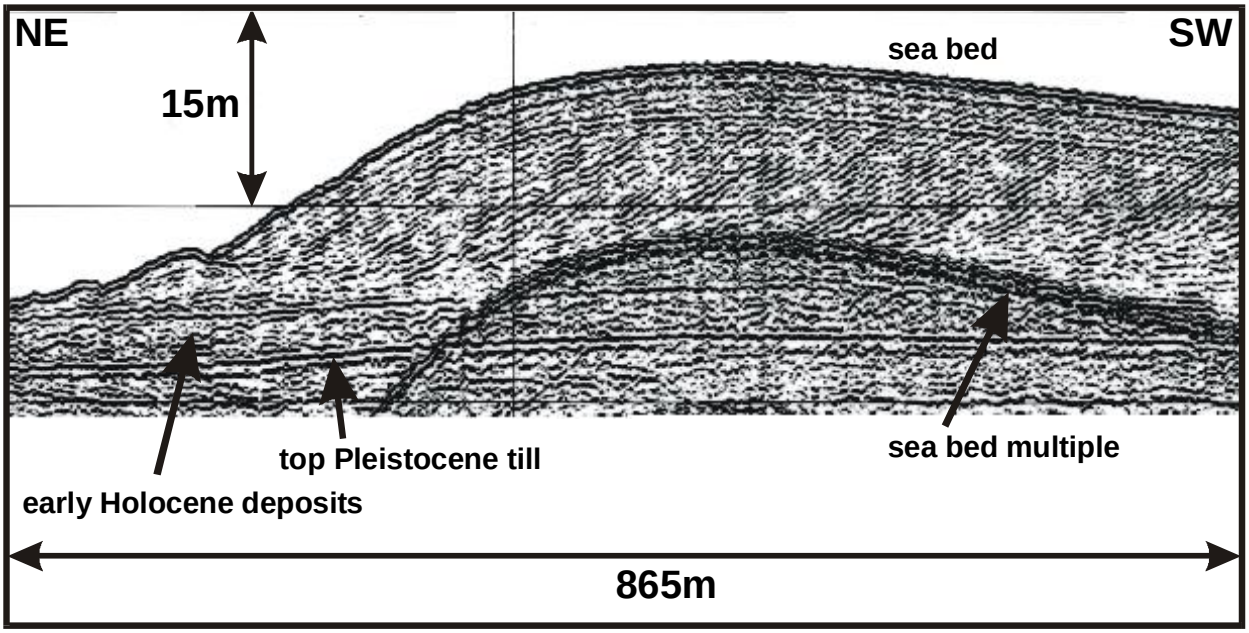


Figure 6 Shallow seismic reflection profile across Well Bank showing internal reflectors resulting from migration to the northeast. The sandbank overlies early Holocene intertidal sediments and Pleistocene glacigenic deposits (after Balson, 1999).

