Hydraulics Research
Wallingford

A MACRO-REVIEW OF THE COASTLINE OF ENGLAND AND WALES

2 The East Coast. The Tees to the Wash

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ABSTRACT

This report is a review of the coastline between the Tees Estuary and The Wash. In it are described the various natural and man-made processes which affect the behaviour of this particular stretch of Britain's shoreline. The report includes a description of the major coastal defences, areas of erosion and accretion and various other aspects of beach behaviour. Information is given about winds, waves and tidal currents and how these affect the formation of the coast and its future behaviour. Various stretches of coastline which for coastal engineering purposes can be treated as independent or semi-dependent cells are also identified. This report is the second of a series covering the coastline of England and Wales which Hydraulics Research are carrying out for the Ministry of Agriculture, Fisheries and Food.

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1 INTRODUCTION

In 1985 the Ministry of Agriculture, Fisheries and Food commissioned Hydraulics Research, Wallingford to carry out a review of the coastline of England and Wales. The aim of this review is to give a broad description of coastal processes within clearly defined coastal 'cells' and information on winds, waves and tidal activity and coastal defence works for each stretch of coast examined. Because of the scale of the project, it has been necessary to divide the coastline into large regions. This volume is the second in the series and covers the coastline of Eastern England from Hunt Cliff, Tees Bay to The Wash (Fig 1).

When coastal defence attracts attention, it is usually focussed on the immediate locality where the problem occurs, be it flooding, cliff falls, damage to and deterioration of existing defences or loss of beach material. These problems should be viewed as the result of the dynamic interaction of a range of natural and man-made processes operating within the wider context of the coastal system. Any imbalance within the system will create changes in the behaviour of the coastal regime. An inappropriate coastal defence scheme might, for example, create problems, exacerbate existing ones or merely transfer them along the coast. Such situations are most likely to arise in areas dependent on a supply of material from updrift.

It has been a primary objective of this review, therefore, to identify areas which can be considered as individual coastal units or cells. Such cells are defined as stretches of coastline within which beach changes take place largely independently of changes in adjoining cells. As such, the cells may be considered 'self contained' and have defined the coastal units covered by this and subsequent volumes of this review (Fig 2). Any one unit may in fact consist of several smaller sub-units. For example, a long stretch of sand coastline may be divided by a stretch of rocky cliff line. The two stretches of sand coast can be considered as sub-units if there is little in the way of sediment exchange between them.

Coastal engineering is becoming an increasingly precise study, not only as a result of advances in technology but also necessitated by the high cost of new coastal defences and the maintenance of existing systems. Thus, proposed schemes these days are carefully evaluated. This may require the collection of comprehensive field data and in some cases the use of predictive or physical models. A further purpose of these reports is thus to highlight sources of existing data and the availability of such modelling techniques.

The major points derived from this study are summarised in Chapter 2. Here, information is drawn together about the important features which characterise Eastern England its geology and geomorphology, coastal development etc. From here onwards the various chapters of the report are broadly in sequence with respect to time, beginning with the evolution of the coast and ending with a description of present day coastal defences. Chapter 3 gives a general description of the geology of the coastline and relates it to existing sea defence problems. Information about wind, waves and tidal phenomena is given in Chapter 4. In Chapter 5 the coastal processes are described, paying particular attention to areas of sediment supply (sources) and areas of accretion (sinks). A systematic regional survey of coastal features and defences follows in Chapter 6.

Potential problem areas are highlighted in Chapter 7 with emphasis being given to the definition of coastal cells along the east coast. Any additional information which is relevant to coastal engineering has been included in an extensive although presently not exhaustive bibliography, which it is hoped to update regularly, as and when fresh sources of information become available.

2 EXECUTIVE SUMMARY

The coastline from the Tees to The Wash forms three markedly different topographic units.

The rugged coastline of North Yorkshire is characterised by high cliffs of shales, sandstones and limestones, extending southwards from the Tees to Flamborough Head. The coastline is incised by many large bays, formed by valleys infilled with rapidly eroding boulder clays. Erosion of the clay cliffs has produced sand beaches which rest on wide foreshore reefs. Outside the bays the open coastline has nearly sheer cliffs fronted by very sparse rocky beaches. The net littoral drift which is in a net north to south direction is thus weak and fragmented. Movement of beach material is generally contained within individual bays and because of their strong indentation the action of waves tends to push deposits to the centre of the bays. There are several large promontories such as that at Scarborough Ness and at Filey Brigg which also reduce the littoral transport of beach material to a very low level. The southern end of this "coastal unit" is Flamborough Head a very large promontory of hard chalk. This is effectively a zero transport boundary for beach material, since it extends seawards several kilometres and its tip is surrounded by deep water. The centres of population are generally restricted to embayed areas and coast protection works are needed primarily to protect the toe of the boulder clay cliffs against wave induced erosion. Cliff instability is also a widespread problem and much amenity and farmland is continually being lost to the sea.

The Holderness coastline is the gently undulating land which stretches from Flamborough Head to the Humber estuary. It has a nearly continuous line of boulder clay cliffs whose rate of recession (averaging over the whole stretch at 1-2m per annum) is unmatched over such a long frontage anywhere in the British Isles. The coastline has a gently curving shape in plane, indicating that although present rates of recession may vary markedly from one area to the next, the long term rate of recession is fairly even over the frontage as a whole. The toe of the cliffs is continuously being cut back by wave action and material slips downwards as a result of aerial weathering. While vast quantities of material are eroded in this manner a large proportion of this, consisting of silts and clays, is transported offshore in suspension. The coarser fraction, consisting mainly of sand but also with a small proportion of pebbles, is transported southwards within the littoral zone by wave action. The foreshore only has a thin cover of sand over the boulder clay base and provides very little protection to the toe of the cliffs. Most of the land on the cliff top is agricultural or amenity land (holiday camp sites) and is unprotected against erosion. Coast protection works are only found at Bridlington, Hornsea and Withernsea, the three main centres of population in this coastal strip. The defences consist typically of concrete sea walls while the beaches of the towns are maintained by groyning. There is sufficient supply of beach material to maintain healthy beaches immediately to the north and satisfactory beaches at the centre of the town frontages. However, there is serious downdrift erosion to the south of each of these three towns. Erosion due to the interruption of littoral supply is also causing the neck of the Spurn Peninsula, on the north side of the Humber estuary, to become more liable to breaching with time. Littoral drift has previously provided Spurn Head with a sufficient volume of sand to maintain its stability. However, the neck of the spit just south of Kilnsea is receding landwards rapidly and due to the lack of adequate coastal defences it is in danger of breaching. The mouth of the Humber acts as a sink for much of the material eroded from the Holderness coastline. Eventually some of this material is transported by waves and tidal currents to Donna Nook, Lincolnshire, on the south side of the estuary. Here there is extensive salt marsh and sand dune development.

The coast of Lincolnshire from the mouth of the Humber to The Wash is very low lying, substantial areas being below the level of high water. Indeed much of this stretch is at risk of flooding in severe storms. The whole of the east coast is exposed to a wave climate dominated by north and north-easterly gales. Meteorological conditions also give rise to surges the most common of which are propagated in a southward direction. These "surge waves" increase in height as they travel southwards within the gradually narrowing confines of the North Sea basin. The surges pose a serious threat of flooding in Lincolnshire and to the low lying stretches of coast in East Anglia and Essex. The 1953 surge is a prime example of how serious the flooding can be. Embankments along the coastline of Lincolnshire breached in many places between Mablethorpe and Skegness causing extensive flooding. This coast is particularly vulnerable to damage since the boulder clay is overlain by peat deposits and salt marsh clays all of which are very easily erodible.

The threat of erosion and flooding is less serious between Mablethorpe and Cleethorpes where the foreshore is very wide and fringed by offshore banks. The foreshore dwindles in width to the south of Mablethorpe and there are serious erosion problems as far south as Skegness. The coastal strip in this area is protected by sea walls and there are extensive groyne systems, though many are in a state of disrepair. Large scale accretion begins at the mouth of The Wash. The development of sand dunes and salt marshes has resulted in the seaward extension of the coastline at Gibraltar Point, which is just to the south of Skegness. This area is well protected against high tides by earth embankments in front of which the foreshore tends to accrete.

Within the large stretch of coastline from the Tees to The Wash a large number of semi-dependent and independent cells can be identified. From the Tees to Flamborough Head there are many bays separated by long stretches of cliff line. These bays are so indented that they act as almost independent coastal cells. The rocky promontories further subdivide the coastline with regard to littoral movement. Filey Brigg and Flamborough Head should be considered as almost complete boundaries to littoral drift. The Humber estuary is a vast "sink" for fine sediments and does not form a boundary in this respect. Much of the material in the outer part of the estuary is reworked by waves and tidal currents and is transported southwards to the Lincolnshire coast. The stability of the Spurn Peninsula also affects the coast to the south. For example, substantial breaching of the peninsula could result in an increase in wave activity on the south shore of the Humber. However, it is unlikely that changes on the Lincolnshire coast could affect beach processes at Holderness, since there is very little movement of beach material in that direction. From a morphological viewpoint the whole of the coastline from Flamborough Head to The Wash should therefore be treated as one unit.

3 COASTAL GEOLOGY AND TOPOGRAPHY

3.1 Geological framework

The effect of the local geology on the coastline of the area is broadly outlined here in as far as it provides some background on the formation of the present coastline and helps to explain current marine processes, especially where problems arise requiring some coastal defence measures. These are discussed later in the report. The coastal geology in this area is very complex and a detailed account may be found in other sources (Refs 1, 2, 3). A simplified regional geology of the area, however, is shown in Figure 3.

From the Tees estuary to south of Flamborough Head the rocks are sedimentary in origin, laid down during the Jurassic and Cretaceous periods (66-205 million years BP). However, more recent folding and faulting and the effects of the Ice Age together with post glacial changes in sea-level add complexity to the geological picture of the area. This is reflected in the coastal configuration and topography. The cliff and bay coastline from the Tees to Flamborough Head clearly contrasts with the lower, smoother coastal outline south of Flamborough. The coast of Holderness and Lincolnshire, which are divided geographically by the Humber estuary, are almost entirely formed in unconsolidated glacial and other superficial deposits of Pleistocene and more recent origin. At the southern extent of this study area, The Wash forms a major indentation fringed by tidal flats where silts and muds are actively accreting.

3.2 Regional geology

3.2.1 North Yorkshire

The most northerly point considered is Hunt Cliff, forming a distinct promontory at the southern limit of Tees Bay (the coastline of the North East is covered by Volume 1 of this Macro Review, Ref 4). From the Tees estuary to south of Filey, the rocks are entirely Jurassic (laid down 135-205m yrs BP). The nature of these rocks show considerable variation (depending on the environmental conditions under which they were laid down). The older rocks outcropping in the north of this region are overlain by successively younger rocks towards the south. The lower, older Jurassic beds are of Lias, consisting of interbedded shales, calcareous sandstones, clays and limestones. Some ironstone deposits in these beds have been of economic importance in the past. The Middle Jurassic is characterised by Oolitic limestones and this is followed by various clays during the Upper Jurassic. From Speeton to Sewerby, younger Cretaceous chalks (66-135m yrs BP) are exposed to form the impressive cliffs at Flamborough.

During the Pleistocene (1.8 million to 10000 yrs BP) advance and retreat of ice sheets scoured the bedrock and in places deposited thick sheets of glacial drift. Along the Yorkshire coast, boulder clay is therefore present in nearly all the bays and also caps many of the cliffs, obscuring the bedrock beneath. Boulder clay, glacial drift or till are general terms given to a heterogeneous mixture of materials of glacial origin, varying in colour and texture and containing material of all sizes. Larger boulders (erratics) indicate their origins further north having been moved to their present position by the ice. Where unconsolidated boulder clay outcrops at sea level, it has been subject to rapid erosion and is a major source of localised beach material.

The effect of wave action and differential erosion on such a varied geology has been to produce a bay and headland coastline with high cliffs. This forms the general pattern of coastal topography from Hunt Cliff to Flamborough. Hunt Cliff is an impressive flat topped promontory formed of shales overlain by boulder clay. The shales form extensive reefs and nearshore rock ledges at the cliff foot. Shale cliffs predominate southwards to Boulby and Staithes interrupted only by small becks such as at Skinningrove. At Boulby Cliff the face is scarred by disused alum excavations for the works at Loftus. These cliffs consist of Lias capped with sandstone and are among the highest on the east coast of England, reaching to 200m. For the most part they are fronted by a wave cut rock platform and any small pocket beaches that exist consist of large pebbles and boulders.

The village of Staithes is situated in a sheltered position in a steep sided ravine formed of more resistant strata showing distinct horizontal bedding. The river flows into a small harbour to the east of Cowbar Nab which is protected by low breakwaters. At Port Mulgrave to the south of Staithes ironstone was once mined from the cliff face of clays and shales, and was transported by sea to Middlesbrough.

Runswick Bay forms a marked embayment backed by boulder clay cliffs and contains a sandy beach. The promontory to the east of the bay at Kettleness is composed of harder, more resistant bands within the Lias. Southeast of Sandsend, the cliffs are lower and the Jurassic rocks are once again overlain by thick boulder clay. The sand beach widens towards Whitby where the cliffs behind West Beach are artificially graded. The River Esk at Whitby flows through a preglacial gorge situated on a fault line. East of the river mouth the beach is narrower in front of the cliffs of shales and sandstones. The alum contained within these shales was once worked during the early 19th century. The oblique jointing in the beds has been exploited by wave action to form many caves. At Saltwick there is a small bay enclosed by the headlands of Saltwick Nab and Black Nab.

Between Saltwick and Robin Hood's Bay there are once again shale cliffs up to 200m high which are fronted by a wave cut platform. Robin Hood's Bay is enclosed by the headlands of North Cheek and South Cheek, composed of resistant sandstone. The bay itself is formed in an anticlinal structure (upfold) in the Jurassic strata where the less resistant shales have been eroded away. This is clearly seen in the pattern of rock ledges of more resistant calcareous sandstone and limestone exposed at low tide. Boulder clay forms low cliffs surrounding the bay. The combined action of wave attack and rain wash on the clay matrix has produced many slumps and slides and resulted in talus fans and pinnacle formations.

To the south of Robin Hood's Bay, the cliffs at Ravenscar form a high flat topped plateau. From Ravenscar to Scarborough the coastline is fairly straight in a north to south direction being influenced by a series of faults running in this direction. The rocks, mostly limestones, become buried and obscured by glacial drift. Both Hayburn Wyke and Cloughton Wyke form 'lows' in the cliff line. From Long Nab to North Bay Scarborough the cliffs are almost wholly in glacial drift and fronted by reefs of sandstone.

At Scarborough the boulder clay cliffs in the North and South Bays are separated by Castle Cliff, a promontory of resistant sandstone. Cayton Bay, between Osgodby Point and Yons Nab, is formed by faulting. Between Gristhorpe and Filey the vertical cliffs are formed of interbedded clay and calcareous grit and are overlain by boulder clay. Since the rocks dip to the south, the steep scarp slope faces north and is exposed to severe wave attack which exploits the jointing within the rock to form buttress-like projections and excavating many small coves. The cliffs terminate in the narrow promontory of Filey Brigg. The reef of calcareous grit is submerged at high tide and wave action has clearly exploited the dipped strata to form rock ledges and hollows. On the south side of the Brigg the boulder clay reaches almost to sea level and the cliff face is deeply runnelled by rain wash.

Filey Brigg forms a natural boundary between the more resistant rocks to the north and the weakly consolidated boulder clay cliffs to the south in Filey Bay. It also forms a natural boundary with respect to littoral movement. For the most part the cliffs in Filey Bay are vegetated but where this cover is removed, gullies and slips are frequent. The boulder clay has been eroding at a fairly consistent rate to form a gently curving sandy bay.

At Speeton Beck, chalk from the Cretaceous period is exposed. The resistant chalk with flints (Lower Chalk) forms the cliffed and indented promontory of Flamborough Head. The cliffs are high and sheer on the north side and are fronted by a very narrow wave cut platform. The whole headland is covered by boulder clay. This is clearly seen in the cliff profile. The boulder clay overburden is much slipped and slumped but is mostly grassed and has a lower gradient above the almost vertical chalk. The chalk is well jointed and wave action has created numerous interesting features especially on the exposed northern side. King and Queen rocks, High Stacks and Adam and Eve (now collapsed) pinnacles are but a few examples of stacks while arches can be found between Chatterthrow and Little Thornwick and at North Landing. Small coves such as at North Landing, South Landing and Selwick Bay have been formed at local weaknesses within the chalk. These contain small beaches composed of sand on the north side of the headland and chalk cobbles on the south side. The wave cut chalk platform is wider on the south side of Flamborough Head. The cliffs become lower towards the west and end at Sewerby.

3.2.2 Holderness

At Sewerby, just north of Bridlington, the chalk dips southwards below sea level and is replaced by boulder clay. During preglacial times (Pliocene, 2-5m yrs BP) the area south of Flamborough to The Wash was once a large bay within a syncline (trough) formed by the chalk which underlies present day Holderness and Lincolnshire. The less resistant Upper Chalk layers were eroded by marine action exposing the harder Middle and Lower Chalk of the Wolds and Flamborough. The coastline at this time followed approximately the present day 60m contour line. During the Pleistocene ice covered the whole area. As the climate ameliorated the ice sheets receded depositing boulder clay and infilling the bay. Coastal recession progressed rapidly with the post glacial rise in sea level to form the present day outline of Holderness and Lincolnshire. This process continues today at a relatively slow rate, at approximately 1-1½mm per year (Ref 5).

The Holderness peninsula forms a gently sweeping curve to the south east from Bridlington. The boulder clay forms a low cliff line uninterrupted for some 60km. The boulder clay cliffs are steep and are generally between 3 and 10m in height but reach a maximum of 30m at Dimlington. The boulder clay has a high clay content and is therefore vulnerable to slumping and collapse under the combined effects of rain wash and wave attack. The cliffs along the Holderness coast are being eroded at a rapid rate, 1-2m/yr (discussed later). In previous centuries whole villages have been lost to the sea (Ref 6).

In contrast, south of Kilnsea the coastline has been extended by accretion. At Kilnsea Warren the boulder clay (which is close to sea level) is overlain by more recent deposits of wind blown dune sands which terminate in the spit feature of Spurn Head. The spit extends for about 5km south-south-westwards into the Humber Estuary in response to the net southerly longshore drift. At present the 'neck' is less than 50m wide at high water and the dunes are only 1-2m high. Reduced beach levels have exposed the underlying boulder clay base at low tide. There is now a threat of breaching at this point. A few kilometres south the spit widens to form a spatulate shape at it distal end with well established dunes rising to approximately 10m in height. Salt marsh has developed in the shelter of the spit. The position and form of Spurn Head is continually undergoing change and the development of this coastal feature is discussed in more detail later (see Chapter 5).

The process of siltation and salt marsh development within sheltered parts of the Humber estuary has been encouraged by artificial reclamation, for example at Sunk Island. Much of the Humber is now protected against flooding by earth banks.

3.2.3 Lincolnshire

From the Humber to the Wash the land is very low lying and is fringed by either salt marsh or sand dunes. Lincolnshire (east of the Wolds) is underlain by a foundation of chalk covered by boulder clay. This clay is exposed south of the Humber in the low cliffs at Cleethorpes, but these are now protected from wave action by coastal defences. Along most of the coast of Lincolnshire the boulder clay is covered by postglacial deposits of clays, silts and peat.

Until the 13th Century, the coastline of Lincolnshire extended further to the north and east, protected from marine erosion by an offshore ridge of moraine. This ridge was successively breached to create a large inshore saltmarsh region called the Outmarsh. As post glacial sea level rise has continued, the coastline has retreated. The remains of trees dating from 2500 BC are sometimes exposed near the low water line of spring tides at Sutton-on-Sea (Ref 7). Reclamation of the Outmarsh for agriculture began in Medieval times with the construction of a high clay bank parallel to the coastline at that time. The 'Roman Bank', as it is called, can be traced along much of the south Lincolnshire coast especially between Huttoft and Chapel Point and still remains a valuable secondary defence against the sea (Ref 8).

Sand dunes and saltings form the present coastline of Lincolnshire except between Mablethorpe and Skegness where it is entirely man-made sea defences. Muds and silts are predominant in the north and these have accumulated to form the foreland at Donna Nook. Further south, away from the mouth of the Humber, the exposure to wave action increases and the foreshore becomes predominantly sand and backed by dunes. The sand beaches continue southwards to Skegness with the foreshore gradually decreasing in width. Between Mablethorpe and Skegness the sand cover is thin and during storms the underlying boulder clay becomes exposed over large stretches. South of Skegness The Wash provides sheltered conditions and this has led to the development of an extensive system of saltings and sand dunes at Gibraltar Point. However, between Mablethorpe and Skegness the dunes are thin and discontinuous and form an inadequate natural defence for the land behind which in most places is below MHWS. Coastal erosion here, while not on the same scale as at Holderness, is often associated with flooding, although the extensive flooding in 1953 was associated with a storm surge which overtopped the existing embankments and was therefore not particularly related to "coastal erosion". The 1978 flooding (which was on a much smaller scale) was due to very stong on-shore winds blowing spume and wave tops over the wall and again not directly related to coastal erosion. The events in 1953 prompted the construction of more substantial sea defences along this stretch of coast.

The coastal indentation of The Wash, at one time much larger, was created by a breach of the chalk to form an 'inland' sea. This has gradually become infilled by fine marine sediments and the accumulation of estuarine and alluvial silts. The Wash now forms the estuary of several rivers namely the Witham, Welland, Nene and Great Ouse. It acts as a large 'sink' for marine sediments carried southwards as littoral drift and effectively marks the southern limit of the coastal 'cell' under consideration here. The shores here are low and marshy and bordered by mud flats. Much of The Wash is filled with shoals of mud and silt such that wave action is very limited. Large areas have been artificially reclaimed to form valuable agricultural land and much of the coastal outline is now formed by man-made embankments.

