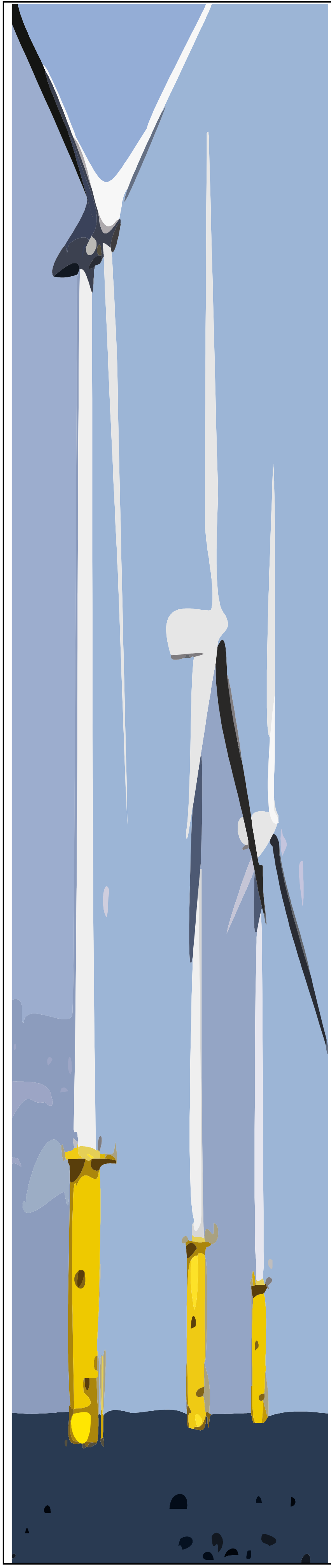

Sand banks, sand transport and offshore wind farms

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Author Biographies

Neil Kenyon is a consultant sedimentologist with an honorary position at the National Oceanography Centre, Southampton. He has been doing research into the processes of continental shelf sand transport and sand body geometry on continental margins for 40 years and was previously in the Marine Geology Group of the National Institute of Oceanography, Wormley (later Institute of Oceanographic Sciences).

Bill Cooper is Head of Modelling at ABP Marine Environmental Research (ABPmer) and lead author of the study examining the potential effects of offshore wind developments on coastal processes. Bill has since been responsible for carrying out coastal process investigations for several of the Round One offshore wind farms, and is also now involved with a number of Round 2 projects. Bill is a member of the DTI Offshore Renewable Energy Environmental Forum and a participant in the DEFRA Steering Group in Offshore Wind Farm Research.

CONTENTS

Summary

The introduction of a second round of offshore wind farm leases, that will enable larger wind farms than was previously permitted, poses questions concerning sand transport, especially on sand banks. Because of engineering expediency, shipping routes and other considerations they are likely to be sited on tidal sand banks. What are the existing sand transport systems and will any scour or deposition upset the existing sand transport systems? Could this have an impact on neighbouring coasts? What is the experience from existing or planned wind farms, or wind farm analogues such as platforms, located in areas of mobile sand?

This is a report of a generic study which establishes that tidal sand banks are a regular bedform and that they can be used to predict net sand transport paths provided that they are active. It describes a classification of sand banks depending on shape and setting and shows their different relationships to overall and to local bedload transport paths. A new map of sand transport paths for the entire shelf around the British Isles is drawn up and the significance of dominance is introduced. Consideration of current dominance, which currents act at any particular part of the shelf, should be an aid to the understanding of the benthos as well as to the sedimentation processes. New sand transport path maps are drawn for the three strategic areas, the Greater Wash, Thames and North West/Liverpool Bay. The impact of interference by humans on this type of natural sedimentation system is considered.

The initial analysis of a valuable set of new survey data, collected in the North West/Liverpool Bay strategic area in 2004, is for the most part in support of the hypotheses and opinions of the generic study. It was found that some banks are unlike the type examples of the bank classification scheme. For instance there may be hybrid types. There was some success in demonstrating whether and how near coastal banks are linked with nearby beaches. New sand transport path maps and a new bedform zonation scheme for the eastern Irish Sea should help support considerations of benthic habitat, submarine archaeology etc.

1. Introduction

1.1. Strategic environmental assessment

The Department of Trade and Industry (DTI) has commissioned this research as part of a series of supporting technical investigations related to the Strategic Environmental Assessment (SEA) for marine renewable energy. The work builds on the Phase 1 SEA for Offshore Wind (BMT Cordah, 2003) which was completed in anticipation of the second round of site leasing (Round 2) for the three strategic interest areas commonly referred to as: Thames, Greater Wash and North West (Liverpool Bay).

1.2. Round 2 developments

In July 2003, potential developers were invited to bid for sites in the three strategic areas, an open competition which attracted submission of 41 projects. The Crown Estate announced the results of successful applications for Round 2 leases in December 2003 to reveal the likely size and location of 15 new projects (Fig. 1).

Some initial comparisons can be made at this point between Round 1 and Round 2 lease requirements:

Round 1	Round 2
No minimum distance from coast	Coastal exclusion zone to provide a buffer of between 8 to 13km from the coast
Schemes restricted to Territorial Waters	No lease restriction to Territorial Waters
Lease areas limited to 10km^2	Lease areas limited to 250km^2
Maximum of 30 turbines per lease	No restriction on number of turbines
Lease sites dispersed around England and Wales	Lease sites restricted to 3 strategic areas
Minimum installed capacity of 20MW	Minimum applied capacity of 64MW Maximum applied capacity of 1,200MW

Consequently, Round 2 projects are generally much larger than the limits imposed for Round 1, with schemes located further offshore, but also occupying positions closer together. Issues which remain similar include a preference for shallow water locations which, in the main, are associated with sand bank areas.

The tender provisions for Round 2 developments (The Crown Estate, 2003) outline the main criteria for the new projects and recognize four size categories. In terms of the 15 allocations for site lease the breakdown on size is as follows:

Scale of Round 2 project	Plan Area (km^2)	Number of Projects
Extensions to Round 1 project	<5	1
Small Project	>5 to <35	3
Medium Project	>35 to <75	5
Large Project	>75 to <250	6

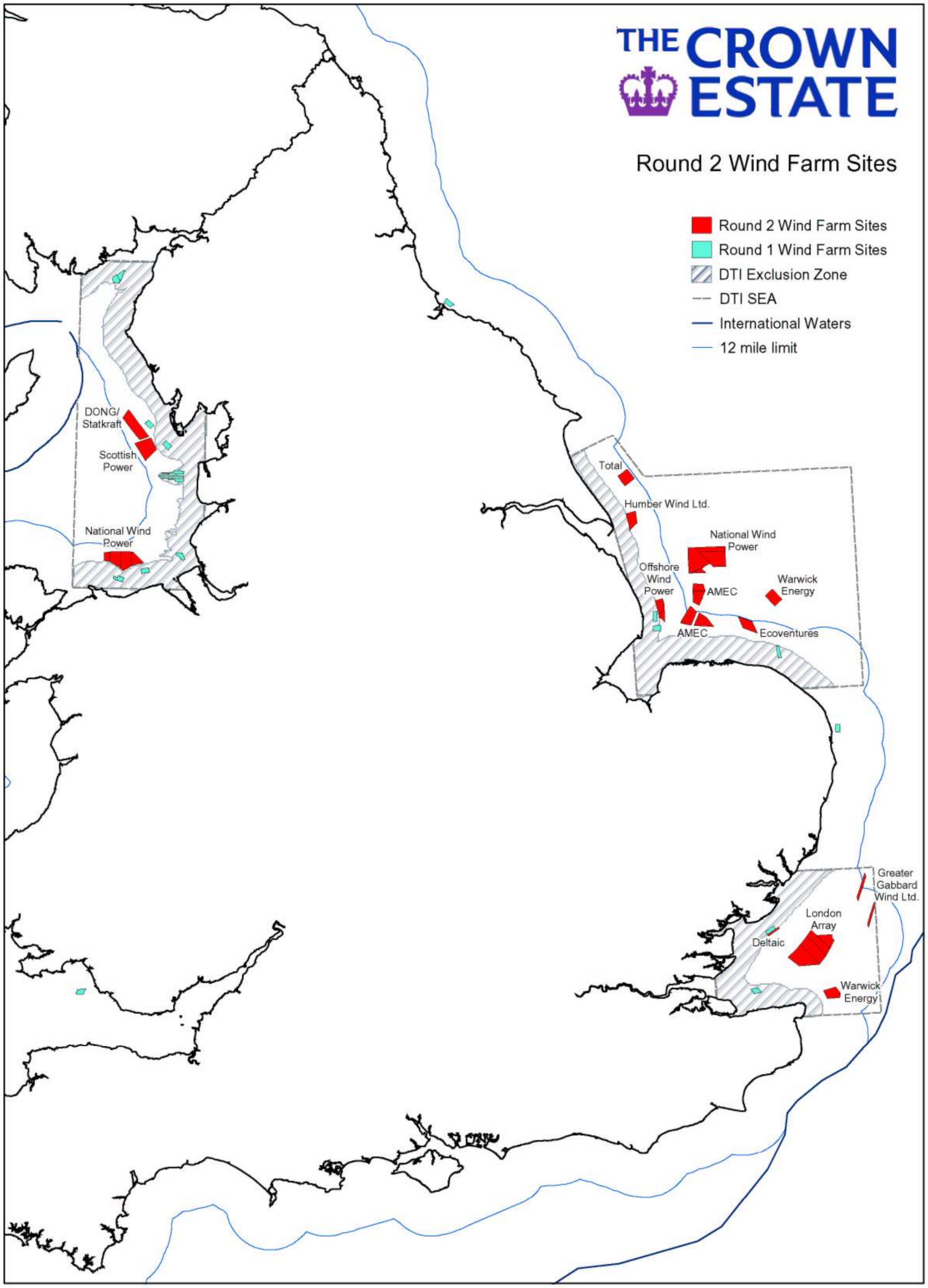


Figure 1. Locations of Round 1 and 2 Offshore Wind Farms (www.thecrownestate.co.uk/a4planuk_04_03_16.pdf)

These lease areas are closely related to the awarded installed capacity with projects ranging from 64 to 1,200MW. At the beginning of Round 1 2MW turbine technology was considered cutting edge. Since then technology has advanced with 3.6MW turbines commonplace. Today, most developers intend to install 5MW turbines, or larger, in the larger scale Round 2 developments. With this consideration the likely number of turbines for installation averages out at around 100 installations across the 15 projects, with the largest scheme potentially having around 240 turbines. This compares to the maximum number of 30 turbines allowed in Round 1 developments.

In addition, the larger capacity turbines planned for Round 2 installations will be powered by larger blades with larger swept diameters and held at greater hub heights. Consequently, the engineering structures (towers and foundations) to support the larger devices are also likely to increase in scale, as well as the separation between adjacent turbines. For Round 1 the majority of sites have opted for mono-pile foundations with diameters circa 5 m, and separations of around 400 to 600 m. In Round 2, larger diameter mono-piles are likely to be required as support structures, and best estimates indicate diameters of around 6 m. With consideration of increased blade diameters, Round 2 projects are likely to be planned with arrays using larger turbine separations, probably in the region of 800 to 1000 m. These estimates are provided as present indications only and each project will be considering the detailed engineering requirements for finalizing layouts and foundations.

To summarize, the Round 2 schemes are generally larger projects and spread over a larger area of seabed than comparable Round 1 projects. The position of Round 2 is also further offshore relative to Round 1. Over the larger development areas moderately bigger foundations will be used to support more turbines, but these foundations are also likely to be spaced further apart to maintain efficient wind energy capture.

1.3. Potential Sedimentary Concerns

A key question raised by the SEA Steering Group, and an issue also noted in the Phase 1 SEA, relates to uncertainty as to how these larger offshore wind developments might interact with sandbanks and sediment pathways. To address this issue a detailed review has been provided on present knowledge of sandbank dynamics and sand transport pathways leading to a refinement in the mapping of sand transport paths for the entire continental shelf around the British Isles. Special consideration is also given to each of the three strategic areas to identify and review the latest available research. Newly acquired data from the North West/Liverpool Bay, obtained on the SEA6 commissioned cruise from the RV Meridian, reinforces the generic study of sand banks and increases understanding of the sedimentary processes in this poorly known region.

2. Sand banks

The most comprehensive review of sand banks in recent times is by Dyer and Huntley (1999), based on a report that they prepared for MAFF. The findings summarised in their review are followed here with considerable amendments, mainly to take account of more recent published and unpublished work, of which there is a large amount.

Sand banks are found widely on shallow continental shelves where there is an abundance of sand and where currents are in excess of a certain peak speed. This speed is much stronger than is needed to move sand. For there to be a plentiful supply in such currents there needs to be a local convergence of sand transport paths towards the crest of a bank from both sides or the sand needs to be trapped by the coast, as it is in most estuaries. The former Marine Geology Group of the Institute of Oceanographic Sciences (IOS), whose views are largely followed here, placed much emphasis on tidal sand banks being a regular bedform that is characteristic of tidal dominated shelves where there is a plentiful supply of sand and strong tidal currents (Kenyon et al 1981, Johnson et al 1982). They considered that peak current strength needs to be relatively high to maintain the banks. Belderson (1986) showed that the peak currents need to be greater than 90 cm/sec (about 55 cm/sec at I m above the bottom in water 30 m deep), which places them in the zone of scour or the sand ribbon zone of the widely accepted

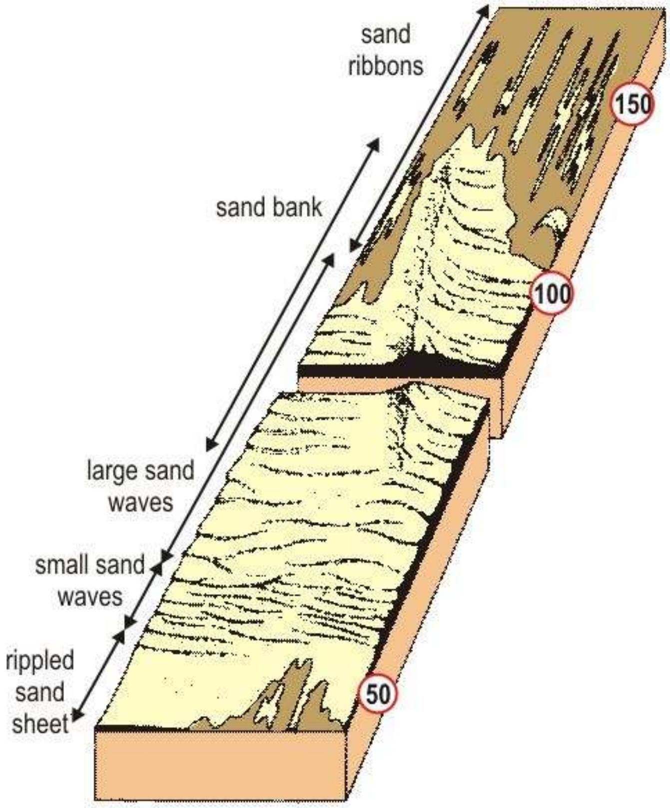


Fig. 2 Scheme of bedform zones from a tidal sea where sand is abundant, with corresponding mean spring peak near surface tidal currents in cm/sec (Belderson et al 1982). Open shelf linear sand banks are usually found in regularly spaced groups rather than the single one shown here.

bedform zone scheme (Fig. 2) of Belderson et al (1982). In fact it is shown here that banks tied to fixed headlands can be maintained by currents so strong that they are entirely within the scour zone, and sit on bare rock. If there is sufficient water depth and space then tidal sand banks can become very large bedforms, perhaps the largest of all bedforms found in water currents. As such they contain very large amounts of sand. There is emphasis by Dyer and Huntley (1999) on the banks being formed at coasts and being left behind as sea-level rises, eventually becoming moribund, a term introduced by Kenyon et al (1981). In this report both of these scenarios are considered valid. However it is agreed with a number of mathematical physicists (see section 3.1.2.) that the best approach to the consideration of sand banks is to first consider them as a regular bedform that arises from an inherent instability of a seabed subject to tidal flow and bed load transport. At the same time it is recognised that they can go through a cycle from an active to a dying state (moribund) as sea level rises and they are left stranded in weak currents.

3. Sand bank classification

A classification is presented here (Fig. 3) that is greatly modified from Dyer and Huntley (1999) to take account of preferred names and to include the differences in net sand transport paths and in local transport paths associated with each type. Types which are not presently relevant to the location of offshore wind farms around the UK, such as non-tidal sand banks and ebb-flood tidal deltas, are dealt with only briefly.