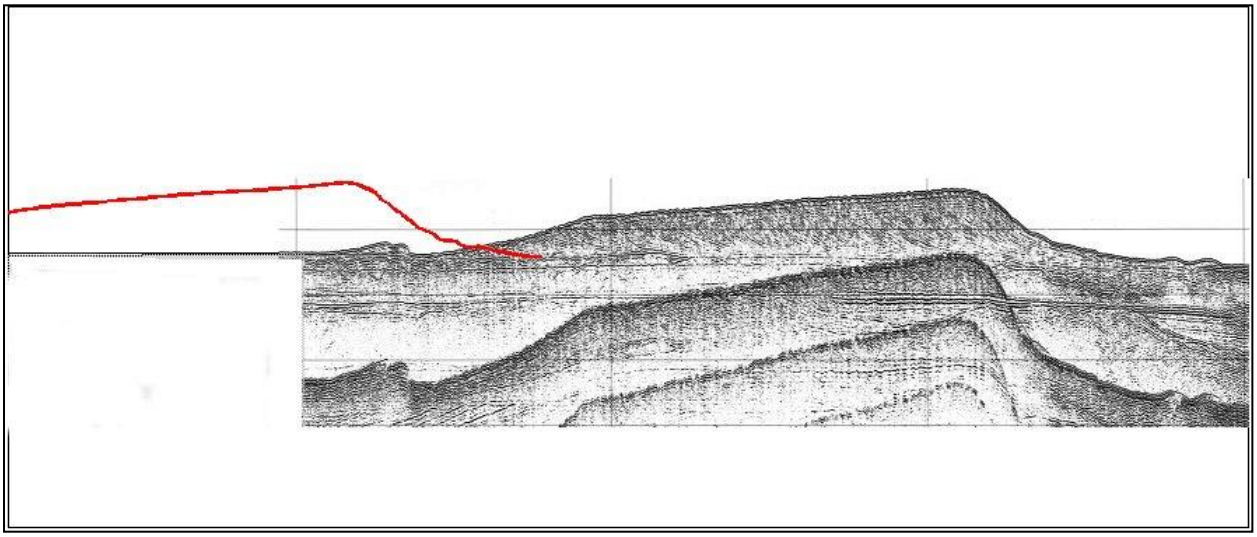
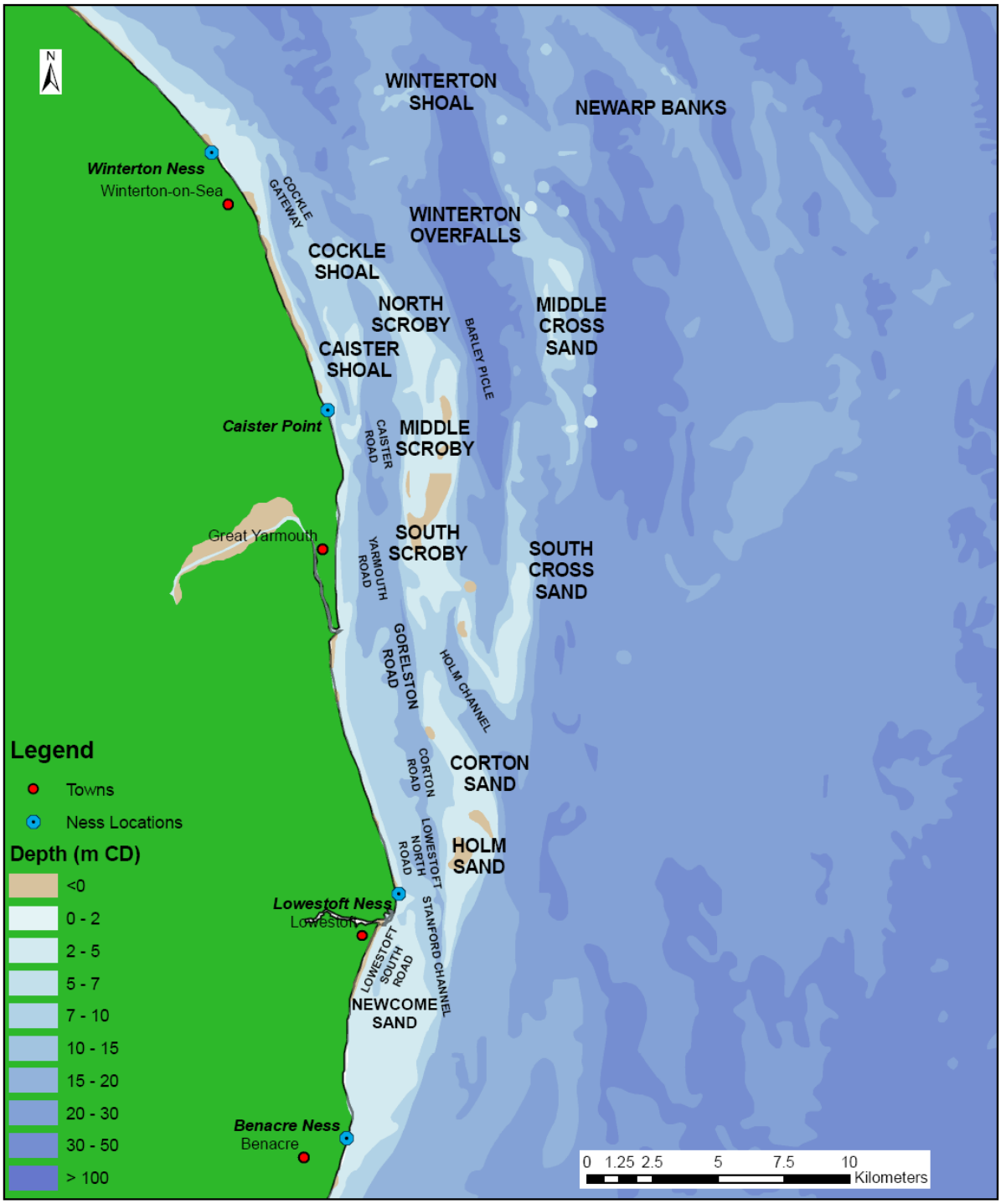


Figure 8 **Seismic Profile across Ower Bank showing dipping internal reflectors parallel to the steep (NE) face. Red profile depicts a former location of the bank showing minimum distance of migration indicated by the internal structure (after Balson, 1999)**