4 WINDS, WAVES AND TIDES

4.1 Wind-wave climate

The coastline from the Tees to The Wash is exposed to waves from the NW clockwise to the SE. The only Meteorological Office Anemometer Station sited along this stretch of coast is at Spurn Head. The nearest to the north is at South Gare, Teesmouth and to the south is at Gorleston (Ref 9). The Meteorological Office supply a frequency analysis of hourly wind records by speed and direction tabulated on a monthly or a yearly basis. For Spurn Head this shows that the most frequently occurring onshore winds are typically from the north and the highest onshore wind speeds ($\geq$ 38 knots) are associated with northerly gales. This, together with the large wind fetch generate the highest waves from this direction.

Wave records in this area are rather sparse. Offshore wave information has been collected at oil and gas fields in the North Sea, but is of a confidential nature. More readily available data is derived from shipborne recorders installed and analysed by the Institute of Oceanographic Sciences. The wave recorders operate typically for periods of one year. Additionally, some vessels also have visual observations which cover a longer timespan. Such wave recordings off the East coast are limited to the Dowsing Light Vessel (53°34'N, 0°50.2'E) off the mouth of the River Humber. Recordings have been made there since 1950 but the best coverage exists between 1970 and 1984. The data between 1970-1979 has been analysed using Tucker-Draper statistics and the results published by the Institute of Oceanographic Sciences (Ref 10). Other records are available from the Smith Knoll Light Vessel (52°42'N, 3°18'E) off Great Yarmouth. A recent review has been carried out by Hydraulics Research, listing all known sources of instrumentally measured wave data around the coastline of England and Wales (Ref 47).

There is also much information in the form of visual observations of wave height and period, this data being held at the Meteorological Office, Bracknell (Ref 11). These estimates are made from passing ships and as such are somewhat subjective. However, the number of readings is high particularly in the main shipping lanes, and they therefore provide a useful data base from which to predict offshore wave heights. The results should be used with care; the values of wave period in particular should only be treated as order of magnitude estimates.

Existing data have also been analysed to give predictions of the 50 year storm around the coastline of the UK. The results have been presented by Noble and Denton for the Department of Energy in the form of a contoured chart (Ref 12). This is an update (including a wider use of wave observations) of the Department of Energy Guidelines for offshore installations (Ref 13). Off the East coast the offshore 50 year maximum wave height is estimated to be of the order of 20m decreasing southwards to about 8m in The Wash. These values correspond to a significant wave height of approximately 10m and 4m respectively. The 'crest to crest' period associated with the extreme wave height is about 13 to 15s but would obviously vary for each storm. Some wave measurements using a wave-rider buoy are currently being collected and analysed by the Institute of Oceanographic Sciences at a position 7 miles offshore of Hornsea in approximately 20m of water. Measurements commenced in March 1986 and are likely to continue for 12 months. This data will provide valuable information on the wave climate off this coastline where presently there is little data available.

The inshore wave conditions will vary due to seabed topography (wave refraction) and coastline configuration (diffraction). Inshore wave observations are also notable by their scarcity. Waves have been recorded using pressure gauges at several positions in The Wash between 1972 and 1979 in connection with The Wash Feasibility Study (Ref 14). However, this information is extremely site specific. So too are studies using wind data from Spurn Head to calculate wave conditions within the Humber Estuary (Refs 15, 16).

Some visual inshore wave data have been collected by the Hornsea Coastguard (Ref 17). These have been used to calculate the net littoral drift rates along Holderness (see Chapter 5). It appears that approximately 50% of the waves approach from an ESE direction and north easterly waves account for a further 25%. Such wave directions may apply to the coast south of Hornsea to Kilnsea also, but wave heights are likely to be larger south of Withernsea as the 10m isobath swings inshore. Wave conditions along the Lincolnshire coast are affected by the complex offshore bathymetry.

For other particular locations wave conditions in the littoral zone would have to be calculated by transforming waves from offshore using refraction models (Refs 18, 19) or by using one of the number of wind-wave numerical techniques or forecasting curves now available (Ref 20, 21, 22, 23).

4.2 Tides and tidal currents

The tide off this coast floods southwards and ebbs northwards. The mean spring tidal range increases from 4.6m at the entrance to the Tees to 6.1m at Skegness. Similarly the level of mean high water springs increases from 5.4m CD to 7.0m CD respectively (see Admiralty Charts of the area in the Bibliography).

Tidal currents generally flow in a southward direction during the flood following the coastal outline and in a northward direction during the ebb (Refs 24, 25). The strength of these currents is proportional to the size of the tidal range so that maximum current speeds also increase in a southward direction.

From the view point of sediment transport it is the spring tides which are most important. Off Tees Bay the maximum tidal currents during mean spring tides are of the order of 0.7m/sec increasing to 1.0m/sec in The Wash (see Admiralty Charts).

While tidal current flow offshore is more or less northward or southward, that closer inshore is affected by coastal and sea bed topography. Tidal streams run strongly off prominent headlands, eg 1.5m/sec off Flamborough Head, giving rise to turbulence and eddies on both sides of the Head. Tidal streams in some large embayments (eg Filey Bay) are barely perceptible. In other places they may cause localised problems (eg at Whitby where streams may reach 2.5m/sec across the harbour entrance under westerly and southwesterly gale conditions).

In general the movement of material on the open coast is dominated by wave activity leading to a net southward drift. The maximum flood flow velocity is generally higher than the maximum ebb flow, thus there is a southward trend of material in suspension over the sea bed as well as in the littoral zone. The configuration of nearshore banks and their associated tidal streams along the East coast are also thought to be important in the transfer of sediment from the nearshore to the littoral zone. This is discussed in Chapter 5 in relation to Spurn Head and the South Lincolnshire coast.

The tidal activity within the Humber is strong, and complex tidal currents flow within a network of interdigitating channels and sandbanks. At the entrance to the Humber Estuary the streams run very strongly on the north side and around Spurn Head but streams are generally weaker on the south side of the estuary. The currents can attain sufficient speed to enable them to transport fine sands, silts and muds from the north to the south side of the estuary.

Within The Wash the shoals of mud and silt are subject to constant change. The tidal streams set in the direction of the principal channels. The incoming stream is usually a little stronger than the outgoing stream leading to deposition and gradual accumulation of sediment.

4.3 Extreme water levels and surges

While tidal variations in sea level are well predicted, there are also random variations due to the fluctuation of atmospheric pressure, related for example to the easterly passage of depressions. High water levels or surges occur quite frequently along the North Sea coasts most typically when an intense, fairly static, low pressure area is situated to the north of Scotland and when strong northerly winds persist over the North Sea. For each millibar reduction in atmospheric pressure, there may be a corresponding increase in water level of 10mm or more. The combined effect of atmospheric pressure and wind stress on the water surface together with the configuration of the North Sea Basin causes a build up of water. The effect of the surge is intensified as it travels southwards and around the North Sea in an anticlockwise direction. High water levels may be sustained for periods up to several hours.

Results of research at the Institute of Oceanographic Sciences, Bidston, indicate a maximum likely 50 year storm surge residual elevation for the East coast of the order of 1.5m at the Tees increasing southwards to 2.5m in The Wash (Refs 12, 26). These values do not, however, represent the joint probability of highest surge, tide level and wave set up. Extreme water levels arise if these conditions coincide with high spring tides and extreme wave heights as in January/February 1953 (Ref 27).

The effect of the 1953 surge was disastrous along the East coast. Damage was not severe in North Yorkshire but on Holderness the sea broke over the dunes near Easington and flood water entered the Humber near Skeffling. There was flooding along both the north and south Banks of the Humber but it was most severe along the Lincolnshire coast especially between Mablethorpe and Skegness where the hinterland is particularly low lying. Similar water levels have been reached on at least three occasions since 1953; in September 1969, January 1976 and January 1978. Each of these would have had serious consequences but for the improvement of coastal defences subsequent to the 1953 surge.

The severity of the 1953 floods emphasised the need for adequate prediction of surges to minimise loss of life and damage to property. Traditionally surge prediction have relied on the correlation of observational data of storm surge residual elevation to other parameters such as atmospheric pressure and wind speed. More recently dynamic numerical models of storm surges have been developed at the Institute of Oceanographic Sciences and are now routinely used at the Meteorological Office. A grid of mesh $\frac{1}{2}°$ longitude by $\frac{1}{3}°$ latitude is used to compute flows in the seas around the British Isles using tidal and bathymetry data as well as input from the atmospheric model used for weather forecasting. The model is run twice daily and gives useful information up to 30 hours ahead. These results are monitored by the National Storm Tide Warning Service (STWS). Surge predictions are made for five divisions down the East coast each having a reference port; North Shields, Immingham. Lowestoft, Felixstowe and Sheerness. The degree of danger is assessed and appropriate warnings are given to the authorities concerned (Ref 28).

Alongside the need for warning of surge events is the need for design and construction of adequate coastal defences. This requires a valid statistical basis for assessing the recurrence of extreme sea levels. Maximum sea levels are actually increasing with time and will probably continue to do so along the East coast as a result of the progressive rise in sea level (approximately 1-1.5mm/yr). Observed sea level maxima in the form of annual extremes have been analysed for numerous ports around the British Isles (Ref 29). Storm flood conditions are known to have a bimodal distribution with peaks centred around October/November and January/February. Traditional methods of extreme analysis are based on the assumption of randomness. However, sea level maxima are shown to have both independent and dependent components that combine in complex ways such that methods which rely on uni modal distributions may not be reliable. Added to this, these techniques do not take into account superimposed wave effects and their associated probabilities.

There is also a long term change in sea level, which is rising at approximately 1-1.5mm/yr along the East Coast (Ref 5). This is the result of the complex interaction of isostatic and eustatic processes initiated by the melting of the Pleistocene ice sheets. A eustatic rise in sea level results directly from the volume of water added to the oceans following melting. Isostatic uplift of the land results from a re-adjustment of the Earth's crust following release from the weight of ice. A sustained decrease in atmospheric pressure over the last 20 years is thought to be a contributory factor. Sea level rise must ultimately contribute to coastal recession in the future. This is unlikely to cause problems for coastal defence along the resistant rocky coastline of Yorkshire. However, where less resistant boulder clay is exposed, such as along Holderness, and where the land is low lying as in Lincolnshire, the progressive effects of such a sea level rise have significant implications for the planning and design of effective coastal defence structures.

5 COASTAL PROCESSES

In 1911, the Royal Commission on Coastal Erosion used map evidence and information from local authorities and private individuals to assess shoreline change around the British Isles (Ref 30). The Commission concluded that gains in area were almost entirely confined to the tidal estuaries and losses were chiefly on the 'open' coasts. Figures quoted show that, between 1848 and 1893, Yorkshire lost about 800 acres mostly along Holderness and gained 2200 acres by accretion and reclamation within the Humber. North of Flamborough Head losses were slight and erosion was localised within some embayments. Lincolnshire (between 1883 and 1905) showed losses of 400 acres on the open coast and gains of 9100 acres (mostly in the Wash). These natural processes are still operative today but are complicated by man-made attempts to defend the coastline artificially.

In this chapter, the interaction of processes within the coastal environment are examined in the context of changes along the East Coast. The dominant tactors controlling the processes of supply and transfer of material within the littoral zone are wave action and the available wave energy. Other processes such as cliff slippage along Holderness and nearshore tidal circulation off south Lincolnshire play an important role in the supply of material to the sediment budget. Areas of sediment supply (sources) and areas of accretion (sinks) are identified. Zones of zero transfer of material delimit sub cells within this coastal unit. The localised effects of these processes and the implications for coastal defence are considered in more detail in Chapter 6.

North York Moors and Cleveland

The coastline from Hunt Cliff to Flamborough Head is characterised by high cliffs and promontories generally aligned west to east and enclosing marked embayments. This is the result of differential erosion of varied rock types by wave action over a geological time scale. The cliffs of more resistant rocks such as at Hunt Cliff, at Boulby and at Flamborough Head are some of the highest in Britain. Where it is capped with boulder clay, the cliff face shows a marked break of slope. The boulder clay overburden often shows the scars of rotational slips and slumps and has a flatter gradient than the more resistant rock beneath. Sub-aerial erosion and cliff undercutting supplies material to the cliff foot. This is quickly sorted by wave action. Finer materials such as silt and clay are carried offshore in suspension leaving a generally thin beach deposit of sand, pebbles and rocks on the nearshore wave cut platform. Where the unconsolidated boulder clay is found at sea level, it has been subject to more rapid erosion to form larger embayments containing more substantial sandy beaches such as at Runswick Bay. The boulder clay is the major source of beach material in these bays.

The relative rates of cliff recession have been determined by Agar using Ordnance Survey maps (Ref 31). Cliff recession at sixteen locations between the Tees and Ravenscar have shown an average retreat of 0.09m/yr on shale outcrops compared with 0.28m/yr where glacial till was exposed. Thus the coast of North Yorkshire is in general becoming more irregular over time.

The direction of net littoral drift is from the north to south. The orientation of promontories such as Hunt Cliff and Flamborough Head in relation to the direction of waves striking the coastline produces divergence of beach movement at these points, and therefore zones of zero transfer of beach material. In other words waves impinging on a pronounced headland will tend to drive material into the centre of each bay and only sediment in suspension is likely to escape from individual bays. Hence the promontories effectively mark the boundaries of coastal cells, within which beach movement is independent of that in adjacent cells. It is likely that very little, if any, beach material moves south out of Tees Bay or similarly south into Bridlington Bay. Rates of littoral drift are not known for this stretch of coastline but the scale of accumulation against the breakwaters at Skinningrove and Whitby indicate the quantities are small. Alongshore movement is confined for the most part within individual embayments, where extensive rock platforms at the headlands also provide a partial barrier to the transfer of material from one bay to another. More extensive sandy beaches have developed where headlands provide sufficient shelter from northerly winds, and south-east exposure may result in localised reversals of drift direction, eg Filey Bay and Bridlington.

Holderness

The indented coastline of Flamborough Head is replaced to the south by the smooth curving coastline of Holderness. The coastline from Bridlington to Kilnsea has very high rates of erosion, due to the boulder clay outcropping at sea level. Cliff recession here is known to have continued over hundreds of years and shows no signs of abating.

The lithology of the cliffs make them highly susceptible to erosion. The weakly consolidated boulder clay consists of a clay matrix containing a mixture of coarse sediments and pebbles. Erosion takes place intermittently and at variable rates by mass movement as a result of subaerial weathering processes. Alternative wetting and drying of the clay leads to cracking, rotational slips and slides. Surface cracking and potential slips are seen at the cliff top. Dislodged material is quickly removed from the base of the cliff by wave attack, so steepening and destabilising the cliff face. The result is that the cliff top recedes intermittently and irregularly as a series of bights.

The rate of recession of the Holderness cliffs was the subject of a study by Valentin (Ref 32). A comparison of Ordnance Survey maps from 1852 to 1952 enabled quantitative assessments to be made. Valentin measured some 307 cross sections. He found the maximum recession over this period was of the order of 200m near Withernsea with an average of 120m (1.2m/yr) along the whole coast. Valentin suggested that overall the rate of erosion increased southwards in response to the energy input from wave action from the North Sea. This is illustrated by the following averaged rates:

Sewerby to Earl's Dyke	0.29m/yr
Earl's Dyke to Hornsea	1.10m/yr
Hornsea to Withernsea	1.12m/yr
Withernsea to Kilnsea Warren	1.75m/yr

Most of the cliff line is unprotected by coastal defences. Where these have been built (eg at Hornsea and Withernsea) rates of erosion are locally reduced and groyne systems have been successful in capturing sand and maintaining beach levels. However, as a direct result, erosion is severe immediately to the south or 'downdrift' of these frontages. At Hornsea the 'set back' is presently about 40-50m.

Robinson (Ref 33) has observed erosion of the cliff top at one location (Holmpton) of the order of 6m over a period of one year. Clearly Valentin's results conceal the range of such short term temporal and spatial fluctuations of cliff retreat and more recent work shows that the nature of erosion depends not simply on wave exposure. The configuration of the beach itself plays an important role. Erosion is accelerated with the passage of pronounced runnels (locally known as ordS) parallel to the cliff base. These features are a marked characteristic of the sandy beaches along the east coast of Holderness and Lincolnshire. Between Barmston and Spurn Head as many as ten ords may exist. Once developed, they migrate as a continuous system southwards under north and north-easterly wave conditions. The fact that ords are not found north of Barmston may be due to the sheltering effect of Flamborough Head.

The precise mechanism for the development of 'ords' is not known. Studies have shown that the 'normal' beach profile is modified by the presence of an ord (Ref 34). The lower beach widens and, as a ridge of sand gradually moves landwards, it encloses a water-filled runnel at the cliff foot, often exposing the boulder clay shore platform to erosion. Profile measurements show that levels may be reduced by up to 3.9m (2.2m on average) at the centre of the ord, allowing larger waves to reach the upper beach and facilitate direct wave attack to the toe of the cliff. Measurements of cliff erosion and cliff height have been used to calculate volumetric losses of material from the cliff face between Withernsea and Easington. The volume removed may increase approximately eight-fold from an annual mean of $9m^3/m$ to $72m^3/m$ in the presence of an ord, the majority of the erosion taking place in the winter months.

Such rates of erosion contribute large quantities of material (of the order of millions m^3) to the sediment budget. However, only a relatively small portion is retained on the beach. Particle size analyses (Ref 35) show that only about 30% of the till constitutes the sand and coarser fractions on the beach. The finer silt and clay fractions are carried offshore in suspension by waves and tidal currents. Hence the beaches fringing the Holderness coast are narrow and consist of a thin veneer of material with a depth of the order of only 1-2m over the shore-platform. Exchange between the beach and nearshore zones takes place as a result of beach drawdown under storm wave conditions and onshore movement in calmer conditions. Such exchanges may be important in the development of ords but there appears to be no long term source of beach material from offshore, rather the opposite may occur.

The open exposure of this stretch of coast means that there is high potential for alongshore movement of sediment both northwards and southwards. The net effect of wave action is a southward transport of sand along the whole of the Holderness coast. In the absence of instrumental measurements, some visual estimates of wave parameters have been used to quantify the potential wave energy and longshore sediment transport rate. Pringle (Ref 34) uses data collected at Withernsea between October 1969 and September 1970 to compute a potential net southward movement of sand of the order of $144000m^3/yr$, incorporating within this figure considerable seasonal fluctuation. Probably little sediment input occurs alongshore from Bridlington, which experiences lower levels of wave energy than the more exposed Holderness coast further south. The beaches between Barmston and Hornsea are relatively low and narrow with the clay substratum being frequently exposed. By contrast, the beaches south of Withernsea are higher and broader and the rate of erosion of these cliffs is greater.

Spurn Head

At Kilnsea, the boulder clay cliffs come down to sea level and from here south-westwards the long narrow sand peninsula of Spurn Head projects into the Humber Estuary. The evolution of this feature is the result of supply of material from erosion of the Holderness cliffs under a net southerly drift and constructive swell waves from the south-east. Historically it can be seen from cartographic evidence that the position of the spit has moved north-westwards in response to cliff retreat at the 'hinge' link to the mainland. De Boer (Ref 36) has used such evidence together with other historical documentary records to produce a 'cyclic' theory of growth and erosion of the spit. However, the evidence used is somewhat unreliable and the 'cyclic' inference must be considered rather simplistic. However, Spurn Head has undoubtedly undergone periods of severe erosion and subsequent accretion. The neck of the spit has been breached many times. Records show that in December 1849 the spit was seriously breached near the tip. Subsequent breaches in 1850 and 1851 widened the gap to 458m and 4.88m depth at high water. Two more breaks occurred in 1851 and 1856. Later the breaches were eventually healed artificially. The spit, however, remained intact during the 1953 floods.

The threat of breaching is ever present at the narrowest point south of Kilnsea Warren. The artificial defences have tried to fix the position of the coastline but have failed to accumulate sand. At the same time, these have increased its vulnerability to destructive wave action by making the spit unable to 'roll back' and maintain an equilibrium plan shape with the Holderness cliffs.

Material is rapidly moved around Spurn Head and accumulates on the wide foreshore. The central core of dunes reaching approximately 10m in height appear stable and well vegetated with a cover of marram grass and buckthorn. Robinson suggests that the Binks-Chequer shoals just east of Spurn Head in fact provide additional material as part of a tidal circulation within the Humber Estuary (Ref 37). He has demonstrated by the use of drifters that material carried out of the Humber on the ebb tide is returned to the seaward side of Spurn Head on the flood. Some tracer experiments have confirmed the movement of beach material in that direction (Ref 38). If this is so, it may account for the growth and relative stability of the Head itself but may also act as a self regulating system thus limiting the length of the spit.

The scale of cliff erosion along the Holderness coast is so large as to suggest that Spurn Head should be a much larger feature than it is. Valentin (Ref 32) suggests that as little as 3% of the material eroded from the cliffs may actually reach Spurn Head by littoral drift. However, vast quantities of suspended 'fines' derived from the Holderness cliffs move in and out of the Humber Estuary with the ebb and flood tides. This material feeds both the estuarine mud flats and the north coast of Lincolnshire.

South of the Humber, the Coast Protection Survey (Ref 39) indicates the general direction of drift to be southwards and eastwards along its southern bank. However, waves penetrating the Humber and possibly the effect of tidal streams produce reversal in the direction of littoral drift just south of Cleethorpes pier and a corresponding lowering of beach levels in this area. South of Cleethorpes, away from the shelter of Spurn Head, the net southerly drift gradually increases, with large quantities of material being transported towards Donna Nook. Drifter experiments by Robinson (Refs 37, 40) indicate that some sediment believed to originate from the erosion of Holderness, eventually travels across the estuary to augment the foreland of silt and sand at Donna Nook in the vicinity of Saltfleet on south Humberside. The meeting of the south moving ebb current from the Humber and north moving ebb current along the open Lincolnshire coast is considered partly responsible for the outgrowth of the coastline which is extended seawards by about 5km at low tide. Accretion here has resulted in the formation of large offshore sand banks, landwards of which salt marsh has developed. The salt marsh inshore is very well established and is only submerged at very high tides.