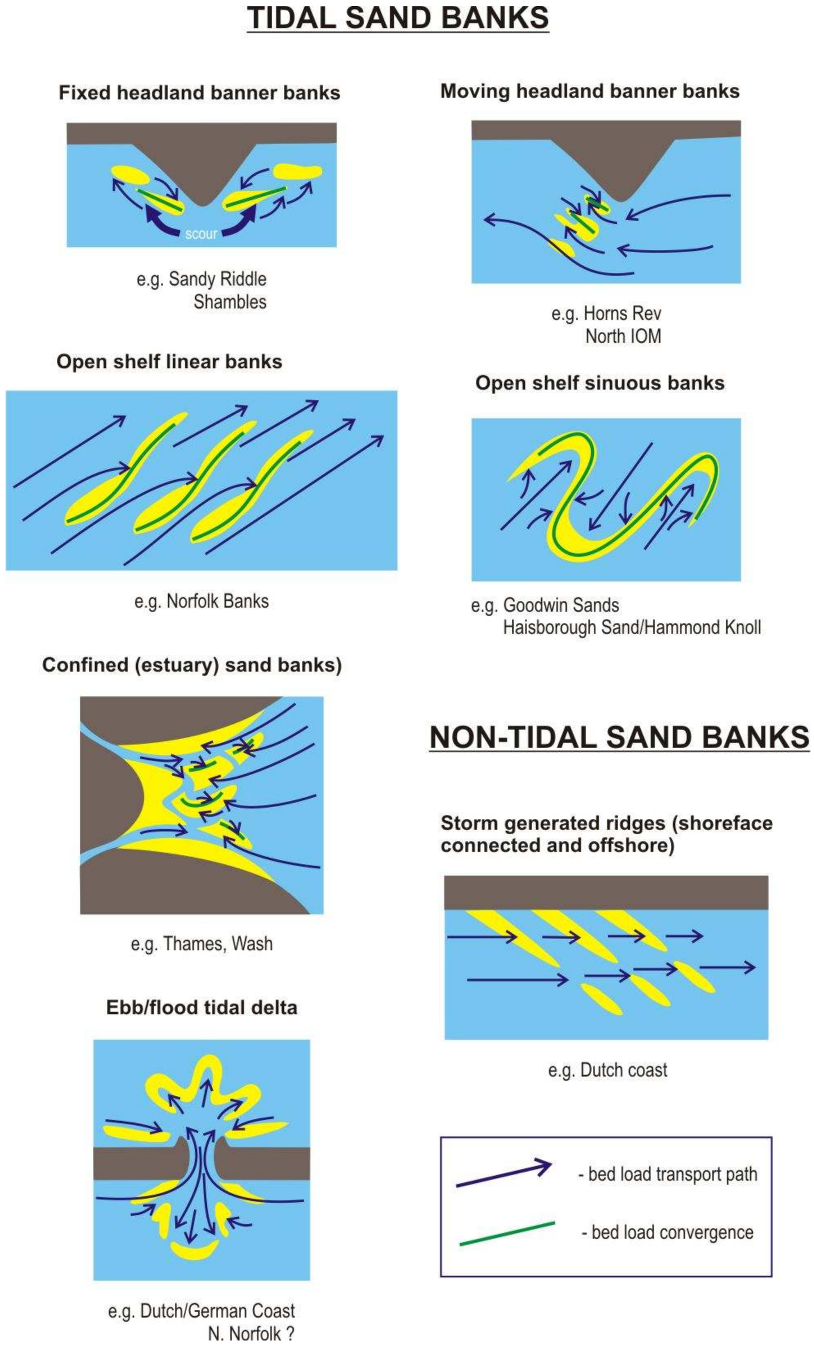


Fig. 3 Classification of sand banks (modified from Dyer and Huntley 1999) with their relation to the local and regional sand transport paths.

3.1. Tidal sand banks

3.1.1. Banner banks

Around the British Isles there are over a hundred banks that are located near headlands, islands or large rocks and separated from them by a channel that is swept clear by strong currents. These were called banner banks by Cornish (1914). Often the bank(s) on one side of the obstacle will be better developed than on the other but in areas of tidal currents where the sand supply and current speeds are similar on either side, then the arrangement of banks will be symmetrical. In areas of unidirectional flow (non-tidal) there will be banks on only one side e.g. near Torres Strait, Australia, and they will be attached to the obstacle rather than separated by a channel (Fig. 4).

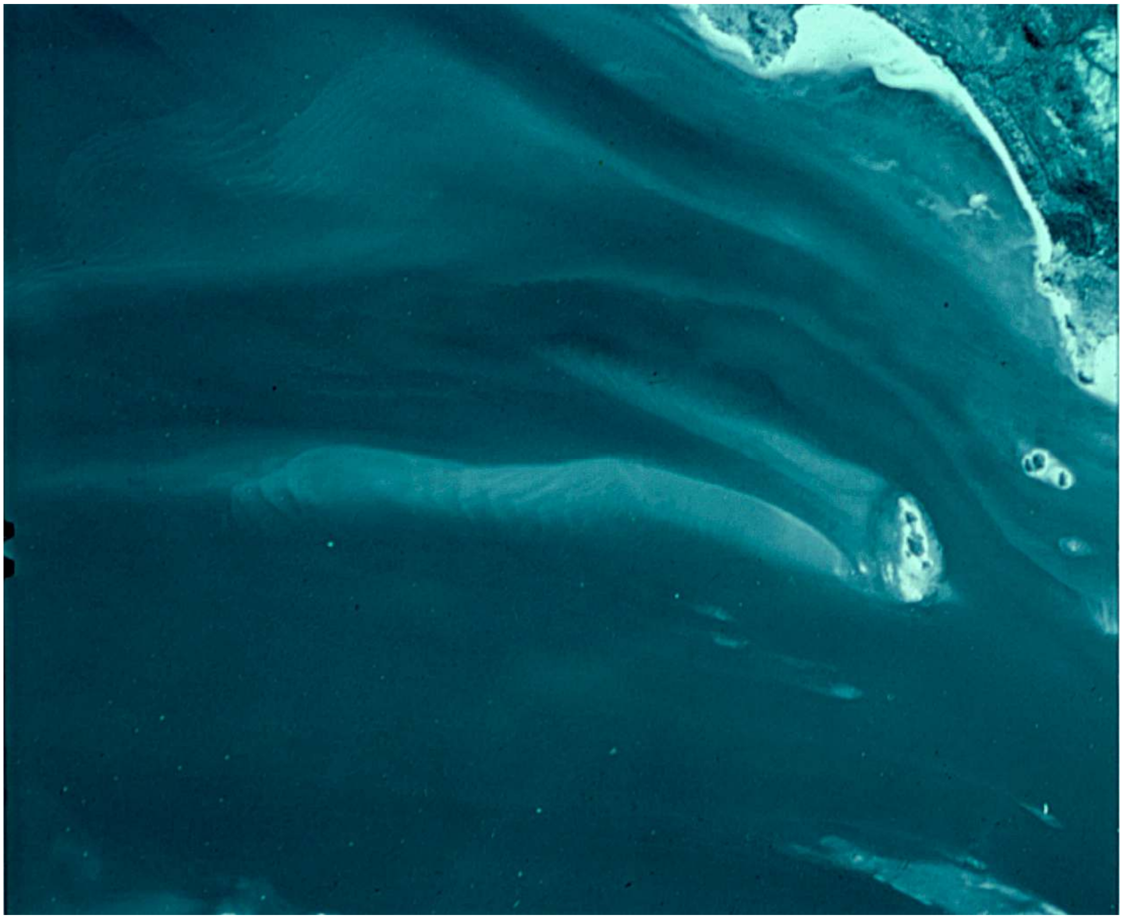


Fig. 4 Banner banks in a near non-tidal sea. Torres Strait, Australia. From Belderson et al 1982.

The location of banner banks is attributed to tidal eddies that are known to exist to either side of headlands. The flows near headlands have been modelled by Pingree (1978), for the Shambles Bank off Portland Bill, and also by Signell and Harris (2000), Bastos et al (2002) and Duffy et al (2004). The sense of sand circulation as deduced from sand wave asymmetry is in the same sense as for the eddies, i.e. away from the headland in the outer area of sea and back towards the headland near to the coast (Fig. 5). However the sand does not simply circulate within the

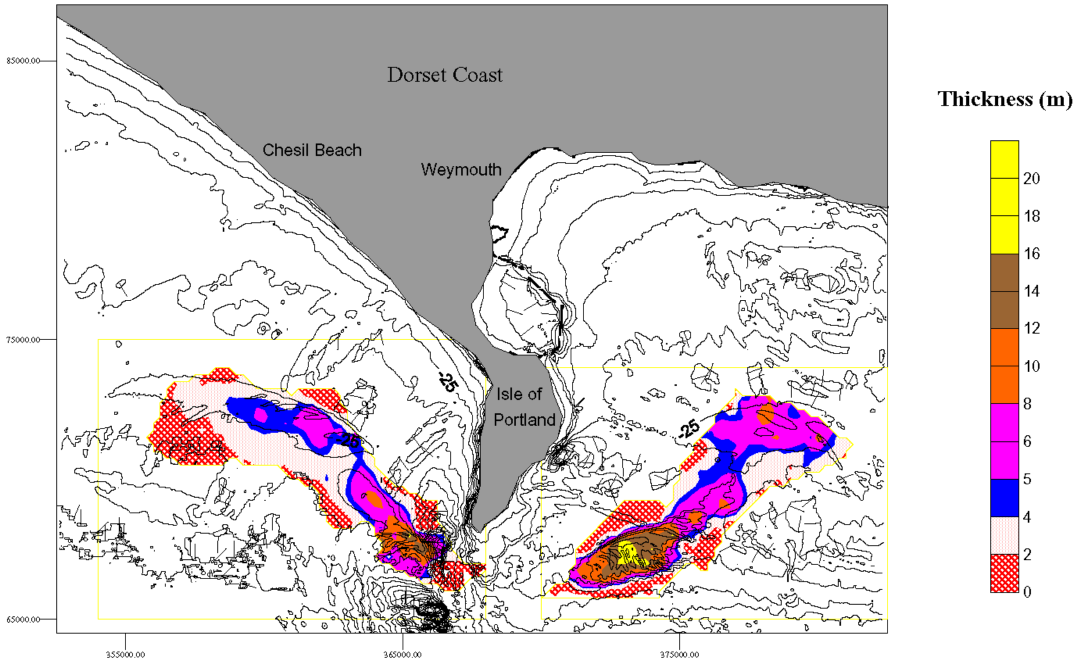


Fig. 5 Thickness of sands for the fixed headland banner banks and sand sheets tied to Portland Bill, UK (Bastos et al 2003).

eddy. There is a line of bedload convergence located at or near the crest of the elongated banner banks. The eddy hypothesis is too simple as an explanation because:

1. The bank and its convergent crest can extend well out of the area of the eddies (e.g. Bastos et al 2002, 2003). In the case of Portland Bill there are multiple, regularly spaced sand accumulations on either side of the headland (Fig. 5). Near the end of the headland are the banks (sensu stricto) and beyond them are thick sand sheets. Both the bank and the sand sheet are located on a long, sinuous line of bedload convergence which extends beyond the eddy.

2. The eddy hypothesis requires that there is a gap between the headland and the bank (Johnson et al 1982). This is not so for non-tidal banks which are attached to the headlands that cause the eddies, as stated above, and yet eddies are set up by the headland obstacle within the unidirectional flow.

Signell and Harris (2000) believe that shear stress and sediment flux better explain headland associated banks. Bastos et al (2004) suggest that the pattern of sand transport at the Shambles Bank is best explained as a result of two distinct processes. During the flood phase of the tide it is indeed the tidal eddy that drives bedload movement whereas during the ebb phase it is bottom-friction induced by the presence of the sandbank that drives bedload movement (Fig. 6). This is similar to the explanation of Johnson et al (1982) for tidal banner banks.

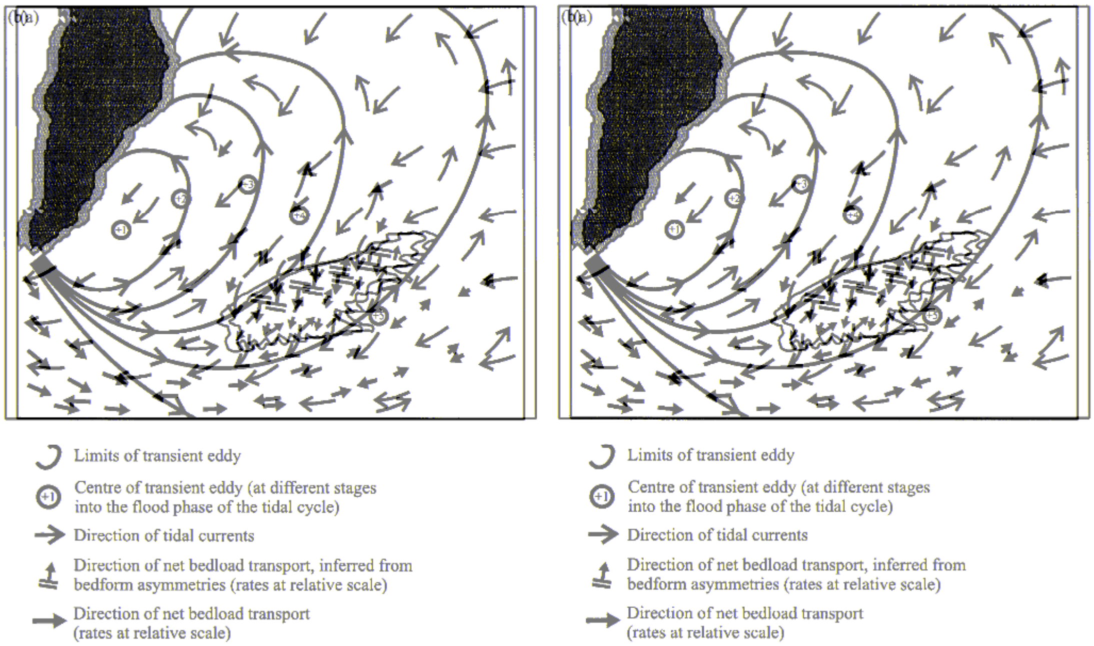


Fig. 6 Concept of how a banner bank is maintained (Bastos et al 2004). Transient eddies develop in the flood phase and bottom friction induced by the bank presence during the ebb phase.

Because of the bedload convergence and the near closed system of sand circulation it is possible for banner banks to exist in places where the current speeds are very high and where grain sizes of bank sediments are well below the equilibrium size for that current speed. Typically such banks sit on a bare rock platform, swept clean of all but stones and boulders. In the case of the Sandy Riddle, tied to the rocky islets (skerries) of the eastern Pentland Firth, Scotland (Fig. 7) the currents are amongst the strongest in any shelf sea. Up to “16 knots has been reported close W of the skerries” (Admiralty Pilot, Scotland east coast). During storm surges there will be easterly directed currents (Flather, 1987) that, when added to peak tidal currents, will be the occasions of most bedload transport. Wave induced currents, which are non-directional, will be added to the directional currents, and will be especially significant during storms and will increase in significance in shallower water. Storms are probably frequent even though the area is less exposed than the shelf to the west of Scotland, where the sediments are considered to be controlled by the battering they get from the frequent and severe storms (Light and Wilson 1998). The top of the Sandy Riddle will thus be one of the most active places for bedload transport in this region. Peak tidal current speeds decrease rapidly to the east and the Admiralty Pilot states that “4 miles ESE of the skerries they are relatively weak”.

The sediments of the Sandy Riddle consist almost entirely of broken shelly material of coarse sand or gravel size (99% is quoted for the banks on the Scottish shelf). The shelly faunas and the highly calcareous sands of the nearby and similar shelf environment to the north and west are dealt with in Light and Wilson (1998), Farrow et al (1984), and references therein. The shelf in these areas is described as a carbonate factory and the benthic fauna is described as sparse, of low abundance and of low diversity (Wilson 1982). The highest diversity and abundance is on the middle of the shelf (Light and Wilson 1998).

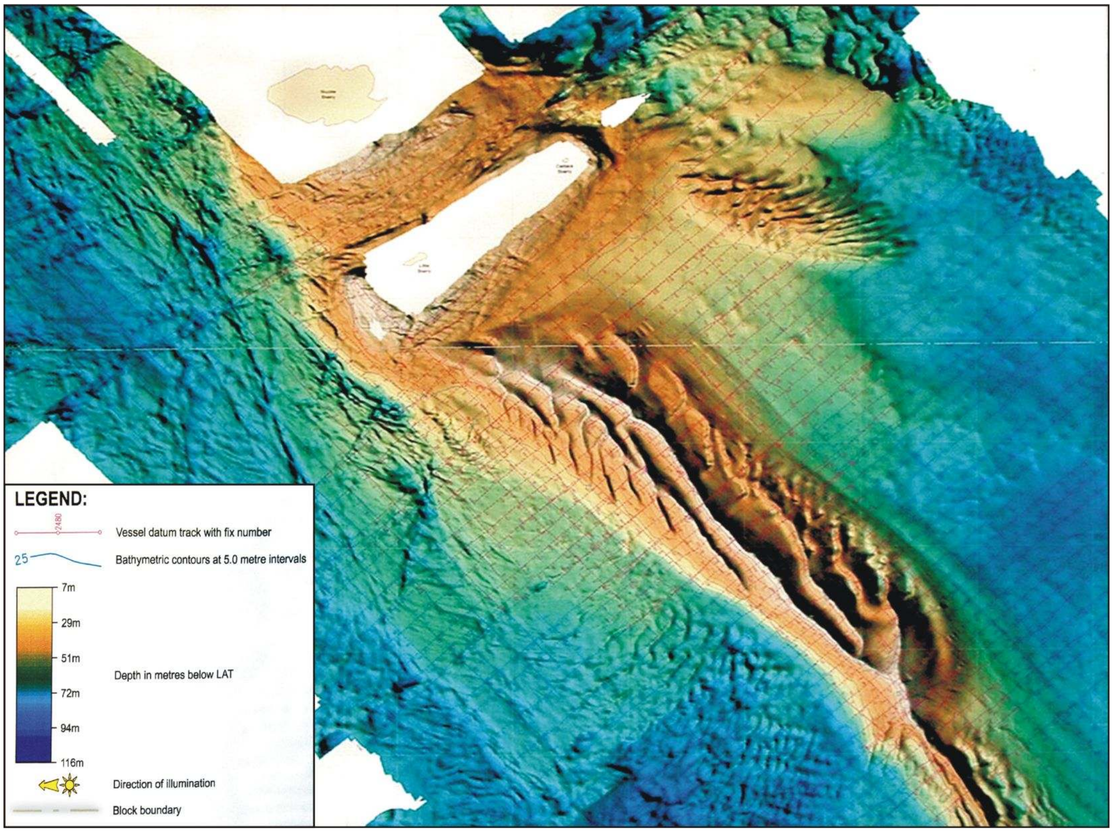


Fig. 7 Shaded relief from a swath bathymetry survey of banner banks tied to either end of a rocky shoal (white area). The larger bank, the Sandy Riddle, and the smaller bank have large sand waves converging towards the crest from either side (courtesy of SEA5). Small sand waves have been filtered out.