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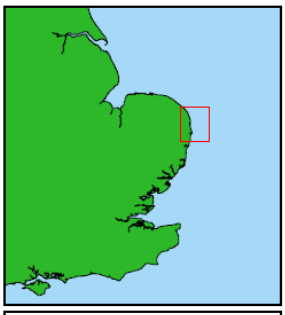

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Great Yarmouth Banks

Figure 9

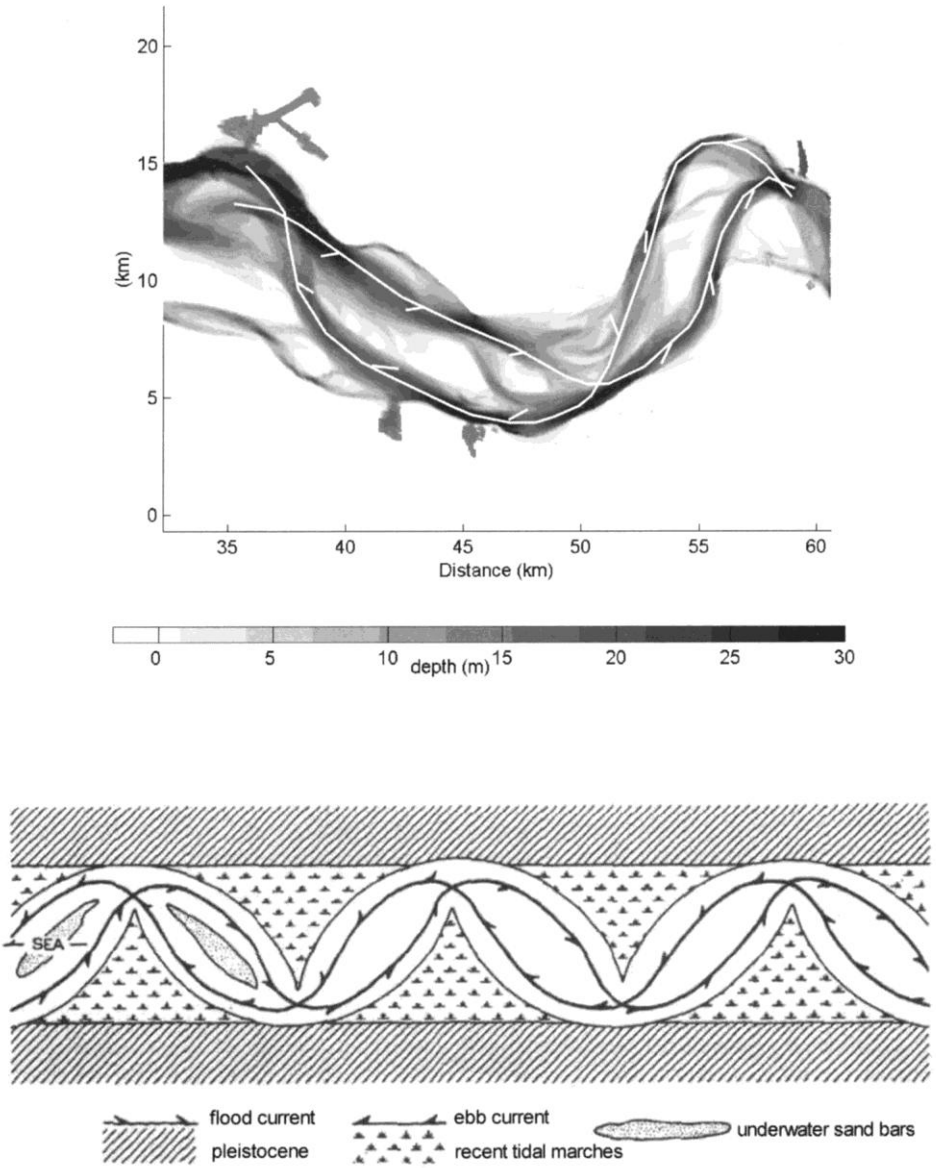
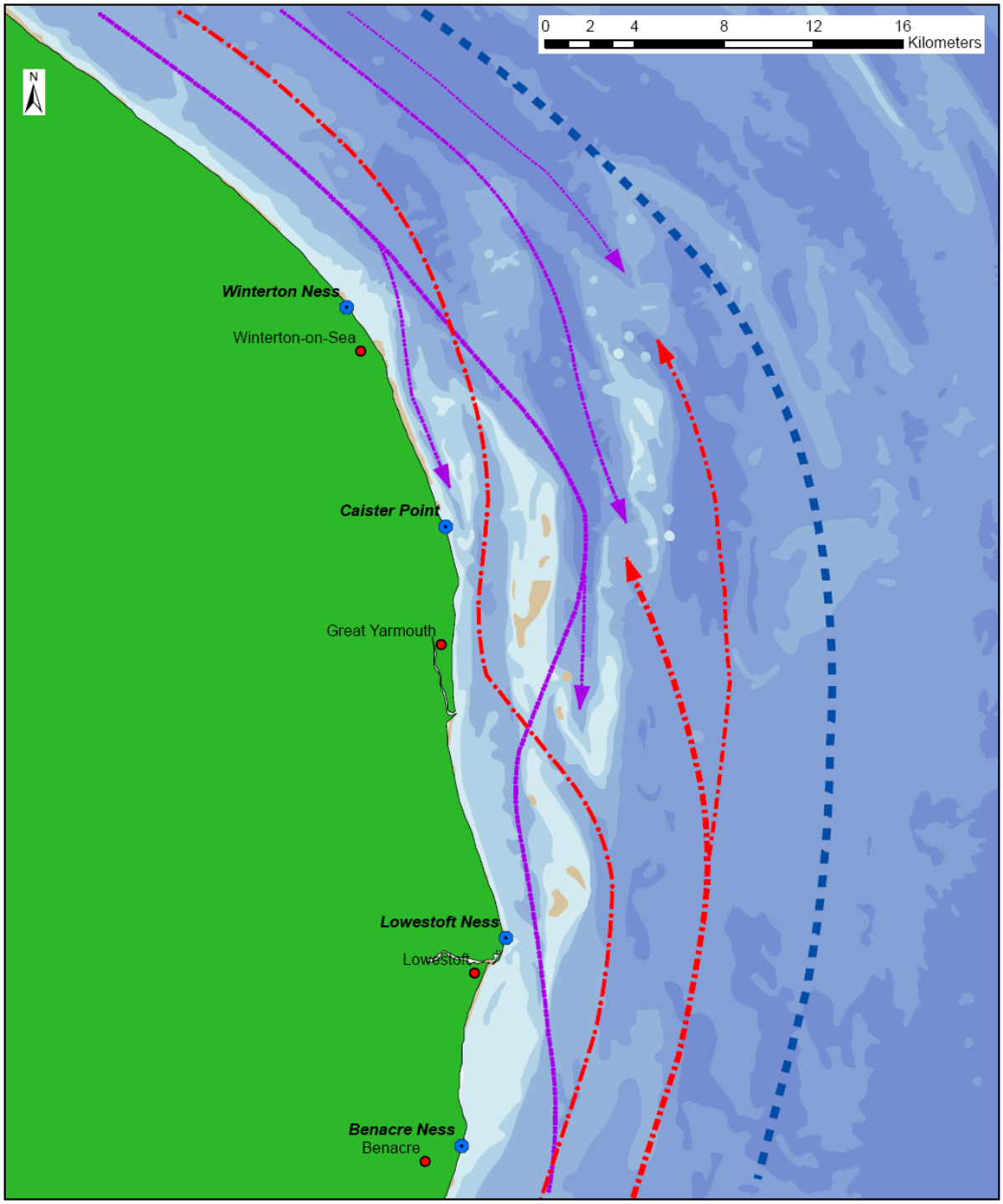