Further to the east and beyond the protection afforded by Spurn Head, the coastline becomes more and more exposed to wave action from a wide sector and the finer fractions of silt and clay are removed in suspension. Combined with the effect of strong onshore winds, wind blown sand accumulates into dunes. The remains of older dunes at a former position of the coastline, are found landward of the clay embankment, and are now far removed from any source of wind blown sand.

From Saltfleet to Theddlethorpe the dunes are well developed and fronted by a high wide sandy foreshore. For the most part these dunes are stable and well vegetated but some trampling and overuse, particularly at access points, has caused localised problems. Sand fencing and faggotting are being used to stablise and maintain the dunes which are a valuable natural defence against the sea. Dunes provide a 'reservoir' of beach sand which may be returned to the foreshore under offshore wind conditions or during storms thus maintaining beach levels.

At Mablethorpe, the coast changes dramatically. While accretion predominates to the north, severe coastal erosion has persisted for many centuries to the south, extending as far south as Skegness. Most of this coast is very low lying, some land well below the level of MHW as a result of the rise in postglacial sea level. The narrow foreshore is backed by low, thin and poorly developed sand dunes providing inadequate coastal protection. Man-made defences now have a major effect on the coastal processes along the Lincolnshire coast.

Documentary evidence provided by Owen (Ref 41) gives some indication of the loss of land to the sea in historical time. While rates of erosion along Lincolnshire are by no means comparable to those measured along Holderness, erosion is of great concern because it is often associated with coastal flooding. This coastline has frequently been inundated by the sea, most recently in the storm surge of 1953 when many of the coastal defences were destroyed. Indeed the sea walls then in existence may have helped to intensify destructive wave activity at nearby points of weakness. Many of the breaches occurred at points immediately to the south of concrete walls (Ref 42). At other places walls were overtopped and then undermined from behind. The most serious breaches and damage occurred between Mablethorpe and Sandilands, and at Ingoldmells further south, where low narrow beaches in front of sea walls allowed large waves to break inshore. Flooding was much less severe in areas where dunes and a high wide beach provided sufficient protection to absorb the incident wave energy.

A long term study of the coastal geomorphology of the Lincolnshire coast from Mablethorpe to Gibraltar Point has been carried out by Professor C A M King. Beach profiles were surveyed both before and after the 1953 surge and some measurements are continuing. By the comparison of sweep zones (that is the 'envelope' of variation in beach elevation) compiled for different periods of time, King has been able to assess the recovery of the beaches after the surge and has been able to relate this to the operation of coastal processes and construction of new coastal defences. Surveys showed that many of the beaches had largely recovered from the storm within two years (Ref 43). Those beaches between Mablethorpe and Sea Bank Farm recovered quickly, being supplied by sand under the net southerly drift. At Anderby Creek the dunes survived the storm well but there were persistent losses in beach volume for some period after the surge. These losses were related to the reduction in supply of beach material from the north (with the implementation there of new groyne schemes), while longshore drift of material continued to supply beaches further south.

Immediately after the surge, the sea defences were raised and upgraded. Artificial defences are now almost continuous from Mablethorpe to Skegness. Such structures as concrete walls, while necessary for flood protection in this instance, do little to improve the condition of the beach in the long term. The sea reaches the sea wall for approximately half the tidal cycle. Wave reflection and scour reduce beach levels and promote the deterioration of the foreshore. Groyne construction has, on the whole, failed to retain sediment on the upper beach and now after 30 years many are in a state of disrepair. Beach levels between Mablethorpe and Sutton-on-Sea have tended to deteriorate over time and these long term trends have been confirmed by the statistical analysis of 25 years of beach data (Ref 48). Recent extensions to the toe of the wall are in evidence for example at Mablethorpe. The beach now consists of a very thin veneer of sand over the clay foundation, which is often extensively exposed at low tide. Erosion of the clay substratum leads to a permanent lowering of the beach because even if the same amount of sand does return to the beach after the storm, it will be at a lower level.

Between Sutton and Skegness the beaches are variable, partly in a response to the effectiveness of the coastal defences (see next chapter). The beaches are lowest where there are slight promontories such as Chapel Point, Vickers Point and Ingoldmells Point. These points are artificially defended outfalls of drainage channels which act as small 'headlands', focussing wave energy and making it difficult for beach material to build up adjacently. Beach conditions are better and are generally more stable in the intervening embayments. There is a continual exchange of material between the intertidal and nearshore zones in response to destructive and constructive wave conditions. This takes the form of ridges of sand aligned NW to SE ie obliquely to the coastline. In 1947 Duvivier noted that the foreshore could change from a scoured clay platform to a covering of sand of up to a depth of a metre within a matter of days. These ridges often enclose runnels which when confined to the upper beach may cause scouring and erosion especially in front of sea walls. However, it is suggested that the offshore tidal circulation is not conducive to the transfer of sediment to the littoral zone (Ref 40). In drifter experiments (released from the Humber) the absence of recoveries between Mablethorpe and Sutton contrasts with landings both to the north and to the south. This pattern may also be a reflection of the lack of protection afforded by offshore banks. In any case a number of factors contribute to an overall net deficit of sediment in this area. Artificial defences have cut off any input of sediment from the backshore and the potential for sediment transport is such that any available material from the north is rapidly moved southwards alongshore by wave action. There is therefore little possibility of any permanent accumulation where a low narrow beach exists in front of a sea wall and this may account for the continued erosion in this vicinity.

Immediately south of Skegness Pier, however, the foreshore again becomes very wide. This marks the beginning of a major zone of accretion. The slight change in the alignment of the coast south of Ingoldmells to a more north-south orientation provides some protection from the effect of northerly waves, such that sand is more likely to accumulate to the south. Further protection is given by drying sand shoals situated only about 1km offshore. The foreshore along this coast is characterised by beach ridges. As the ridges migrate landwards and southwards they become stabilised by dune vegetation and continue to grow by the addition of wind blown sand. Their height is a function of the available material on the foreshore and the rate of movement is related to the volume of sediment transfer (Ref 44). The runnels enclosed by successive ridge growth often collect mud and silts and eventually salt tolerant plants become established. When the tide is eventually excluded, these hollows become dune slacks.

The nearshore sand banks and channels have the characteristics of tidal ebb and flow features which form in areas where there is much sand available. These form a zone of convergence of a southerly flood residual flow which complements the southward drift in the nearshore zone. Robinson has inferred such sediment paths from drifter strandings in this area (Ref 40). Dugdale (Ref 45) has also used drifter and tracing experiments to measure tidal currents and inferred sediment transport paths. Recent work at the University of Nottingham is applying remote sensing techniques and radioactive tracers to this problem. Results would suggest that the area of Skegness Middle represents a location of entry of sediment from the nearshore system to the littoral zone. This may be responsible for the outgrowth of the coast or 'ness' feature at Seacroft to the south of Skegness. Thus tidal currents in this area reinforce and supplement the transfer of sediment southwards by wave motion.

The pattern of accretion between Skegness and Gilbratar Point has been studied since the 1950's by the analysis of beach profiles (Ref 46). While the area is accreting as a whole, the gain in material has been rather slower immediately south of Skegness. Changes in rates of accretion may be related to changes in the position and configuration of the offshore banks in response to the available material in the near shore zone. In addition there is an area of serious erosion currently causing problems north of Skegness that could be a result of downdrift erosion from the effect of groynes (although now in a state of dereliction) constructed at Winthorpe during the late 1950's. These may have reduced longshore movement of sediment from the north. This area of erosion appears to be spreading to the south towards Skegness Pier.

The alongshore movement of sand continues to build up spit features at Gibraltar Point, elongating the coast in a southward direction at the entrance to The Wash and deflecting the course of the Steeping River. The Lincolnshire coast, being uncliffed and artificially protected provides relatively little sediment compared to Holderness. While the present spit is a relatively recent feature, formed early this century, other similar features have preceded it situated further to the west. The spit is in fact an extension of the southward migrating dune ridges described earlier, and as they do so they create shelter for the development and expansion of salt marsh to the west. Changes in the height and length of Gibraltar Point are directly related to the supply of beach material from updrift (Ref 45).

Most of the beach sand transported in the littoral zone is effectively trapped at Gilbratar Point. However, finer sediment may be carried offshore in suspension and into The Wash under the dominant influence of the flood tide. Sediment movement out of The Wash and eastwards along the north Norfolk coast may be possible but only under very exceptional storm conditions, when material is resuspended and transported sufficiently far seaward to escape out of the system. Under normal wave conditions, the mud and silts are deposited forming banks which are eventually exposed at low tide. Siltation at the margins of the Wash aided by the accumulation of alluvial and estuarine deposits discharged by the rivers, is gradually colonised by salt tolerating vegetation. Large areas of 'new' land have been artificially drained and reclaimed in the 19th Century. Thus The Wash acts as a vast sink for fine muds and silts and marks the southern limit of a coastal 'cell'.

6 REVIEW OF COASTAL DEFENCE

6.1 Tees Bay to Flamborough Head

The Cleveland Hills and the North Yorkshire Moors are aligned on an east to west axis and their dissection at the coastline gives rise to steep high cliffs separated by valleys. The cliffs are generally of weak rock and are overlain by a large thickness of boulder clay, hence there are numerous landslips and clay is brought down to sea level. Hence, in terms of coast protection cliff instability is the most widespread problem. It is particularly serious to the east of Whitby harbour where a stretch of boulder clay cliffs is unprotected. It also gives rise to problems in areas already protected by coastal defences such as Runswick, Robin Hood's Bay, Scarborough and Filey. These are problems associated with the terminal scour of boulder clay cliffs as well as damage due to earth movements. Whitby, Scarborough and Filey are the major centres of urban development and adjacent to all three are major holiday camps situated on or near the cliff line. These holiday areas are unprotected and have to contend with the problem of continuing land loss.

Though there are many areas of erosion coastal defences are isolated from each other and in general erosion problems at one stretch of coast have little impact on adjacent stretches. The exceptions are Sandsend and Whitby, both of which are situated in the same bay.

As mentioned in Volume 1 of this review the coast between Redcar and Saltburn by the Sea are situated within the Hartlepool and Tees Bays (Ref 4). Beach and sea bed changes within these bays affect coastal development as far east as Saltburn by the Sea, at which point the beach ends abruptly against the massive promontory of Hunts Cliff. From Hunts Cliff, eastwards to Flamborough Head the coast can be treated as a unit which is largely independent of the coastline to the north or to the south of it.

This stretch has been divided here for convenience into several "semi-dependent" stretches of coast:

6.1.1 Saltburn to Whitby

The greater part of this coast is undeveloped and unprotected by coastal defences. The cliffs are very scenic, not withstanding the despoilation due to mining activities, and the coastline lies within the North York Moors National Park. It also forms part of the North Yorkshire and Cleveland Heritage Coast.

From Hunts Cliff to Skinningrove the cliffs of layered limestone and clay are fronted by a wave cut platform free of beach material. However, the build up of sand against the derelict jetty at Skinningrove indicates a weak west to east littoral drift. How much of this is derived from local erosion and how much from the beaches within Tees Bay is open to question. However, the accumulation is limited in volume and is localised so the littoral transport volume is clearly small.

At Skinningrove there is a small mining village set in the bottom of a steep river valley and situated a short distance upstream of the river mouth. There are no coast protection problems here, thanks due to the shelter against northerly waves provided by the jetty. A sand and shingle ridge has developed across the river mouth and gives protection against waves from the north-east. The only "defences" consist of a short stretch of parapet wall on the east side of the stream protecting the road edge. The build up of sand and shingle to the east of the jetty indicates a local reversal in the direction of net littoral drift. This is due to the sheltering effect of the jetty. Because material is "captured" on both sides of the jetty the volume of drift able to pass further eastwards is very small indeed.

The cliffs in this area are mined for iron ores and cliff slippage is prevalent. The coast between Skinningrove and Staithes has been intensively worked in the past but this does little to detract from the scenic beauty of the coast. Cliffs are very nearly sheer and their toe is bare of beach material except within small embayments (Plate 1). There is very little accretion of beach material against any of the promontories, again showing that the drift of material is very weak. The boulder clay overburden is easily erodible by aerial weathering and is the most likely source of material in the pocket beaches.

Staithes village is bounded by rocky headlands and has developed on the steep sides of a rocky gorge. There is severe erosion, mainly due to aerial weathering, at the Cowbar promontory west of the harbour. Both the road and a number of houses to the landward are now at risk. The shelter provided by the promontories and the extensive nearshore reefs is insufficient to prevent overtopping of the harbour arms and of the island breakwater even in moderate wave activity. Indeed waves are attenuated as they travel inshore over the gently shoaling rock ledges and are used for surfing! The island breakwater, designed to give protection to the harbour entrance is so low that it is nearly submerged at high tide. There is no sand accretion against the promontories and very little sand on the rock ledges, but a small sand beach has developed within the eastern corner of the harbour. Possibly this material has been brought from offshore in suspension during storms. It may also have been brought down by the stream which exits through the harbour. The harbour walls are sufficiently high and robust to prevent serious damage by wave action. The houses which line the quays thus do not appear to be seriously at risk from wave action.

From Staithes to Runswick the cliffs which are of shale and clay are unstable and there are many large slips. The now dilapidated harbour at Port Mulgrave, which once served the mining industry, now provides shelter for a small number of boats.

The first coastal defences proper are found at Runswick, which is situated in a sheltered position in the west end of the bay. The houses are protected by a concrete wall built between 1950 and 1970 and which is generally in a sound condition. However, the boulder clay cliffs to the south are very weak and this end of the wall is at risk. There are also a number of houses at risk from cliff slippage and wave induced cliff erosion in the unprotected part of the bay. The long term recession of the boulder clay cliffs which outcrop at sea level has resulted in the bay having a very strong indentation. The sand derived from local erosion tends to be swept away by wave action into the central part of the bay, forming a wide sand beach. The fines are carried out to sea.

The cliffs from Kettleness at the east end of Runswick Bay to Sandsend are also spoilt by former mine workings. Here the cliffs are unstable but their erosion has only produced thin beach deposits and littoral drift is low.

The long shallow embayment between Sandsend and Whitby is for the large part backed by boulder clay. Sandsend village though tucked in the shelter of Sandsend Ness and protected from north-westerly storms has suffered damage in recent years. The westernmost part of the sea wall collapsed several years ago and has recently been rebuilt. The sea wall and groynes along the main frontage of Sandsend appear to be in satisfactory condition although the latter may become ineffective due to tidal scour. Further east a concrete revetment protects the coast road and the beach is also groyned. No properties are at risk.

The concrete sea wall at Whitby dates back to the 1920's. It is situated at the toe of high boulder clay cliffs which are partly stabilised but some stretches still liable to slippage. The coastline between Sandsend and Whitby includes a central stretch where both aerial and wave induced erosion is still taking place rapidly. The remains of old sea walls can be seen at the toe of the cliffs which are particularly unstable in this exposed section of the coast. The sand beach immediately west of Whitby harbour is relatively stable. It is groyned and backed by a concrete sea wall. With the exception of a local outcrop of more resistant rock the cliffs are also graded (Plate 2). The harbour at Whitby is effectively a "stop" as far as littoral drift is concerned. The beach to the west is wide and sandy while the rock platform east of the harbour is free of beach material. What little sand is transported across the harbour mouth tends to be swept into the outer harbour area. Here it has settled out to form a beach on the east side of the entrance. There are no sand beaches east of the harbour entrance.

6.1.2 Whitby to Filey Brigg

The coastline is not heavily developed and the shale and clay cliffs are rugged and the scenery is good especially from Whitby to Scarborough. This stretch of coast is within the North York Moors National Park and forms part of the North Yorkshire and Cleveland Heritage Coast. Some of the cliff top areas are owned by the National Trust and large stretches are GCR sites (ones marked for geological conservation). Scarborough has a large urban frontage which is protected by sea walls and groynes but to the south the coast is generally unprotected and has important SSSI's and GCR's.

East of Whitby harbour the cliffs are quite durable and erosion has produced very little beach material. The coastline is not strongly indented with the exception of Saltwick Bay in which there is a small sand beach. Otherwise the foreshore is narrow and rocky as far east as Robin Hood's Bay. There is little evidence of any strong littoral drift.

Robin Hood's Bay owes its formation to an upfold in the Jurassic strata which brings soft red clays to the surface. Erosion has led to a very strong indentation and has left more resistant rocks outcropping as massive ledges at low tide. The village is situated in the north corner of the bay and is partly sheltered from northerly waves by Ness Point. Faulting in the rocks at the north end of the bay is evident in Plate 3 taken from near Ness Point. The village is in fact perched on steep, unstable slopes with a massive concrete sea wall at the toe of the cliffs. (Erosion caused several houses to fall into the sea and in 1974 a new massive 12 metre high concrete sea wall was constructed at the north end of the village.) The strength of the rocks towards Ness Point is variable and weak sections of cliff between more resistant outcrops north of the sea wall have also been faced with concrete (Plate 3). The beach within the bay is sandy and is reddish in colour, being derived from cliff erosion. There is a narrow upper beach of pebbles and boulders also from local erosion. In the centre of the bay aerial weathering has led to the formation of spectacular clay "stacks". The sand beach rests on a wave cut platform extending as much as ½km seawards at low water. Despite the obviously rapid erosion of the boulder clay cliffs in the centre of the bay the beach is relatively narrow and thin. The present sea wall appears to be adequate from the point of view of sea defence, though it remains to be seen whether it has sufficient mass to prevent slumping of the cliff slopes above it. There is severe "terminal erosion" at the junction between the south end of the sea defences and the unprotected clay cliffs beyond. However, there appears to be no cliff top development at risk in this area. Remnants of old concrete walls at the south end of the village suggest that the sea wall may have extended further south once. Clearly erosion at the southern end of the wall will continue to be a problem in future years. Due to the high reflectivity of the massive sea walls protecting the village it is likely that beach scour will also become a problem in the future

The stretch of cliff line between Robin Hood's Bay and Scarborough is undeveloped and has no coastal defences. The greater part of the cliff line from north of Robin Hood's Bay village to the north end of Scarborough is designated as a GCR site. Much of it is very unstable and is a rich source of fossils. The North York Moors National Park extends south to Cloughton Wyke (Fig 2) while the North Yorkshire and Cleveland Heritage coast continues further southward, to Scalby Ness.

Urban development begins at Scalby Ness, north of Scarborough. There is a sand beach backed by a sea wall which stretches south to Scarborough Rock, the promontory on which the castle is situated . The sand beach, being ungroyned, is presumably stable, being held between the promontories of Scalby Ness and Scarborough Rock. The sea wall continues around Scarborough Rock with its toe submerged at all tidal stages. Judging by the seaward projection of the Rock it is unlikely that there would be much interchange of sand between the north and south beaches. Though there is little evidence of any large scale littoral drift, the net direction is undoubtedly from north to south. The cliffs backing the promenade are chiefly of boulder clay and have been graded to reduce slippage. South beach, Scarborough (Fig 3) is more sheltered from wave action and the harbour is situated at the southern end of Castle Rock. Beach sand can be found within the harbour in significant quantities. Judging by the configuration of the harbour entrance, sand is transported into it during southerly storms. The east harbour arm is in poor condition and exposed to wave action by easterly and southerly storms. The sea wall skirting the Rock, being in deep water at high tide, is also subjected to severe wave activity and requires regular maintenance. The seaward face of this wall is clad with concrete panels and these tend to be dislodged by wave action. There are also signs of damage to the decking of the promenade. Boulders have also been placed at the toe of the north face of the sea wall to prevent damage by wave scour. The beach in South Bay appears to be stable but the cliff slope above the promenade is continuously slipping. The instability of the terraced gardens does not appear to be posing any danger to the coastal defences below them. The wave energy potential for littoral transport (see Chapter 5) is such as to encourage a net north to south transport of beach material. The fact that the sand is not being "lost" out of South Bay points to the likelihood that the volume transported southwards past the Black Rocks promontory is negligible (Fig 3). The Coast Protection Survey (Ref 39) indicates that littoral drift along the coast is variable. It is generally understood to be southward on the flood tide and northward on the ebb tide. This would suggest that the net drift is small and that some material is also transported by tidal currents which are invariably weak near the shoreline.

The coast from Scarborough to Filey is undeveloped and unprotected by coastal defences. At Wheatcroft, just south of Scarborough urban development is away from the cliff edge. The cliffs from Wheatcroft to Gristhorpe have major slips. At Cayton Bay there is a sandy beach also backed by unstable clay cliffs. The Yorkshire Water Authority pumping station is protected by a sea wall, but otherwise there are no coastal defences in the bay. However, cliff slippage is on a major scale and extends back almost to the edge of the coast road. There are also a number of holiday camps near the cliff top in this area. South of Cayton Bay the foreshore gradually narrows and there appears to be very little beach material transported southwards to Filey Brigg.

Filey Brigg is a narrow promontory consisting of hard grit capped by boulder clay. The end of the Brigg extends out to sea in the form of submerged rock ledges. Because it projects seawards by more than 1½km and extends to a water depth of at least 5 metres, it forms a very effective natural groyne. Also due to its orientation only waves from the north to north-west sector can transport beach material towards the Brigg. Waves from all other offshore directions would tend to move sand northwards against the net direction of littoral drift. This and the fact that the promontory projects so far seawards means that it is a zero transport boundary as far as littoral drift is concerned. Any sea bed material transported southwards does so as a result of tidal current action.

6.1.3 Filey Bay to Flamborough Head

The clay cliffs on the south side of Filey Brigg extend southwards to Flamborough Head. The area is one of fairly intense development with town of Filey at the north end of the bay and holiday villages stretching to the south end of the bay. Some of the holiday villages are situated at the cliff top above major land slips. Towards Flamborough Head the cliffs become steeper and more resistant to wave attack. The whole of the coast from Speeton to Sewerby is within the Flamborough Head Heritage Coast. There is also an important RSPB reserve at Bempton Cliffs on the north side of the Head. The largely unprotected stretch of coast from Filey Brigg to Flamborough Head has eroded back to form a crenulate shaped bay a feature which indicates that the beach plan shape is tending towards an equilibrium form. The net littoral drift is very small and is probably in a southwards direction.

