Appendix 10

A geological background to sediment sources, pathways and sinks

Southern North Sea Sediment Transport Study, Phase 2
Sediment Transport Report

Appendix 10 A geological background to sediment sources, pathways and sinks

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As the title indicates this report describes the geological context to sediment transport in the SNS2 study area covering sediment sources, pathways and sinks. The report is subdivided into 5 Sections:

1. HOLDERNESS COAST – Flamborough Head to the Humber Estuary. (Subcells 2a & 2b).
2. LINCOLNSHIRE COAST - Humber Estuary to Gibraltar Point (Subcell 2c)
3. THE WASH – Gore Point to Gibraltar Point (Subcell 2d).
4. SUFFOLK AND NORFOLK COAST – Gore Point to Orford Ness (Subcells 3a, 3b and part of 3c).
5. THAMES ESTUARY – Orford Ness to North Foreland (Part of Subcell 3c plus Subcells 3d and 4a).

Appendix 14 contains a complementary summary of published information on sources and sinks prepared by HR Wallingford.

1. HOLDERNESS COAST – Flamborough Head to the Humber Estuary. (Subcells 2a & 2b)

This is the most extensive, rapidly eroding, coastline in the area of study. In the past during the last glaciation of the Devensian period (which began to retreat around 17,500 years BP – Before Present), ice advanced along the North Sea Basin from Northern England and Scotland depositing Tills (Boulder Clays). This area has a similar glacial history to that of the Lincolnshire coast. However here there are two Devensian Till sheets interspersed with glacial sands and gravels, the Skipsea Till, that is overlain by the Withernsea Till, the latter only occurring between Easington and Tunstall. These overlie an infrequently exposed, older till, the Basement Till. The Skipsea Till is chalkier, has a lower silt and higher sand content and also contains a higher proportion of gravel and erratic boulders than the Withernsea Till. The latter makes up the higher ground along this coastline and provides the greatest volume of sediment to the eroding sea whilst on the whole having a lower compressive strength and therefore being less stiff and more easily erodible. Throughout recorded history there has been extensive loss of land along this coast and it is most probable that this has been continuing since rising sea level reached the foot of these till cliffs some 7,500 to 8000 years BP. At present day, average retreat rates of 1-2 m /year, the cliffs might have receded approximately 7 – 16 kilometres since then. There is a sharp break of slope in the seabed between 10 and 13 kilometres offshore that might represent the starting position from which erosion took place.

a) Sources

The whole of this coastline from Kilnsea in the south to Skipsea in the north is eroding rapidly and providing sediment to the beach and to the offshore zone.

The volume of this material has been calculated by Balson, et al 1998, as between 3 and 4 million cubic metres / year. This is thought to consist of approximately 62% silt and clay, 27% very fine sand and 11% fine sand to gravel. If one assumes a median volume is being eroded, then this converts approximately to 2.17 million cubic metres of suspension load, 0.945 million semi suspension load and 0.385 million cubic metres of bedload. Of the latter only the coarsest fraction would remain on the beach to be moved towards the south by longshore drift. It has been estimated by Valentin, 1971, that 3% of the material that is eroded from the cliffs is deposited on Spurn Head; this is equivalent to 105,000 cubic metres/year. This would leave only 280,000 cubic metres of sand as bedload to be moved southwards offshore, towards *The Binks, New Sand Hole*, the Humber Estuary, Donna Nook, and beyond towards the Lincolnshire coast and The Wash. This is a small volume with which to supply the various bedload sinks that lie to the south and include the Wash.

b) Pathways

For the relatively small amounts of bedload (see section 5a), the principal pathway is southwards towards *The Binks* and the Humber Estuary. This pathway extends for up to 7 km offshore from Spurn Head, to the west of the erosional area around the *Inner Silver Pit* (Cox 2002). Surveys using sidescan sonar reveal that bedload moves as ribbons, streaks and rippled sand patches across *The Binks* and is then moved westward, as revealed by similar bed forms, towards the Humber Estuary. It is likely to move in an extended pathway under the influence of successive flood and ebb tidal actions, across towards the Lincolnshire coast where a little of it moves southward towards the Wash, some of it comes ashore on *Haile Sand Flats* before becoming wind blown sand and moving into the coastal dune system and some is incorporated into the sand flats of the Humber mouth. Monitoring of the coastal area from the Humber Estuary to Mablethorpe shows an overall stability, with some accretion (2.4%), taking place over the period 1991 to 1996 (Leggett et al. 1998).

Further offshore sand movement is complex and poorly understood, with bedload indicators showing both southerly and northerly directions. Sparse bedload mobility indicators show that there might be bedload convergence in the area, approximately 20 - 30 kilometres due east of Hornsea.

Within the nearshore zone of Bridlington Bay there will be some movement towards the northeast under the influence of the longer ebb tidal flow in the area between the Smithic Bank and the coast. At the coast the position of this sediment divergence area will vary depending upon tidal and wave factors. It is possible that some sand might move shorewards from Smithic Bank under a combination of onshore wind wave activity, strong ebb tidal flows and then later, offshore winds causing an onshore current.

Of the fine grained sediment that is released from the cliffs of Holderness a little of it is deposited on the saltmarshes within the Humber Estuary whilst the rest is transported towards the Wash and the German Bight (ABP 1996).

c) Sinks

The present peninsular of Spurn Head is only the latest in a series of curved sandy gravel spits that have projected from the north across the mouth of the Humber. Each has grown progressively longer, been breached and then subsequently reformed further west. Due to mans' intervention the present one has lasted much longer than its predecessors: if left it would undoubtedly go through this depositional/erosional cycle. On the Lincolnshire side the Spurn spit was matched by the Saltfleet/North Somercotes spit which grew in a northwesterly direction across the River Lud estuary. This spit now lies inland, south of Donna Nook behind accreting sand dunes (Berridge & Pattison 1994).

To the north, the *Smithic Bank* is a Headland or Banner bank formed by eddy flow south of Flamborough Head. Circulation of sand around it is clockwise as shown by the asymmetry of megaripples on its flanks but it is unknown whether sand is being lost from its southern end. It is unlikely that there is an equivalent 'escape' transport pathway to the north and it is more likely that some sand is moving in from erosion of the cliffs to the north of Flamborough Head. The source for the sand of the bank is also likely to be from the glacial till covered cliffs around Skipsea and north past Bridlington that is sometimes moved alongshore towards the Head and then southwards into the Bank.

In the south *The Binks* is composed of gravelly sands and is a continuation of those making up Spurn Head. Its extension eastwards marks the southern recurved sections of a succession of spits that have formed, been breached and then reformed further to the west.

The Humber Estuary is a mature sink with little available volume for a large influx of sediments except through sealevel rise (Binnie, Black and Veatch, 2000). However, O'Connor (1987), estimated that 2.22 million cubic metres of sediments is transported into the estuary from the sea each year, in addition to 0.3 million cubic metres brought in by the river. From a magnetic characterization dataset a sediment budget for the Humber Estuary has found that modern estuary sediments are composed predominantly (98%) of materials derived from the Holderness glacial tills with only a small fluvial source (2%), (Cox 2002). McCave (1987) estimated that approximately 60,000 tonnes of sediment, accumulated on the saltmarshes each year. In addition some 3.41 million tones of dredged sediment is dumped in the area each year.

2. LINCOLNSHIRE COAST - Humber Estuary to Gibraltar Point (Subcell 2c)

Bordering the coastline from Gibraltar Point northwards to Donna Nook and into the Humber Estuary as far as Cleethorpes is the Lincolnshire Marshland.

A lobe of Devensian ice moved south from Scotland and Northern England across the North Sea floor and into Lincolnshire as far as the Wold uplands. In around 5000 years, between 18,000 and 13,000 BP, the ice sheet and its melt waters deposited vast quantities of detritus between 20 to 30 m thick. These deposits, called the Dimlington Silts, Skipsea Till, Withernsea Till and their associated melt water gravels, sands, silts and clays are equivalent to those of the Yorkshire coast and to the Bolders Bank and Botney Cut Formations that are found extensively offshore. On land, overlying these glacial deposits are those sediments of the Lincolnshire Marshland. These are very similar to those of the Fenland and the Wash as will be discussed in Section 3. The sea entered the district about 7,500 to 8,000 years ago depositing a sequence of marine and estuarine clays, silts, sands and shingle over freshwater lake and river deposits. Those rivers, including the Humber, drained eastwards across the offshore area towards the *Silver Pit*. Tidal flats and salt marshes would have bordered them initially, as sea level rose.