Accumulation rates for this and nearby banks have been estimated by Farrow et al (1984), based on an accumulation period of 6000yr, as up to 67cm/1000yr. However this is not a relevant figure as most of the sands in a banner bank are “captured” by the bank forming process and recirculated over and over. The bank will have formed from nearby sands as soon as sea level rose and, because sited in very strong currents, we believe it to have rapidly built up to near the sea surface within a few years. In fact these same authors quote a seasonal change in bank height, with the crest being shallower in the summer when storms are less severe. After formation the bank will have continued to grow by extension rather than by upbuilding, as the carbonate factory surrounding it kept up production.

3.1.1.1. Fixed headland banner banks

There are two types of tidal banner bank. There are those tied to rocky headlands or islets (Type 3A of Dyer and Huntley, 1999), of which the Sandy Riddle, western Pentland Firth, Scotland (section 3.1.1.), is an example (Fig. 7), and those tied to moving sedimentary headlands (Type 3B of Dyer and Huntley, 1999), of which the Horns Rev, Denmark (Larsen, 2003) is probably an example (Fig. 8). Both of these are detached from the headland or rock to which they are tied. A further type is attached to its anchoring point and is non-tidal, found in unidirectional or very strongly asymmetrical bidirectional currents, such as in the

Torres Strait (Fig. 4). No examples of non-tidal banks are known around the tidally dominated UK.

Recently the first repeated swath bathymetry surveys of banner banks have been carried out by Duffy et al (2004) on a bank in the Bay of Fundy, Canada, and by Schmitt et al (2004) on a bank in the Bristol Channel. These will test some of the hypotheses presented here.

Where the headlands are of resistant rocks it is expected that the position of the banks will be fixed in the same or similar positions during the present as well as the previous time of high sea-level. Hence the banks will have a complex internal structure (Fig. 9A), including the remnants of similar banks that were tied to the headland during previous sea level highs. This is what seems to have happened near Portland Bill (Bastos et al 2003).

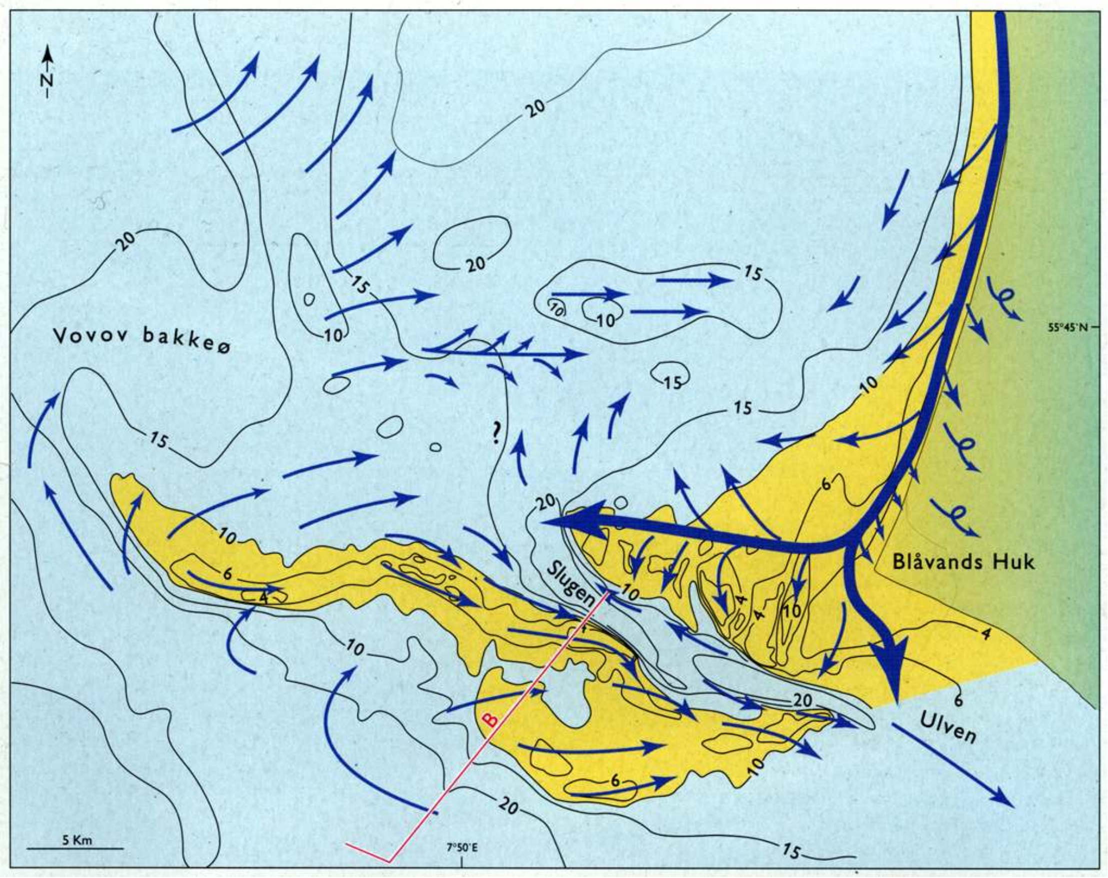


Fig. 8 Sand transport paths from a moving headland banner bank, Horns Rev, Denmark, derived from bedform asymmetry, current measurements and modelling (Larsen 2003). The red line is the profile in Fig. 9B.

3.1.1.2. Moving headland banner banks

Banks that are tied to coasts in retreat should develop differently. Dyer and Huntley (1999) propose that most sand banks start tied to coasts and, following headland retreat, develop towards an equilibrium type that is the open shelf linear (en echelon) bank. Such may have been the case for the outer Horns Rev, tied to a

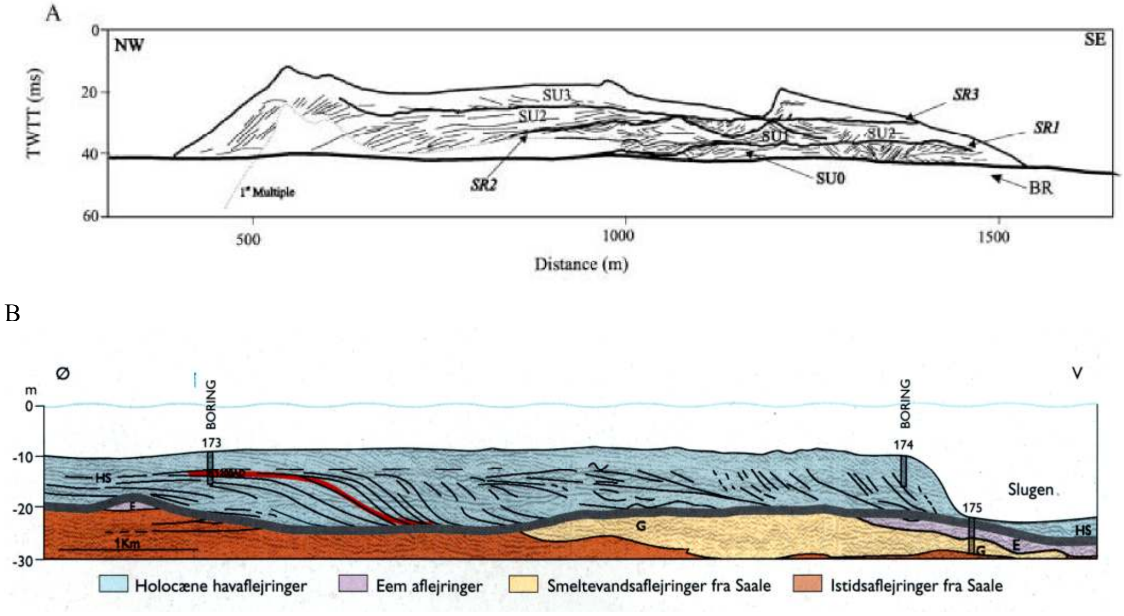


Fig. 9. **A** - Seismic section through Shambles Bank, a fixed headland banner bank, showing traces of probable earlier banks fixed in the same position and not destroyed by earlier sea level rise(s) (Bastos et al 2003); **B** - Interpreted seismic line across the Horns Rev, showing northern progradation of c. 3.5 km in 800 years (Larsen 2003). The red horizon in borehole 173 is dated 1200 A.D.

headland along the west coast of Denmark where there is a high rate of longshore drift (Fig. 8, Larsen 2003) but it seems more likely that this is an advancing headland rather than a retreating one. Unlike banks tied to long lived rocky coasts, this type will probably have little trace of previous bank structures but rather have dipping internal structures with the same sense of direction, as seen in the Horns Rev (Fig. 9B). Another example where the coast is formed of soft rocks that will have been subject to movement as sea level rose (and where the coast is still moving), and which has detached banks, is at the north end of the Isle of Man. Here there are several en echelon banks, of which only the innermost ones are currently tied to the Point of Ayre (section 6.2.3.2).

3.1.2. Open shelf linear sand banks

Groups of parallel banks that are regularly sized and spaced are found on open tidal shelves. These are the “open shelf ridges”, Type 1 of Dyer and Huntley (1999). The active banks reach up to near sea level where the sea is less than about 40 m deep. They are mostly asymmetrical with steeper sides consistently on one side. They are moving slowly towards the steeper side as confirmed by their internal structure (Fig. 9B). The tops are flat where they reach into the shallowest water and the effects of waves are at their greatest. Larger sand waves being confined in this case to the flanks. In addition to their asymmetry in profile some banks have a plan view asymmetry with wide upstream ends (heads) and narrow downstream ends (tails) (Caston 1981). An example would be the Norfolk Banks which are wider in the south than in the north and steeper on the east flank (typically about 6°) than on the west (typically less than 1°). They were originally thought to be parallel to the tidal currents (Off, 1963) but it was later realised that they are oblique to the peak currents (Kenyon et al 1981, Huthnance 1982). For the linear banks of the southern North Sea and elsewhere the banks are 5-20° to the principal component of tidal flow and sand transport direction. The majority of banks looked at by Kenyon et al (1981) were offset in an anticlockwise sense from the principal component of flow and the regional net transport path. However they were all from the northern hemisphere and it was not possible to test whether Coriolis force controls this offset by looking for clockwise offsets in southern hemisphere banks. Mathematical analysis of sand banks by Carbajal and Montano (2001) shows that Coriolis force affects bank orientation. As low latitudes were approached the offset angle decreased. However Harris and Jones (1988) find about equal numbers of clockwise and anti clockwise offsets in banks from a wide estuary at 27° S. Mathematical modelling also shows a Coriolis induced preference of a bank system in the northern hemisphere for cyclonically oriented features (i.e. anticlockwise offset, clockwise circulation) (Roos and Hulscher 2003).

The ridges are maintained by the convergence of sand towards the crest from opposite sides. A further common feature of the Norfolk Banks is a kink about a third of the way up from the southern end, that is consistently offset in the same sense, i.e. to the left of the net transport path.

The theory of how open shelf linear banks form is developed by Huthnance (1982). They are explained as a morphodynamic instability of a flat seabed subjected to tidal flow. In sedimentologists' terms this means that they are a regular bedform. Subsequent theoretical work has considered other flow conditions, such as the role of waves and supended load and included more emphasis on Coriolis force (e.g. Roos and Hulscher 2003). Improved equations for sediment dynamics relevant to sediment transport predictions and bank modelling have been made by Soulsby (1997). The theory has been tested by predicting where banks should occur in the southern North Sea and showing that the predictions fit well with the known distribution (Hulscher and van den Brink 2001).

Off (1963) thought that there was a tendency for bank spacing to increase in deeper water even though the banks in the North Sea have much the same spacing and height (Fig. 10). (Banks off the Dutch coast that are described by, for instance Roos et al (2004) are regarded as a different longitudinal bedform from tidal sand banks as they occupy only a small proportion of the water column.) The banks in the shallower Moreton Bay (Harris and Jones 1988) also have a similar, but smaller, spacing and height. This fits with the linear banks being a regular oblique bedform rather than a longitudinal one formed by parallel secondary flow currents with helical spirals.

The internal structure of open shelf linear banks has been little studied. The classic structure of such banks is from hypothetical models such as that of Stride et al (1982) in which prograding reflectors, the master bedding surfaces, dip at up to 5 degrees in the direction of the steeper side (Fig. 11) and result from bank growth or migration. Within the main sets there is smaller cross-stratification due to sand wave migration, with a maximum dip of about 30 degrees. Kenyon et al (1981) noted that the direction of transport indicated by this higher angle cross-stratification will be in the opposite direction to the overall sand transport path. One of the most detailed studies of internal structure is that by Trentesaux et al (1999) who studied Middelkerke Bank, one of the Flemish Banks. In the south of the bank is a core of probable storm dominated ridge formed at lower sealevel. The tidal bank is probably tied to this and extends to the north. It shows the classic bank arrangement with beds prograding in the direction of the steeper flank.

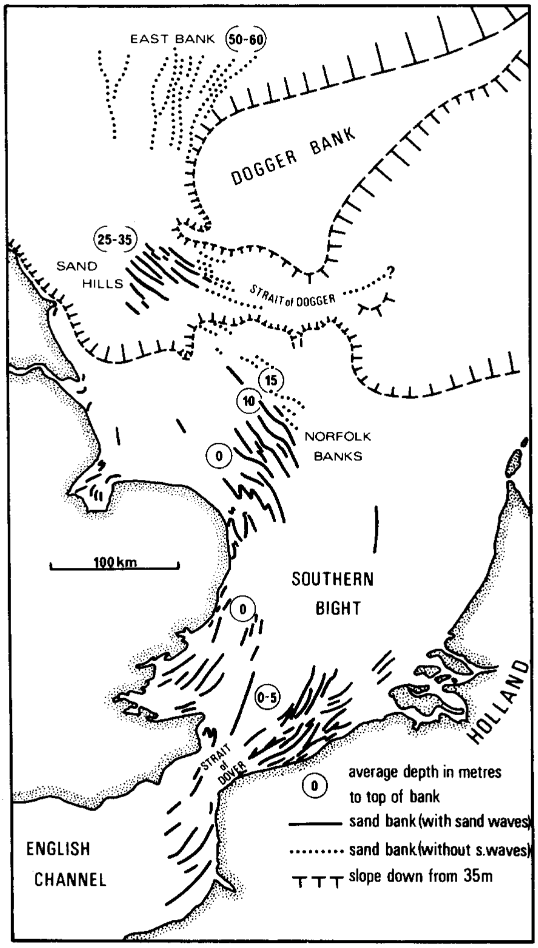


Fig. 10 Distribution of sand banks in the southern North Sea. Sand banks without sand waves (dotted) are regarded as moribund (Kenyon et al 1981).

Several sand banks from outside the Thames Estuary are of the open shelf linear type. The Inner Gabbard, Outer Gabbard and the Galloper Banks are very similar in shape and size (Fig. 12). They are 1 km to 1.5 km wide, up to 26 m high/thick and up to 15 km long. This similarity confirms that they are best considered as regular bedforms. They are fairly symmetrical, though with a slight tendency to be steeper on the west side, and are rotated at an angle of about 10 degrees in an anticlockwise sense from the orientation of the southwesterly directed sand transport paths, as derived from nearby longitudinal wreck marks. It has been suggested that the banks are anchored to cores of older sand bodies or to London Clay (D'Olier 1981). A seismic survey (courtesy of Greater Gabbard Offshore Wind Ltd) shows that this is not the case and that the banks are free to move laterally. The classic pattern of prograding master bedding surfaces, dipping at about 1 to 2 degrees, is found in the northern part of the Inner Gabbard and the northern part of the Galloper (Fig. 13). The sense of this progradation, and hence of the most recent bank movement, is westwards in the Inner Gabbard and eastwards in the Galloper. The internal structure on seismic profiles shows that the southern part of both banks has not recently moved.

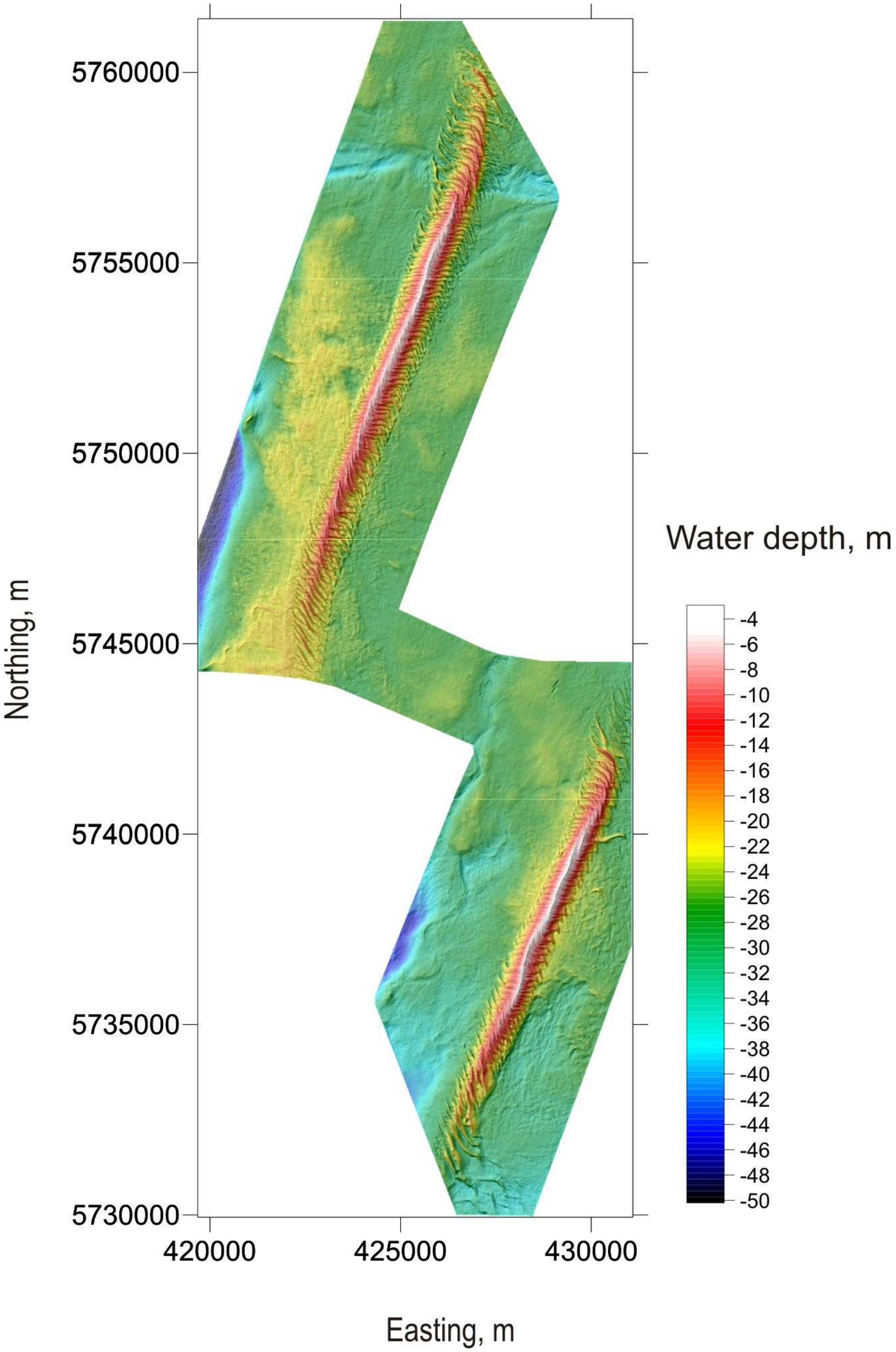


Fig. 12 Swath bathymetry of the Inner Gabbard (westernmost) and the Galloper (easternmost) Banks showing the cross sectional and longitudinal symmetry of these open shelf linear banks and the similarity between them. This similarity is confirmation that they should be considered as regular bedforms. (Courtesy of Greater Gabbard Offshore Wind Ltd).