Figure 5.5: (a) Section of the Western Scheldt estuary, the Netherlands, 1996. The trajectories indicate the direction of the residual velocity. (b) Sketch of meandering channel system by Ahnert (1960).

Figure 10 Illustration of meandering flood and ebb channels in an estuary (from Hibma, 2004).

Reprinted from Estuarine Coastal and Shelf Science, Volume 57 (2003), Hibma, A., de Vriend H.J., Stive M.J.F., Numerical modelling of shoal pattern formation in well-mixed elongated estuaries, pages 981 – 991 (figure page 988), Elsevier, 2003, with permission from Elsevier.



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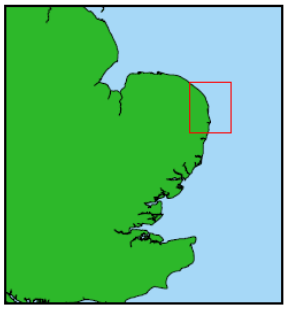
- Ebb
- Streamline



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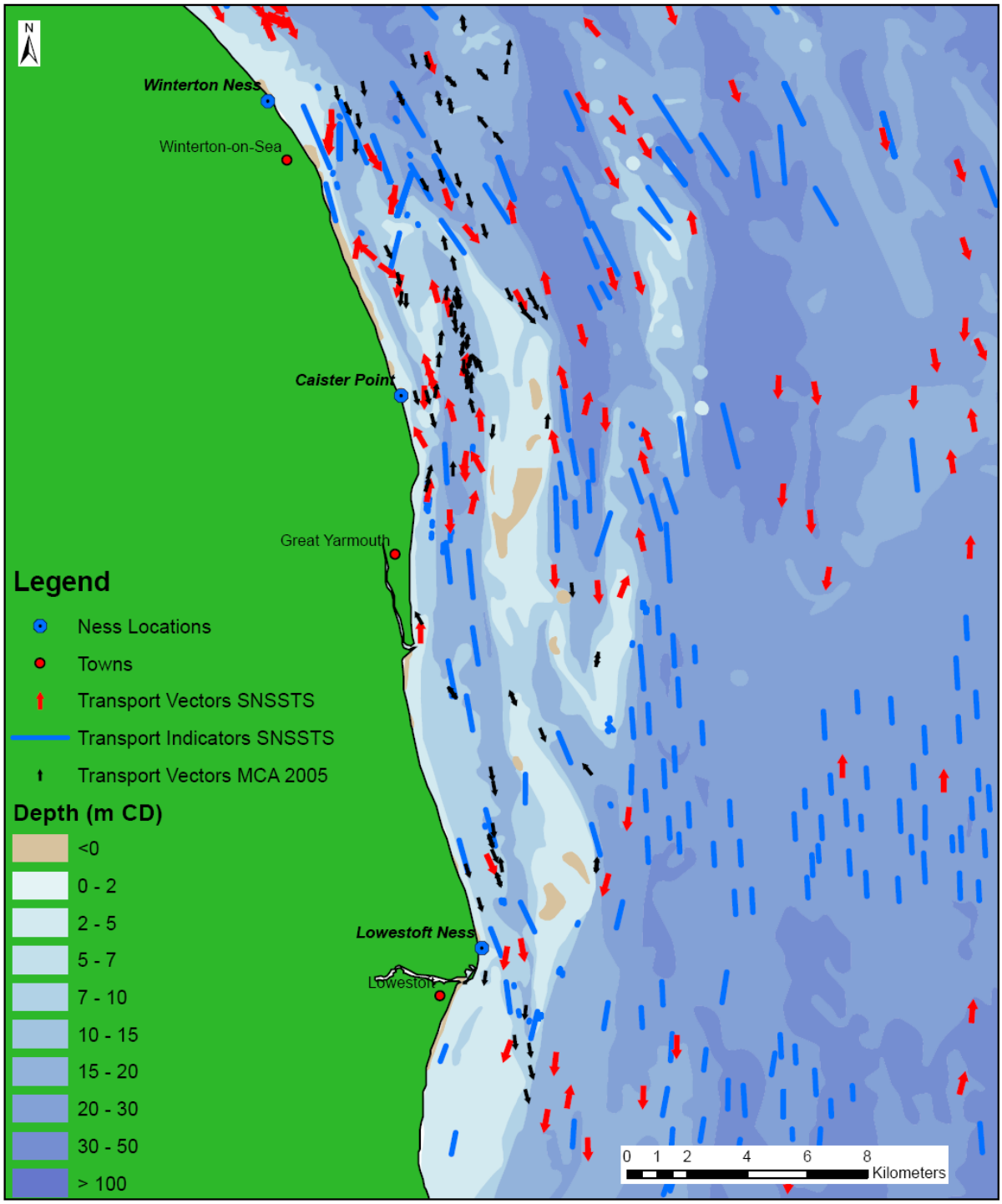
Headland attached flood-ebb meander channels

Figure 11



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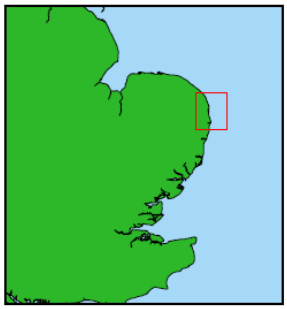

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Sand wave vectors from SNSSTS and MCA