The rocks which form the Brigg dip southwards so that the overlying boulder clay only reaches sea level on the south side of the promontory. These cliffs are regularly washed by waves, and weathering by rain gives them a "badlands" appearance (Plate 4). By contrast with the resistant cliffs to the north the boulder clay plateau on the south side of the Brigg has been eroding rapidly for many centuries and has given rise to the large sweep of Filey Bay. A wide sand beach has developed within the Bay. The fact that the sand beach in front of the vertical sea wall at Filey is not groyned suggests that, if any beach lowering has taken place, it has not been severe. Certainly there is no evidence of recent beach lowering in front of the near vertical sea wall along the general frontage of the town. This wall was constructed at various times from before 1900 to 1979 and is generally in good condition. Downdrift erosion is evident at the south end of the town. Here there is a quite noticeable recession of the cliff line and attempts have been made to prevent outflanking of the sea wall by means of a concrete block revetment. Too few blocks have been placed on the beach to have had a marked effect on the rate of erosion.

Filey Bay has a wide sand beach and has attracted holiday development. There is also private development in the form of bungalows and chalets set within the undercliff at Hunmanby. The short stretches of wall (in private ownership), are in poor condition. Serious erosion is taking place and the cliffs are generally very unstable in the Bay. At the south end of the bay the foreshore width reduces and sands are replaced by rock and pebbles. The unstable clay cliffs give way to near vertical, wave resistant chalk cliffs.

Flamborough Head extends many kilometres into the sea like Filey Brigg forms a "zero littoral transport" boundary. The coast between Filey and Flamborough can therefore be considered as an individual coastal cell. The chalk cliffs from Bempton eastwards become gradually lower and are covered by thick deposits of glacial drift. Differential erosion has led to the development of a number of coves within which there are small sand beaches. Differential erosion of the chalk has also led to the development of many stacks and caves. The sand is almost certainly derived from the erosion of the boulder clay. There is a particularly severe area of cliff instability within Selswick Bay at the east end of Flamborough Head.

6.2 Flamborough Head to Spurn Point

The boulder clay plateau stretching from Bridlington to Spurn Point forms the Holderness coastline, notorious for being the most rapidly eroding stretch of coastline in the United Kingdom. Despite erosion of the boulder clay cliffs over many centuries the beaches have not attained an equilibrium profile and erosion in the future is likely to continue at much the same rate as at present. The fines eroded from the clay cliffs by wave action are transported in suspension seawards and southwards. Much of this material settles out within the Humber Estuary. The sand and pebbles derived from the erosion of the glacial drift are also transported southwards by wave action. This movement takes place within the nearshore zone.

Spurn Spit, a long narrow ridge of sand extending into the Humber Estuary is derived from the erosion of the boulder clay cliffs to the north. At present the Spit is undergoing severe erosion at its narrowest point and breaching is imminent.

The coastline is not heavily developed with the main urban centres being at Bridlington, Hornsea and Withernsea, all of which are protected by traditional types of coastal defence. There are also a large number of coastal villages and holiday camps which are unprotected from coastal recession. Spurn Spit is designated as a Heritage Coast. The Spit and the mud flats westwards to Hull are an SSSI. The lagoons and marshland at Easington are also within an SSSI. Protection of the Spit has been carried out in a piecemeal fashion and the results are less than satisfactory both from a hydraulic and an aesthetic point of view.

6.2.1 Bridlington to Hornsea

The chalk on the south side of Flamborough Head (Fig 4) is jointed and is easily eroded by wave action. Chalk pebble beaches predominate at South Sea Landing and pebbles are transported by wave action to North Sands, Bridlington. The sand and chalk pebble beach in this area is groyned and backed by concrete sea walls or revetments. The groynes have generally been successful in maintaining a reasonably stable if not very high beach. The littoral drift is from north to south and some sand bypasses the harbour, forming a bar at its entrance.

Immediately south of Bridlington harbour there is serious beach erosion. Hence, although sand is transferred across the entrance, clearly the drift southwards is greater than the supply from the north. Here the wall has shown signs of underscour and has heavy toe protection in the form of a rock sill. The foreshore is intersected by sandbars and by tidal gullies which drain southwards. The groynes immediately to the south of the harbour are in poor condition and have little effect on inhibiting gully flows. Further south along the town frontage the beach widens and the groyne system is well stocked with sand. The foreshore is reasonably stable, with the sea wall preventing further recession and the groynes generally maintaining adequately high beach levels. The net rate of littoral drift is relatively small, mainly due to the sheltering effect of Flamborough Head. There are only a few chalk pebbles this far south, presumably because of dispersion away from the supply source and because of rapid attrition. The sea wall and groyne system extends southwards to Hilderthorpe and the foreshore becomes very wide in this area, presumably because of cliff erosion prior to the construction of the sea wall. It becomes wider still at the golf course beyond the end of the sea wall. However, the recession of the cliffs in this area is still quite low and the end of the sea wall is not seriously at risk.

From Hilderthorpe southwards to Hornsea the coast is undefended with the exception of rubble dumped over the cliff edge at the frontages of several caravan sites. Attempts made to stabilise the cliffs in this manner are largely unsuccessful. Recession rates increase southwards away from the protection of Flamborough Head being as much as 1½km per annum at Barmston. In the foreground of Plate 5 one can see the rubble which has been tipped over the cliff edge from the access road at Barmston. The Barmston main drain, visible in the background of Plate 7 has a culvert which discharges near the low water mark. The sides of the culvert are protected against scour by riprap, while the low lying land on which the pumping station is situated is protected by a flood embankment. Plastic coated gabion mattresses are used as a facing to the embankment. These are showing signs of damage and are unlikely to have a lifespan of more than a decade. Some concrete blocks have also been laid out in a line perpendicular to the beach contours on either side of the embankment. The intention is to maintain high beach levels locally. The beach south of the culvert is markedly narrower than that to the north indicating a strong southerly drift of sand.

The foreshore is littered with the remains of World War 2 defences, the concrete blocks, presumably having been set out as anti-invasion measures along those stretches of coast where the cliffs are low. In places these act as wave breakers and have succeeded in trapping sand between them and the cliff foot. However, they do not appear to be having a significant effect on the rate of recession since this occurs at high tide when the blocks are submerged. Aerial weathering, of course, accounts for much of the cliff instability along the Holderness coast and this is difficult to combat even with traditional forms of coast protection.

The rate of erosion varies both spatially and temporally (see Chapter 5) and at present the cliffs between Barmston and Hornsea are retreating at mean rates varying from about 0.5 to about 1.5 metres per annum. There are numerous caravan parks along this stretch of coast, together with private chalet type bungalows which are at risk. The bungalows are generally set out parallel to the cliff line and many are in imminent danger of falling in the sea. Local roads have already been cut off in places and the coast roads are at risk in other areas. At Ulrome, for example, part of the cliff retreated about 5 metres from October 1985 to October 1986. The erosion is evident from the undermining of an old concrete platform for caravans.

At Cliff Top Farm about ½km to the south, the erosion is equally serious. A bungalow which stood near the cliff edge in 1985 has now disappeared and only the foundations remain. The cliff line in this area has receded about 2 to 3 metres during the past year. The coast road just south of the Cliff Top Farm will probably be at risk within the next decade, if the present erosion rate persists. Further south at Skipsea, on the other hand, little change has taken place in the last year. However, large cracks have recently developed in the road surface several metres back from the cliff edge, indicating imminent cliff slippage. This demonstrates the uneven rate at which erosion takes place and throws doubt on the accuracy of cliff top recession rates based on infrequent mapping of the area.

6.2.2 Hornsea to Withernsea

Urban development on this stretch of coast is centred around Hornsea and Withernsea. Although the town centres are protected from coastal erosion there are caravan parks to the south of the towns which are at threat. At Sandle Mere, near Tunstall, the land is low lying and is protected from flooding by a short length of embankment.

Hornsea has had coastal defences since the 19th century and long term cliff recession both to the north and the south has now resulted in the town becoming a promontory. The coastal management policy is one of defending the urban frontage while recognising that it is impractical to defend the less heavily developed holiday camps adjacently. The net littoral drift at Hornsea is from north to south and the groyne system has been successful in capturing sand and maintaining relatively stable beach levels.

Beaches to the north of the town are particularly wide and healthy and despite some cliff instability (mainly due to aerial weathering) the toe of the cliff is fairly well protected from wave attack at most times. The coastal defences on the town frontage have been recently upgraded. Although there is a wide beach in this area differential levels across the groynes can be large, due to the high rate of drift. This has led to a large exposure of the sea walls in the lee of the groynes on certain occasions and some wave overtopping. Work is now in progress south of the town centre where a high vertical wall protects low lying land from the sea. The wall has clearly been subject to subsidence and is presently being given added toe protection. At the southern end of the town's defences there is a sloping concrete revetment which acts both as a sea wall and an earth retaining wall. South of this wall is a shore parallel breakwater consisting of raked timber piles braced with steel ties and enclosing a line of concrete and stone blocks. This breakwater has been reasonably successful in retaining a sand beach immediately to the landward. South of the crib breakwater, downdrift erosion is a serious problem (Plate 6), estimated at being about 2½ metres of horizontal retreat per annum.

The net rate of littoral drift along this stretch of coast has been estimated at 200,000m^3 per annum southwards. This calculation is based on estimated values of the wave conditions and represents the potential volume of material that could be transported given sufficient supply and no barrier to alongshore movement. Since the beaches on the Holderness coast generally have a thin veneer of sand overlying boulder clay it is doubtful whether this rate is achieved in nature.

Coastline retreat between Hornsea and East Newton has also been very rapid in recent years. Between 1952 and 1971 it was estimated to have been about 2½ metres per annum at South Cliff Farm, Hornsea and of the same order of magnitude at Great Cowden. At Mappleton, at Aldbrough and at East Newton it has been 1½ metres per annum or more. From East Newton to Withernsea the recession has traditionally been lower and presently it is on average about ¾ metre per annum

At North Cliff, Withernsea recession has reduced very markedly since the end of the 19th century. At present it is estimated to be of the order of ¼ metre per annum. A wide sand beach protects the cliffs from wave action, with the wave swash line being normally seawards of the cliff foot. Undoubtedly the groyning of the foreshore has helped to stabilise this area. The north end of the town is well protected, the wide sand beach being groyned and backed by a concrete sea wall The boulder clay cliffs have been graded and are sheathed with a sloping concrete revetment wall. Beach levels along the central part of the town are also healthy. The sea wall despite being very old appears to give adequate protection against wave attack. The groynes along the central frontage are almost completely buried in sand and allow some material to travel southwards. At the south end the beach is considerably narrower than that to the north (Plate 7). Here the groynes are very dilapidated and are well proud of the general profile of the beach, indicating a possible lack of supply of sand from the north.

6.2.3 Withernsea to the Humber

From south of Withernsea to Easington Beach the rate of cliff retreat has historically been very rapid and presently is up to 2 metres per year. The rate is quite variable, not only because of the changing orientation of the shoreline contours but also because of the varying nature of the cliffs. These run down to sea level at Easington and coastline retreat at this point is quite low. Between Easington and Kilnsea the hinterland is very low and marshy and protected by flood banks. The lagoons and inland marshes lying between the beach line and the flood bank at Easington are an SSSI. Long Bank extends along a 1½km frontage, joining into the rising land at Kilnsea Grange. The embankment is faced with mattress gabions on its "seaward" side, which because of their careful siting in a sheltered area are in good condition.

The boulder clay cliffs rise again (locally) at Kilnsea; they are subject to rapid erosion. Both coastal and World War 2 defences are in a state of complete dereliction. The former were damaged badly in a storm in the 1960's and never repaired. South of Kilnsea the cliff disappears and low lying land is again protected by earth embankments.

The foreshore from Kilnsea southwards along the northern half of the Spurn peninsula has been denuded of beach material and the underlying clay is exposed over large areas of the foreshore. The area has been designated a Heritage coast and is an SSSI. It has received little in the way of protection and the coastal defences are either old and fragmentary or are inadequate. There is now a serious danger of a breach about 1km south of Kilnsea Warren (Plate 8). The distal end of the peninsula is subject to much fluctuation but no serious loss of volume. The "reservoir" of beach material at the Head is probably sufficient for it to recover from serious storms without danger of breaching.

The low lying land on the north shore of the Humber has been reclaimed from the sea and is protected by clay embankments. Salt marsh development is taking place in the vicinity of Sunk Island and the area is generally well sheltered against wave action. Although the present defences are adequate they would be put under great stress were a breach to form along the neck of the Spurn peninsula. The consequence of a breach would be increased wave activity and, equally serious, a set up of water level. Such a combination could lead to wide scale flooding. Further up estuary on the north bank of the Humber there are few serious problems. Erosion of the clay bank has taken place locally at Brough and at Paull, both areas being open to the predominant south-westerly winds.

6.3 The Humber to The Wash

The coastline between the Humber and The Wash is flat and very low lying, the greater part of it having been reclaimed from the sea in historic times. The process of change is active with redistribution of silts and mud taking place in the Humber Estuary, salt marsh and sand accretion in North Lincolnshire, erosion of beach sands in Central Lincolnshire, and salt marsh and sand accretion adjacent to The Wash.

Large stretches of the coast are defined as SSSI's. They include the mud flats at Pyewipe, west of Grimsby, the developing salt marshes and sand dunes from Humberston to Theddlethorpe and sand dune and salt marsh accretion at Gibraltar Point. There are also a number of SSSI's along the "sea bank" between Sutton-on-Sea and Chapel St Leonards. There is an RSPB reserve at Tetney Haven, a Nature Reserve between Salt Fleetby and Theddlethorpe and another one between Skegness and Gibraltar Point.

The coastline is not heavily developed, with the main urban centres being Grimsby, Cleethorpes, Mablethorpe and Skegness. There are also a number of small coastal villages at Sutton-on-Sea, Chapel St Leonards and Ingoldmells and extensive holiday camps stretching over much of the frontage from Cleethorpes to Humberston and from Mablethorpe to Skegness.

The industrial areas on the south bank of the Humber from Stallingborough to Grimsby are protected by stone revetments. Cleethorpes, at the mouth of the estuary, has concrete sea walls and part of the frontage is groyned. The accreting coastline from Cleethorpes to Mablethorpe is protected by flood banks, with sand dunes south of Saltfleet Haven. Most of the eroding coast between Mablethorpe and Skegness is heavily groyned and backed by sea walls or revetments. Finally south of Skegness the land is naturally protected by large scale salt marsh and sand bank development.

6.3.1 Stallingborough to Cleethorpes

The low lying land bordering the Humber Estuary is protected by a variety of coastal defences. In the semi-sheltered reaches between Stallingborough and Grimsby serious foreshore lowering has taken place and the asphalt grouted stone revetments protecting the river bank have been extended downwards in response to falling beach levels. In this area some wave activity penetrates from the open sea and the embankment is faced with asphalt grouted stone and is surmounted by a concrete return wall.

West of Grimsby docks there is a flood embankment faced with concrete panels. It protects land owned by the British Transport Docks Board. The condition of this embankment appears to be generally satisfactory.

Further south, the town frontage of Cleethorpes is protected by concrete sea walls which extend to the Leisure Centre. Inspection of the wide, sandy, groyned foreshore north of the pier indicates a net northerly littoral drift due to waves penetrating into the estuary from the North Sea. However, the Coast Protection Survey (Ref 4) suggests that the littoral drift is southerly. A recent report includes an assessment of the Cleethorpes groynes (Ref 17). This too indicates that the predominant drift direction is from north to south. The orientation of the coastline and the shelter provided by the Spurn peninsula would indicate a predominance of waves from the south. Thus the question of the direction of net drift along the Cleethorpes frontage is not satisfactorily resolved. The area in the vicinity of Cleethorpes pier may in fact be a point of divergence with respect to littoral drift.

South of Cleethorpes pier the upper foreshore becomes narrower and there is now definite evidence of a southerly net drift. The groyne survey (Ref 17) indicates that the beach width in this area was significantly greater 50 or so years previously.

6.3.2 Cleethorpes to Mablethorpe

South of Cleethorpes the foreshore becomes increasingly wide and there is large scale salt marsh and sand accretion extending to Saltfleet. Accretion consists of the formation of large offshore sand banks probably of material derived from the erosion of Holderness. Within the shelter of these banks salt marshes develop rapidly. The fines are probably derived from the Humber Estuary which in turn receives muds and silts from the eroding boulder clay cliffs of Holderness.

Between Cleethorpes and Humberston Fitties protection against flooding is by means of earth embankments and sand dunes. The latter are badly trampled by holiday makers and are presently being stabilised by fagotting and the planting of marram. The area has traditionally been liable to flooding despite the protection given by the offshore sand banks. At Humberston Fitties there are two lines of defence against the sea, a revetment of gabions and a flood bank situated some distance to the landward.

From Humberston Fitties southwards to Mablethorpe the low lying land is protected by embankments. The area is accreting and large areas of salt marsh are developing south to Saltfleet. Thus the embankment protection is largely redundant under normal conditions when the high water line is some distance to the seaward. Only in conditions similar to the North Sea surge of 1953 (Ref 27) are the defences likely to come under direct wave attack.

South of Saltfleet Haven the foreshore becomes narrower and increased wave activity makes it relatively free from mud deposits. Sand blown landwards from the foreshore forms extensive sand dunes. The dunes are particularly well developed at the Theddlethorpe Nature Reserve. Some damage to these dunes has occurred, possibly due to over use, and they are being stabilised by sand fences and fagotting. However, the problem of erosion and the risk of flooding in this area are not serious. The dunes continue southwards to North End, Mablethorpe.

6.3.3 Mablethorpe to Skegness

The low lying land from Mablethorpe to Skegness is under increasing threat from the sea. The primary form of defence against flooding are embankments which in places are fronted by concrete sea walls. The beaches taken as a whole are deteriorating and in many areas the groynes have deteriorated to such a degree as to be ineffective. The coastline appears to be suffering from a dearth of littoral material despite the fact that sand accretion continues to take place on a massive scale to the south of Skegness.

From North End to the town frontage of Mablethorpe the toe of the sand dunes is faced with a gabion revetment. This is almost completely buried in wind blown sand and plays little part in modifying beach movements. The beach is relatively stable and is ungroyned.

At Mablethorpe the concrete sea walls have been in place for many years and the promenade now projects seawards of the general line of the coast due to some recession adjacently. The sand beach is still quite wide but is not very thick over the boulder clay. Certainly it is insufficient to give protection against wave attack during storms, when the material is eroded down to the clay base. Onshore/offshore sand movement is particularly marked in this area and the groynes are insufficiently long to trap much of the net southward drift. The groynes were maintained until the 1970's but repair costs have now become prohibitive. Plate 9 shows the very poor condition of the groynes and low beach levels opposite the Convalescent Home, Mablethorpe. The town is situated on low lying land and is protected against flooding by the sea wall. This wall extends southwards to Huttoft. Certain key stretches of coast have not been allowed to recede and the sea wall forms small promontories, eg at the south end of the town frontage. At these points beach levels are particularly low. The sea wall at the south end of

Mablethorpe is being reconstructed, with the addition of massive concrete footings. The defences south to Trusthorpe are in poor condition and the wall shows signs of being overtopped, even in relatively calm weather.

At Sutton-on-Sea the sand cover is also very thin and the clay substratum becomes exposed over very large stretches of the foreshore. Plate 10 shows the almost complete disappearance of the sand and the exposure of an old wreck embedded within the boulder clay.

Between Sutton and Sandilands there is an embayment within which there is a marked improvement in beach conditions. The groyne system in this area is dilapidated and hence provides little indication of the magnitude of the net southward drift. There are large sand bars within the intertidal zone testifying to a strong seasonal onshore/offshore movement of sand.

South of Sandilands beach conditions deteriorate again and the sheet steel piled toe of the concrete stepped sea wall is regularly exposed to wave action. The groynes along this stretch of coast are almost completely ineffective, being very dilapidated.

From Whitehouse Farm, Huttoft to Chapel Farm, Chapel St Leonards there is a marked improvement in beach conditions. The embankment is an old one, consisting of steel slag faced with asphalt grouted stone. The groynes are dilapidated but the beach is wide and sandy and the backshore covered by wind blown sand. Much of the embankment is also covered in dune grasses. At Anderby Creek approximately midway along this frontage a stretch of the revetment is of clay construction and faced with stone. The groynes are almost buried in sand. The embankment is almost completely vegetated and the beach is healthy (Plate 11). As with the stretch of coast further northward it is difficult to discern the magnitude of littoral drift.

The more densely populated stretch of coastline from Chapel St Leonards to Ingoldmells is protected by concrete sea walls. The beach condition is variable, being low at promontories such as Chapel Point and Ingoldmells Point and being high and relatively stable in the intervening embayments. Plate 12 shows such an embayment, which is situated at Chapel Pullover, Chapel St Leonards. In this area the groynes are long and still in reasonably sound condition. They are sufficiently effective to build up sand on their northern face and to have a large exposure of timber whaling on their southern faces. There is clearly a strong net southward movement of sand in this area. The sea defences along this stretch are somewhat piecemeal and the condition of the groynes very variable. There is strong seasonal onshore/offshore movement, with sand bars and associated gullies moving across the foreshore. The development of gullies such as those at Butlins Camp, Ingoldmells (Plate 13) poses a potential threat to the stability of the coastal defences. At Seathorne to the south of Ingoldmells there are asphalt grouted stone groynes of hog-back cross section. They appear to be particularly effective. To the north of them the high water line does not normally reach the base of the concrete stepped sea wall. However, to the south the ungroyned sand beach becomes very narrow. At the end of the Seathorne wall the backshore is protected by means of a gabion mattress type revetment extending south towards Skegness Pier. The toe of the revetment has been undermined by low beach levels and the gabion baskets are damaged to such an extent that many of them are empty (Plate 14). Due to the lowering beach levels fronting the revetment, a scour channel has formed immediately seaward of the gabions. This attracts tidal flow to the toe of the revetment, further exacerbating the situation.