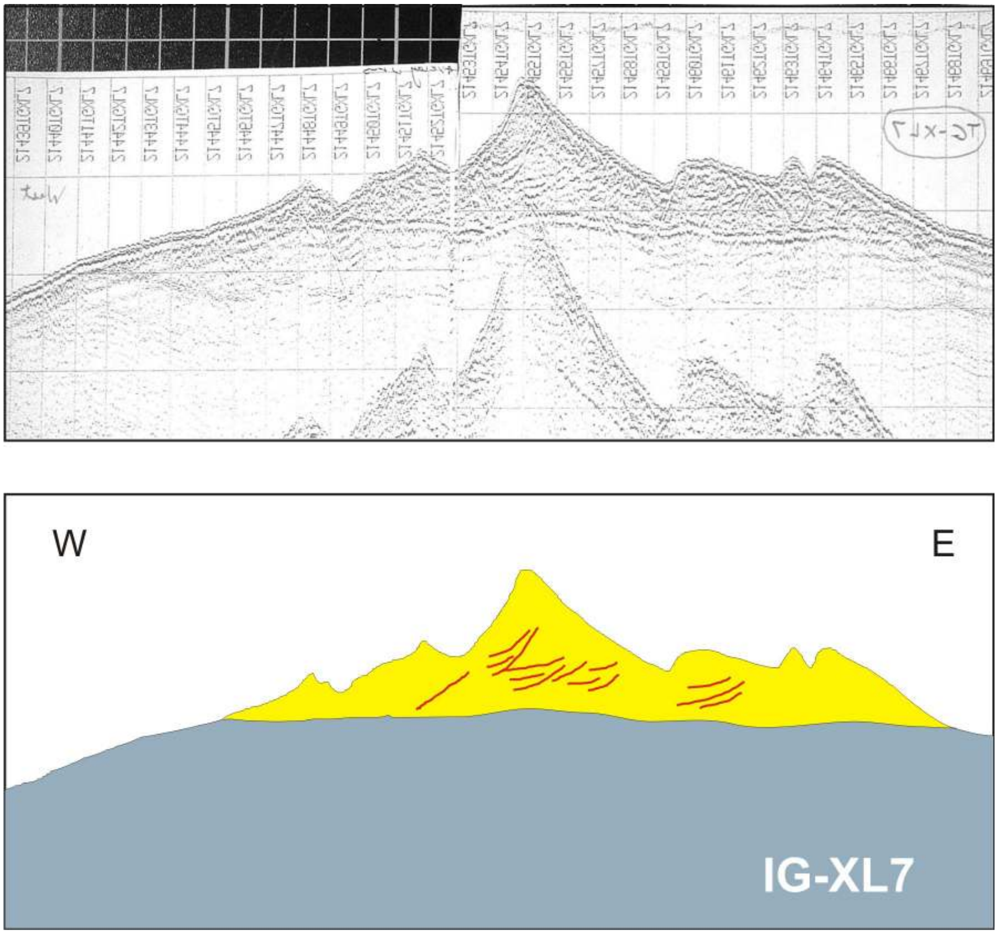


Fig. 13 Seismic profile and interpretation of a crossing of the northern Inner Gabbard showing westwards progradation and master bedding dipping at about 1 to 2 degrees. (Courtesy of Greater Gabbard Offshore Wind Ltd).

Groups of banks in deeper water that have gentler flanks than usual and an absence of sand waves were proposed to be in a dying (moribund) or dead state (Kenyon et al 1981). Examples include those near the Dogger Bank which seem to be related to a broad channel, the “Straits of Dogger”, present at times of low sea level (Fig. 10). Some of the banks in the outer Celtic Sea are also free of sand waves and they are all attributed to tidal currents at low sea level (Belderson et al 1986). Dyer and Huntley (1999) propose an overall evolutionary scheme whereby banks form at a retreating coast as banner banks, and then develop into an equilibrium state as open shelf linear sand banks, their “alternating ridges”. If sand supply does not keep pace with coastal retreat they end up as moribund, without large sand waves and with lower slopes than for active sand banks (Fig. 11).

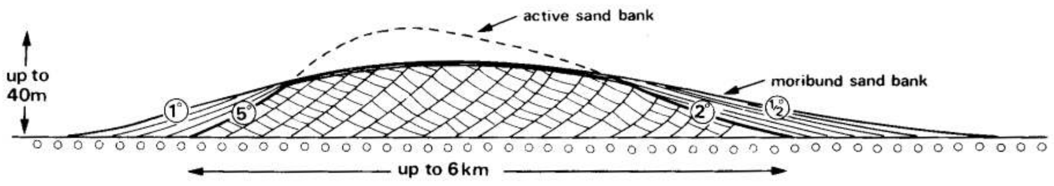


Fig. 11 Idealised cross section of an open shelf linear sand bank during its transition from an active to a moribund state showing the expected slope gradients (Stride et al 1982).

3.1.3. Open shelf sinuous sand banks

Sinuous banks are commonly found with a linked parabolic shape in plan view (Fig. 14). They seem to be present relatively close to the coast (see examples from Greater Wash and Thames, sections 6.2.1. and 6.2.2.) and may be more often found in areas of greater bottom stress than are open shelf linear banks. They have been thought to be divided into mutually evasive ebb dominant or flood dominant channels (Robinson 1960). Caston (1972) considered that they might evolve into a series of linear banks. Because there is no preferred plan view asymmetry, unless only one channel is present (which does not commonly occur), they are taken in this report to indicate no preferred direction of bedload transport. Those in the North Sea like Haisborough Sand/Hammond Knoll and Race Bank/Dudgeon Shoal thus fit into their position on a bedload parting (Fig. 15), which is consistent with the transport paths determined from the sand wave asymmetries around them. Goodwin Sands, Strait of Dover, another near coast sinuous sand bank, may be located at a bedload convergence where there would also be no overall (net) bedload transport. Open shelf sinuous sand banks may be an inherently unstable type.

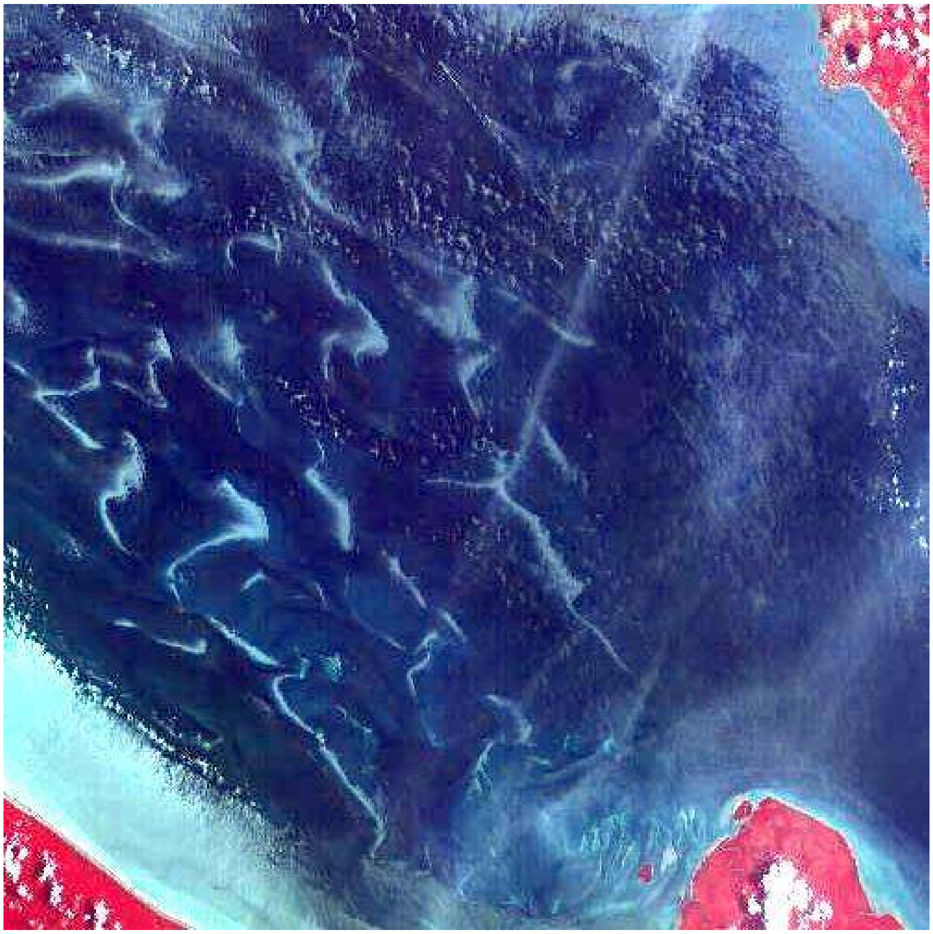


Fig. 14 SAR image of a regular pattern of sinuous tidal sand banks in the Strait of Malacca. The straight line is probably an aircraft vapour trail. *(from www.ifm.uni-hamburg.de/ers-sar/Sdata/oceanic/)*

3.1.4. Confined (estuary) sand banks

These are the Type 2A of Dyer and Huntley (1999) who called them “Estuary mouth Ridges”. Stride et al (1982) call them “Confined sand banks”. Tidal currents increase toward the head of the estuary because of the increasing constriction. Flood currents tend to be dominant with resultant sand transport from the mouth toward the head of most estuaries around the British Isles. It is common to find a pattern of flood transport inshore and of ebb transport in mid estuary because of a time lag in the ebb flow which is prolonged beyond the time of low water (McDowell and O’Connor 1977). However this is not always the case (as for the Wash where the opposite seems to occur, section 6.2.1.2). The sand forms mainly linear banks which build up to sea level and increase in width, eventually forming extensive intertidal flats (Fig. 16). The outer channels tend to be flood dominant and the inner channels tend to be ebb dominant, resulting in a bedload convergence within the estuary. Along part of their length these channels are mutually evasive. Dyer and Huntley (1999) state that “Because of the lateral constraints, the banks are generally aligned with the water flow, rather than being at an angle”. However this is not strictly true for the Thames Estuary where sand wave asymmetries show that the flood is dominant on the south flank of the banks and the ebb is dominant on the north side of the banks (Fig. 17), producing the same clockwise/cyclonic sense of sand circulation as found for most open shelf linear banks in the North Sea. Also in Chesapeake Bay the banks are oblique to the flood streams (Ludwick 1974). Thus many channels are not totally flood or totally ebb dominant. There is insufficient sand wave asymmetry data from the other wide estuaries around the UK, such as the Wash and Morecambe Bay, to say whether this applies also to them. However new data from the SEA6 survey of the outer Solway Firth (section 6.2.3.2.3.) implies that the outer banks are aligned with flow. In the embayment approaching Seoul, Yellow Sea, there are very wide banks (up to 30 km) that are oblique to the currents and also offset in an anticlockwise sense (Kenyon et al 1981). Banks in the mouth of Moreton Bay, Australia (latitude 25 S), are offset in both senses in near equal numbers (Harris and Jones 1988).

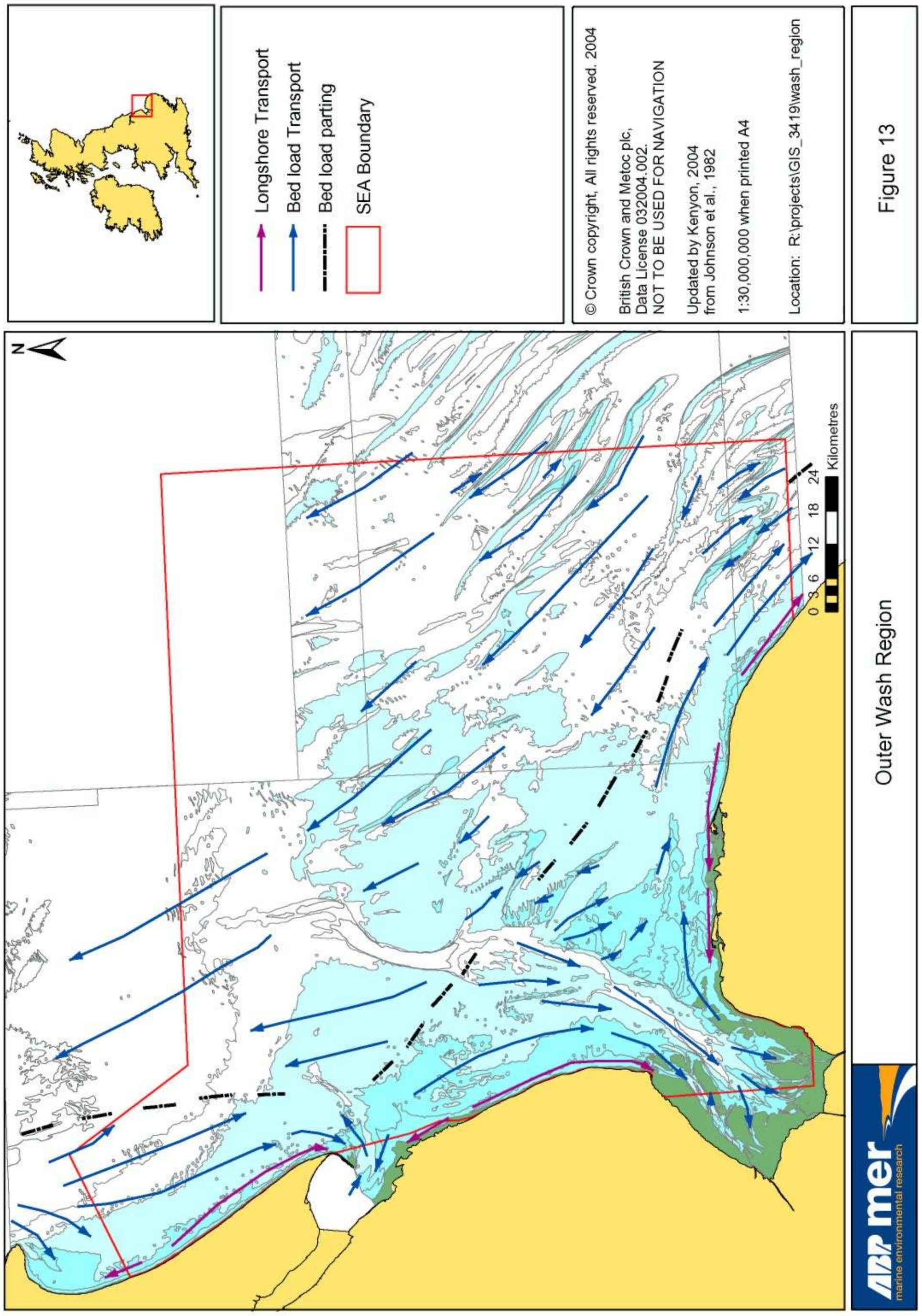


Fig. 15 New map of net sand transport paths in the Greater Wash strategic area. Contours at 10 m intervals.

Fig. 16 Aerial photograph of the Wash showing wide estuary sand banks. The net sand transport into the estuary results in the sand banks widening once they reach sea level. From G. Evans.