The surface over which the sea transgressed was a gently undulating one varying from 5 to 15m below OD, one that is approximately indicated on the offshore charts of the area – 107, 108, 109 and 1190.

It is probable that the sea reached its maximum lateral extent in Lincolnshire about 3,500 BP. Subsequent deposition has extended the land surface eastward to its present position. As sea level rose, a number of sand bodies were formed as headland banks from upstanding outcrops of till, one of them extending northwards from around Saltfleet (Berridge & Pattison 1994). This particular till outcrop could extend offshore to the northeast as the *Rosse Spit* whilst the Saltfleet sand body provides a base for the now, completely buried North Somercotes / Saltfleet storm beach, the modern beaches of the Donna Nook to Saltfleet coast and their offshore extension in *Haile Sand* and *Haile Sand Flat*.

It is tempting to suggest that a similar feature could have formed south of Skegness and is the base for the sands in the locality of *Skegness Sands* and the *Wainfleet Sands*.

a) Sources

There are no cliffs to provide any material due to the low lying character of the Lincolnshire Marshland behind the coastline. The rivers of which the Humber is the principal one contribute little, estimated as around 100,000 cu. m/year (Veenstra 1971, McCave 1987). A potential source for this area is offshore where the sea floor is of glacial till of the Bolders Bank Formation. This is composed of calcareous, gravelly, sandy, silty clay with erratics[1] of chalk, sandstone and mudstone and Scottish rocks. During the period when sea level was rising appreciably, from about 7,500 – 3,500 BP, intertidal and saltmarsh deposits which had been previously deposited after the retreat of the ice sheet, would have been eroded from the offshore areas. Cores containing saltmarsh peat have been taken in the offshore area here (Balson 1999). The material released was transported into the appreciable sinks that were in existence at the time - the Humber Estuary, Lincolnshire Marshland, The Wash and the Fenland. At the present time it is likely that a major source is the Holderness coast to the north (see section 1), though there has been severe

[1] Rock fragments or boulders carried large distances from their source

deflation of the beaches and intertidal zone south of Mablethorpe in recent years. This has necessitated the renourishment of these beaches. Prior to that there was a 15% loss of material from these beaches in the 5 years, 1986 – 1991(Leggett et al 1998). As reported by Dugdale and King 1978, the southward movement of the *Skegness Middle Sand*, some 3km in 150 years, would lead to the erosion of the beaches to the north as the protection afforded by this bank was lost.

In the past, the beaches have been the source for the wind blown sand dunes that were to be found along the full length of this coast and are the principle, though indirect source for the rapidly accumulating dunes at Donna Nook.

b) Pathways

Offshore most of the bedload mobility indicators west of 0º 30' E show sand movement to the south and inclined slightly towards the coast. To the east of this line there are several indicators giving a northerly transport direction though this is contrary to the recorded direction of strongest tidal flow. Mapping of the magnetic and heavy mineral properties of North Sea sediments has revealed a large (2,700 km²) erosional area surrounding the *Inner Silver Pit*, directly offshore from the Humber Estuary and the north Lincolnshire coast (Cox 2002).

Inshore transport is directed by wave action with transport being recorded as being both to the north and the south, though most authors favour a net southerly direction (Chang Shih-Chiao & Evans 1992, King 1972, Steers 1964). Ingoldmells Point appears to be a critical area for sand movement from both directions. Robinson (1964) showed that Woodhead Drifters released off Spurn Head reached this point from the north, whilst Dugdale and King 1978 show a similar destination for drifters released off Gibraltar Point in the south. This latter finding does not accord well with *Skegness Middle Sand* moving so far to the south during the last 150 years. However they did show that there was a strong correlation between drifter strandings and times of spring tides and high wave activity, particularly when winds were blowing in an offshore direction. They suggest that sediment is more likely to move onshore during periods of fast tidal current flow in the nearshore zone and that there is a nearshore/foreshore coupling during periods of strong offshore winds.

Whilst tidal action in the near coastal offshore zone shows largely a southerly transport direction the coastal foreshore/nearshore zone appears to be dominated by wind wave activity and resultant nearshore currents that vary year by year, decade by decade and cyclically over longer periods (Lamb 1967).

N.B. This sedimentary connection between the shore and the nearby offshore zone is likely to be important in many areas along this coastal stretch and throughout the study area, and particularly so where nearshore sandbanks are found e.g. Smithic, Mablethorpe, Skegness Middle, Inner Knock, Sunk Sand, Gore Middle, Caister, Newcome, Dunwich/Sizewell, Aldeburgh Ridge, Whiting and Margate Hook.

c) Sinks

There are no substantial sinks in this sector. The Humber Estuary does show some accretion on its north side around Sunk Island and in Spurn Bight (McCave 1987) but is not a major depository due to its small size and its maturity as a sink.

The coastal dunes have formed due to wind blown sand from the beaches.

In some places these dunes have been flattened or removed by human activity. In other places, such as on the south side of Donna Nook, construction of seawalls has initiated further dune formation, where 4 sub - parallel lines of dunes, over 250 metres wide, have formed in the 150 years since the last sea wall was constructed. In all, nearly a kilometer of sand dunes have formed there since the building of the 1638 sea wall and the process is continuing at present.

Immediately offshore and to the south is the *Mablethorpe sandbank* that has been reported as extending in recent years towards the south. Further south still is the *Skegness Middle Sand* that has migrated southwards, along with its shore-connected ness, some 3km in 150 years. Further offshore the *Inner Dowsing Bank* is a deposit of fine medium sand. Whether this bank is now moribund or is a temporary sink in a pathway bringing sand from the north towards the Wash, is not known at this stage. However it is close to an area where bedforms seem to indicate a southerly movement of sediment.

3. THE WASH – Gore Point to Gibraltar Point (Subcell 2d).

The huge inlet of the Wash was formed by a number of processes over an extended period of time, but the most important was the movement of ice through this area during the Anglian stage of the Pleistocene approximately 450,000 years BP. This resulted in the deposition, elsewhere in Suffolk and Norfolk, of the Lowestoft Till, a silty, clayey deposit (diamicton) with chalk, flint and mudstone clasts. Glacial transport was from Scotland, across the bed of the North Sea, east of Yorkshire and Lincolnshire and through the Wash and Fen Basin. Along the way it picked up many fragments of different rock types but in particular chalk from the deposits that stretched across the entrance of the Wash to Lincolnshire and the very soft and easily erodible Cretaceous sands and Jurassic clays and mudstones that lay immediately to the southwest.

At times of low sea level, river systems have drained the hinterland of the Wash with the chief fluvial valley running under the *Wrangle* and *Friskney Flats* and cutting through the chalk outcrop that stretches across the mouth of the Wash from Hunstanton towards Wainfleet, in the locality of *The Well.* The continuation of this fluvial course was in the present day deep offshore valley that runs northeastwards towards the *Inner Silver Pit.*

This inlet was later touched by the Devensian ice age that began its retreat around 18,000 BP. This later ice sheet had progressed down the east coast of England depositing glacial till on the Holderness coast of Yorkshire, in Lincolnshire and around Hunstanton in Norfolk. Offshore it deposited wide spreads of till (Bolders Bank Formation). It also cut deep sub-glacial channels previously and later used as fluvial valleys, of which the *Inner Silver Pit* and its southerly extension projecting into the Wash from the north, is one.

Before the sea first transgressed into the Wash about 8000BP a freshwater peat was deposited, similar to that found east of Gore Point. As the sea transgressed it deposited silts and fine sands in tidal creeks surrounded by salt marshes and mudflats similar to those in the nearby, *Burnham Flats* (Barroway Drove Beds). Later, about 4000BP, sea level rise was outstripped by the influx of sediments from the Southern Bight and peat growth commenced over much of the Fenland (Nordelph Peat). In about 2600BP the sea once more transgressed over large areas of the Fenland and deposited silts and fine sands (Terrington Beds). It was upon this surface that the Romans settled but their habitations were inundated when the sea once again transgressed in the 3rd century AD. The Terrington Beds have continued to be deposited up to the present day with the exception of the transgression and consequent erosional phase in the 13th century. It has been suggested that the width of the Terrington Beds saltmarsh around the Wash stabilizes at about 1km. If reclamation takes place of any part of this, then rapid accretion takes place until the salt marsh once again reaches its former width (Kestner 1962).