Conditions continue to be very serious as far south as Skegness Pier. There is a strong littoral drift along the frontage and at Sea View Road, sand captured by groynes causes a very pronounced zig-zag plan shape. The gabion mattress along the whole frontage is now in poor condition.

The southward drifting sand is clearly settling out south of Skegness Pier. There is reason to believe that the improvement in beach conditions is related to the protection given by offshore sand banks. There may also be some movement of material from these banks to the shoreline, see Chapter 5. The beach between Skegness Pier and Gibraltar Point is so wide that the backshore (formerly the foreshore) is now extensively duned. At Seacroft the accretion is so massive that there is now very little possibility of flooding.

In Lincolnshire as a whole, the sea defences are largely the responsibility (at least in the rural areas) of Anglian Water. They are mostly built to a common minimum level of 6m A.O.D. except where wide exposure to wave action makes it necessary to add extra height. For example bank heights at Skegness and Mablethorpe are thought to be generally about 7m A.O.D. rising to a maximum of 8m A.O.D. along the exposed coastline in between.

6.4 The Wash

The Wash Estuary is a vast "sink" within which muds and silts have been accumulating for many centuries. The process of salt marsh development is taking place to this day and it is on such a scale that the risk of flooding of inland areas is small. While tidal currents are able to transport muds in suspension into the furthest corners of The Wash, sands tend to settle out in the outer margins. The development of the sand dune/salt marsh complex at Gibraltar Point is an example of this. There are few coast protection problems from Gibraltar Point around the margins of The Wash and eastwards as far as Snettisham. During the 1953 surge flooding took place at King's Lynn but otherwise this stretch of coast was unaffected.

It is likely that any sand which reaches the outer margins of The Wash from the north is trapped at Gibraltar Point and is not transported across the Wash Estuary. The wave climate in the Estuary is a mild one and the tidal currents not capable of transporting anything but muds and silts in suspension. The Wash thus forms a natural boundary from a coast protection point of view.

7 CONCLUSIONS

There are a number of natural major boundaries between the Tees and The Wash which allow one to subdivide the coastline into a number of independent cells with regard to littoral drift and hence with regard to coastal management.

The mouth of the Tees acts as a major sediment trap for muds, silts and sands. Littoral drift on either side of the harbour entrance is towards the centre of the bay. Also the major headland at Hunts Cliff at the south end of Tees Bay prevents any major interchange of beach material between the Bay and the coast further southwards.

The coastline of North Yorkshire from the Tees to Flamborough Head is incised by bays which are infilled with glacial till (boulder clay). Sand beaches are generally restricted to individual embayments and are the result of local erosion. Thus the net north to south littoral drift is weak and fragmented. Whitby Harbour is an effective barrier to littoral drift as is Castle Rock at Scarborough. Both Filey Brigg and Flamborough Head are major promontories which intercept nearly all littoral drift. From a coast protection viewpoint the area should be treated as one unit, since it shares similar problems. However, within this unit there are many coastal cells which act independently of each other. Thus all urban areas from Saltburn by the Sea south to Sandsend have coastal defences which do not "interact" with each other. However, from Sandsend to Whitby there is a long stretch of sand beach and coastal defences in this area certainly do have measurable effects. South of Whitby urban development is restricted to Robin Hood's Bay, North Bay and South Bay, Scarborough, Cayton Bay and Filey Bay. Coastal development within each of these bays has little effect on adjacent areas.

The coastline of Holderness from Flamborough Head to Spurn Head is a continuous line of rapidly eroding till cliffs. Coastal defences at Bridlington, Hornsea and Withernsea interrupt littoral drift and hence affect coastline stability. This stretch can be considered as one coastal unit, and the unstable nature of the coast should be fully considered when future coastal defence works are being designed.

The Humber estuary acts as a "sink" for fine silts and sands but it is not an effective barrier to littoral material. Sediment derived from the erosion of the Holderness coast finds its way to the area of large scale accretion at Donna Nook, Lincs. Thus, coastal changes at Holderness can have an effect on the material arriving on the Lincolnshire coast. There is, however, little transfer of material across the estuary in a northward direction and thus it is very unlikely that coastline changes in Lincolnshire would affect Holderness.

The Lincolnshire coastline should also be treated as one unit. The relatively stable north and south extremities of this are separated by a very volatile stretch of coastline. Where coastal defences have been built they have generally stabilised the immediate area but this has often led to problems of instability elsewhere. Beach changes are also affected by changes relating to offshore banks and gullies. It has to be said that the relationship between coastal defences and natural beach processes is as yet very imperfectly understood.

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FIGURES

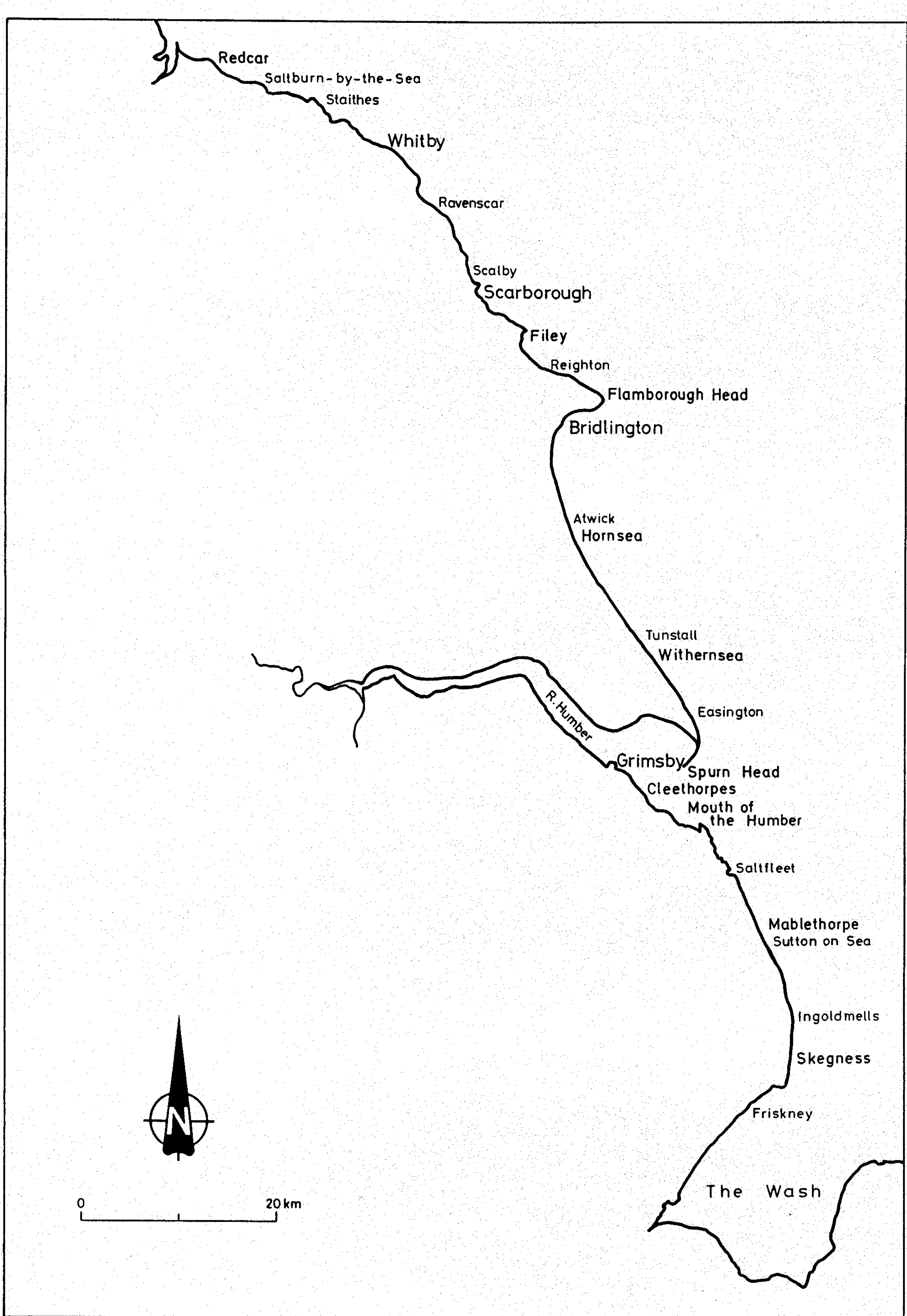

Fig 1 Location map

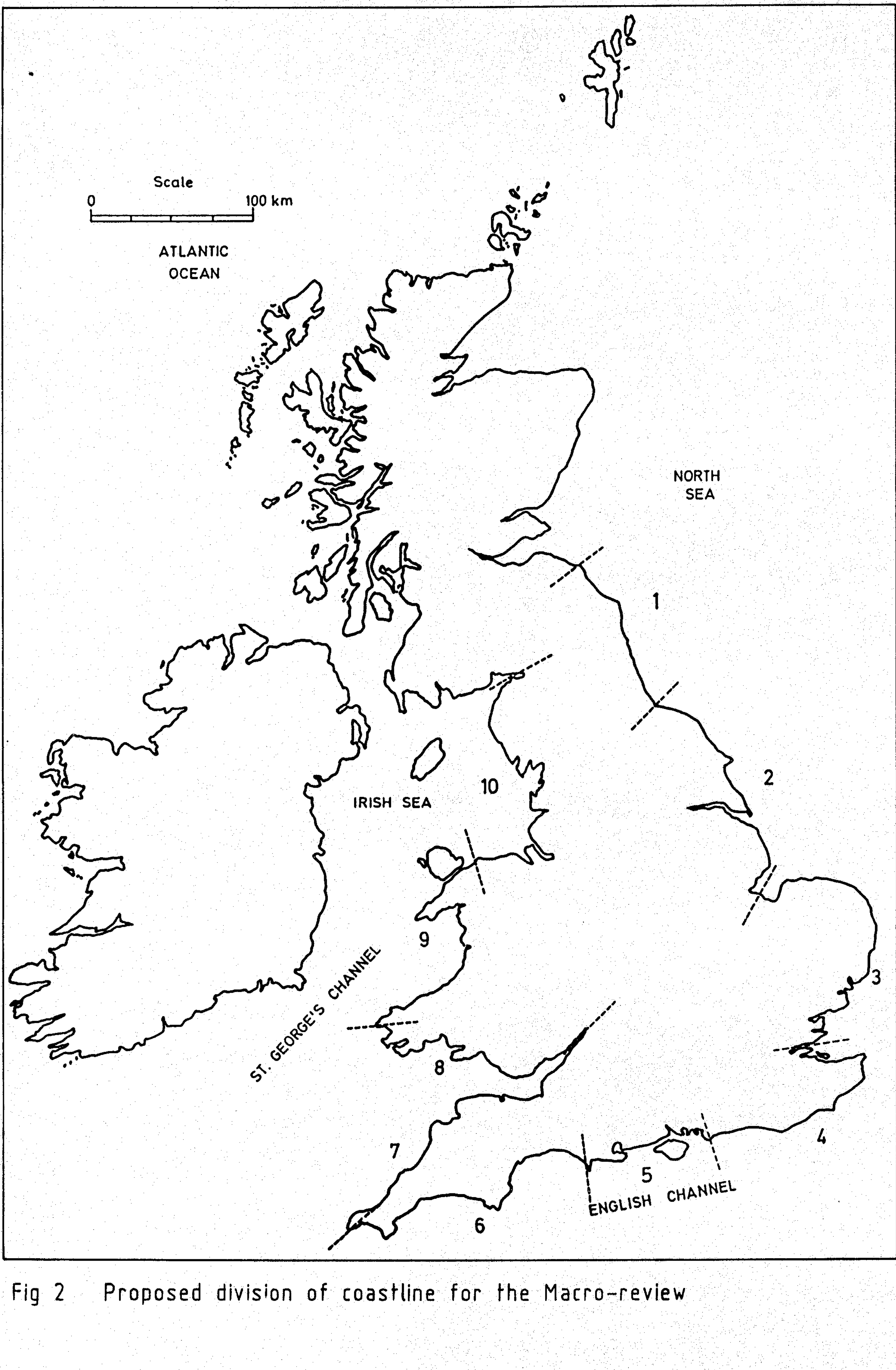

Fig 2 Proposed division of coastline for the Macro-review

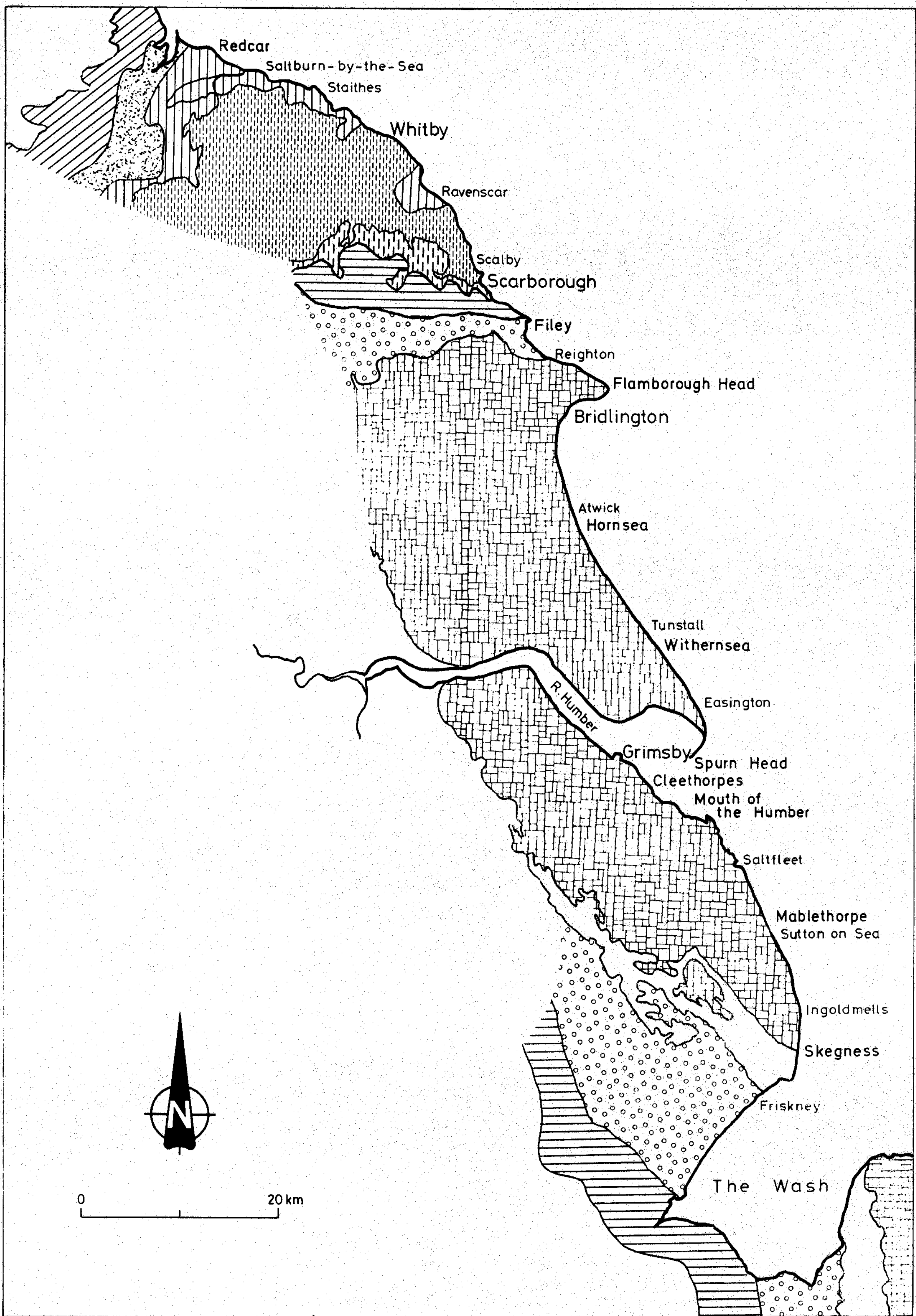

Fig 3 Simplified geology of the East coast

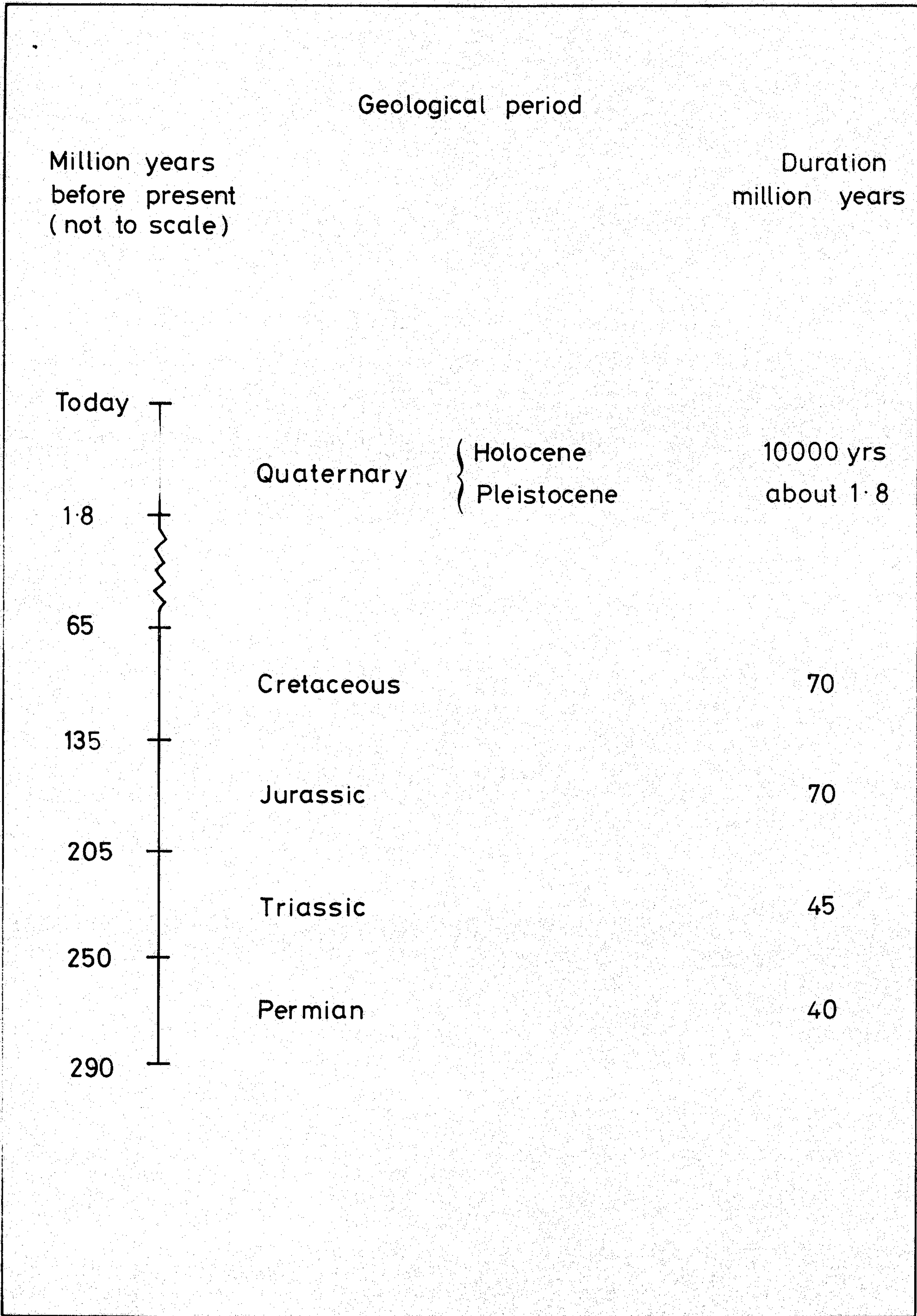

Fig 4 Summary of divisions of geological time in the East coast

Legend for figures 5 to 14

These figures show the coastline in sections from Hunt Cliff, Tees Bay in the north to Gibraltar Point and The Wash in the south.