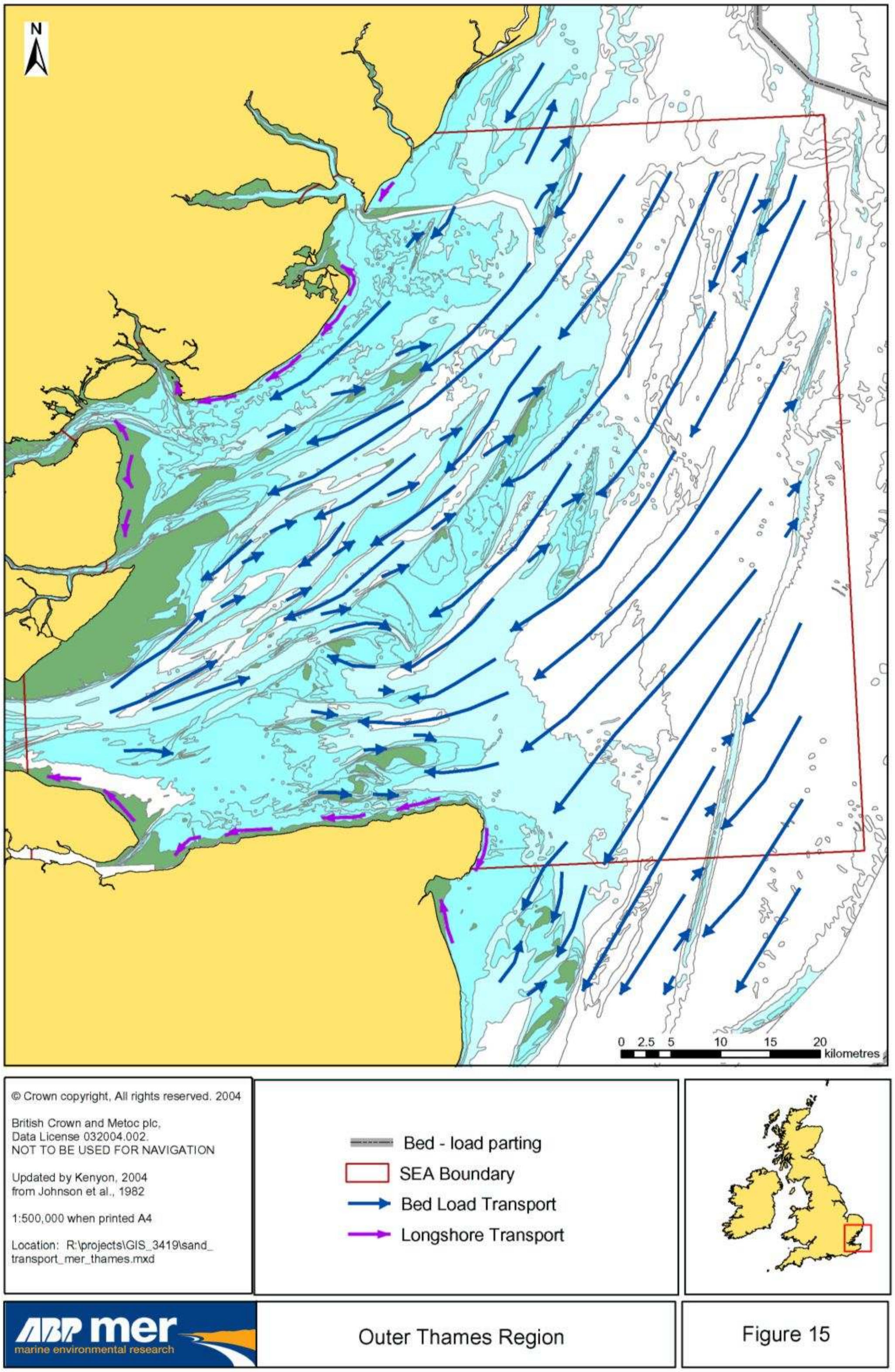


Fig. 17 New map of net sand transport paths in the Outer Thames strategic area. 10 m contour interval.

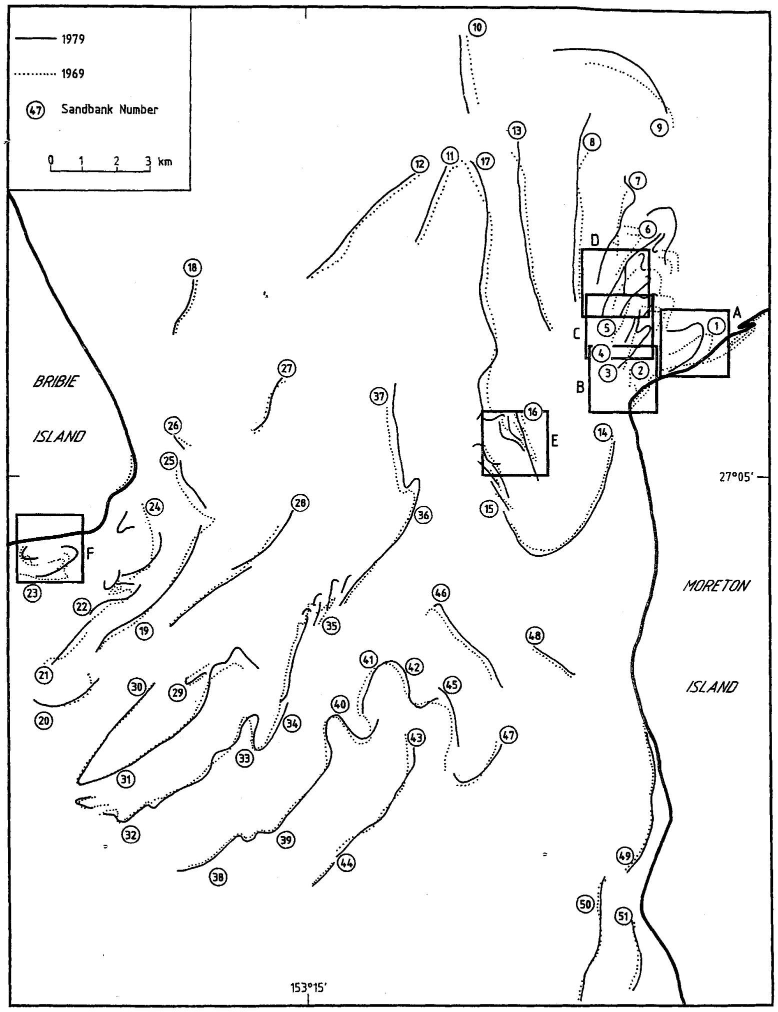


Fig. 18 Movement of sand bank crests in Moreton Bay, Australia, over 10 years determined from aerial photographs (Harris and Jones 1988).

Whereas open shelf linear banks migrate fairly consistently in the direction of their steeper face the situation in estuaries is different because of the constricted space. Erosion rather than deposition on some of the steep flanks is said to occur (Dyer and Huntley 1999). The migration of one bank produces interaction with the next and cyclical movements are common (see section 4.2). The new SEA6 survey showed shifting shoals on top of the Two Feet Bank in the outer Solway Firth (section 6.2.3.2.3.).

It should be noted that in some wide-mouthed estuaries the banks are not like those described above, i.e. wide and built up to near sea level. In those estuaries, or parts of estuaries, where the ebb current is dominant then fewer and narrower sand banks are found, as in the outer Bristol Channel (Harris 1988) or Korea Bay, Yellow Sea (Kenyon et al 1981). In the mouth of Moreton Bay, Australia, rather than wide banks with extensive intertidal flats there are narrow sinuous banks and narrow linear banks (Fig. 18). There appears to be room for these banks to shift position as they are not as confined as banks in many estuaries, which are forced to broaden after they have reached sea level.

3.1.5. Ebb-flood tidal delta

Formed at the narrow mouths of estuaries and at inlets through barrier islands, these are the Type 2B of Dyer and Huntley (1999) and are described by Hayes (1975). The flood delta is landward of the mouth and the ebb delta is seaward and modified by wave action and shore parallel currents. The sand is transported along the beach towards the spits which constrict the mouth. A terminal lobe occurs outside the mouth where the expanding current flow causes deposition (Fig. 19). A significant feature is the trench formed in the mouth which can persist on the shelf after coastal retreat. There are many examples of ebb-flood tidal deltas on the coast of Germany and the Netherlands but few around the UK, where waves and currents tend to be too strong to allow build up of the seaward delta. A modified form of ebb delta, with highly mobile flanking spits, has been studied off the mouth of the River Exe (Robinson 1975).

3.2. Non-tidal sand banks

3.2.1. Storm-generated ridges

These are also called shoreface connected sand ridges and were first described from the eastern inner shelf of the USA, where they were subdivided into shoreface ridges and offshore ridges (Swift and Field 1981). They are very different from tidal sand ridges (Belderson 1986). They are attached to the coast and make an angle with the coast, and the current direction, that is typically 25-40° rather than the less than 20° for tidal banks. Large sand waves are not present. The ridges are lower, with heights of 3-12 m and they are usually rounded in profile. They have gentle slopes (usually less than 1°) and they are generally closer together and shorter than tidal sand banks.

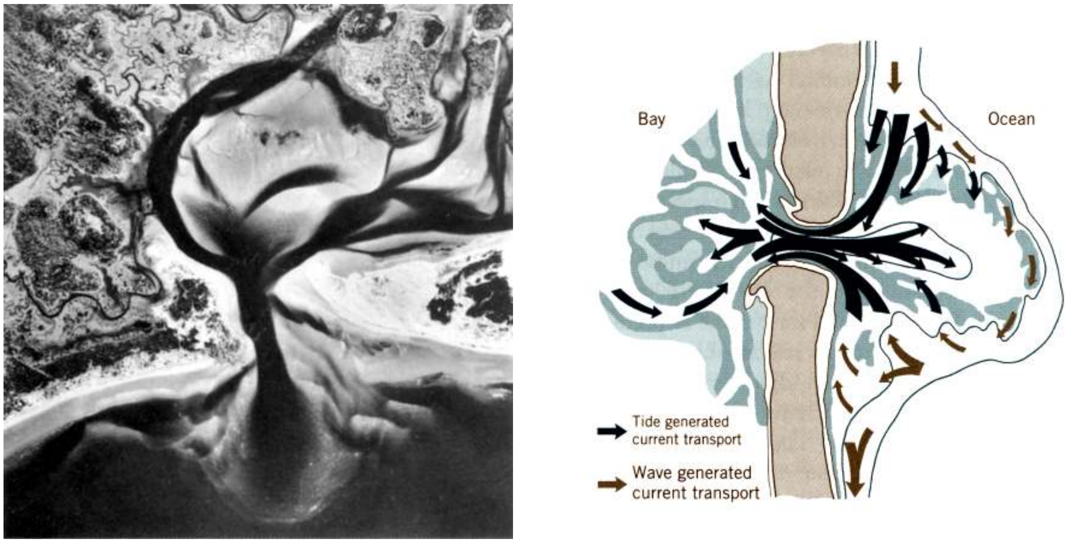


Fig. 19 Aerial photograph of an ebb-flood tidal delta and diagram of typical bedload transport paths. (from Hayes 1975)

They are also recognised from the coast of Holland (van de Meene, 1994) and from the coast of Belgium (van Lancker 1999). The Zeeland Ridges are thought to be storm generated ridges which explains their being anomalously rotated clockwise with respect to the tidal flow (Roos et al 2004). Ridges near the coast of France (Tessier et al 1999) have both a storm influence which builds them landward, and a tidal influence which builds them seaward and along shore. Their characteristics are between those of tidal sand banks and storm generated ridges. It may be that the ridges mapped as open shelf linear sand banks off the coast of northern Holland by Dyer and Huntley (1999), the Dutch Banks of Roos et al (2004), are more closely related to storm generated ridges than to active tidal sand banks, as has been suggested by Belderson (1986) because they are in an area dominated by storm surges and waves and they have not built up to near sea level. Whatever they are they are anomalous and have thus been left off the map of tidal sand banks in the North Sea (Fig. 10).

4. Sand transport

4.1. Introduction

Sand can move faster than small sand waves and can be mobile in weaker currents. Small sand waves can move faster than large sand waves and large sand waves can move faster than sand banks. However there is no fixed ratio between the speed of one and the speed of the other. In places where the ebb and flood tidal currents are equal then there will be little net movement of large sand waves or sand banks even though the strong currents make the sand highly mobile. For all moribund and fixed headland banks movement will be near zero, though the flux of sand will be at or near zero for the former and very high for the latter. In areas of strong asymmetrical tidal current the sand can be regarded as by-passing the sand waves (Smith 1988). Radioactive tracer studies show that in a sand wave field, near a bank off Cap Gris Nez, the sand has travelled up to 2 km in 75 days (Fig. 20) with little movement of large sand waves (Beck et al, 1991).

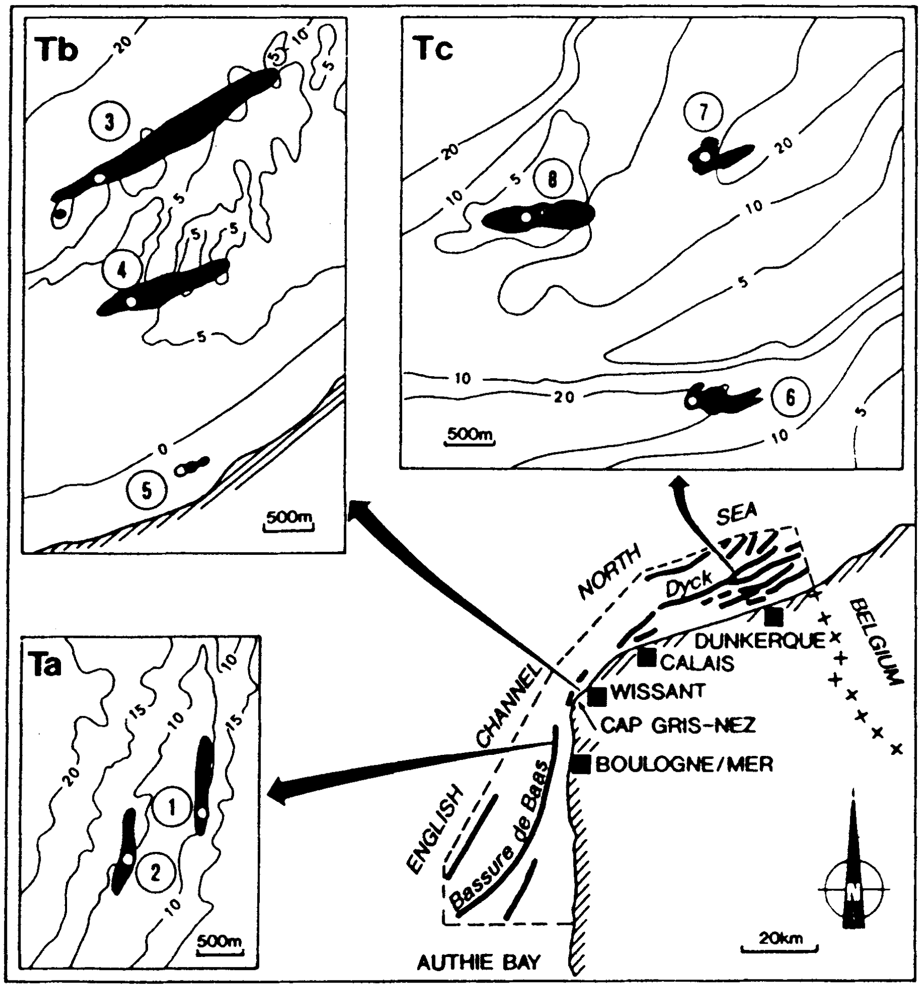


Fig. 20 Distribution of radioactive tracer after 75 days. In Tb it crosses a banner bank tied to Cap Gris Nez, France, at an angle of about 20 degrees to the crest (Beck et al 1991).

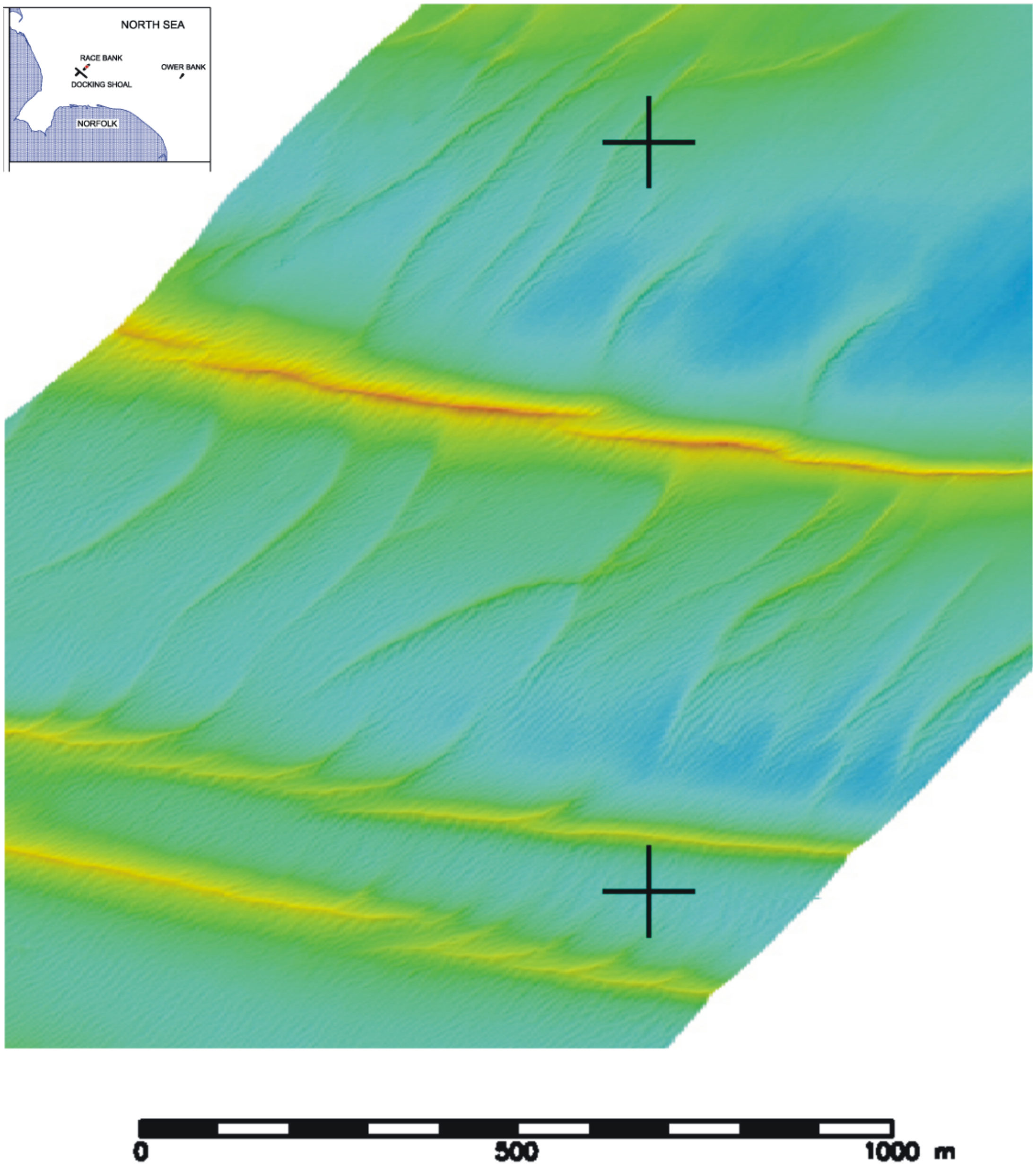


Fig. 21 Swath bathymetry of tidal sand bodies near Race Bank showing smaller bank-like sand bodies with large sand waves moving towards their crests from opposite sides (as in Fig. 2) and also small sand waves. Thus there is an extra order of tidal sand body here. From SEA5 survey.