The whole of the Fenland area within Norfolk, Cambridgeshire and Lincolnshire resulting from these depositional phases has been reclaimed since Roman times. Surrounding it is the so-called 'Roman' Bank, a 100 km long earth bank that formed a continuous barrier to the sea between the Lincolnshire Wolds and the Norfolk uplands. It is thought to have been built in the late Saxon period, before the Domesday survey of 1086 and was used as the outer sea defence when marine transgression took place during the 13th century. It is thought that extensive reclamation, seaward of the Bank, was made between the 9th and 12th centuries but these were inundated during the 13th century high sea levels. In the 17th century extensive reclamation work seaward of the Bank, began again, which continues to the present day as Terrington Bed sediments continue to be accreted. (Gallois 1994).

a) Sources

At present the only direct source material from the surrounding coastline are the Hunstanton cliffs. These are composed of a basal iron stained sandstone (Carstone) overlain by a red limestone with quartz pebbles (Red Rock) and the Chalk. These 20 metre high cliffs are being actively eroded and have retreated to the southeast between 3 and 4kms since sea level rose and marine erosion began about 8000 years ago. However, only the sand unit provides any material to the sediment budget within the Wash. A small amount of material may enter from the northern coast of Norfolk as discussed under the section 4.4.

A number of rivers-Witham, Welland, Nene and Ouse, discharge into the Wash but carry, at present, very little sediment load (Evans 1965). The principal source is the tidal currents that bring sediment in from the Southern Bight of the North Sea where the Devensian, Bolders Bank glacial deposits cover most of the seafloor to the northeast. In addition the erosion of the Holderness cliffs of Yorkshire may well provide suspension load material. Fine to medium sand is moving southwards down the Lincolnshire coast as evidenced by the southward migration by 3km of the Skegness Middle Sand over a 150 year period (Dugdale 1980).

Also the sandbanks off Gibraltar Point appear to have continued their expansion since the recent LINCSHORE beach replenishment scheme for the coastline to the north, was completed.

b) Pathways

These include the fine, suspension load materials brought in by tidal currents that continues the Terrington Bed deposition of the intertidal and saltmarshes around the borders. This fine sediment may be partially derived from the Holderness coast and also from the seabed northeast of the Wash. In addition fine to medium sands are being brought in from the north along the western edge of the *Docking Shoal/Burnham Flats* as shown by the asymmetry of bedload indicators. How this particular supply enters the Wash or is moved eastwards off the North Norfolk coast through *Middle Sand* and *Gore Sand* is unknown. A similar process is occurring on the Lincolnshire side through the *Inner and Outer Knock*, and *Outer and Inner Dogs Head sandbanks*. These banks are covered with a complex system of bedforms that indicate sand movement around each of the separate banks. In the nearshore area the Skegness and Inner Knock banks appear to have an anticlockwise sediment movement pattern whilst the more offshore banks – *Outer Knock, Outer Dogs Head* and *Inner Dogs Head* show clockwise circulation. These pathways possibly supply sand for the major sandbanks further within the Wash though the precise pathways are unknown.

Sediment transport pathways through the deeper water areas including *The Well*, at the central mouth of the embayment, are also unknown, though computational modelling and fieldwork suggests this is the chief point of entry for sediment.

Unlike the bedload sediment pathway that brings sand from off the east Suffolk coast into the Thames Estuary there does not appear to be a similar major pathway entering the Wash. This is largely due to the seafloor to the north and northeast of the Wash being covered by the Bolders Bank Formation, a deposit that is largely composed of clay, silt or very fine sand sized material with pebbles of chalk and other eastern England sedimentary rocks.

The fine to medium sands found within the sandbanks are therefore not being presently transported into the Wash in any great quantity.

c) Sinks

The Wash is a large sink made up of marshland and intertidal flats for the finer sediments (Terrington Beds) and fine to medium sand for the major sandbanks offshore that include *Long Sand, Roger Sand, Gat Sand, Thief Sand, Seal Sand, Sunk Sand* and others. This Terrington Beds deposition of fine sediments, slowly accreting northwards and covering the landward ends of these sandbanks, has been continuing intermittently since 2600BP (see sections 3 and 3a above).

This fine sediment is being deposited at a rate between 790,000 – 6,800,000 million tones per year (ABP 1996; McCave 1987) and the bedload sediment at the rate of 14,000 tonnes per year (ABP 1996).

4. SUFFOLK AND NORFOLK COAST – Gore Point to Orford Ness (Subcells 3a, 3b and part of 3c).

This area extends eastward to approximately 2º 5' E on the east coast and to approximately 53º 15' N off the north coast and from Orford Ness, Suffolk to Gore Point at the entrance of the Wash.

Prior to the glacial events that have so shaped the North Sea, the area was largely dominated by marine conditions with large rivers bringing sediment in from much of England and the Continent (Gibbard 1988; Rose 1999 & 2002).

Following this period, two glaciations can be identified from deposits both on the North Sea floor and within mainland England. The former, the Anglian glaciation, covered all of Norfolk and Suffolk, and parts of Essex. At the time of the last glacial maximum some 18,000 years B.P. the ice front lay within the Wash and extended northeastwards into the central North Sea. Between these two glacial events there might have been a third, and in addition a whole series of interglacial sediments were deposited. The result is that at the present time, the sediments of the seabed off this coast and the sediments of the cliffed coastal sections, are of very mixed provenance and type. It is from these that the mobile sediments within the present marine environment are being largely derived by erosion.

4.1 Gore Point to West Runton (Subcell 3a)

This sector includes a section of eroding cliff line from West Runton to Weybourne and then an accreting section that extends along the rest of the coastline to Gore Point at the mouth of the Wash. It is around Sheringham/West Runton that the coastal drift direction changes from easterly to westerly (Clayton et al 1982). The exact position varies under different wind wave conditions.

a) Sources

The principal source of sediment for this sector is the cliffs between West Runton and Weybourne. Here the cliffs are about 10m high, increasing to 30 m to the east. The sequence of deposits is:

- Valley gravels
- Briton's Lane gravels
- Gimingham sands
- Contorted Drift – ice disturbed deposits of sands, glacial till, sands and gravels with large Chalk erratics.
- Cromer Forest Bed – marls, muddy sands, gravels and shelly muds.

Thus there are a wide variety of sediment types for distribution along the coast and off it, though sand makes up at least 60% of these sediments with gravel content at approximately 10-15%. Erosion rates along this stretch of coast are highly variable and an average rate of approximately 1.0m/year (0.3 – 2.0) has been estimated (Clayton 1989). This stretch of coast is characterized by the presence of shingle banks and sand dunes protecting a zone of marshland that is between 1 and 3 km in width. Within it are found barrier islands, spits, dunes, intertidal channels, sandflats, mudflats, and saltmarshes. Behind this 40 km length of coast, lies a very straight, low cliff line that terminates the Norfolk plateau. It has been suggested that this cliff line was formed by marine action during a previous high sea level, possibly that of the Ipswichian (130,000 to 125,000 years BP). However Andrews et al (2000) suggest that it was the southern margin of an eastward trending ice front channel.

North of the coast, between Gore Point and Wells next- the- Sea lies the *Burnham Flats* and *Docking Shoal*, that northward merge into the sandbanks of the *Race Bank, The Ridge and Dudgeon Shoal*. Whilst the sandbanks have the usual elongate form of these structures and feature trains of sandwaves, the

Burnham Flats and *Docking Shoal* do not. However they do represent a large reservoir of sediment that can release sand to the eastward. Though not cored as yet, from geophysical evidence there is up to 10m of sediments within these features.

Elsewhere in the North Sea there are extensive deposits of peats, saltmarsh and intertidal sands and muds that were deposited during the early phases of the recent sea level rise between 9000 and 7500BP (Eisma et al.1981). In areas immediately to the east there were such areas where tidal flat and saltmarsh sediments were deposited, as evidenced by peat and intertidal bivalves found within cores (Balson 1999). It is very likely that the *Burnham Flats* and *Docking Shoal* are remnants of such an intertidal sedimentary environment, deposited on the eastern border of the southern part of the *The Well/ Inner Silver Pit* channel and to a receding coastline to the south where these sedimentary environments still exist.

b) Pathways

There is essentially a single pathway by which sediment is moved both by beach drifting and by immediate subtidal action, leading from the eroding cliffs to the east into the temporary sink of the barrier/marsh coastline. Sediment is sorted by tidal and wave action and deposited in areas appropriate to the grain size of the material. A further pathway leads from this sink towards the west and into the Wash. Along the way and over extended periods of time, the sediment is deposited, eroded and deposited once more, with this action being repeated several times. There are therefore many smaller pathways within this complex system. It is possible, but not proven as mentioned above, that there is some sediment interchange with the offshore zone including sandbanks such as the *Blakeney Overfalls*.