——→	Direction of longshore drift
●●●●●●●●●●●●	Coastal defences
– – – – – –	Boundary of Sites of Special Scientific Interest

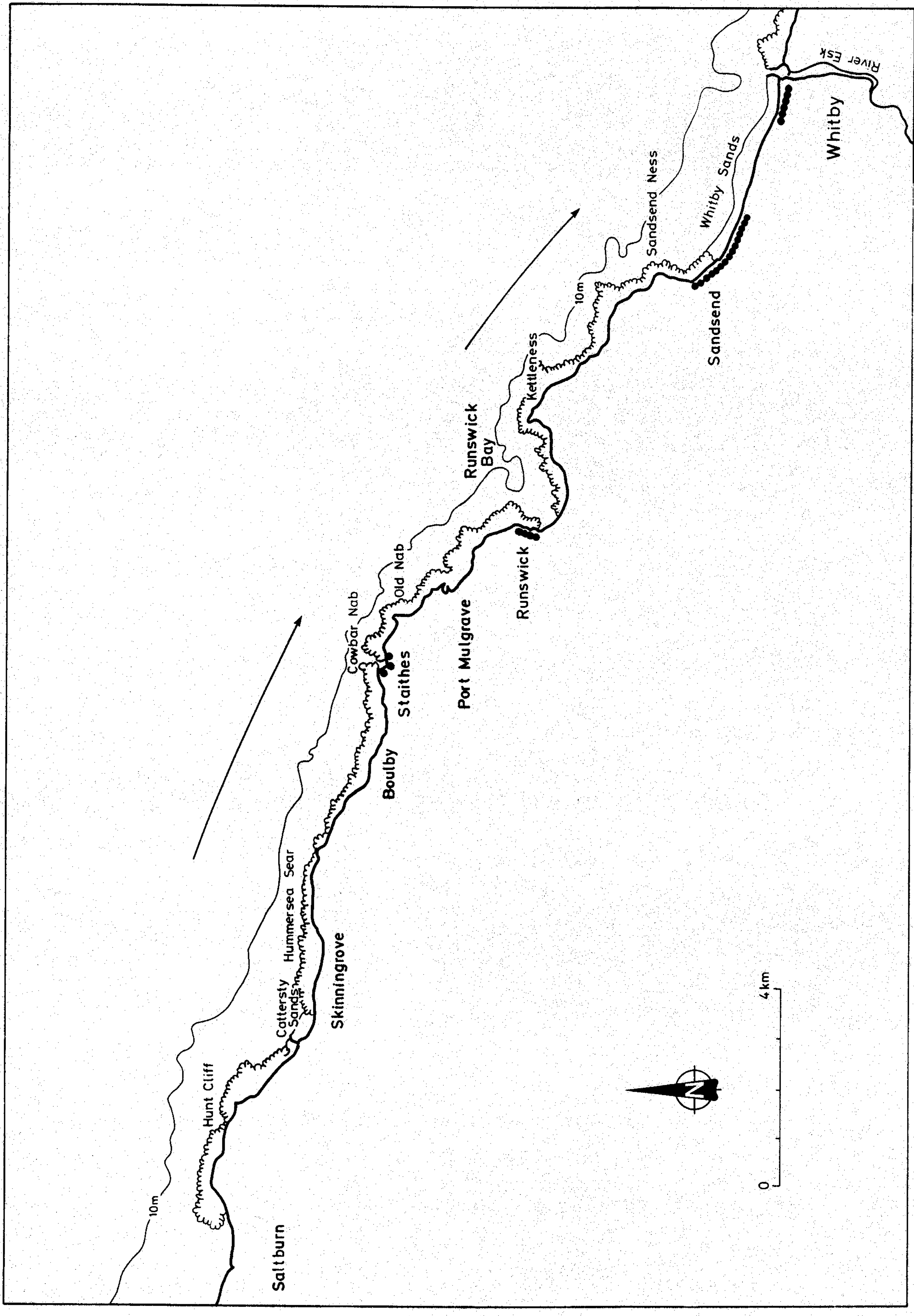

Fig 5 Saltburn to Whitby

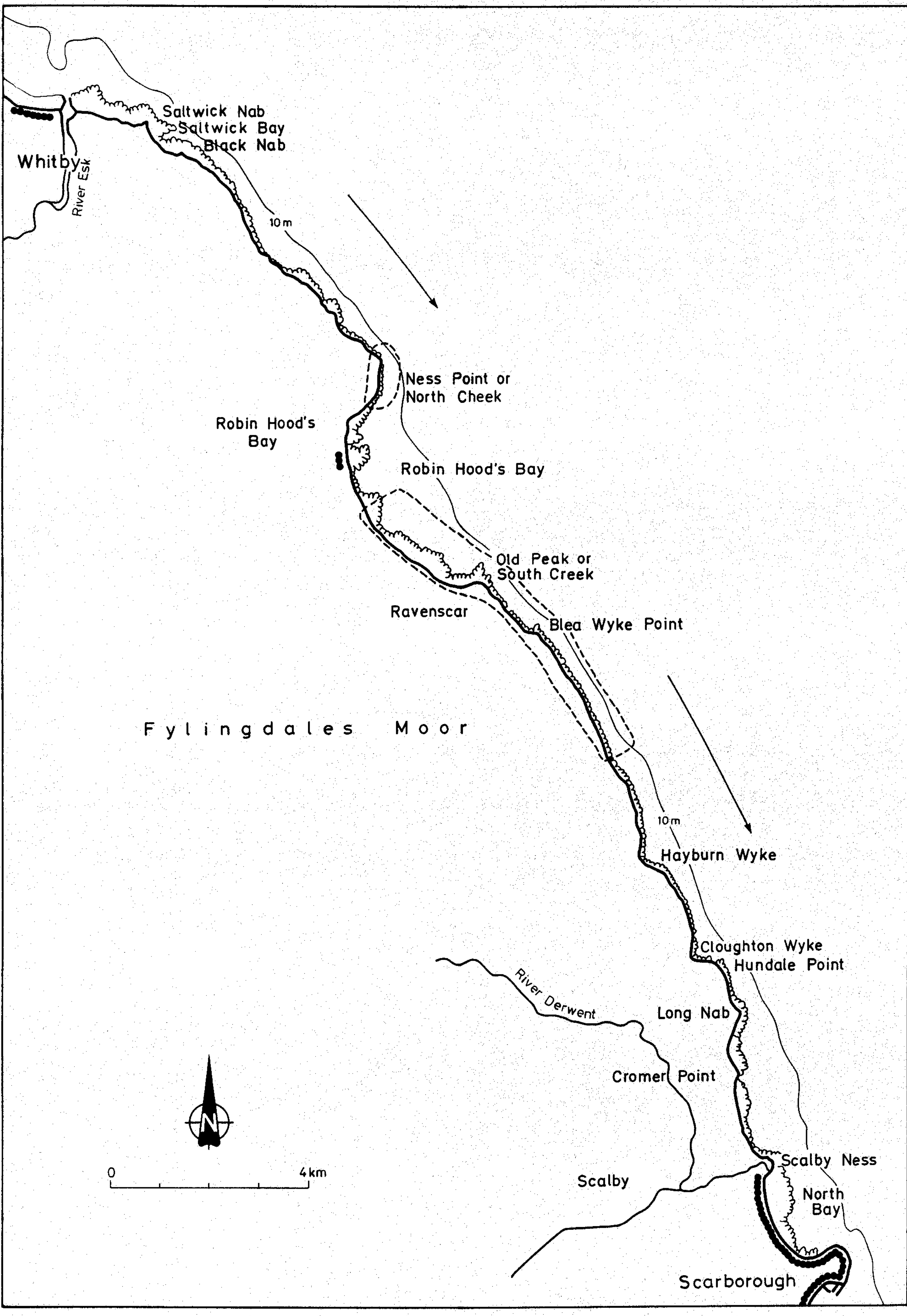

Fig 6 Whitby to Scarborough

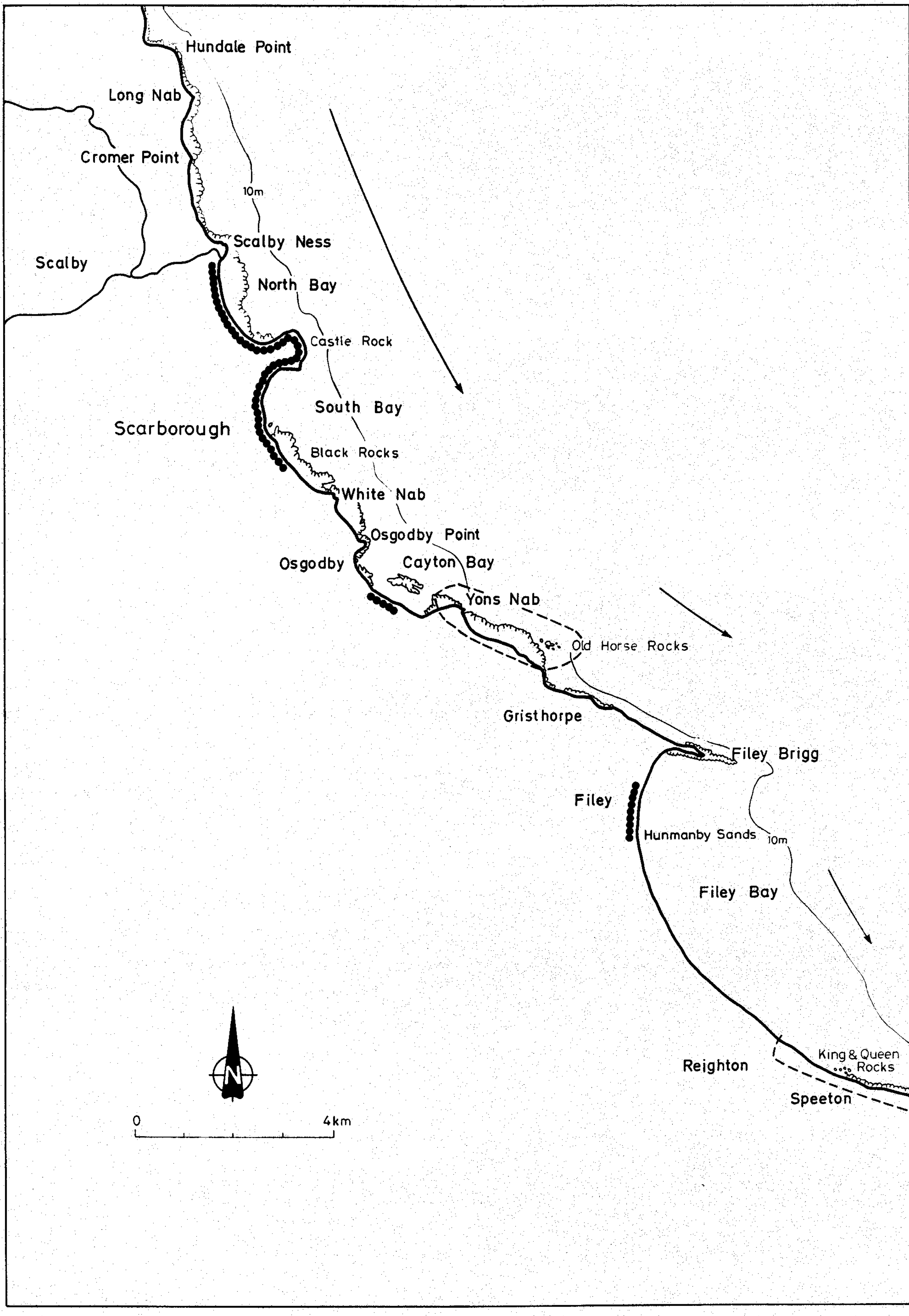

Fig 7 Scarborough to Speeton

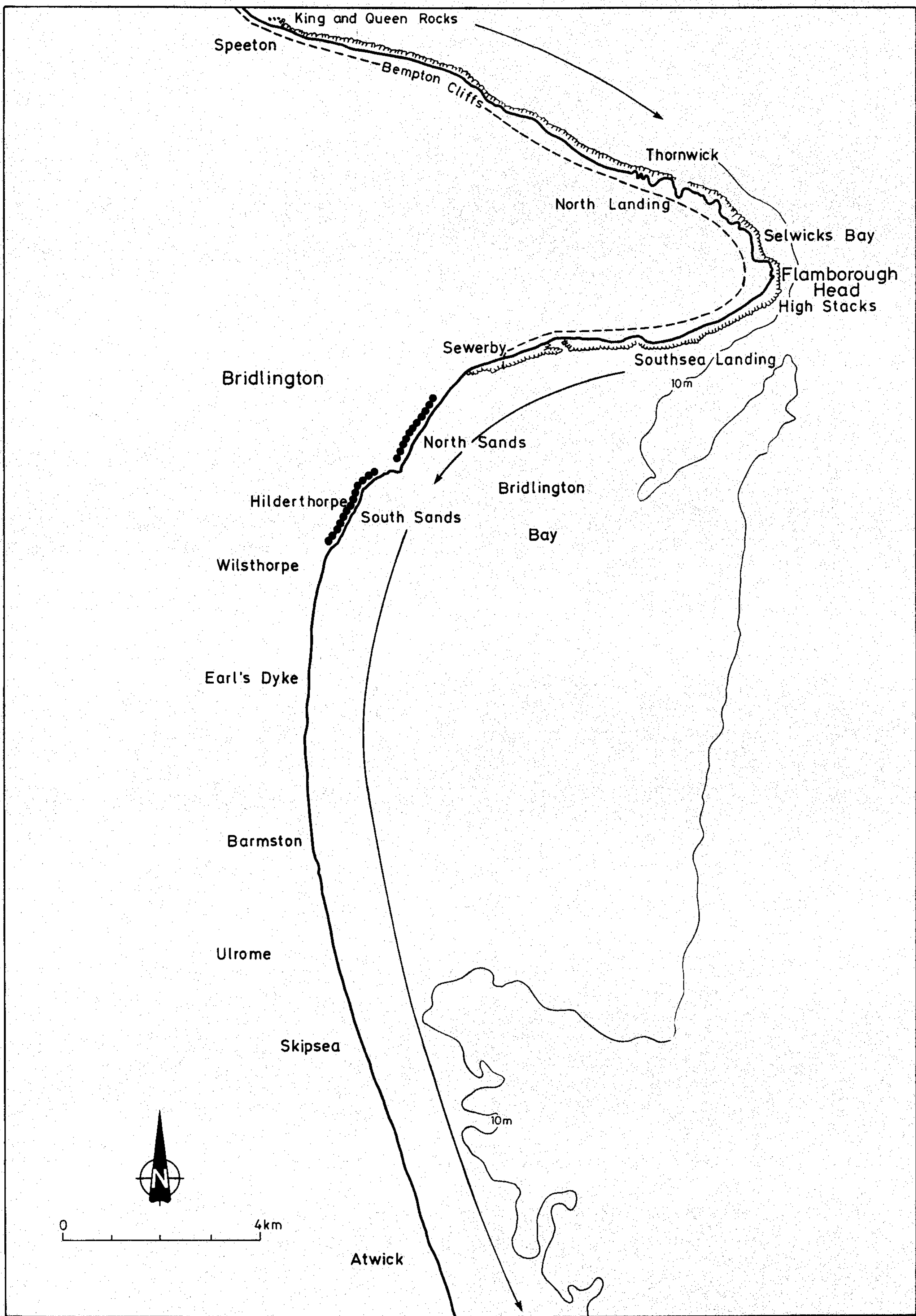

Fig 8 Speeton to Atwick

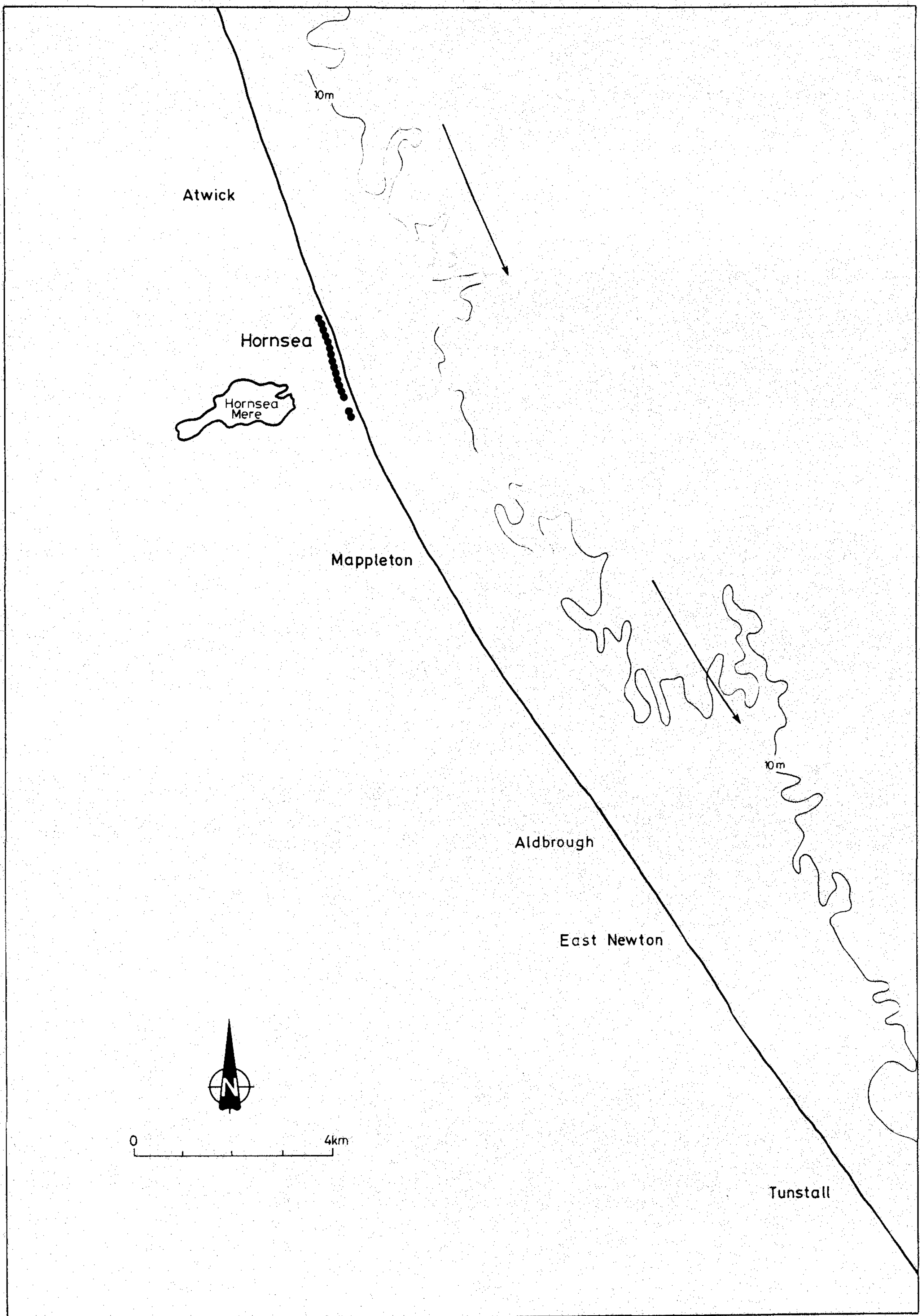

Fig 9 Atwick to Tunstall

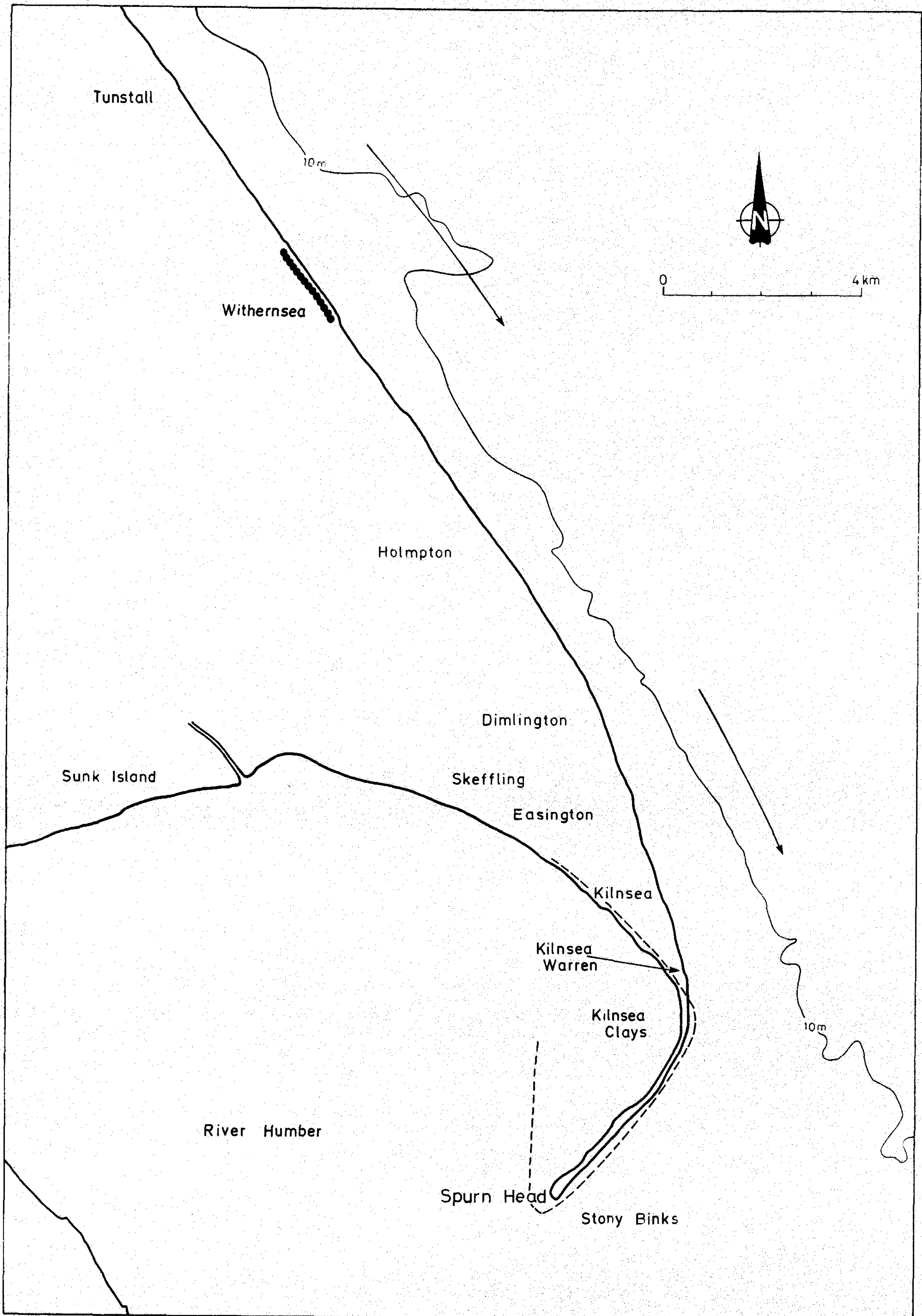

Fig 10 Tunstall to Spurn Head

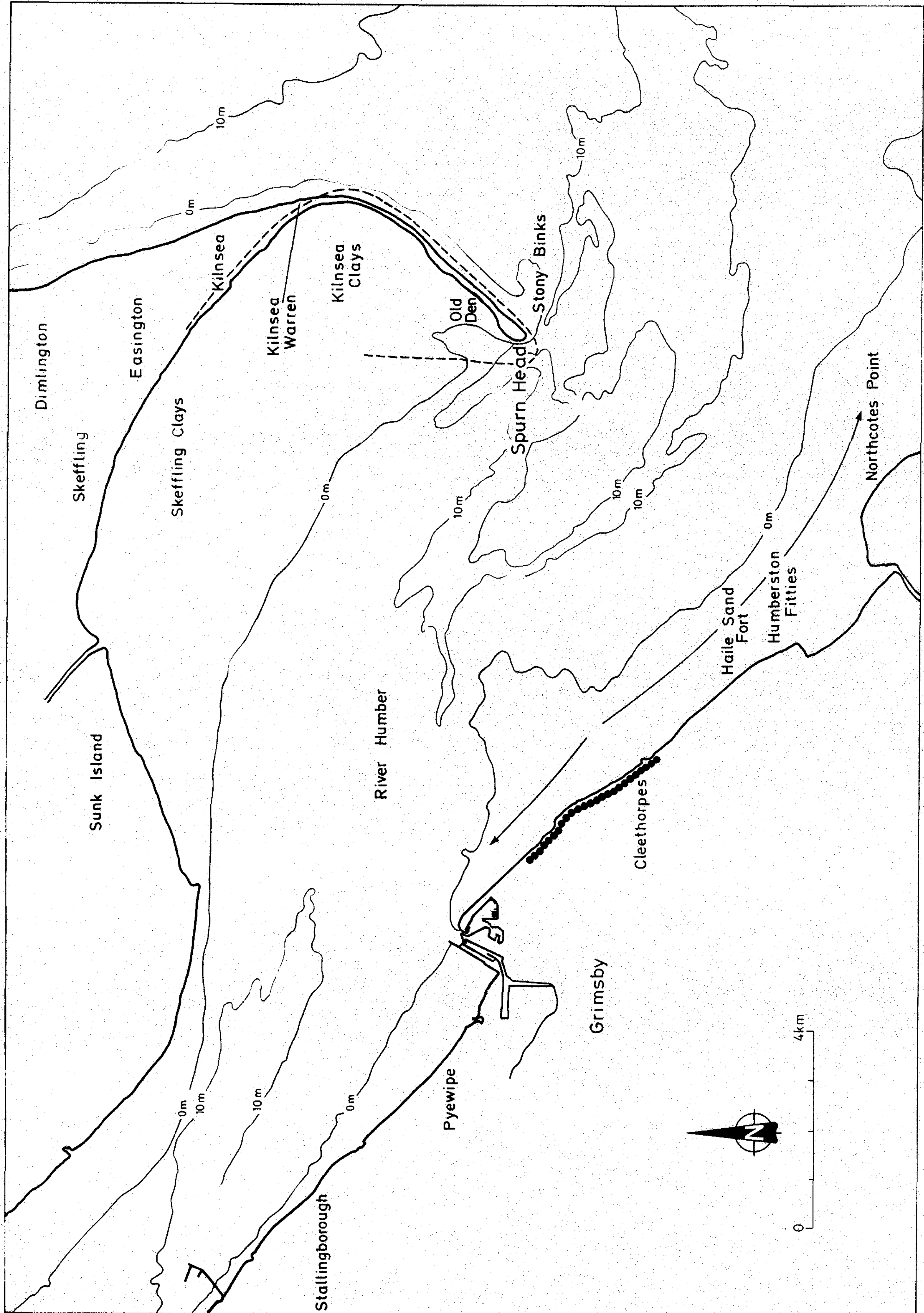

Fig 11 The Humber Estuary