The complexities of tidal sand bodies are shown by the discovery near Race Bank of an extra order of tidal sand body in the hierarchy. Race Bank is one flank of a sinuous bank and it appears to be being modified by obliquely trending small banks, which also have large sand waves approaching from either side towards a local bedload convergence at their crest (Fig. 21, SEA5 2004), the same arrangement as for large tidal sand banks. In addition there are the ubiquitous small sand waves and (though unseen at the scale of the imagery) there will be the ubiquitous sand ripples. Such a bedform, between large sand waves and sand banks, is also seen on the swath bathymetry survey of the Ballacash Bank (see section 6.2.3.2.2.). Knaapen (2001) has shown that the advent of swath bathymetry is enabling the discovery of new sandy bedforms. He describes a bedform resembling the near longitudinal ridges found in areas of small sand waves that have been shown by Belderson et al (1972), Belderson et al (1982) and that is also discussed in section 6.2.3.2.

4.2. Movement of sand on sand banks

The banks can be considered as groups of regular asymmetric bedforms in which the asymmetry is an indication of the overall sand transport direction. Sand is thought to leak away from the downstream ends, perhaps seen as patches of sand waves to the north of the Norfolk Banks. The transport paths are usually taken to be in the direction indicated by the peak currents and by the smaller bedforms-sand ribbons, scour holes, sand shadows, sand waves etc. This is the direction shown on the established bed load transport maps and is usually parallel to the coasts and slightly oblique to the banks.

However, the transport of sand in these very high currents, when assisted by waves, can be as sand suspension rather than along the seabed (Vincent et al 1998). The tidal currents are usually rotary and there is a lag effect (the transport being to the right of the peak current direction in a clockwise rotating current and vice versa). Thus Stride (1974, 1988) presents the hypothesis that this will lift the sand across the crest and onto the steeper flank. He goes further than this and proposes that the sand transport paths in the strongest currents may in fact be oblique to that previously assumed, i.e. it is not parallel to the peak current direction. Thus sand may be moving towards or away from the coast and the sense of this direction can be predicted. From the map of sense of rotation of tidal current (Sager and Sammler 1975) one can predict that in the area of the Norfolk Banks sand would be moving away from the coast, whereas the transport in the Bristol Channel would carry sand to its northern side, accounting for the much greater abundance of sand there compared to the southern coast. Likewise the transport in the approaches to the Thames Estuary would be to its northern side, accounting for the greater concentration of broad banks and tidal flats there. This hypothesis could be tested by tracer studies. However, it does not seem to work for the occasions when tracer has been used on the Middelkerke Bank, Belgium (Williams et al 2000). One reason for it not seeming to work is that the sense of rotation of tidal currents is not always the same at the sea surface as it is at the bottom (J. Howarth, Pers. comm.).

Sand transport is much enhanced by waves, especially near to the sand bank crest. There is evidence for banks being lowered after storms and building up during fair weather. This is reported for banner banks (Farrow et al 1984) and for the linear open shelf Middelkerke Bank, Belgium (O’Connor 1996). The tops of those banks that are near sea level are devoid of sand waves because the currents are too strong and the water depth is too shallow.

Sand wave movement is best measured by diver observations of movement relative to fixed stakes but few such measurements exist. The increasing accuracy of satellite based positioning systems, which have improved from tens of metres in the 1980’s to less than 2 m today, means that in future repeated echo sounding will give reliable measurements of sand wave movement. Small asymmetrical sand waves (the mega ripples or dunes of some authors) are able to move faster than large sand waves e.g. several m's per hour in rivers and tidal inlets. Some small sand waves can form seasonally in areas of flat sand sheet, an apparent movement of sand rather than a real one (Johnson et al 1981), because the waves form in weaker currents when the water viscosity is lower due to it being warmer (Fig. 22). Small sand waves require current speeds (peak speeds near the seafloor) of about 50 cm/sec. Large sand waves are formed at higher peak near seafloor speeds of 65 cm/sec or more. The movement of large sand waves depends very much on the asymmetry of the peak currents. Symmetrical sand waves, such as those at the bedload parting in the southern North Sea should not move at all. A long time series of echo sounding in the southern North Sea demonstrates that there is a correlation between sand wave asymmetry and migration rate (Knaapen, in press), with strongly asymmetrical sand waves migrating at up to 9 m per year.

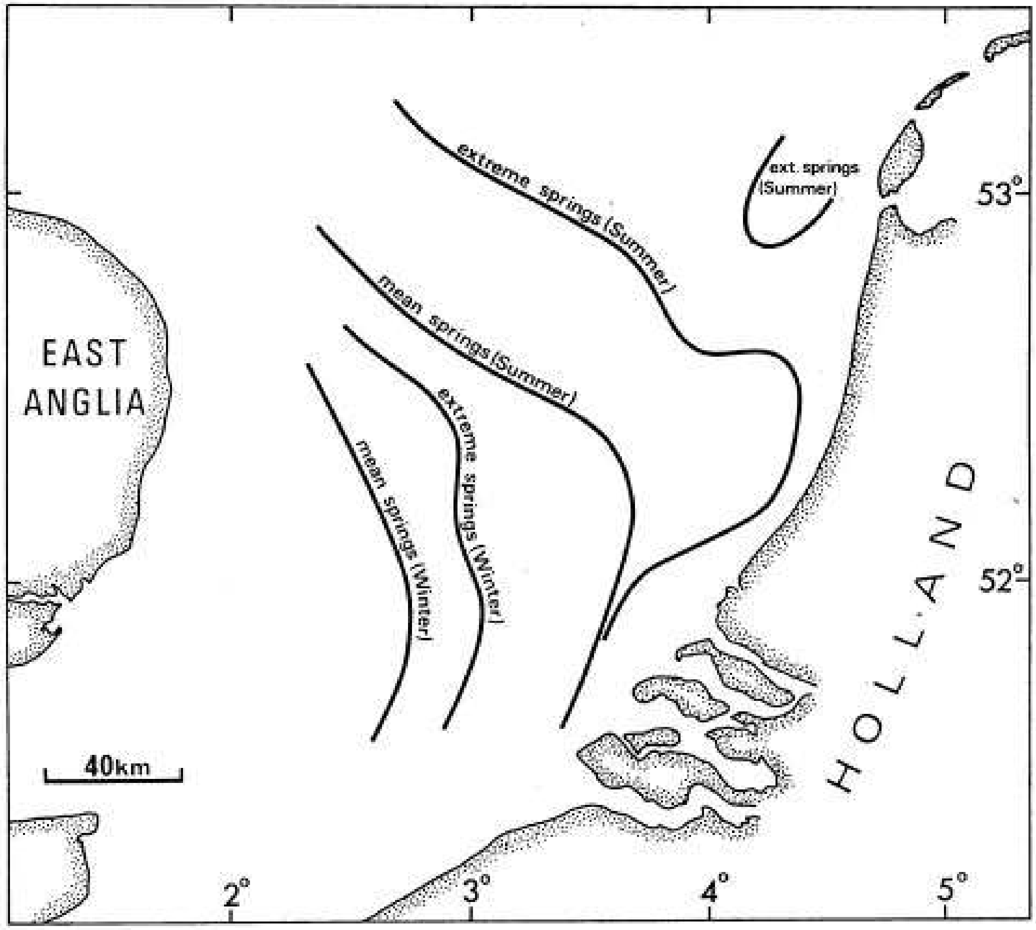


Fig. 22. The predicted area of small (1 m high) sand waves is more extensive in the summer, when temperature is higher and viscosity less, than in the winter. This takes no account of non-tidal water movements such as storm waves and surge currents, which should enhance the winter currents to a greater extent. Shown for the southern North Sea.

Large sand waves in rivers can move by 100's of metres per year, whereas in tidal seas they typically have net movement of 10 metres to a few 10's of metres per year. Large sand waves on sand banks are close to the bedload convergence at the crest of the sand bank. Thus they may not move much or even reverse in direction despite the very strong currents that occur and the relatively rapid movement of sand and of small sand waves (Fig. 23).

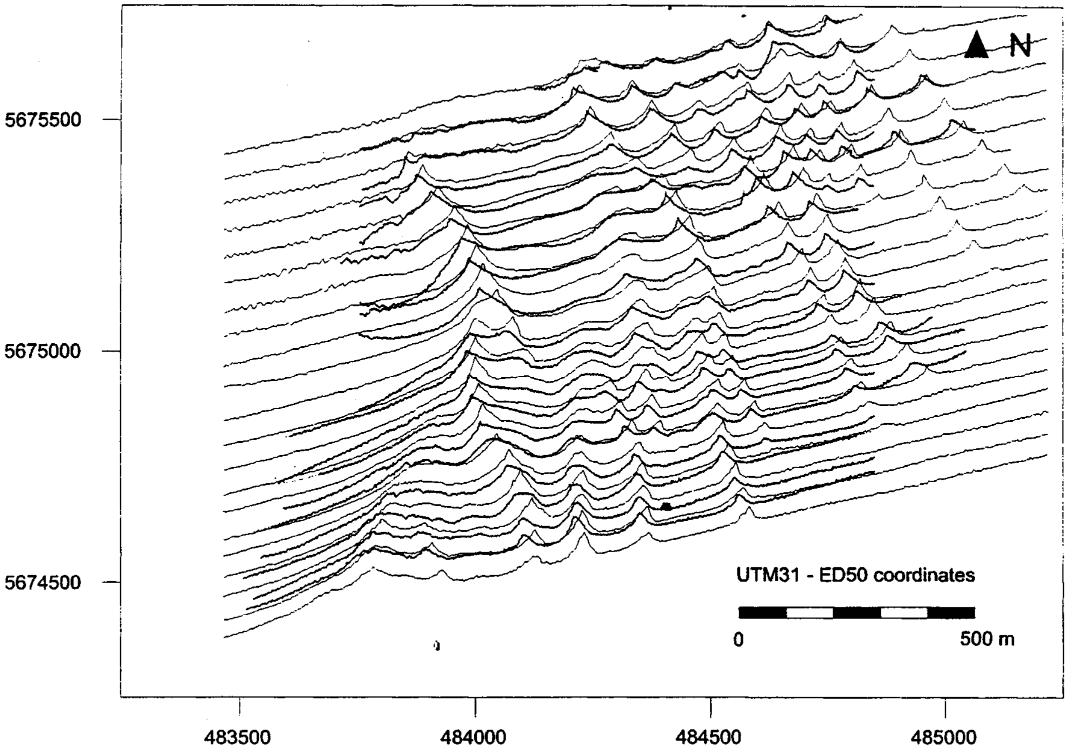


Fig. 21 Repeated surveys of 3 m high sand waves on Baland Bank, Belgium, show complex changes after 18 months. There is in general an advance of an average of 20m in the direction of the steep face but there are some reversals of asymmetry (van Lancker 1999).

Sand wave migration rates have been the subject of a modelling approach (Besio et al 2004) which takes account of the residual current direction together with the direction, strength and phase of tidal constituents. However the technique needs further refinement as it does not predict the movement of the small sand waves that are present on the large sand waves in the area that they are studying in the North Sea. Nor does it take complete account of viscosity, which is greatly effected by water temperature as shown for this same area (Johnson et al 1981). Nor does it include superimposed currents due to waves and surges.

4.3. Movement of sand banks

Because sand banks are very large the rates of movement of the whole bank will usually be small compared to those for sand waves. As for sand waves the rate of movement will depend on the type of bank and its place within its evolutionary sequence (whether active or moribund, a situation usually controlled by sea level).

Fixed headland banner banks. Banks fixed to headlands should not move horizontally. This is confirmed by the finding of probable traces of former banks beneath the Shambles (Fig. 9A) (Bastos et al 2003).

Moving headland banner banks. Banks tied to moving headlands should move with the headland. There is little information available over a long enough term. However repeat surveys over about 100 years show that offshore of the Dunwich Cliffs, Suffolk, which are retreating by up to 18 m/year, the offshore banks are moving landwards by up to 11m/year. One bank was progressing northward at 49 m/year (Carr 1979). The Horns Rev, is a bank attached to a sandy headland west of Denmark. It is not known (by this author, NHK) whether the headland is moving but it appears to be shedding sand in large amounts to the bank. The offshore bank has a relatively high rate of progradation in the direction of its steeper, landward, side of 3.5 km in the last 800 years (Larsen, 2003), i.e. over 4 m/year (Fig. 9B). A bank off Gibraltar Point, Lincolnshire, has moved south, together with the headland by 3 km in 150 years (20 m/year) (Dugdale et al 1979).

Open shelf linear banks are typified by the Norfolk Banks which extend from active, sinuous inshore banks near the Norfolk coast to the active, NW trending, linear, en echelon, banks. The outermost banks of this group have low slopes and are regarded as moribund (Kenyon et al 1981). Charts of 1851 were compared with charts of 1966 and 1967 by Caston (1972). He counteracted regional shifts in navigation by superimposing isobaths and only looking for local changes. Bank movements were mainly to the NE, in the direction of the steeper slope and averages were up to 11 m/year. Pravotorov (1983) compared charts of the Norfolk Banks between 1956 and 1980, with relatively good navigational control. For a particular bank movement may be to the SW followed by movement to the NE, and bank shortening may be followed by bank extension. All of the banks extended their tails to the NW over the 25 years or so and most banks extended their heads to the SE. Two banks, Swarte Bank and Broken Bank, apparently moved to the SW whereas the majority moved to the NE. The extensional and retreating movements at the head and tail were quite high compared to the sideways shifts. Surveys by the oil industry of Ower Bank (reported in Johnson and Caston 1984) show an uneven NE movement, (the direction of the steeper slope) that had a maximum of 40 m/year, but was typically about 15 m/year. The Baland Bank near to the coast of Belgium, in depths of only 10 m, thus perhaps nearer to a storm-generated ridge, moved between 14 and 25 m/year over a period of 18 months of repeated surveying (van Lancker 1999). Other Flemish Banks off the coasts of Belgium and Holland also move. Kwinte Bank, which is steeper on its north flank, has shifted several hundred metres to the north with respect to a 2-5 m thick core of relict sediment (Marechal and Henriet 1983). They believe this shift to be during the early build up of the bank. Middelkerke Bank shows clear shifts to the north (Trentesaux et al 1999) based on prograding bedding seen on seismic lines.

Open shelf sinuous banks seem to occur nearer the coast than most open shelf linear banks and so would be expected to be fairly active. As pointed out above they also have a convergence towards the crest and are rather symmetrical in plan view. Thus overall movement in a preferred direction may not occur. Having neighbouring ebb and flood dominated channels is an inherently unstable shape and lead Caston (1972) to predict a tendency for them to change into a number of linear (en echelon) banks. Many of the sinuous banks whose movement was determined from sequential air photos (Fig. 18) were placed in their most dynamic category by Harris and Jones (1988). Typically the parabolic crests moved about 10 m/year. For many banks the movement was non-uniform and could be by growth and decay as opposed to the linear banks in their study, which tended to move progressively in the direction predicted from the asymmetry of the bank in cross section. Haisborough Sand, one flank of a sinuous system, moved laterally at 2.5 m/year (McCave and Langhorne 1982).

Confined (estuary) banks. Whereas open shelf (en echelon) banks migrate fairly consistently in the direction of their steeper face the situation in estuaries is different because of the constricted space. It is claimed that erosion of some of the steep flanks occurs (Dyer and Huntley 1999). The high tidal currents in many wide estuaries mean that banks are particularly dynamic. Overall the area of the bank tops should be increasing as they tend to be areas of accretion due to the flood directed asymmetry. This is demonstrated for the Ribble Estuary by van der Wal and Pye (2003). The migration of one bank produces interaction with the next. This is shown by rapid changes to bank morphology in the inner Thames Estuary (Fig. 24) (Cloet 1972) (see section 6.2.2.2), where a 3 km long sand bank grows in about 30 years . In the Bahia Blanca Estuary, Argentina, banks have moved at a rate of 37 m/yr (Gomez and Perillo 1992).