Further offshore, bedload mobility indicators largely show sand moving eastward from the tidal flat source of the *Burnham Flats*. These indicators are restricted to the zone between the coast and 53º 6' N and continue eastward beyond the *Sheringham Shoal*. It might appear that this intermittent and patchy sediment pathway continues southeastward from there to approach the coast in the region of Winterton Ness. To the north of this sand stream, bedload indicators show a northerly or northwesterly alignment towards the *Outer Dowsing* and *East Dudgeon Shoal* areas.

c) Sinks

The accreting sequences here have been building since about 9,000 BP when freshwater peat was deposited. This was followed by marine mudflat and saltmarsh deposits (7000-6000BP), which accumulated behind shingle/sand barriers that are now largely buried beneath later sediments. This process continues to the present day (see Burnham Flats above). Along the seaward margin there are now a number of barriers – Scolt Head Island and Blakeney Spit. These are extending westward at an average rate of 3m /year and landward at about 1m /year (Andrews et al 2000). Blakeney Point has more than doubled in volume since 1600AD, deriving its sandy shingle from the eroding cliffs to the east (Sampson 1981). Evidence from cores shows that the beaches and spits have been steadily pushed landward by rising sea level over the last 6000 years. At the rate of approximately 1m /year this accretionary sediment sink has narrowed from an original width of about 6kms. This narrowing of the coastal sink has been in response to rising sealevel, the continuing erosion of the cliffs to the east, the longshore drift of shingle and sandy sediment to the west, and the temporary trapping of fines within the saltmarshes and mudflats behind the barrier bars. As the barrier bars migrate landwards to eventually coalesce with the higher ground of the Norfolk Plateau this sediment sink will be lost. From this leads the presumption that the sink is only a temporary one with an expected life of approximately 3000 years if conditions of sea level rise and coastal erosion remain largely unchanged. It is most likely that sandy sediment is being lost from this sink to the west, and into the Wash (Steers 1927, 1964) though there may be some transfer offshore particularly under onshore wind conditions (see section 2b). If that were to happen sand could move into the west to east pathway that exists there.

4.2 West Runton to Winterton Ness (Part of Subcell 3b)

This sector has in the past been seen as the source for the continuing development of the Norfolk sandbank sequence that at present starts with the relatively nearshore, *Haisborough Sand* and extends northeastwards as far as the *Indefatigable Banks* and beyond, into a similar parallel sequence of unnamed banks (Swift

1975; ABP 1996). A model might be proposed suggesting that the sandbanks northeast of the *Leman Bank* are the sorted remnants of the Weichselian ice front sediments that they closely parallel. The two inshore groups of sandbanks: **a)** the *Haisborough Sand*, *Hammond Knolls, Hewitt Ridges* and *Smiths Knoll*, **b)** *Cross Sand, Scroby Sand, Caister Sand* and associated banks, were and, are in the case of the b) group, associated with the erosion and retreat of a northeast facing cliffed shoreline. Their differing aspects to the modern coast could be due to the varying aspect of the coast as retreat took place. The difference between these models is that the one suggested here would indicate that most of the eroded and released sediment is now going into the Yarmouth sandbank system and is not passing into the banks lying further offshore. Certainly the bedform evidence does not support that latter pathway. However Stride (1988) does present evidence for suspension transport across the Norfolk Banks in a northeasterly direction.

a) Sources

The coastline from West Runton as far as Happisburgh is composed of cliffs of the Anglian, Corton Formation.

Essentially there are 3 units to this formation – the basal one being the Happisburgh Till, a sandy diamicton - sandy clays with glacial erratics from the North Sea floor, northern England and Scotland. Overlying this is the Runton sands and gravels and at the top, the Corton fine sands. Thus there is a very mixed assemblage of material available, as the cliffs erode. This is supplemented by material eroded from the seafloor that in this area is primarily the clays and sandy clays of the Westkapelle Formation plus a small outlier of sediments of the more recent, Devensian glaciation (Swarte Bank Formation) and the Chalk.

The rate of coastal retreat along this stretch of coast has been calculated as being 0.9m per year (Clayton 1989). If this rate has been maintained over approximately 8000 years since marine erosion began then some 8kms of coastline has been eroded. This earliest coastline would lie close to the present position of the *Haisborough sandbank*.

b) Pathways

Long shore and sub- littoral drift is primarily towards the southeast and south. Offshore, sand ribbons show that sand is moving as bedload and further south these ribbons trend steadily more obliquely in towards the coast. Approaching Winterton Ness, the sand ribbons are inclined towards the coast and indicate that sand is moving from offshore toward the coastline in this area. This evidence supports the view of Stride (1974), that this is approximately the area where the rotation of tidal current vectors changes from clockwise to anticlockwise and thus the net sediment transport direction changes. To the north of Winterton Ness, sand would be moved shoreward whilst to the south, sand would be moved offshore.

Winterton Ness is therefore an important transfer point in which small amounts of sand from the west and offshore, join in the general longshore and sublittoral drift pathway towards the south and the sandbanks of the Yarmouth area.

Further offshore, sandbank shape (Caston 1981) and other bedforms indicate bedload pathways towards the north and northwest.

c) Sinks

The sinks along this coastline are the sandbanks as mentioned above. Bedforms upon their flanks reveal a clockwise sediment circulation system. Assuming a closed system, McCave and Langhorne (1982) estimated that sand took about 550 years to travel around the Haisborough sandbank. However Caston (1981) showed that sandbanks were not closed systems but that sand entered the bank at their broader head and left via the narrower tail. In the case of the a) group of banks, then sand would appear to be entering from the south even though the source might be to the south, or the southwest at the coast.

4.3 Winterton Ness to Benacre Ness (Parts of Subcells 3b and 3c)

This zone is dominated by a number of sandbanks that might appear to be located in a position that is not conducive to their stability. Whilst it is unknown when they began to form, they are however located in a position relative to three important geomorphological features. These are the now, centrally positioned, buried valley of the River Yare, the Northern Upland that previously extended seawards from the area of Caister to Winterton, and the Southern Upland that extended to the east from the area of Gorleston southward as far as Kessingland.

Due to the general southerly drift of sediment along and offshore from Winterton to Benacre, then it might be suggested that these banks – *Cross Sands, Scroby Sands* and *Caister Shoal*, formed originally as banner or headland banks from the Northern, Caister/Winterton Upland. Seismic evidence shows that the bedrock of this Northern Upland consists of the clay rich, lower divisions of the Westkapelle Ground Formation. These units more readily resist erosion due to their high clay content. This northern upland, which quite possibly extended northeastwards as far as the *Newarp Banks*, extended under *Cockle Shoal*, *Winterton Overfalls* and *North Cross Sand* where the sand thickness of the banks is very much thinner.

Before erosion by the advancing sea took place, the Upland was capped by glacial, clay rich deposits, of the Anglian, Lowestoft Formation. At present, the continuation of this headland is the high ground behind Winterton on Sea, which is capped by this same erosion resistant deposit. Immediately to the north of this headland was a less erosion resistant, more sandy deposit, the Cromer or Happisburgh Till deposited by an earlier advance of the Anglian ice sheet (Rose 2002). In this onshore area the present day drainage takes advantage of this same, sandier, more easily erodible deposit, as the Hundred Stream and the Thurne River flow southwestward toward the River Bure from higher ground that once lay **offshore**.

The more volatile elements of the sandbank system are those that lie over the buried valley of the River Yare and consist of the *South Scroby, Corton Sands* and the *Holme Sands*. Here the sand thickness is greatest, allowing the tidal currents to erode, displace and deposit the **upper layers** of these sands without reaching an erosion resistant layer. Thus the navigation channels in this area are constantly changing. It is possible though unproven, that parts of the deep channels of *Barley Picle* and *Caister Road* between these banks were the location of streams that once ran off southwards from the Northern Upland into the River Yare. Certainly the bedrock surface is much lower under parts of Barley Picle than it is under Scroby Sands.

The Southern Upland had an east-west aligned watershed that extended through the high ground north of Kessingland. Small streams probably ran north or northeast from this into the River Yare. This major river valley ran first eastwards (Arthurton et al 1994) but then turned southeastwards some 7/8 kms off the present coastline. Thus the banks are lying between two watersheds and within and upon, the substantial deposits of the old valley system of the River Yare.

a) Sources

The primary source of the sediments for this sector is the cliffs that lie between Cromer and Happisburgh. They consist of a very complex set of units that comprise the Corton Formation (see section 4.1a).