Figure 12

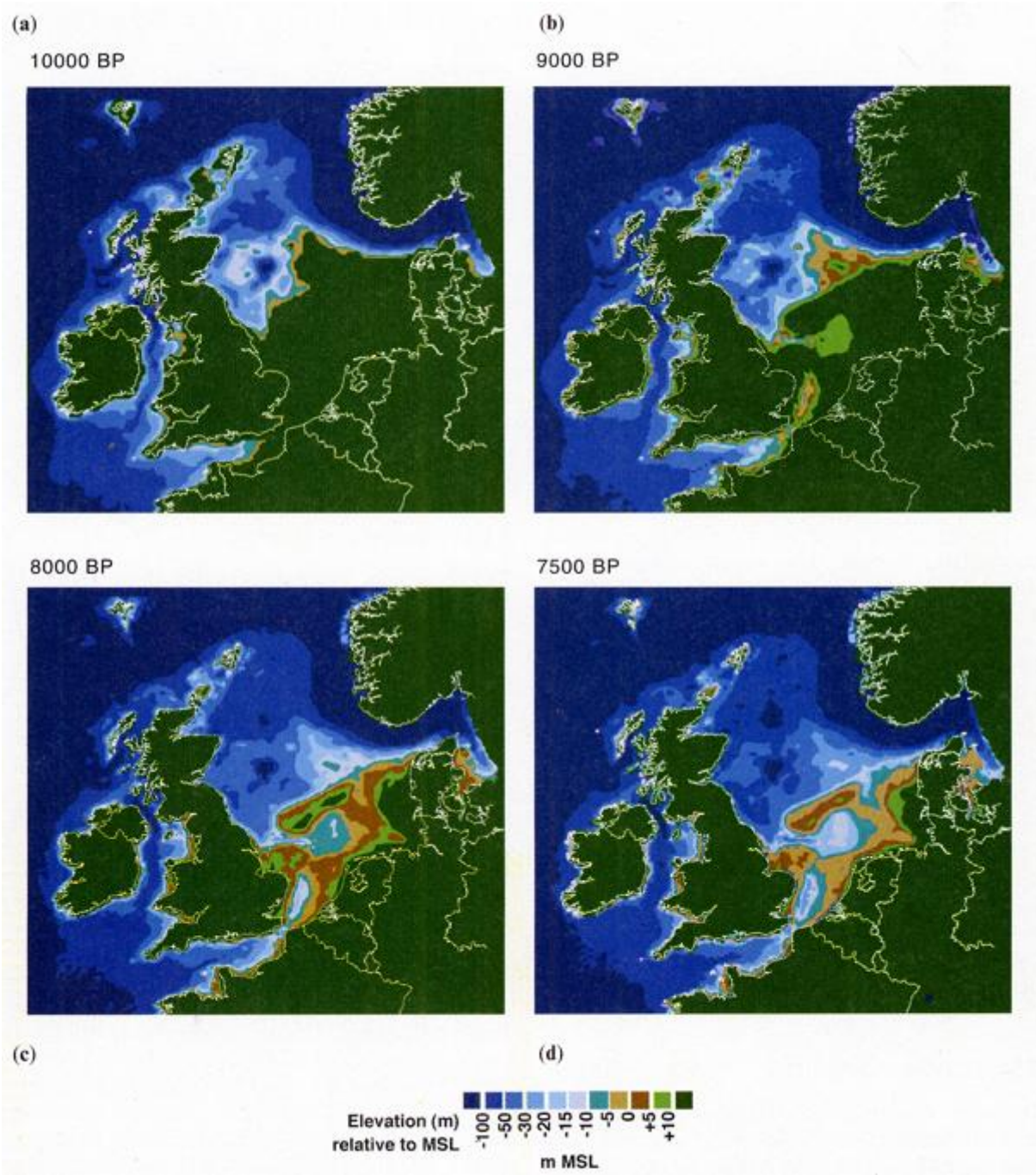


Figure 13 **Palaeogeographic reconstructions of north-west Europe (a) 10ka BP, (b) 9ka BP, (c) 8ka BP, (d) 7.5ka BP (after Shennan *et al*, 2000).**