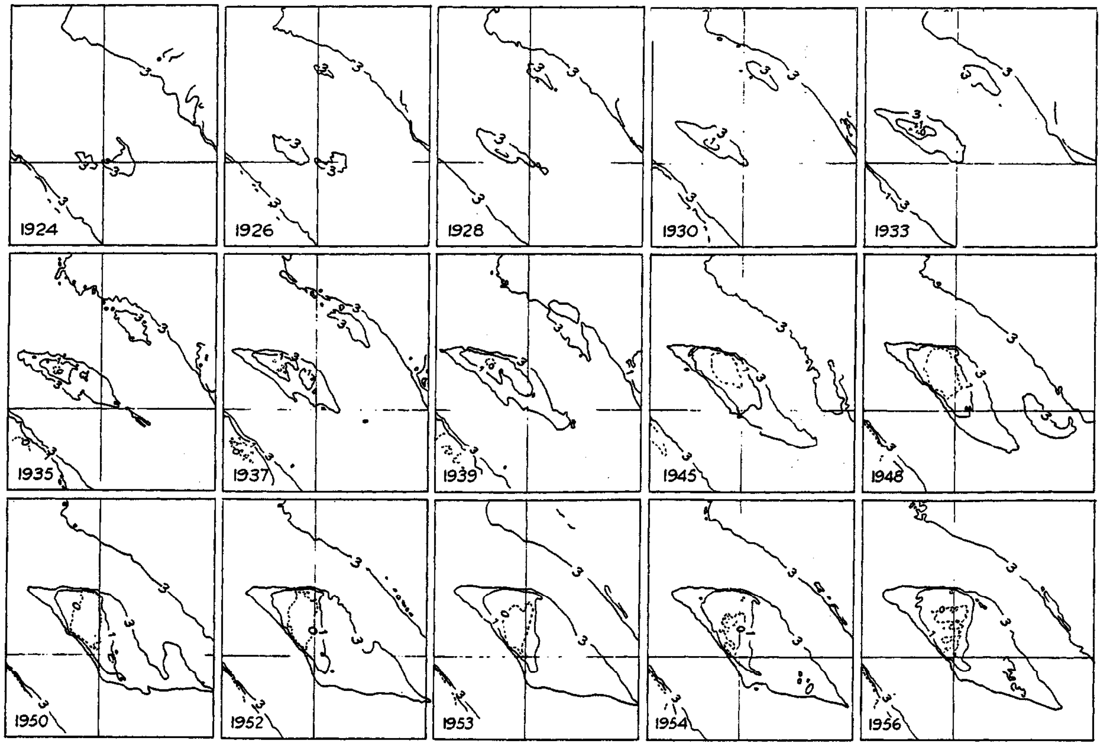


Fig. 24 The high mobility of small sand banks in the inner Thames Estuary (Cloet 1972). The area is about 6 km by 5 km.

Storm-generated ridges, being subject to frequent storms in relatively shallow water, can move at rapid rates. Field (1980) found a constant migration for east USA ridges of 2-120 m/year. The near shore banks off Dunkirk (Tessier et al 1999) are thought to have formed in only a few hundred years rather than in thousands of years. The storm-generated ridges that are connected to or are near to the Belgian coast are highly mobile (van Lancker et al 2004). A detailed study of a small area near to Ostend shows a movement of over 100 m in 42 years (2.5 m per year) for the Wendine Bank but the movements are naturally complex and further complicated by dumping.

Cyclical bank movements may be common especially in the higher energy settings such as for some moving headland banner banks, some sinuous banks found near to coasts, and estuary related banks. Usually sequential historical charts are needed to detect this and for many reasons the data is difficult to use and rarely good enough for determining rates of movement (van der Wal and Pye 2003). However cyclical movement has been noted for the mouth of the Exe Estuary (Robinson 1975) and has been modelled for the Scheldt Estuary (e.g. Schutelaars and De Swart 1997).

5. The concept of current dominance on the UK shelf

The new, updated sand transport path map (Fig. 25) includes work done and new concepts introduced since 1981 including more on the concept of dominance by different types of current. The influence of tides has received much attention but the influence of wind-driven flow and of wind waves has received less attention. A map of areas of the northwest European shelf where wind-driven

(surge) currents, oceanic currents and wind wave currents were dominant was first attempted by Kenyon and Flather (1986). This is extended here. It attempts to distinguish a few bedforms that are characteristic of each type. Recently van der Molen (2002) has used a modelling approach to this problem for the southern North Sea. The latter approach should be able to compute the degree of dominance. A dominance index (Fig. 26) is introduced which fits well with the qualitative approach used in this report and by Kenyon and Flather (1986).

5.1. Tidal current dominance

Most of the offshore shelf of the southern and eastern UK is dominated by tidal currents. The asymmetry of the peak tidal currents, given by measurements (Sager and Sammler 1975) and by modelling (e.g. Pingree and Griffiths 1979), fits well with the asymmetry of bedforms such as sand waves, obstacle marks and sand banks and the peak speed fits well with a scheme of bedform zones developed in many publications of which Belderson and Stride (1966) and Belderson et al (1982) best explain the classic scheme (Fig. 2).

Some bedforms are only developed in tidal current dominated environments. Most sand bank types are tidal as they require a convergence due to both ebb and flood currents. However some estuarine sand banks may be in areas dominated by storm surge currents such as those in the German Bight (see Fig. 26). Symmetrical sand waves, as found at a bedload parting in the southern North Sea, and sand waves with secondary peaks (cat-backs) also require near equal ebb and flood currents and so are tidal indicators.

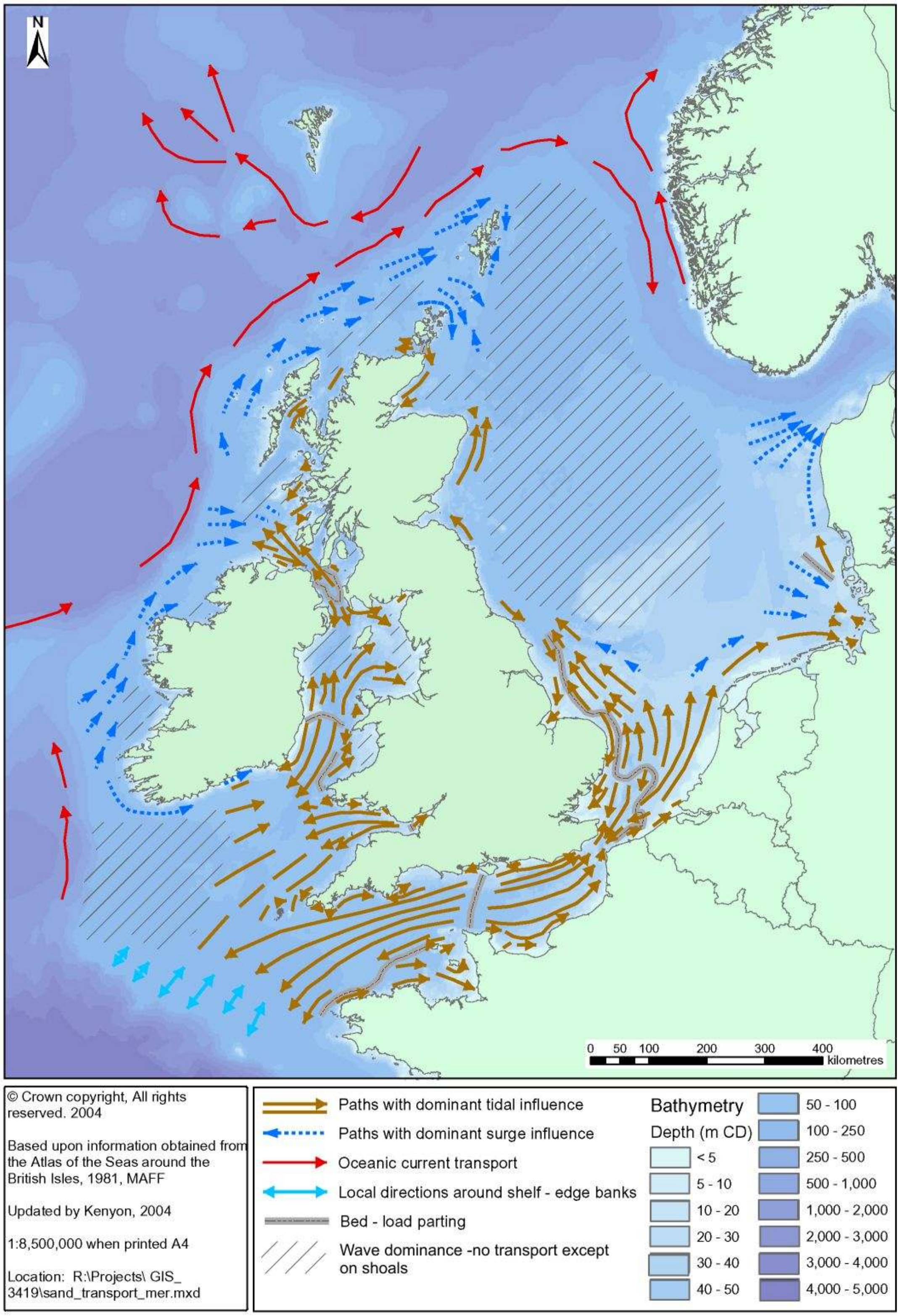


Fig. 25 Sand transport paths around the British Isles, showing the dominance of different types of current. In most places the sand will be moved on occasions when several types of current act together. Waves are dominant in the areas of hatching, and in areas shallower than about 20 m which are not shown for reasons of graphic expediency.

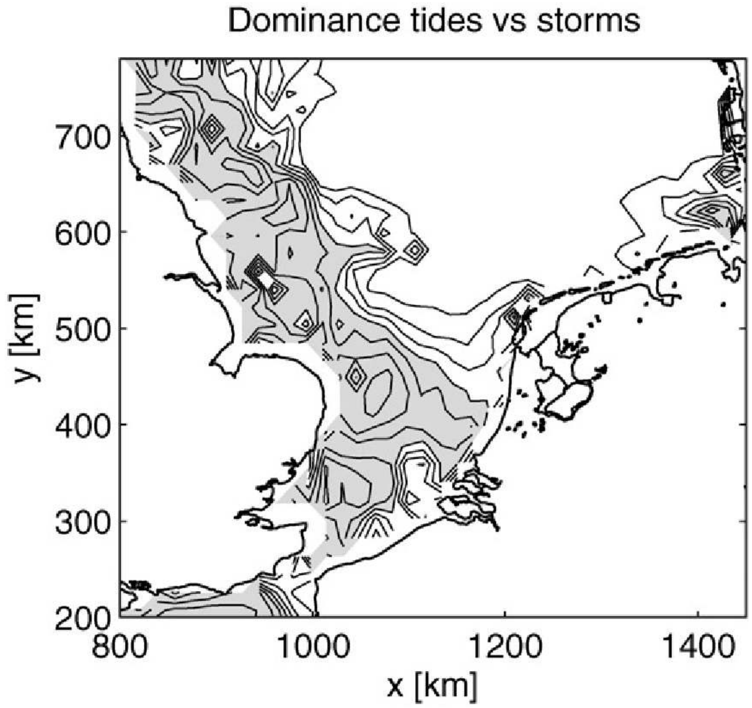


Fig. 26 Areas of tidal dominance (shaded) and areas of combined wind and wave dominance (white) in the southern North Sea (van der Molen 2002). Contours are of a dominance index.

5.2. Surge current dominance

Bedforms are an integrated response to all water movements. Where the tidal currents are weak, not exceeding 25 cm/sec, say, the non-tidal currents can be dominant. Seasonal winds in consistent directions cause relatively long term strong unidirectional currents. Relatively short term unidirectional currents are induced by storms. Such unidirectional currents when superimposed on the tidal current will cause greatly increased sand transport but will have a small effect on the obliquity of the sand transport direction (Fig. 27).

Areas where the transport of bedload is considered to be dominated by storm surge induced currents (Fig. 25) are greatly extended since the 1982 map, based on the modelling of extreme surge currents by Flather (1987) (Fig. 29). The main area is west of Ireland and Scotland, together with some areas in the North Sea where tidal currents are weak but surge currents greater than about 60 cm/sec occur on rare occasions, such as the Dogger Bank and the shelf north of Jutland. The area north of Jutland has a field of large sand waves in an area where the tidal current is less than 25 cm/sec whereas the surge current can reach 200 cm/sec near the surface during storms (Stride and Chesterman 1973). Another area of surge dominance is between the Orkney and Shetland Islands where the Fair Isle Current helps to cause eastward moving sand waves even where the tidal current is too weak on its own (less than 50 cm/sec) to move sand. A further area where surge currents may dominate is the approaches to the German Bight and the area of offshore ridges, the “Dutch Banks”, shown off northern Holland by Dyer and

Huntley (1999). Large symmetrical sand waves are not found in areas of surge dominance because there are no symmetrical currents and nor are large active sand banks because the currents are mostly too weak.

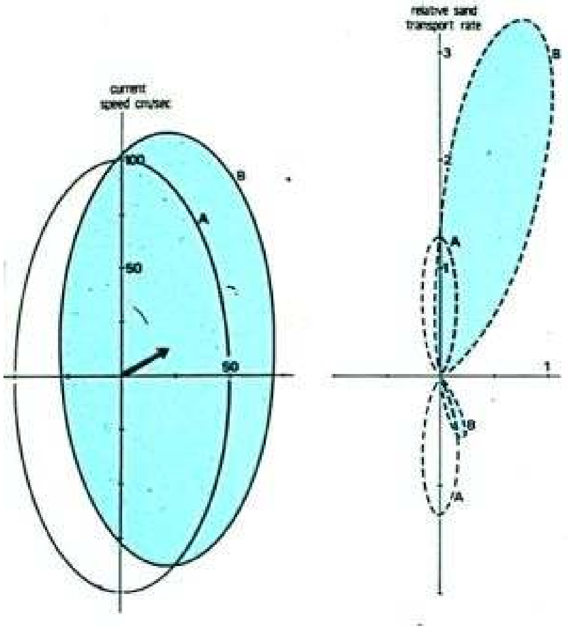


Fig. 27 Equal rates of sand transport result from equal ebb and flood tidal current loops (uncoloured ellipsesA and A). The sand transport rate (blue areas B and B) will be greatly enhanced by the addition of a small non-tidal current, such as a surge or oceanic current, but there will be only a slight change in the direction of sand transport.

5.3. Oceanic current dominance

This is a new category on the sand transport path map (Fig. 25). A new sand transport path due to a poleward directed upper slope current was discovered west of Scotland (Kenyon 1986) in water depths down to 500 m. This path is extended to the south from sidescan sonar data and seabed photographs from the eastern Porcupine Seabight and the northwest Porcupine Bank (Kenyon et al 1998). There has been much recent study of sand transported by the deep water exiting the Norwegian Sea. It has been followed from the Faeroe-Shetland Channel (Masson 2001), across the Wyville-Thomson Ridge and around Bill Bailey Bank (Kuipers et al 1998) and beyond the Faeroe Bank Channel (Kenyon et al 2003). There is also a sand transport path to the south along the eastern Rockall Bank (Kenyon et al 1998).

5.4. Storm wave dominance

Areas where the directional currents (tidal, surge and oceanic) are too weak to move sand on their own but where some sand is moved from time to time are distinguished (Fig. 25). These are areas where the to and fro motion of long period storm waves enhances the weak directional currents. Storm waves effect the seafloor over the entire shelf around the UK (Belderson et al 1982) and currents up to 40 cm/sec, sufficient to move sand, in 200 m depths on the shelf edge west of Scotland were mainly due to storm waves (Huthnance et al 2002). The direction of transport may vary and the net transport will be little or nothing. There are two bedform indicators of wave dominated sea floors that have been used to help map these areas of wave dominance. One is symmetrical gravel waves, mapped by high resolution sidescan sonar and photography, the other is thick tabular sand patches (section 5.4.1). These two sedimentary types are usually found together and are regarded here as a wave dominated facies association.

There are also areas of shallow water where the transport by wave induced currents will be more significant than by tidal currents, though on occasions the directional currents will be able to move sand without the help of waves. McCave (1971) took areas of the southern North Sea where the sea was shallower than about 20 m as typical for wave dominance (his “high effectiveness” areas). This includes tidal flats and the tops of sand banks as well as the approaches to the steeper coastal ramps. It is not possible to distinguish such shallow areas of storm wave dominance on the transport path map (Fig. 25) for reasons of graphical expediency.

5.4.1. Thick tabular sand patches as an indication of storm dominance

This type of sand bedform is very easy to recognise on acoustic backscatter imagery from their sharp boundaries and the great acoustic contrast between the sand and the surrounding gravel (Fig. 28). They have a height and thickness that is usually between 0.5 m and 3 m. They have been widely reported though their significance as indicators of wave dominance has not been fully recognised. They were first described from the northern Celtic Sea, south of Cork (Kenyon, 1970). They are found in two shelf settings of northern Europe (unpublished sidescan sonar data, NOC). One setting is the mid/outer shelf including parts of the western Dogger Bank, southwest of Brittany, south of the Scilly Isles, northwest of Ireland, west of Scotland and in the outer Moray Firth. The other setting is close to coasts exposed to long period storm waves such as west of Chesil Bank, Dorset, west of Devon, west of Pentland Firth, west of the Lake District (in the North West/Liverpool Bay) (Fig. 28) and north of Brittany. They have also been found near Iceland, west of the USA, east of the USA, west of Africa, and in the Beaufort Sea, Canada (Hequette and Hill 1995), etc. They are one of the most widespread of all shelf bedforms.

This bedform has been called transverse sand patches (Belderson et al 1982), but this is misleading as they can have any direction in relation to the dominant current direction. Other suggestions are Two metre sand patches, as this is their typical height; tabular sand patches, because they most commonly have flat tops without cross sectional asymmetry; and 3D starved dunes by Harrison et al (2003) and Donahue et al (2003) because they are an upstanding sandy bedform of a similar scale to submarine sand waves. They are considered to be characteristic of areas where the directional currents (tidal and surge induced) are too weak on their own to move bedload except on very rare occasions. Peak speeds of less than about 35 cm/sec are given for tidal currents in these areas by Sager and Sammler (1975). The modelled extreme depth averaged surge currents over 50 years are about 40-80 cm/sec (Flather 1987) (Fig. 29). From their setting it is clear that they require the currents induced by long period storm waves to enhance the relatively weak, though not extremely weak, directional currents.