These mobile sediments are supplemented by the erosion of the nearby seafloor which comprises the clays and sandy clays of the Westkapelle Ground Formation. At the present time most of the coastline of this sector is protected from rapid erosion by the offshore sandbanks. However due to the movement of the sandbanks south of Lowestoft, particularly the Newcome Sand, parts of the coastline south of Pakefield are once again being eroded (J.Rees - pers. comm.). Here the clay rich Lowestoft Till overlies Corton sands. This region of the coast used to be very actively eroding some 50 years ago[2] when between 1 and 2 metres per year were eroded. The position of these banks and their intervening channels does have therefore an influence upon the rate of erosion at the adjacent coast.

[2] Recent beach loss at Corton has contributed to the failure of the seawall (J. Walker – pers. comm)

b) Pathways

There are sediment pathways around each of the sandbanks and connections with the shoreline at Winterton Ness, Caister Ness, Lowestoft and Benacre Ness. Newcome Sand has moved closer to the shoreline in recent years and as with Caister Sand, interchange of sediment with the shore is likely under certain conditions of wind and tide (see section 2b). It is not certain whether sediment entering the sandbank system at the nesses (McCave 1979) is adding to the bulk of these sinks or whether sediment is being lost in approximately an equal quantity from the southern ends of the sandbanks. Some leakage of sediment is likely as there are several bedload indicators of a southward movement of sand in this region, west of approximately 1º 55' East. If this is the case then the sandbanks are operating as a temporary sink for some of the eroded products of the North Norfolk coastline, and a little sand is then passing southwards towards the Thames Estuary.

c) Sinks

The primary sinks in this sector are the sandbanks: it has been calculated that the total volume of sand within these banks is closely approximated by the volume of sand lost from the nearby Norfolk cliffs over the last 5000 years (Clayton 1989). However changes are continuing, with the *South Cross Sand* extending northwards several hundred metres between 1866 and 1972, *Scroby Sand* by 1km in the same direction and *Corton Sand* by a kilometer to the south. Recently in 2002 it is reported that *Corton Sand* has largely disappeared as a new, wide, *Hewitt Channel* has opened in its place connecting *Yarmouth Roads* with *Barley Picle* and the open sea. This illustrates the mobility of the sand within the thick deposits over the old buried channel of the River Yare.

Small, perhaps temporary sinks, are the ness features. The spit that extends from Caister to Yarmouth grew rapidly during the 11th and 12th centuries reaching as far south as Lowestoft by 1200AD (Green and Hutchinson 1960). An entrance through the spit intoYarmouth, was constructed in 1613 and since then the southward extension has eroded away. However changes to the width and the position of the widest section -Caister Ness, have occurred in the 20th century (Robinson 1966).

Winterton Ness is a less obvious feature and has importance as being in the general area where sediment exchange occurs between the shoreline /sublittoral zones and the offshore sandbanks. Its position over the last 80 years has changed both to the north and the south (Robinson 1966). It is situated on the northern upland and its various positions over this period appear to be related to this shallower, more erosion resistant sector of the sea floor. At present the coastline at this point is an area of deposition by wind blown sand.

4.4 Benacre Ness to Orford Ness (Part of Subcell 3c).

The coastline between these two points is one of rapid erosion thus providing large and steady quantities of sediment to the beach and offshore zone. It also features a number of 'ness' or uncliffed projections that appear to have an important bearing on sediment transport along the coast and as was seen further north, to the development of offshore sandbanks. On this stretch of coastline there are four of these nesses – Benacre Ness, Southwold, Thorpeness and Orford Ness.

a) Sources

The link of Orford Ness to its potential source will be described in more detail in section 5.1a, with cliffed areas to the north providing at times, large quantities of shingle, sands and clays. These deposits include the medium grained Chillesford Sand, the Chillesford Clay, the Easton Bavents Clay and the sandy, shingle rich, Westleton Beds. These units are collectively termed the Norwich Crag. Offshore the seabed is comprised of clayey, silty, fine sands of the Westkapelle Ground Formation overlying the shelly, medium to coarse grained, sands of the Red Crag. A further formation, older than all the previously described units, lies immediately under and to the northeast of Thorpeness. This is the Coralline Crag, a bank-like body of sometimes silty, medium to coarse, shelly sands. That it is relatively resistant to erosion compared with the other deposits is seen from its composition and its concurrence with the bathymetry (see 20m contour northeast of Thorpeness). Seismic evidence confirms this concurrence. It might appear that Thorpeness has a core of this more resistant geological unit and that its position is comparatively fixed by it.

In a few localities offshore, flint gravels are to be found that were deposited by the Middle Pleistocene, Thames/Medway River that ran towards the northeast. These are found overlying in localized patches, all of the previously mentioned deposits (Rose 2002). In a few places are to be found the more recent, small, drowned valleys of the Alde, Blythe, Minsmere and Hundred Rivers. Where still present after marine planation, these are largely filled with estuarine silts and clays that could be subject to erosion at times.

All of these units are therefore acting as either major to very minor sources.

As regards the ness at Southwold it is possible that its position is linked to the headland of Norwich Crag clays and Westleton Beds that limits the alignment of the Blythe River at this point. If the amount of shingle in the Westleton beds to the north were to rise appreciably as erosion proceeded there, then a southward extension of any resulting spit would move the ness position to the south also.

Benacre Ness has been described (Robinson 1966) as having shown the greatest amount of movement of all the nesses along the East Anglian coast. This he ascribes to the presence of a near shore, dominant ebb stream. All the hydrographic surveys, except for that of 1824, show the seafloor bathymetry indicating an ebb dominant tidal stream near to the coast at this point. Subsequently the ness has migrated northwards. Others (Williams 1956) have ascribed the movement of this ness, 1 mile since 1840, to differences in the amount of sediment that is being provided from the eroding cliffs on either side, there being more on the north side. Since its movement northwards, the cliffs to the south at Covehithe have become increasingly exposed to erosion and thus should be providing more sediment but the movement northwards still continues. If supply was the key factor then the ness should have started to move south. What is much more likely to have affected this northward migration are the changes to the sandbank configuration around Lowestoft, to the north. If sufficient flood tide flow can move close to the coast between Lowestoft and Benacre then this flood flow will erode the northern side of the ness whilst depositing the sediment on the south side thus moving it southwards. Study of the charts since 1824, show that there has been a decrease of this flood flow and an increase in the ebb dominance at Benacre. The position of Benacre Ness might therefore seem to be controlled by the configuration of the bank system close to the coast at Lowestoft and whether the inshore channel south of there, is flood or ebb dominant.

Rates of cliff erosion are very variable, being nothing either at or close to the nesses but elsewhere are highly variable. At Covehithe, between 1882 and 1903, 5.2metres were lost each year though it fell to 2.7metres between 1925 and 1952. At Benacre between 1925 and 1958, 5.8metres per year were lost. Further to the south at Dunwich, rates of erosion are just as variable being between 0.06 and 3.53 metres per year between 1587 and 1975, an average of 1.15m/year. At Easton Bavents, rates of approximately 2.80 metres are the average since 1849 (Carr 1979). However, recently due to the protection given by the enlarged Dunwich/ Sizewell sandbanks, erosion has decreased immensely.

From this it can be deduced that the coastline has receded some 10 –16 kilometres since marine erosion began some 8000 years ago. This is equivalent to the coastline being close to the present day, 30 metre, bathymetric contour. Thus huge volumes of sediment have been released for transportation into the nearby sinks both to the north, and in particular to the south and the Thames Estuary. This release, though greatly reduced, continues to the present day.

b) Pathways

The offshore zone, seaward as far as approximately 2º E, has a great number of mobility indicators including sand streaks and ribbons, megaripples and sandwaves. Where there is any indication of asymmetry, the movement is more frequently, towards the south, towards the Thames Estuary approaches though there are contrary indicators. These indicators are largely coast parallel and are part of the Southern North Sea nearshore sediment pathway (Kenyon et al 1981). Farther offshore sediment movement is indicated by bedforms as being more frequently towards the north.

There is a complex pattern of movement around the *Sizewell* and *Dunwich Banks* though there is an essentially clockwise motion of the sediment.

Along the beach and nearshore there is southerly movement, though due to the usual eddy flow around the more indented side of a ness, there can occasionally be a more local change to a northward direction on some coastal stretches.

c) Sinks

Within this area there are a number of sinks. The nesses already discussed are only temporary sinks, storing sediment for a short time before its movement further along the coast or to the offshore zone (McCave 1978).

There are a number of sandbanks that are sinks for fine to medium sand, including *Aldeburgh Ridge, Aldeburgh Napes, Sizewell* and *Dunwich Banks*.