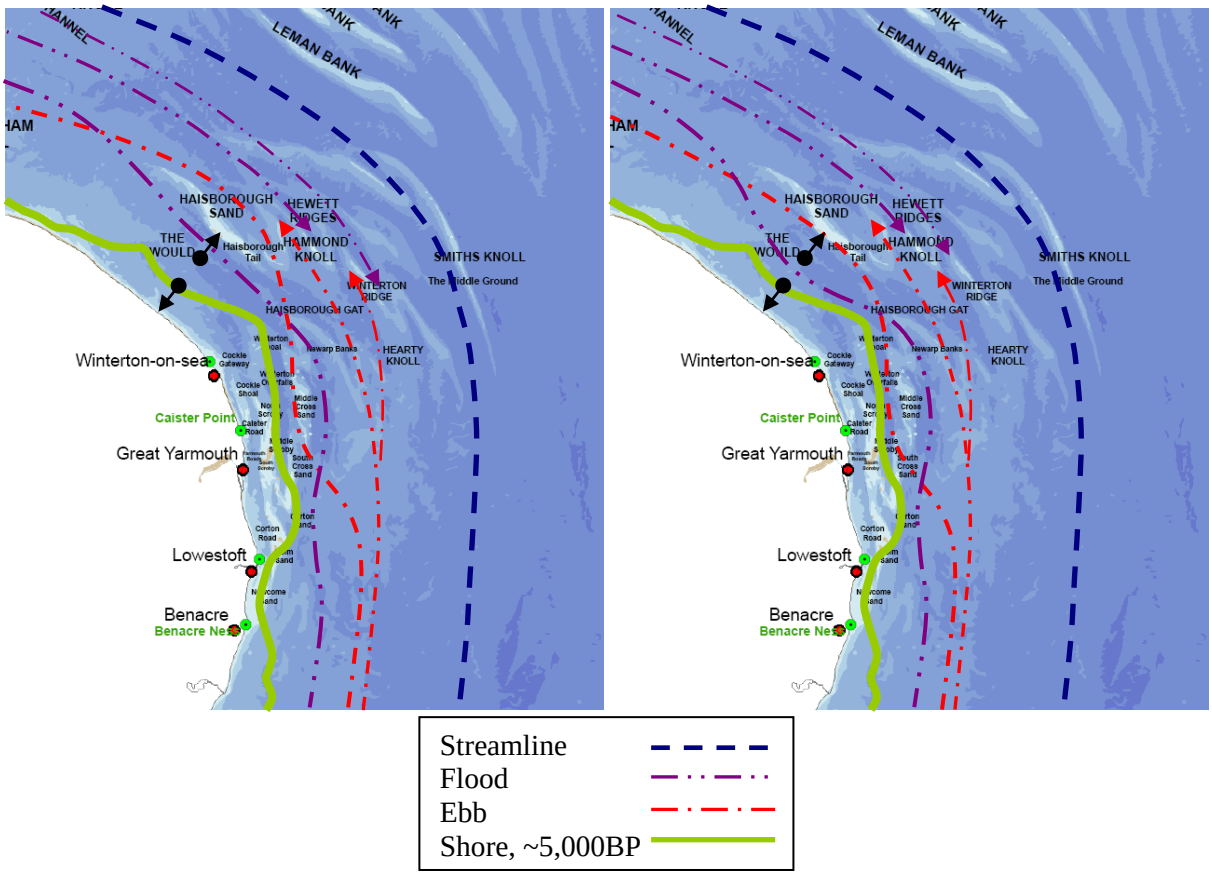


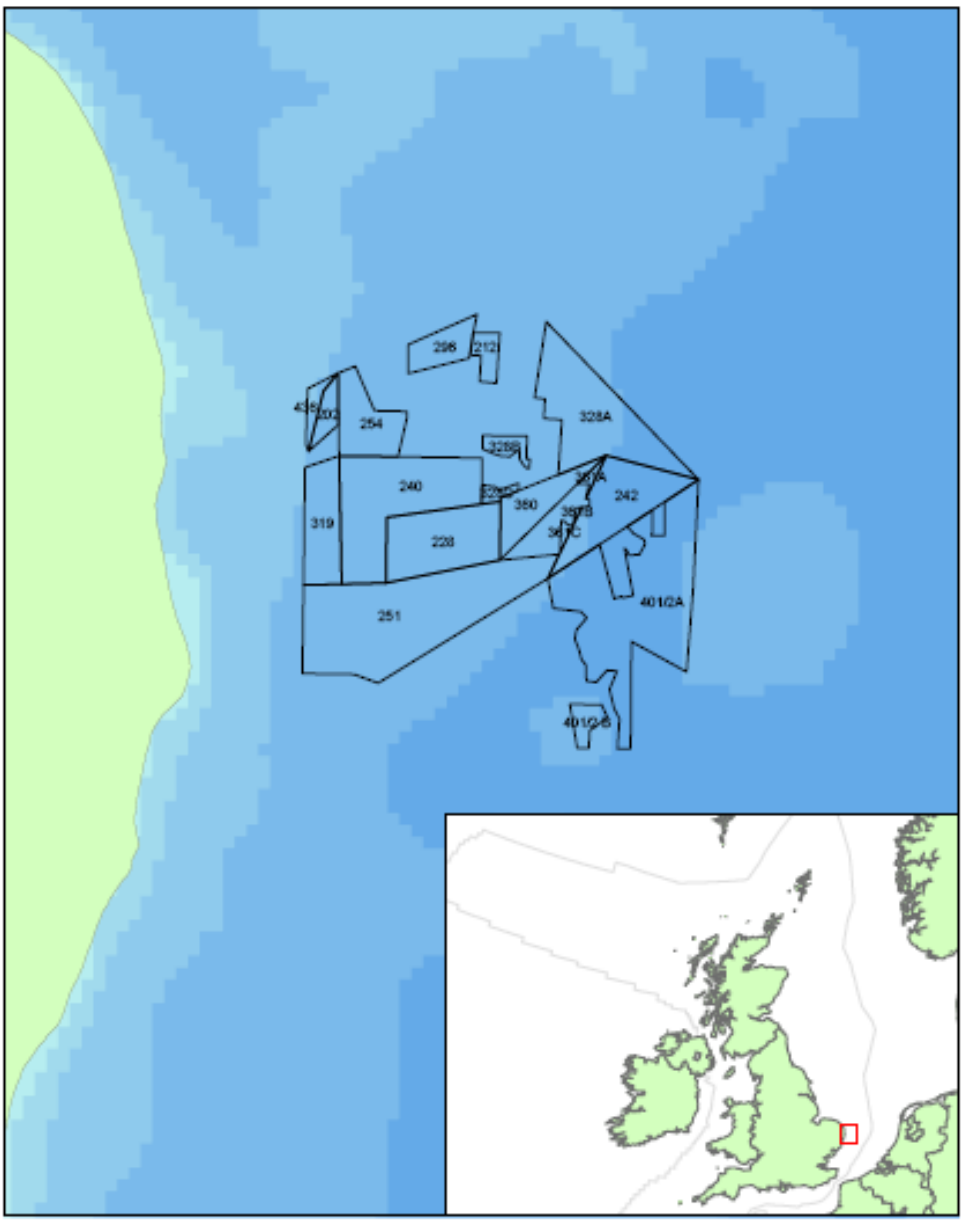
Figure 14 Possible headland attached flood ebb-meander channels in the mid-Holocene.