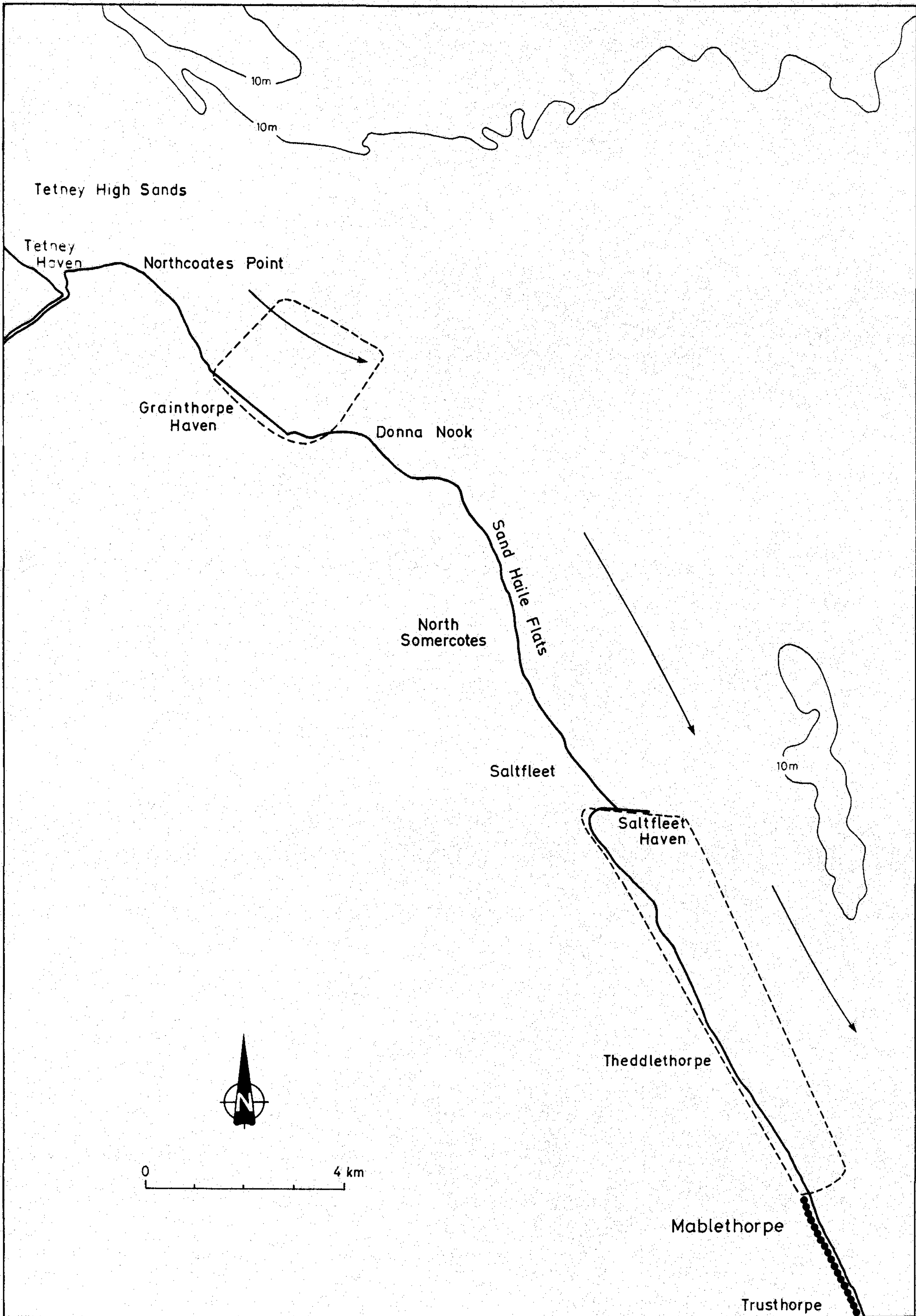

Fig 12 Northcoates to Mablethorpe

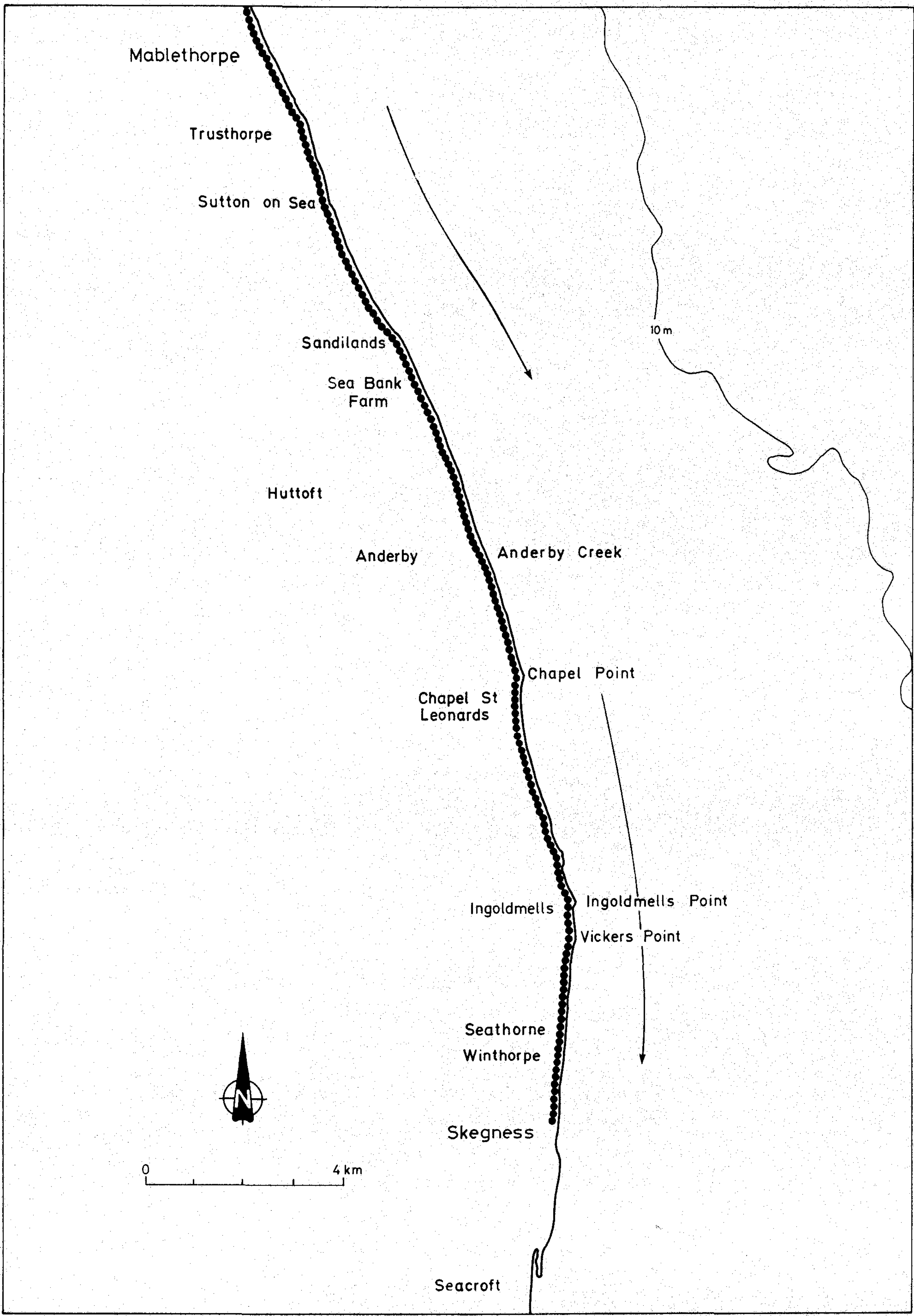

Fig 13 Mablethorpe to Skegness

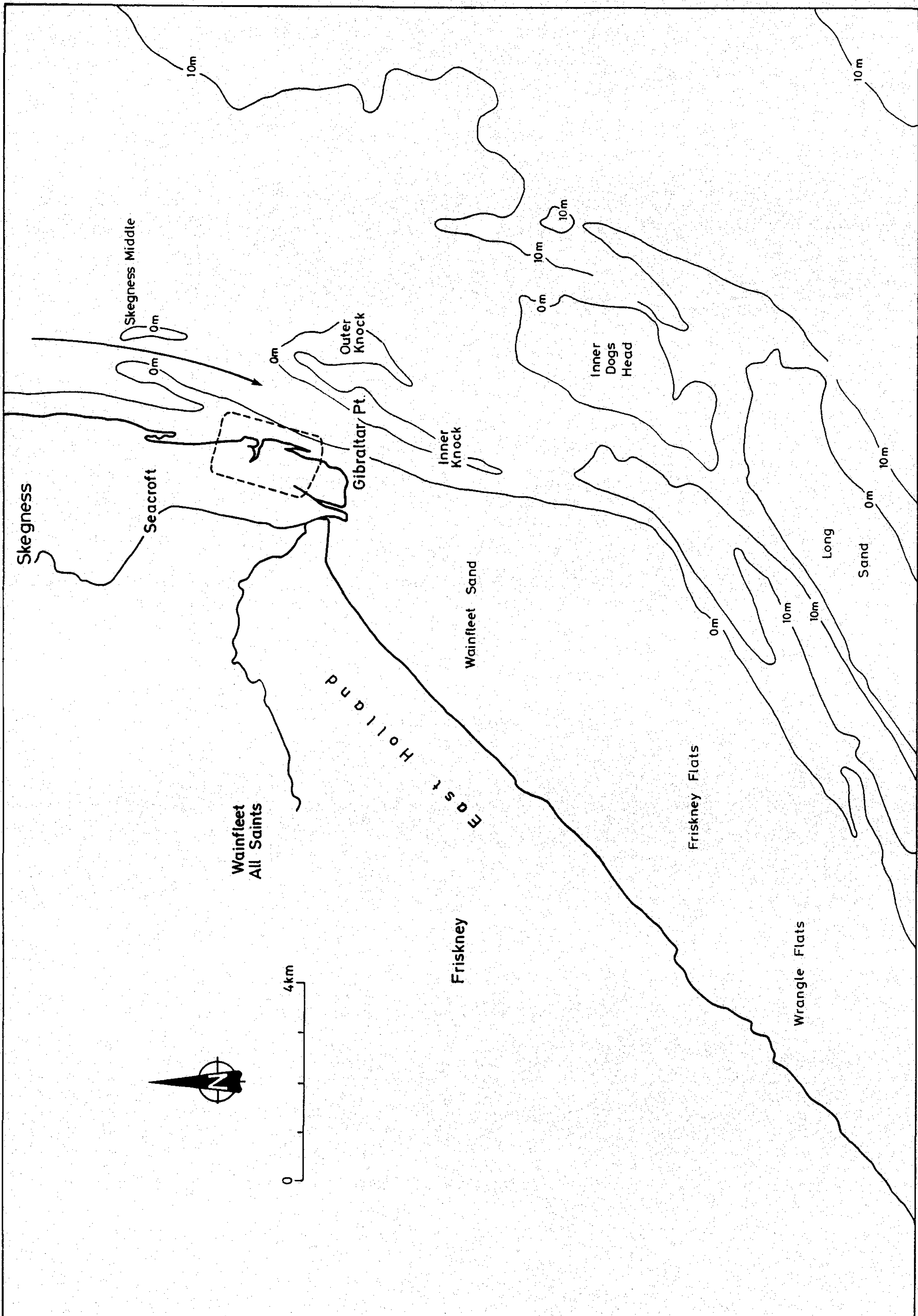

Fig 14 Gibraltar Point and the entrance to The Wash

PLATES

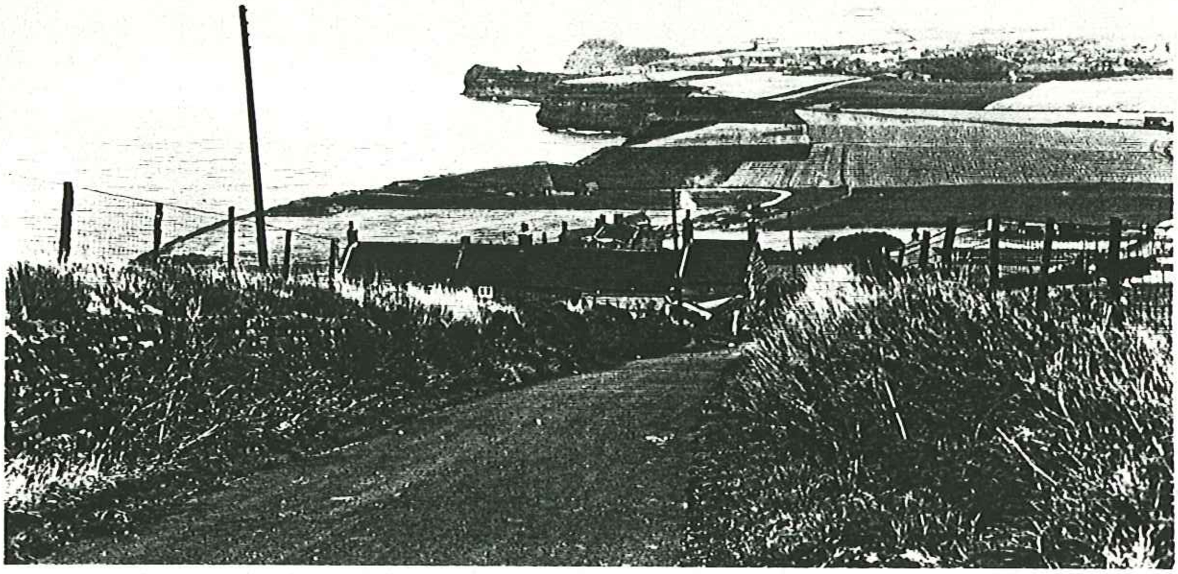

Plate 1 View south to Staithes

Plate 2 Whitby Harbour

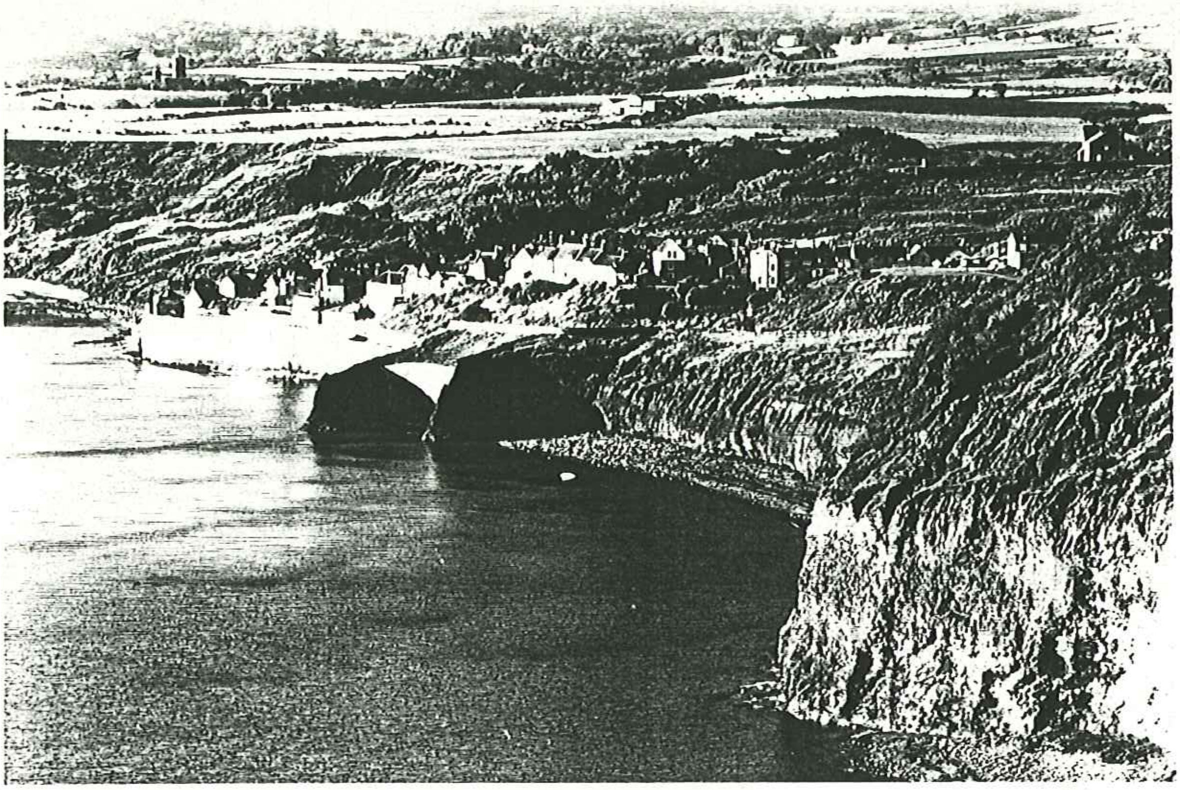

Plate 3 Robin Hood's Bay

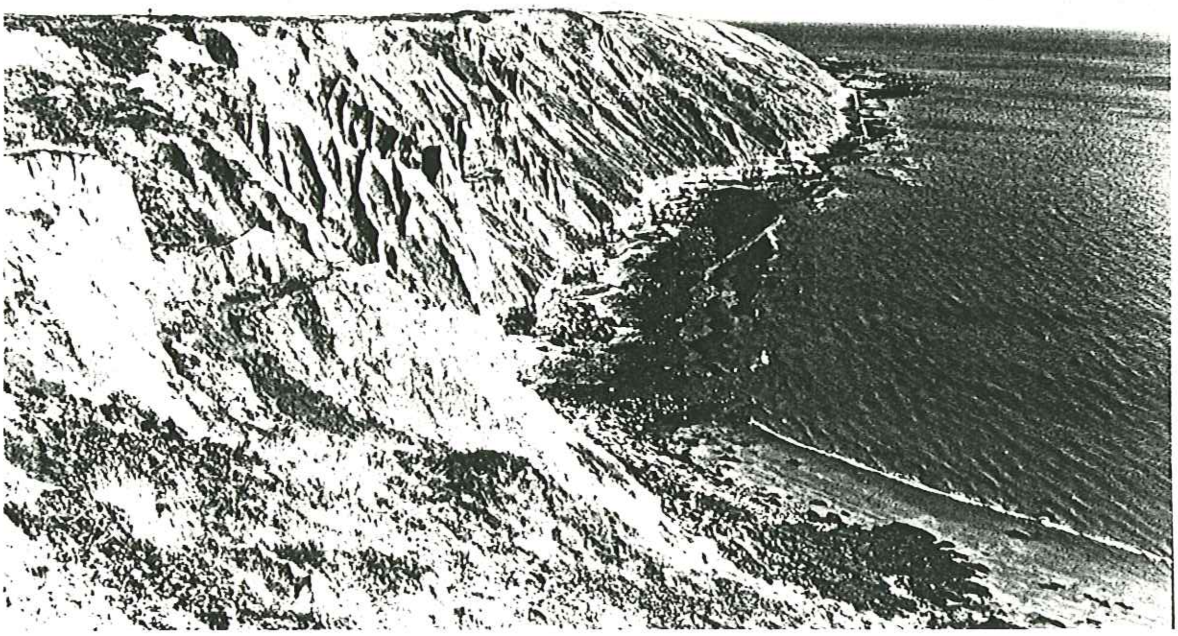

Plate 4 South face of Filey Brigg

Plate 5 Crib breakwater South end of Hornsea

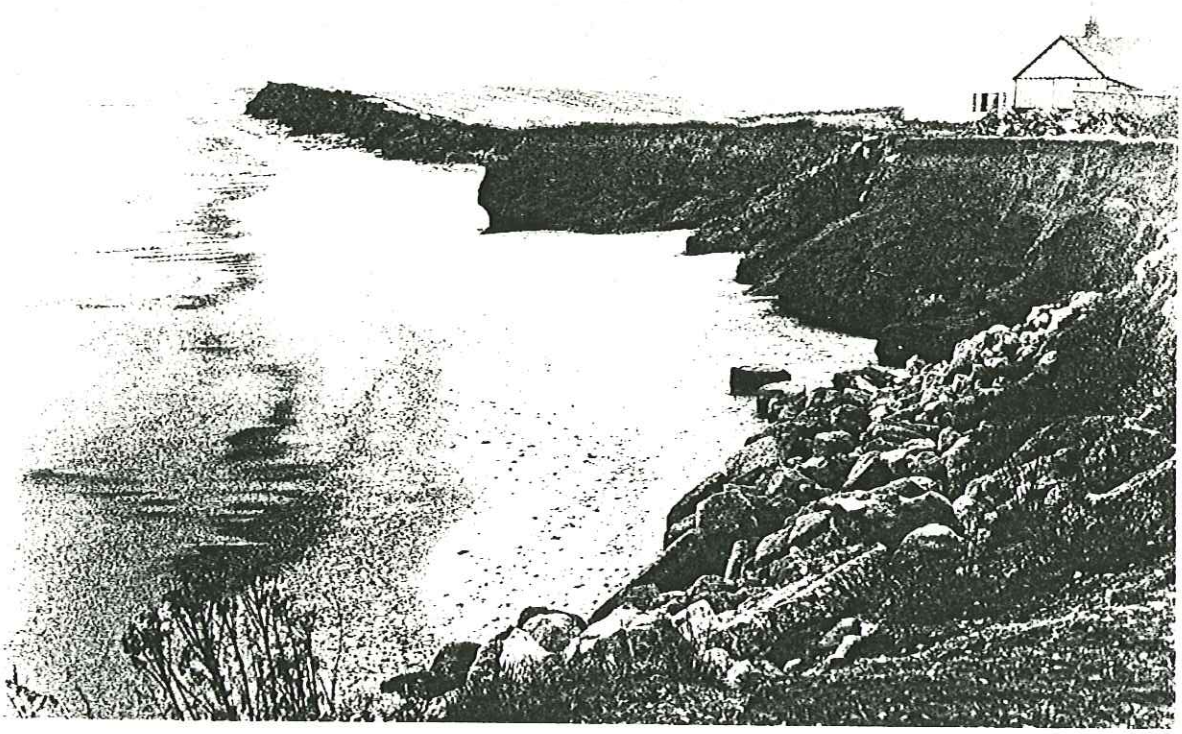

Plate 6 Cliff Farm, Barmston