The *Aldeburgh Ridge* is positioned as a banner or headland bank, receiving sand from the sorting of material at the head of Orford Ness. In that, it is in a similar position to the *Whiting Bank*, nearby in the Thames Estuary. It is possible, therefore that the *Aldeburgh Napes,* further to the east, was also at one time in a similar position but coastal retreat has left it isolated from this shoreline sediment pathway.

The *Sizewell Bank*, a banner bank from the Coralline Crag core at Thorpeness, and *Dunwich Banks* have amalgamated since 1824 when they were separate entities. They have expanded northwards at an average rate of 49m/year up to 1965 (Carr 1979). At the same time the banks have moved shoreward at a rate of up to 10.7m/year. If this rate were to continue, these banks would amalgamate with the coastline by approximately 2150 AD. However it is more likely that the combined bank will become a banner bank to the north of Thorpeness. This could mean, if the channel between the bank and the coast becomes increasingly flood dominant, that the sand volumes moving south will increase in the future along the coastline, with the *Sizewell/Dunwich Bank*, *Aldeburgh Ridge* and the *Whiting Banks* being among the principle recipients. A comparison of the losses of sediment from the nearby coastline and the gains on these two offshore banks, suggest that these are of the same magnitude (Carr 1979). However sand could be moving in from the north or from offshore and thus complicate this simple relationship.

5. THAMES ESTUARY – Orford Ness to North Foreland (Part of Subcell 3c plus Subcells 3d and 4a).

The area under consideration extends from Southend and the mouth of the River Medway, as far to the east as 3ºE and between North Foreland, Kent and Orford Ness, Suffolk. This area, before recent postglacial sea level rise, comprised of 3 separate river valleys containing rivers flowing towards the east to their confluence with the River Rhine (D'Olier 1975). This combined drainage then ran south through the chalk escarpment of the Straits of Dover, into the lowland area of the English Channel, and to the sea.

The 3 parts comprised of the Essex/Suffolk River Stour with its tributaries of the Orwell, Deben and Butley rivers; the Rivers Thames and Medway with their chief tributaries of the Crouch, Blackwater and Colne; and on the southern side, the River Stour of Kent and its principal tributary, the River Swale. This latter river system joined that of the Thames in the area of the outer reaches of the present Thames Estuary. These 3 major river valleys were separated by two narrow watersheds; the Naze to *South Shipwash,* and to the south, Warden Point to *Shingles Patch.* These promontories have been largely eroded away in the 7000 – 8000 years since the sea returned, progressively drowning the lower reaches of the river valleys on either side. Their chief expression at the present day is the eroding cliffs of The Naze, Essex and those of the Isle of Sheppey in Kent. These watersheds provided some of the sediment that is now found in sinks within the Thames Estuary, other sources being the fluvial sediments of these various palaeo- rivers, other small cliffed areas around the palaeo-river valleys and perhaps most importantly, sediments from the coast and floor of the area now occupied by the Southern Bight of the North Sea.

As sea-level rose and marine influence began to be felt within the three estuaries at approximately 8500BP, material that lay in the Rhine/Thames valley to the east and south and from the exposed areas of Tertiary sands in the southeast, was transported westward into the palaeo channels of the various rivers that had drained the area of the present Thames Estuary (D'Olier 1972). Houbolt (1968) believed most of the sand lying in the Southern Bight was derived from the River Rhine during and shortly after the last glaciation. At present there are still huge deposits of these Bligh Bank and Buitenbanken Formation (NERC/BGS 1991) sands and gravelly sands in the Southern Bight: much of these from the western side were transported into the Thames Estuary area during the early phases of the last marine transgression. During the transgression, tidal flat deposits (Elbow Formation) were laid down at the sea edge only to be largely eroded again as sea level continued to rise. Some remnants of the Elbow Formation are still to be found in the *East Swin* channel south of the *Gunfleet Sand*. As this transgression continued, a marine connection with the more northern parts of the North Sea was effected around 7,500 BP (Jelgersma 1979); then the principal tidal influence swung round to be more northeasterly. Sand entering then from these Rhine and intertidal deposits was swept up into the sandbanks and sand flats that overlie the old palaeo valleys and now dominate the later sedimentary sequences.

At the present day the Thames estuary is still a **sink** for decreased quantities of bedload transported sediment from these sources. Suspended sediments largely derived from eroding areas of London Clay cliffs at the Naze, the Isle of Sheppey and several areas of exposed seafloor, are to some extent trapped within these in some places, but a great deal is transported out of the estuary to become an important element within the North Sea 'English River', a current that intermittently flows northeastwards towards the northern Dutch coast and Heligoland Bight (see Web pages – www.mumm.ac.be/OceanColour and the synoptic measurements of surface sediment concentration in Figures 28 and 29 of the main Sediment Transport Report, HR Wallingford EX4526).

5.1 Orford Ness, Suffolk to the Naze, Essex (parts of Subcells 3c & 3d).

The southern boundary of this area is taken as the Naze to *South Shipwash* watershed. This consists of relatively erosion resistant, bedrock elements of the basal part of the London Clay Formation comprising of the Harwich Member. This erosion resistance is due to contained beds of volcanic ash some of which are cemented, particularly the 0.75metre thick, Harwich Stone Band. These beds gives rise to a number of named features of the seabed off the north Essex and south Suffolk coast, such as the *Stone Banks, Naze Ledge, West Rocks*, parts of the *Roughs Shoal, Threshold* and *South Ship Head*.

Elsewhere in the area, the *Wadgate* and *Felixstowe Ledges*, the *Kettle Bottom* that acts as the core of the southern end of the *Bawdsey Bank*, the *Flagstone* that possibly helps to anchor the southern end of the *Whiting Bank*, are all expressions of this same basal unit of the London Clay. **Bedrock[3] is therefore at or close to seabed over much of this area.**

a) Sources

Except for the Naze that will be discussed in the next section, there is very little sediment at present that can be described as a source material. The silty clays to silty sands that comprise the softer elements of the London Clay do provide some material under the action of strong tidal and wave activity, on exposed areas of the seabed, but as even the coarsest grain size from the London Clay is < 0.250mm, most of this is lost to the area as suspension load towards the northeast, or to the southwest into the East Swin (HR Wallingford report EX 3875).

The cliffs at Bawdsey could, if the fronting shingle beach were to be overtopped, provide small inputs of London Clay material and some shelly sand from the overlying Early Pleistocene, Red Crag deposits. These were undoubtedly an important source before the shingle beach had elongated sufficiently from the north to protect them. This applies equally to the cliffs further to the south at Cobbolds Point, Felixstowe.

At Orford Ness the high ground to the north west of the spit and upon which stands the town of Orford, comprises sandy, Pliocene, Coralline Crag with overlying Red Crag. This, the watershed between the southward flowing, Butley River and the eastward flowing, River Alde, once extended further to the

[3] In this case London Clay

southeast and had been progressively eroded back to its present position before the shingle spit extended from the north. Sediment from this cliff source could have been an important component up to the time that the cliff line became protected by this extended shingle spit.

It is possible that the protective shingle ridge had hardly reached Orford by the 12th century, as the town was then a busy port. The shingle of Orford Spit has been largely derived from the exposures of the Pleistocene, Westleton Beds that outcrop on the east Suffolk coast between the Minsmere and Hundred Rivers. At the present day sand is predominant within these deposits though shingle lenses and thin beds are also present. Inland the deposit shows thick beds of shingle and it is therefore very possible that the variable lithology of this deposit has contributed by longshore drift to successive influxes of shingle to the beaches and thus to the formation of the spit, as the cliffs to the north have in the past, eroded rapidly westwards (see section 4.4a). At other times sand was and is now, the principal sediment being released from the cliffs, though this is largely being contained locally at present (see section 4.4c). **If the Minsmere to Hundred River cliff section was to be protected either by mans intervention or naturally as at present by the offshore bank system, and/or as long as sand remains the predominant result of cliff erosion over this section then the Orford shingle spit, due to lack of replenishment, will slowly degrade and drift southwestwards.**

b) Pathways

Sand movement around the *Shipwash, Whiting* and *Cork* sands is clockwise as evidenced by the asymmetry of sandwaves upon their flanks. To the north of the heads of the *Shipwash* and *Bawdsey* banks asymmetric bedforms indicate transport of material from the Southern Bight towards these two converging 'heads'. In the northern section of the *Shipway* a sandwave field with asymmetric bedforms indicates sediment movement towards the north. *Bawdsey Bank* also exhibits this, making it an exception with anticlockwise circulation. Thus there are convergent sediment pathways supplying sediment to these two banks at their northern ends.