Appendix A - Sediment transport threshold calculations

The present aggregate licence areas (see figure below; areas outlined in black) span a range of depths and a range of metocean conditions. In simple terms the metocean conditions vary from west to east in the following manner:

Location (relative to licence areas)	Depth (m)	Peak Spring Speed (m/s)	Waves 50% exceedence (Hs, Tz)	Waves 10% exceedence (Hs, Tz)
West	20	2.2	1m, 4s	2m, 6s
Central	25	1.9	1m, 4s	2m, 6s
East	30	1.7	1m, 4s	2m, 6s

A variety of simple tests can be performed on these metocean parameters to consider potential sediment mobility.



Threshold velocity under waves

The bed orbital velocity (Uw) increases with increased wave conditions and shallowing depths. For the combination of wave conditions described for the area, the maximum near bed orbital current is estimated as 0.23m/s and occurs for 20m depth and 10% exceedence waves. Under more typical wave conditions (50% exceedance) Uw is essentially zero and waves bring no force to bear on the seabed.

The critical near bed orbital velocity (Ucrw) required to mobilise sediments has been estimated for a variety of sediment grades, as follows:

- Sediment grain size, 5mm diameter, Ucrw = 0.41m/s
- Sediment grain size, 9mm diameter, Ucrw = 0.49m/s

A sediment grain diameter of less than 0.9mm would be mobilised by these waves (i.e. Uw > Ucrw). Sediments larger than 0.9mm would remain immobile to wave forces.

a. Threshold velocity under currents

The threshold (depth-average) velocity to mobilise sediments (Ucr) has been estimated for a variety of sediment grades and metocean conditions, as follows:

Grain size	20m deep, 2.2m/s	25m deep, 1.9m/s	30m deep, 1.7m/s
5mm	1.43	1.47	1.51
9mm	1.84	1.90	1.95

For the 20m depth, both sediment grades have the potential to be mobilised at times of peak flow.

For the 25 depth the 5mm sediment grade has the potential to be mobilised. The 9mm grade is at the threshold for sediment mobility.

For the 30m depth the 5mm sediment grade has the potential to be mobilised. The 9mm grade has a threshold beyond the local peak flow conditions and will remain immobile.

b. Bed shear stress

Bed shear stress provides a further means of considering the force exerted on the seabed from metocean conditions.

The threshold bed shear stress under currents has been estimated as follows:

- Sediment grain size, 5mm diameter, Tau-cr = 4.0 N/m^2
- Sediment grain size, 9mm diameter, Tau-cr = 7.9 N/m^2

The actual bed shear stress conditions can be estimated as:

Grain size	20m deep, 2.2m/s	25m deep, 1.9m/s	30m deep, 1.7m/s
5mm	8.90	6.64	5.31
9mm	10.53	7.85	6.29

Unsurprisingly, these results tally to those for threshold under currents, showing again that 5mm sediments are mobile across those conditions considered, whereas the coarser 9mm sediment is immobile for conditions deeper than 25m.

Summary

Waves are unlikely to be important to sediment transport at the depths of water being considered apart from severe conditions in the shallower water.

Currents are generally quite strong and are sufficient to mobilise sediments up to around 5mm at times of peak flow (spring tides).

The coarser 9mm sediment can be regarded as immobile under most conditions apart from the shallower depths where flows become greater.

The Crown Estate
16 New Burlington Place
London W1S 2HX
Tel: 020 7851 5080
www.thecrownestate.co.uk

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