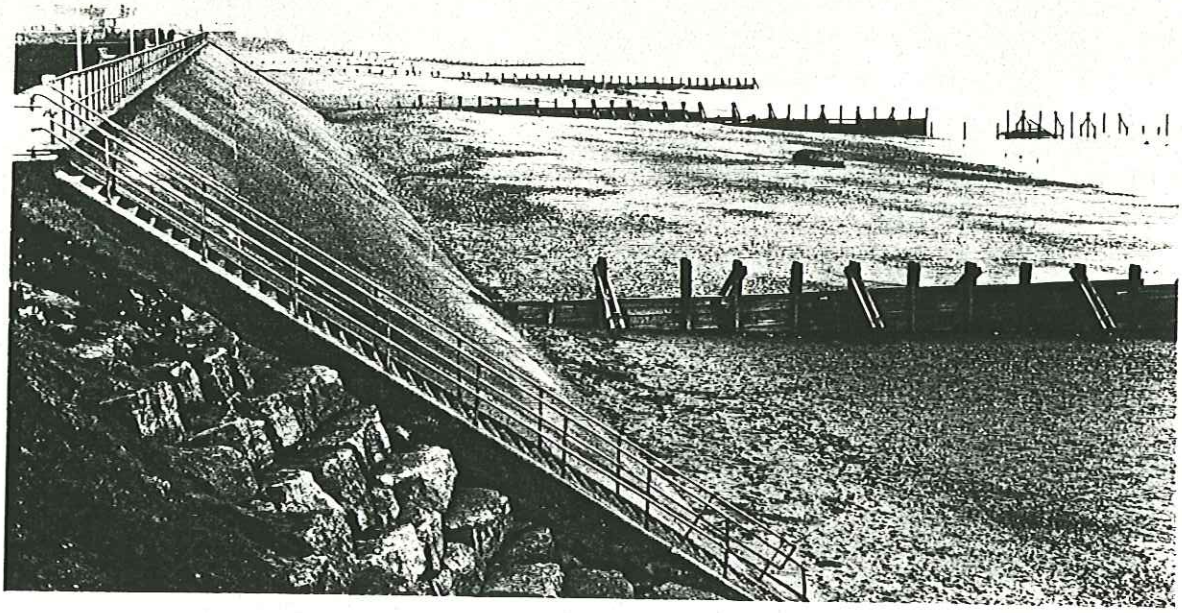

Plate 7 Coastal defences south end of Withernsea

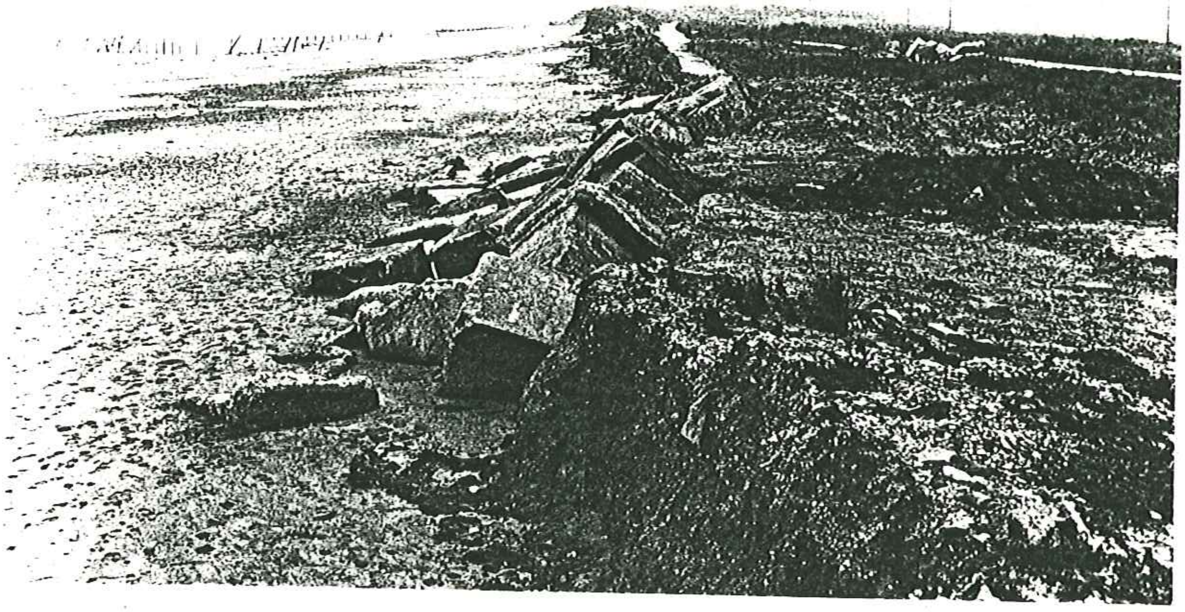

Plate 8 The neck of Spurn Penisula

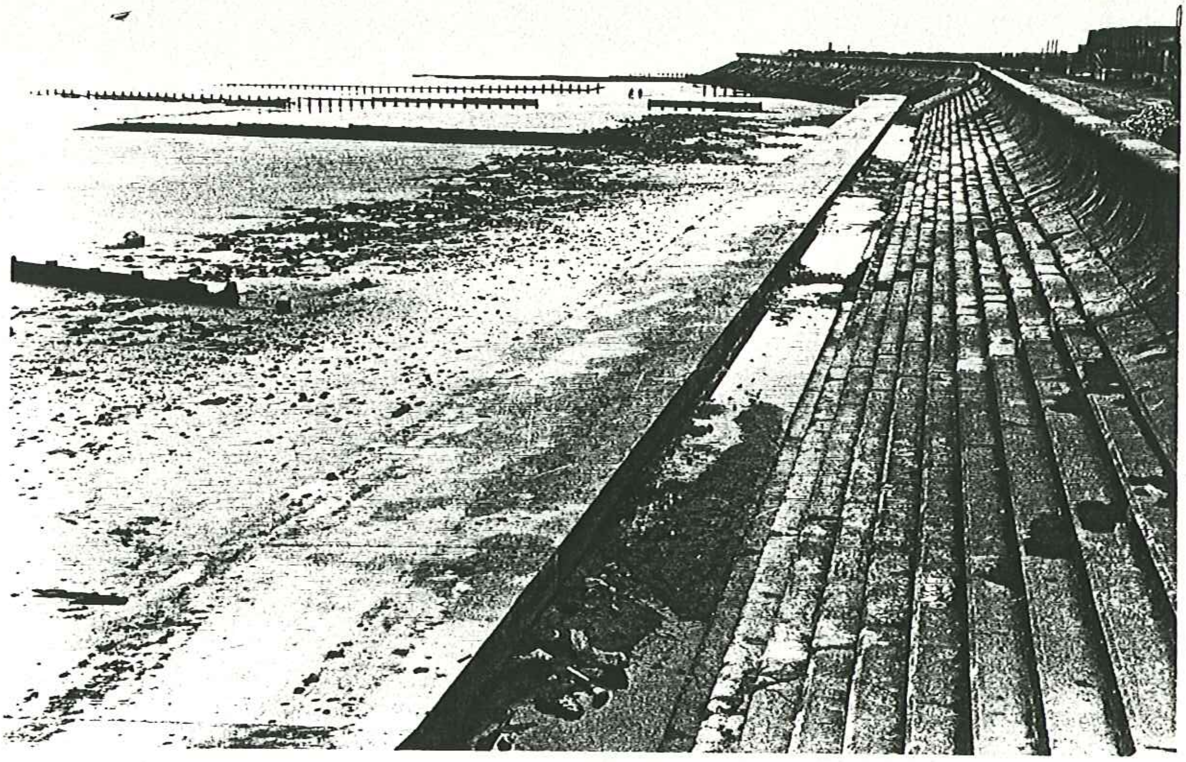

Plate 9 Sea wall at Convalescence Home, Mablethorpe

Plate 10 Till exposures, Sutton on Sea

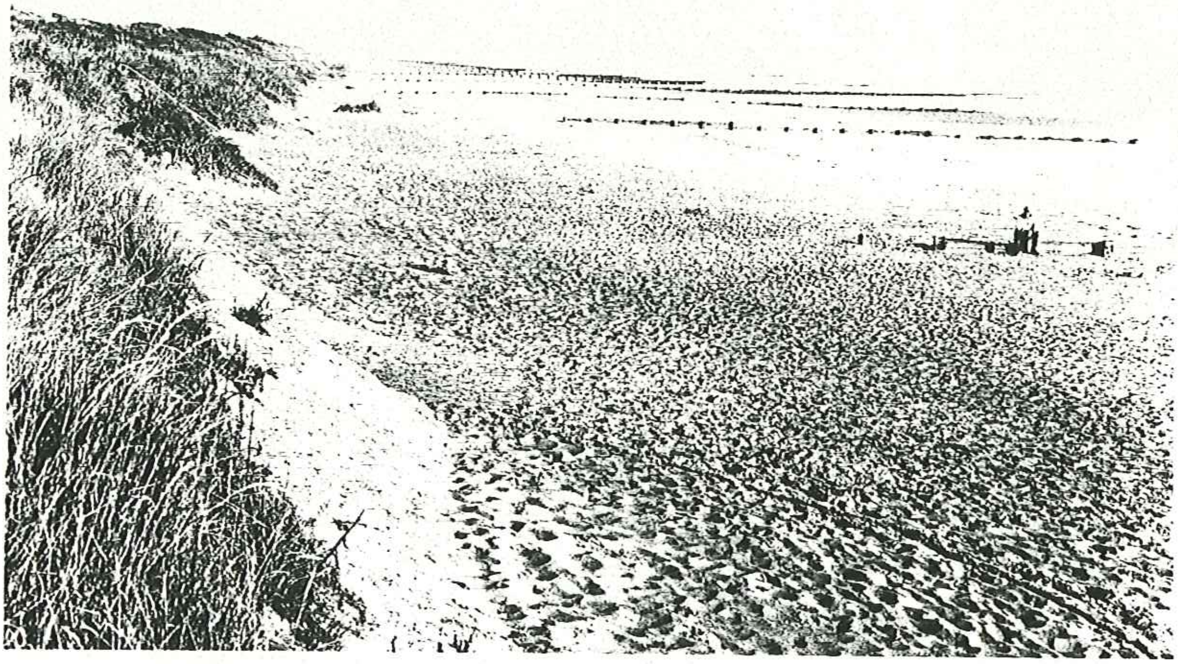

Plate 11 Wide sand beach - Anderby

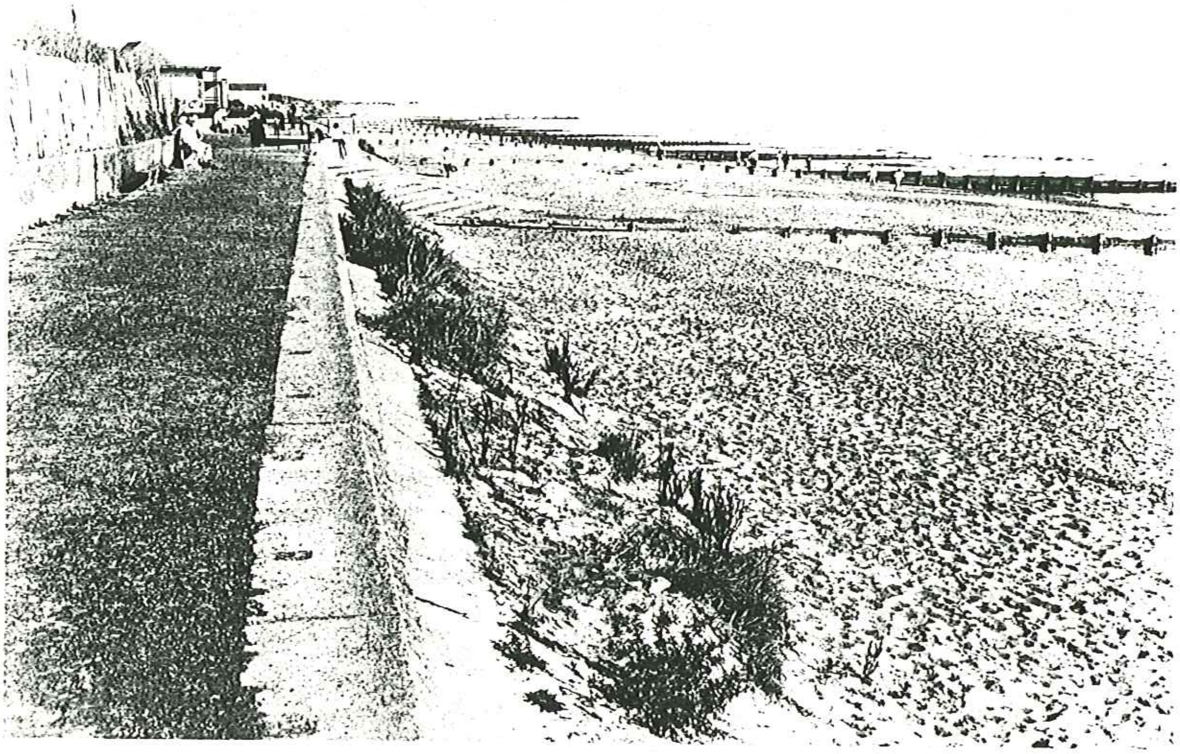

Plate 12 Embayment at Chapel Pullover

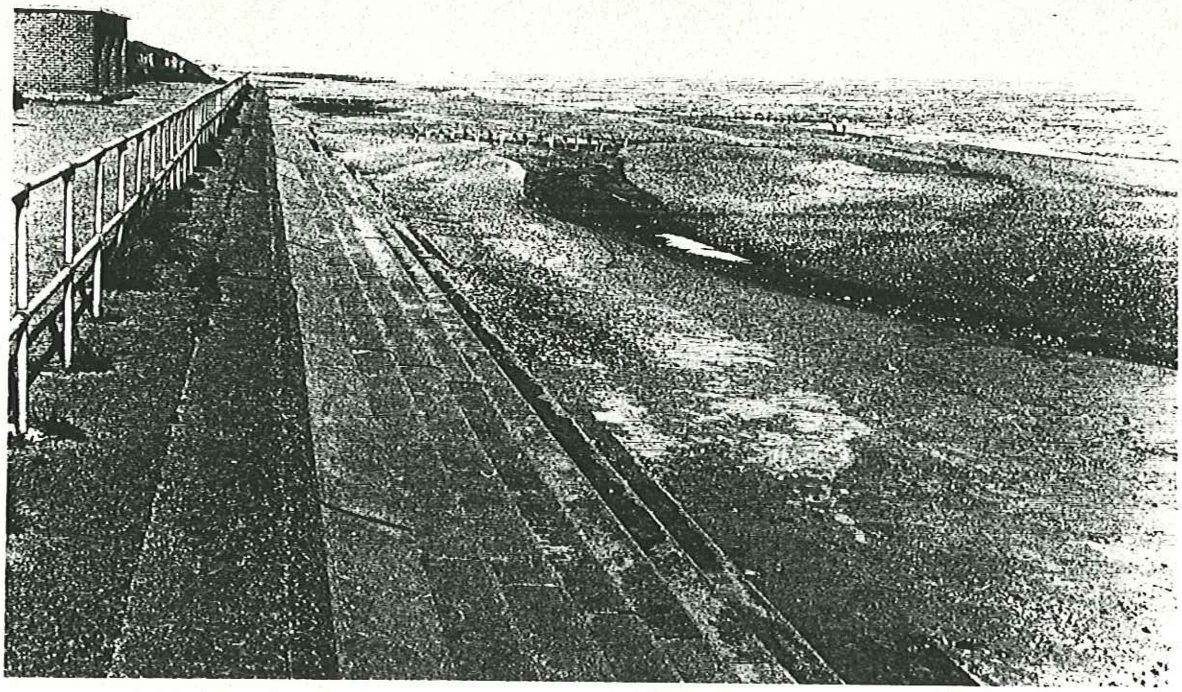

Plate 13 Inshore gullies at Ingoldmells

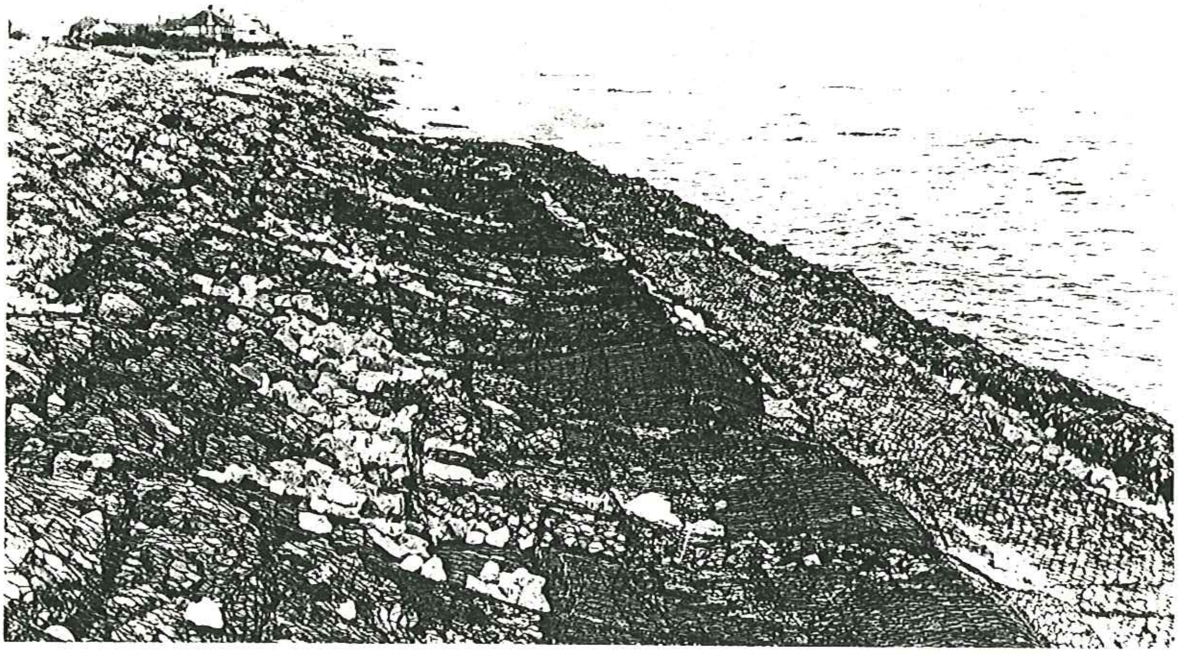

Plate 14 Gabion revetment north of Skegness