At the southern end of the *Shipwash* sandbank a narrow train of southerly directed, sandwaves indicate a sediment pathway into the more central parts of the Thames Estuary. Thus of the five banks only the *Shipwash* appears to be losing some sediment and is therefore not a permanent sink.

There does not appear to be any major sediment pathway linked to the nearshore zone from the *Shipwash, Bawdsey* and *Whiting* banks through their position relative to a once southeasterly extended, Orford Ness headland suggests they may have been initially formed as headland or banner banks in its lee. In that case *Whiting Ba*nk might be receiving sand winnowed from the mobile sandy shingle of Orford Ness spit. Also due to the close proximity of the Whiting Bank to the coast there may be some sediment interchange under severe wind generated current action.(see section 2b).

c) Sinks

There are 5 sandbanks in this area that act as sinks of sediment – *Shipwash, Bawdsey, Whiting, Cutler and Cork*. They are comprised of fine to medium sand, though the *Cutler Bank*, undoubtedly the most recently formed and still comprised only of an elongate train of sandwaves, is composed of coarse to medium shelly sand. Within these sands are found abundant evidence of a Pleistocene, Crag derivation, with distinctive shells indicating their source. This is also the case particularly in the sands of the *Whiting* and *Bawdsey Banks*, and in the sandwave fields that lie between the *Shipwash* and *Bawdsey* Banks.

The buried channels of the Rivers' Stour/Orwell, the Deben and to a small extent the Butley whose drowned channel has been largely lost through later peneplanation[4], are sinks and are almost completely filled with sediments, generally ranging in a fining- upward sequence from gravel through to silty sands. These are partly fluvial sediments laid down by the river, partly estuarine as sea level rose and finally are marine sands. A major section that is not filled is the *Cork Hole*, part of the palaeo- Stour channel, where current velocities are too high at present to allow deposition of anything other than coarse sands and

[4] Downcutting of the rock surface

gravels, of which none are locally available. Also a small sink for fine muddy sands exists in the deeper water of the southern end of the *Shipway* channel where filling of the palaeo-Stour channel is also, as yet, incomplete.

5.2 The Naze to Colne Point, Essex (Part of Subcell 3d)

This represents the northern side of the central and major river valley that contained the rivers Thames, Medway, Crouch, Colne and Blackwater and their minor tributaries, before rising sea levels some 8000 years ago drowned them.

However the southern boundary for this section of the report is taken as the *Gunfleet* sandbank.

It was reported that intertidal sand transport along this coastline was both eastward and westward from around Clacton on Sea, thus requiring a replenishing source from somewhere offshore. At the same time it was postulated that the coastline was supplied by sand from an offshore source – the *Gunfleet Sand*. In addition it had been reported (Tendring District Council) for several years that there was less sand on the beaches than there had been before.

An assessment was instigated within the SNS2 study to evaluate these claims and to put forward a clear understanding of the changes in conditions that might have caused any loss of supply.

As the *Gunfleet* Sands were thus seen as the most likely source of sediment for the coastline a survey was carried out by CEFAS with the aim of discovering the principal sediment pathway(s) into the coastline from this potential source. At the same time, research into other, more probable sediment sources and reasons for the progressive deflation of the beaches was progressed.

a) Sources

In the past, before any sea defences had been installed, the cliffs along this coastline were actively eroding. These defences were progressively installed from 1881 up to the present day, starting in the immediate vicinity of Clacton (Tendring D.C.1989).

The cliffs around Clacton, from the site of the former holiday camp, through West Cliff and on to Holland on Sea were composed of a series of Pleistocene gravels, termed the Lower Holland and Wigborough Gravels (Bridgland 1994), sands and laminated estuarine clays up to a maximum thickness of 25 metres. Additionally the same sands and gravels made up low cliffs and were exposed on the beach to the south, at Lion Point, Jaywick. The gravels and sands represent the deposits of a much older course of the River Thames/Medway that flowed across this area during the Middle Pleistocene.

The erosion of these cliffs and beach platform sediments formed the beach materials along the coastline from Holland on Sea southwestwards to Colne Point. Consequently, Colne Point and the St Osyth marshes that lie behind, are also underlain by these same, cliff derived, beach drifted sediments. Though there are no accurate figures for the rate of recession of these cliffs before sea defences were constructed, marine erosion of such easily erodible sediments over approximately 8000 years (Eisma et al 1981) must mean they extended several kilometers seaward and have therefore been a substantial source.

To the north, from Frinton on Sea to the Naze, beach sediment has been derived from the erosion of the cliffs along this section. The rapid erosion of the Naze, of 1.45m/yr between 1973 – 1988 and up to 0.88m/yr between 1874 and 1973, (Gray 1988), has provided large quantities of Pleistocene gravels, sands, silts and clays in addition to sandy Red Crag overlying the London Clay. As this watershed has been attacked and eroded by the sea for at least 8000 years, then it must have extended at least 8 kilometres seaward. Using the erosion rates cited above, this equates to a position approximately equivalent to *West Rocks*, or even beyond, towards *South Ship Head* at the southern end of the *Shipwash* sandbank. The erosion of this watershed headland has not only provided sediment for the rapidly eroding coastline to its south but also for the mud and sand flats and saltmarshes of the Walton Backwaters to the north and the

Dengie Peninsular to the southwest. This source is now much reduced and consequently fine sediment for the mudflats and salt marshes of these two areas is also reduced.

As Leggett et al 1998 state, 'the negative impacts of sea defence along the Essex coast can be seen. The maintenance of high beach levels at Clacton by beach control structures quite clearly starves the down drift beaches'.

b) Pathways

No bedload pathway was found connecting the *Gunfleet* sandbank to the coast at any point either from its coast facing flank or from its northern end. Bedforms indicate that the sandbank has a sediment circulation pathway along its flanks operating in a complex way but largely in a clockwise mode. In addition no sand was found to be either entering or leaving this sandbank from its northern end. To the north, sand dumping in the spoil ground east of *West Rocks* from dredging operations in the *Harwich Approach Channel* is seen, from investigations using sidescan sonar, to move away northeastwards and not towards the *Gunfleet*.

Defences along the coastline have covered up the major source of supply from the cliffs but only partly prevent sand moving southwestward along the coast.

c) Sinks

It is suggested that the *Gunfleet* was formed as a headland or banner bank when the Naze headland extended much further eastward but as the Naze eroded westward so the *Gunfleet* ceased to be a conduit for sand from this eroding headland and is now largely a moribund sink.
Colne Point acts as a minor sink for beach materials progressing southwards down the Essex coast. Whether some of this material moves across towards Mersea Island and The Dengie is unknown at this time.

However, both Saint Peters and the Dengie Flats are a sink for fine sands and muds, though there is now no major source from the northeast for these materials at the present day, following the extensive, westward erosion of the Naze headland.

However sediments are most possibly moving in from the south and southwest (see section 5.3c).

5.3 River Crouch, Essex to The Isle of Sheppey, Kent, and eastward to the Kentish Knock (Parts of Subcells 3d and 4a).

The northern boundary of this section is the Gunfleet Sand whilst the southern boundary extends from Warden Point on the Isle of Sheppey, northeastwards as far as the *Shingles Patch* at the base of the *Longsand Sandbank* (approx: 51º 33' N/ 1º 17'E.) and then as far eastward as the *Kentish Knock* sandbank. This area encompasses the major part of the, pre-sealevel rise, palaeo-Thames /Medway / Crouch/Colne/Blackwater river valley.

a) Sources

There is a small input of sediment, mostly in suspension load, from the River Thames of approximately 364,000 tons / year (D.S.I.R 1964) or 700,000 tons/year (Odd & Murphy 1992). The River Medway might also provide a similar amount (Kirby 1990).

A major source is the London Clay cliffs of the Isle of Sheppey where the erosion rate is at present 0.95m / year (T. Cosgrove- pers. comm) but was 1.2m/ year between 1965 and 1908 (Steers 1964). However geophysical data suggests that these cliffs extended some 28 kilometres northeastwards when marine erosion began approximately 8000 years ago. This extended Sheppey headland would have been capped by sands of the Tertiary, Bagshot Formation, thus its erosion has released large quantities of sands, silts and clays that continues to the present day. This source also includes London Clay Formation, silts and clays that are being eroded from these cliffs, from the seabed offshore of the Isle of Sheppey and from the Kentish Flats to the east.

A further major source, is sand moving in from the Southern Bight of the North Sea, along a wide sediment transport pathway that lies west of 2ºE down the Suffolk coast and out to 3ºE, south of 52ºN where there is a bedload parting (Kenyon et al. 1981). These sediments are derived from the reworking of Quaternary deposits that floor the Southern Bight (see section 5).

b) Pathways

Sand pathways exist around each of the major banks, circulating sand in a complex of clockwise circulation cells. A lateral, northwestward motion of the inner banks, as described below (section 5.3c), was achieved by an asymmetry of this clockwise motion with more rapid motion on the southern side of these inner banks. These stronger flows were related to the changing width and depth, over the 150 years since these changes could be observed due to accurate charting, of the *Edinburgh Channels*, which carry water through and across the barrier of the *Long Sand* sandbank, nearby to the south. This bank acts as a barrier between the Dover tide from the south and the North Sea tide from the northeast, that are out of phase. This results in water levels on each side of the barrier being at different levels at any particular time. The *Edinburgh Channels* allow water on the flood, from the south of the estuary, in addition to that from the *Black Deep* to the northeast, into this area of sandbank instability and mobility. This area of instability within the Inner Thames Estuary sink continues to effect change at the present time as the *Edinburgh Channels* become shallower and increasingly narrow and the *Fishermans Gat* to the northeast takes over as the principal channel for this balancing of water levels on either side of the *Long Sand*.

The chief inward pathway of sediment occurs between the Suffolk coast and 2º E and further east to 3ºE, below 52ºN. This wide pathway brings sand from Quaternary sources (see section 5) into the heads of the 5 major sandbanks and in particular *Sunk Sand, Long Sand* and the *Kentish Knock*. The outer sandbanks- *Unnamed Bank, Inner Gabbard, Outer Gabbard, Galloper*, and *North Falls* are all part of this southward sand mobility pathway (Caston 1981) that is steadily moving sediment into the outer reaches of the Thames Estuary. In addition, some fine grained sediment is incorporated into the sinks from semi – suspension flow after the erosion of the London Clay of the *Roughs* and *West Rocks* area off the Naze and from the coastal cliffs of the Isle of Sheppey and the shallow area of the Kentish Flats.

c) Sinks

Much of this area is a slowly accumulating sink.
The five sandbanks – *Kentish Knock, Long Sand, Sunk Sand, East* and *West Barrow* and the *Northeast Middle* are sinks for fine to medium sand. *Long Sand* and *Sunk Sand* have extended appreciably towards the northeast during the last 150 years; in the case of the Sunk Sand by approximately 5 kilometres. *Sunk Sand* has also extended at its southern end, whilst in the last 10 years the form of the northern end of *Long Sand* has broadened appreciably.

The *Kentish Knock, Sunk Sand* and *Long Sand* are the main entry points for bedload from the Southern Bight. Clockwise circulation of sand around these banks brings sand into the inner reaches of the estuary and into the much more mobile sandbank elements of the *Knock John, Tizard, Knob Shoal, Shivering Sands, Mouse* and *Oaze* banks. Elements of these have moved northwestwards towards the northern side of the estuary by up to 3 kilometres over the last 150 years, amalgamating with the southern end of the *Sunk Sand* and with the *West Barrow*. In this way sand from the three major sandbanks is being transferred **northwestwards** into the **primary sink** of the *Maplin Sands and Dengie Flats*. Geophysical evidence shows that the *Barrow Banks* extended much further to the west in the past and that their western ends are being progressively covered by the muddy fine sands of the *Maplin Sands* sink as it progrades eastwards. From borehole and geophysical evidence (Maplin Airport/ Seaport studies 1972- 75) the *Maplin Sands* show the typical internal structure of a prograding tidal flat (Evans 1965 and Reineck 1973). Two channels that lie immediately to the northeast of this sink, the *Middle Deep* and the western end of the *East Swin* are part of this extending sink and are filling with sands and muddy sands. This progradation is confirmed by the 3% gain in volume that has occurred between 1991 and 1996, on the sand and mud flats between Dengie and Shoeburyness (Leggett et al 1998).

The complexity of movement of sediments within the estuary is shown by the findings of Whitehouse et.al. (1996 – based on data from the mid-1970's) who found that the net sediment flow in the centre of the main *Warp* channel was ebb dominated whilst on the banks at the channel sides the net flux is flood dominated. In addition Talbot et al. (1982) found that most of their Woodhead Drifters released in 7 different positions throughout the outer Thames Estuary, moved south and westwards into the estuary. They also found that of those released off the mouth of the River Crouch, many moved towards the Essex coast north of Bradwell. This suggested that the general southerly and westerly drift affecting most of the area was partly compensated by a northerly drift closer to the shore; a drift into the primary *Maplin Sands* and *Dengie Flats* sink, mentioned above.

Underlying much of this area are a number of buried river valleys, now almost entirely filled with sediment (D'Olier 1975). Only small parts of these valleys are still not completely full and are therefore continuing to be small sinks for sediment – the *Great Nore*, the eastern part of the *Cant* at *Red Sands* and the *Shivering Sands* channel.

5.4 Isle of Sheppey to North Foreland, Kent (Part of Subcell 4a)

The northern boundary of this area is the *Shingles Patch, Long Sand* to the *Kentish Knock* and seaward to approximately 2ºE. It incorporates the peneplaned London Clay surface of the *Kentish Flats* through which cuts some remaining fragments of the infilled palaeovalley of the River Swale. This river was a tributary of the Kentish Stour that ran northeastwards from North Kent, east of the Reculver to a point under the *Tongue Sand* where it met the River Thames/Medway and their tributaries. Except for a few isolated sections such as the *Gore* and part of the *Queens Channel*, these valleys have been peneplaned out of existence or are completely filled with sediment. However this large, combined river, in turn had its confluence with the River Rhine just to the south and east of the *Kentish Knock* sandbank. The embayment where this confluence occurred is largely filled with sediment though it can be observed by following the 20 metre bathymetric contour in this area (Admiralty Chart 1610). The Rhine channel to the south is almost devoid of sediment except for the *South Falls* bank and the sandwave fields to the bank's north and east.

a) Sources

Minor sources are the London Clay seabed that comprises the *Kentish Flats* and a little from the erosion of the cliffs of the Isle of Sheppey. In the past, before their protection by sea defences, the cliffed sections between Whitstable and Reculver provided some sands, silts and clays from the London Clay Formation, the Oldhaven, Woolwich and Reading Beds, and the Thanet Beds. Erosion rates of up to 1.5 metres/year were recorded for the London Clay cliffs. In addition, the Chalk cliffs of the Isle of Thanet, now also largely protected by sea defences, eroded along fracture zones, by up to a metre a year in the past (So, 1965). The principal source now is from the Southern Bight, where sand pathways from the north and northeast (see section 5) bring sand in from the northeast. Also a platform of partly exposed London Clay immediately due east of the *Kentish Knock* sandbank, releases small quantities of clay, silts and fine sand. From the south, a small input, seen as trains of small megaripples, brings sediment from the region of the *Goodwin Sands*, past the North Foreland and into the major sandbank, the *Margate Sands*.

b) Pathways

This consists largely, as for the previous area, of elements of the Southern Bight sand pathway bringing material from the northeast. The coarser elements are deposited in the outer Thames Estuary, Thames/ Rhine confluence sink, south of the *Kentish Knock* sandbank, and the finer elements into the sandbanks of this area including the Margate Sands. The sandbanks have a clockwise circulation of their surface material though this is particularly complex around the western ends of the *Margate Sand* and the *Tongue*. As mentioned in section 5.4a, a narrow pathway from the south brings sand from the region of the *Goodwin Sands* into the *Margate Sand*. This pathway might be reversed under some northerly wave dominated conditions. In addition there is an intermittent sediment pathway from the *Margate Hook* sandbank to the nearby shoreline, towards Minnis Bay. This is thought to be due to wind wave activity from the north and northeast and this supplies the beach and nearshore sediment pathway that operates along the North Kent coast (D'Olier, 1993).

c) Sinks

There are two sandbanks that act as sinks for fine to medium sand within this area – *Margate Sands* and its associated parts of *Margate Hook* and the *Last*, and the *Tongue Sand* with associated elements of *The Ridge* and *Pan Sand*. In the area to the northeast of *Margate Sands* and south east of the *Kentish Knock* there is a embayment between 1º 25' and 1º 38', the **Thames/Rhine Confluence sink**, that is being filled with medium sand. This is a major depositional area where original deposits from these rivers and materials from earlier phases of marine transgressive infill are now being overlain by this more recent and continuing influx from the northeast.

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