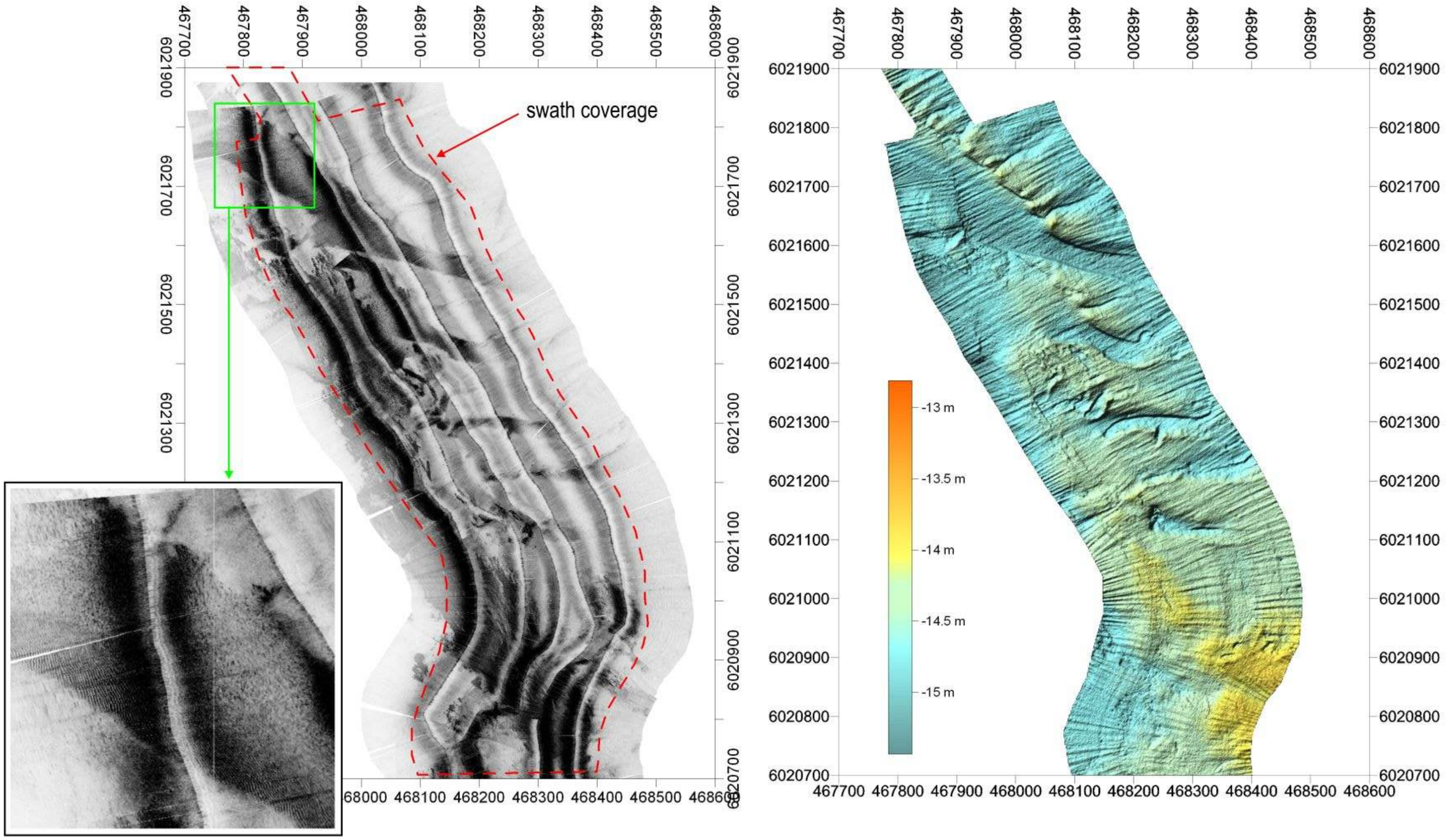


Fig.28 Thick tabular sand patches (light tones representing low backscatter) associated with wave rippled gravel (dark tones representing high backscatter). Close to coast of Cumbria in 15 m water depths. Gravel ripples, seen in the inset, have wavelengths of less than 2 m.. See section 6.2.3.2.7.

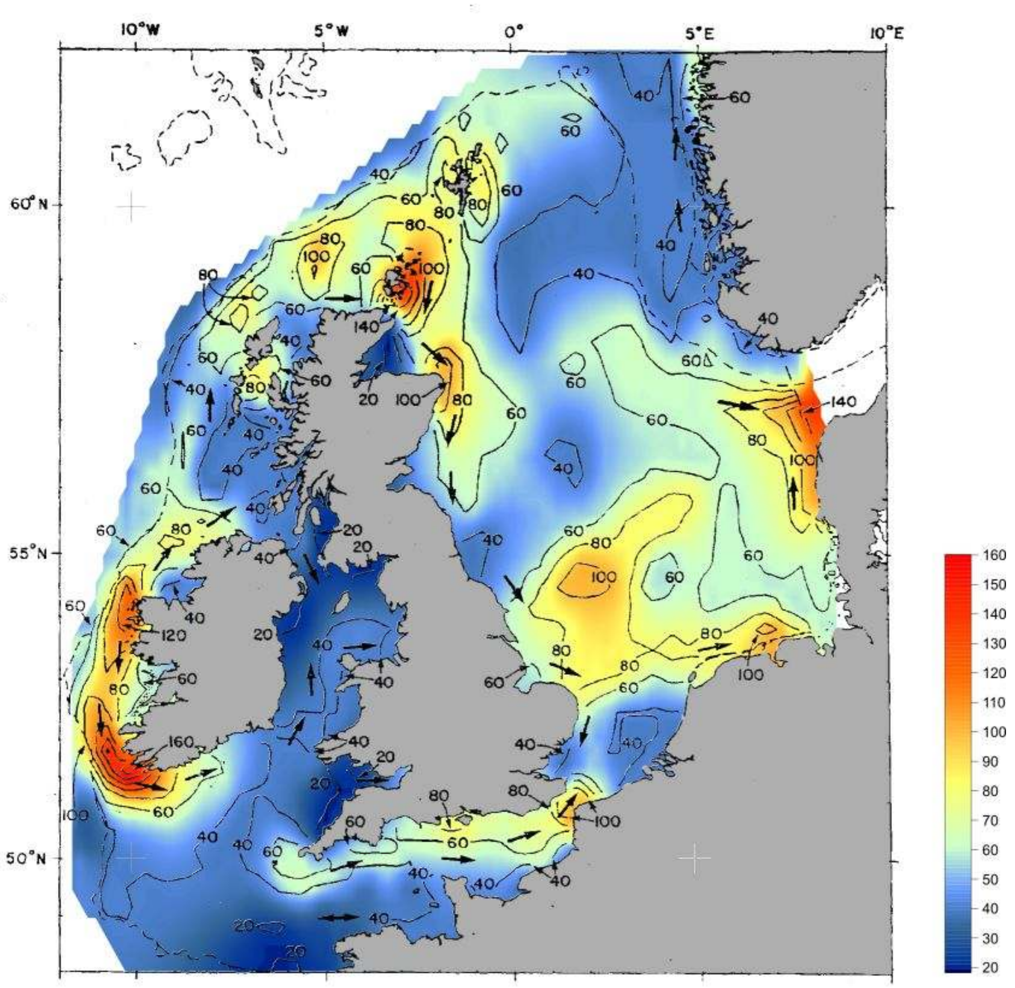


Fig. 29 Depth averaged extreme surge current in cm/sec, with a return period of 50 years (Flather 1987).

Typically the patches are built of fairly well sorted fine sands with some slight mud content and, as yet, no detected internal structure. Mud has been found in lumps that are considered to be burrow fillings (Kenyon, 1970). They are surrounded by well sorted gravel or coarse sands that have symmetrical ripples attributed to wave currents (Belderson et al 1982). It is believed that these gravels extend beneath the sand patches and that the patches are growing outwards. The process by which the patches maintain a fairly constant height and thickness together with steep sides is not fully understood. It has been suggested that the storm wave currents sweep sand from the gravel areas into the patches and that 2 m is the typical height to which the waves can carry the sand into suspension (Belderson et al 1982). The abnormally high patches west of Florida (up to 4 m) may be accounted for by the greater power of the storms there. It may be that there is a continuum of these large, fine sand bedforms on inner shelves from storm-generated ridges of high energy coasts (see section 3.2.1.), such as the coasts of north eastern France, Belgium and Holland, where directional currents are strong, to the thick tabular sand patches of the coasts of the Lake District and Chesil Bank, Dorset.

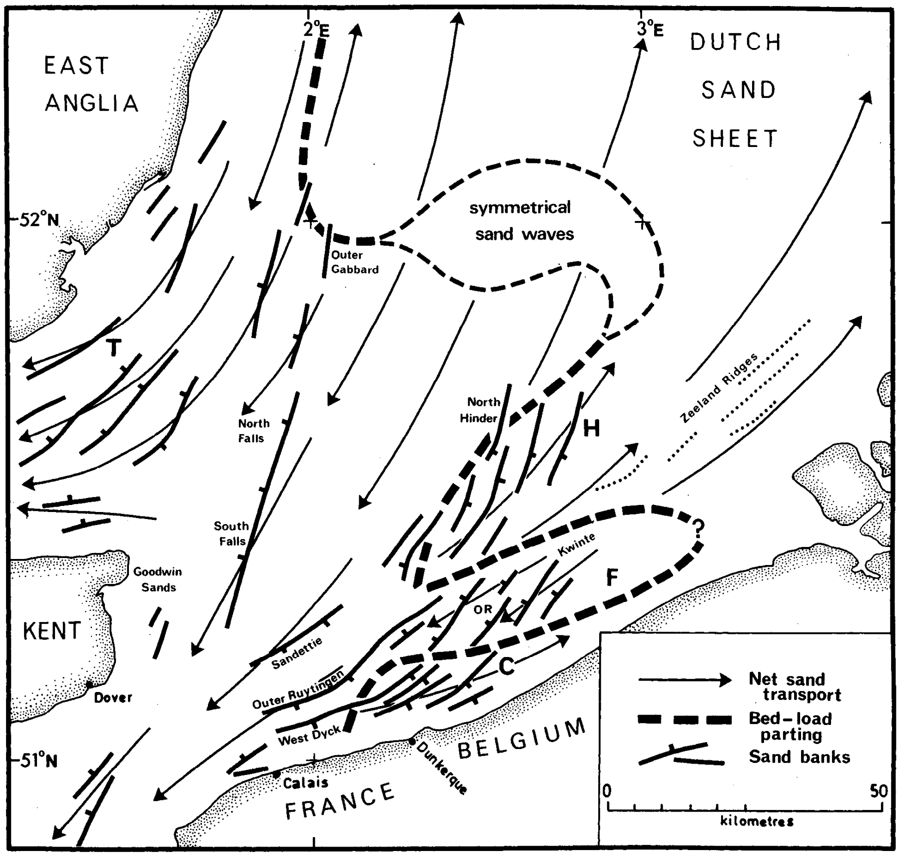
6. BEDLOAD TRANSPORT PATHS

6.1. Transport paths around the UK

A new version of the map of sand transport paths is presented (Fig. 25). It has been refined and extended over the past 40 years from that for the southern half of the British Isles (Stride 1963). This used bedform asymmetry and tidal current asymmetry to determine the major pathways for the offshore areas and introduced the concept of bedload partings and bedload convergences. Major updating for the western Irish Sea was done by Belderson (1964), for the Bristol Channel by Belderson and Stride (1966) and for the eastern Irish Sea by Belderson and Stride (1969). The area to the north of the British Isles and west of France was first included by Kenyon and Stride (1970). The last major revision of this map was by Johnson et al (1982) which distinguished some transport paths where the dominant currents were due to storm surges.

Other workers have made sand transport path maps for smaller areas since 1982, and these are incorporated into this new map where deemed appropriate. The Bristol Channel has been considered by Harris and Collins (1991) and Stride and Belderson (1990), the Moray Firth by Reid and McManus (1987), the English Channel by Beck et al (1991), Grochowski et al (1993) and Paphitis et al (in press), the Celtic Sea by Akhmetzhanov et al (2003), the German Bight by Zeiler et al (2000) and the coast west of Denmark by Anthony and Leth (2002). As a result of EC and Belgian initiatives over the last decade the Belgian shelf is now one of the best studied areas. The BUDGET project (Lanckneus et al 2001), a compilation and critical analysis of available information on natural sand transport on the Belgian shelf, lists and provides abstracts of 112 publications on sand transport in the area. It also includes a detailed sand transport path map.

Among asymmetric bedforms used to determine transport paths are transverse sand waves, both large and small, and longitudinal bedforms such as obstacle marks including wreck marks, asymmetric scour holes, comet marks etc. The use of asymmetric sand banks as transport path indicators was developed by Kenyon et al (1981). Although near to parallel with peak currents and bedload transport paths, most offshore sand banks are aligned at a small angle to them and with an anticlockwise orientation of the bank crest with respect to the transport path in the northern hemisphere. Symmetrical bedforms such as some large sand waves and some sand banks are taken to be indicators of no preferred direction of sand transport. An extensive area of symmetric sand waves is found in the southern bight of the North Sea and marks the bedload parting there (Fig. 30). Sinuous sand banks, with mutually exclusive ebb-flood channels, can be considered a symmetrical bedform occurring in areas where there is no preferred overall bedload transport path. The two large sinuous sand banks off the coast of East Anglia are placed at the bedload parting between the south going coastal path and the north going offshore path (Fig. 15).



Net sand transport directions from the Southern Bight Bed-Load Parting. A tick indicates the steeper side of a sand bank, where known.
C = coastal sand banks near to Belgium (the nearshore banks are not shown). F = Flemish Banks. H = Hinder Banks. T = Thames Approaches Banks. OR = Outer Ratel Bank. After JOHNSON *et al.* (1982).

Fig. 30 Sand banks and net sand transport directions in the Southern Bight of the North Sea (Kenyon et al 1981).

Some bed load tracer studies have been used to look at local sand transport near sand banks but the difficulty and cost of working offshore means that there are not very many. Middelkerke Bank has been investigated (Williams et al 2000), the West Dyck and Bassure de Baas (Fig. 20) (Beck et al 1991) and the Kenfig Patches, Swansea Bay (Heathershaw et al 1981).

Suspended load is not considered here though it is briefly considered in the sections on the three strategic areas. Fine grained sediment in suspension does not always follow the same paths as bed load. A map of mean flow paths around the UK determined mainly from observation is given by Lee and Ramster (1979). Comparison of three modelling studies, run for meteorological forcing data available for 39 years, show the variability of circulation patterns (Smith et al 1996).

6.2. Transport paths in the three strategic areas

The second round of offshore windfarm developments is confined to three strategic areas commonly referred to as:

Greater Wash

Thames
North West (Liverpool Bay)

6.2.1. Greater Wash

A bedload transport map has been constructed for the area from Holderness in the north to the Norfolk Banks and the north Norfolk coast in the south (Fig. 15). There are two large estuaries, the Humber and the Wash. Depths on the shelf are mainly about 25 m in the south with shallower depths (less than 20 m) in the north. A linear deep, the Inner Silver Pit, over 40 m in places, runs at right angles to the coast and extends into the axis of the Wash as the Lynn Deeps. It is Holocene in age and may be formed by tidal scour, as for the Lune Deep, Irish Sea (see section 6.2.3.2) and the trenches in the mouths of tidal deltas that have retreated across the shelf as sea level rose (Dyer and Huntley 1999). Glacial highs are known and the Docking Shoal has a glacial till core, though covered with glacial gravels and mobile sands (Evans et al 1998). Two belts of sand banks, of which the Norfolk Banks are the most prominent, extend out from the coast. The other belt lies east of the Inner Silver Pit and runs from the NE edge of Docking Shoal to beyond the Outer Dowsing Shoal. The nearshore banks include the sinuous banks, Haisborough Sand/Hammond Knoll and Race Bank/Dudgeon Shoal. Those more distant from the coast are linear banks whose crests become progressively deeper in the deeper water (Fig. 15).

The Wash has one of the largest areas of tidal flats in the British Isles and its coast has been prograding over the last 2000 years, enhanced by reclamation. Sand banks are found around the margins of the Wash. As is typical for confined sand banks they are wide and at or near the sea surface. Salt marsh is found in the shallower parts of the intertidal area and sands in the deeper parts, especially flanking the centrally located Lynn Deeps.

6.2.1.1. Currents

Tidal currents dominate the bedload transport over most of this shelf (as modelled by van der Molen, 2002). Mean spring near-surface tidal current strength is everywhere over 75 cm/sec and reaches over 125 cm/sec in the eastern, near coastal part of the area (Sager and Sammler 1975). Current measurements from the Wash by HRS, Wallingford, though made with direct reading current meters and obtained over a relatively short period, are reported on by Ke et al (1996). They give useful data about sediment transport paths (section 6.2.1.2).

Surge currents are modelled by Flather (1987) who shows that depth averaged extreme surge currents are high in this area at between 60 and 80 cm/sec (Fig. 29). The main direction of the surge currents is southerly, which will reinforce some bedload transport paths and briefly reverse others. The 50 year surge height for the Wash is estimated at 2.5 m added on to the normal tide.

Maximum bottom stress from tidal currents is modelled by Pingree and Griffiths (1979). A hydrodynamic model for the Inner Silver Pit gives expected values and directions of current in order to predict transport of sediment (Proctor et al 2001). The modelled currents are strong enough to flush fine sediments out of the deep.

6.2.1.2. Sand transport

The asymmetry of bedforms used to help construct the new sand transport map is taken from largely unpublished sources, in particular the data from the Marine Geology Group of the Institute of Oceanographic Sciences, Wormley (Fig. 31) (now held at the National Oceanography Centre, Southampton). Some of this data is in restricted reports (Caston 1968, Johnson and Caston 1984). Where there was a lack of data then other sources were looked to such as the Southern North Sea sediment transport study, Phase 2 (SNS2 2002) and the Future Coast report (Future Coast 2002).

The main pattern is of a southerly directed coastal sand stream separated by a bedload parting from a northerly directed offshore stream (Fig. 15). The coastal stream carries sand from the Holderness cliffs and offshore sources down to the Humber Estuary and on to the Wash. The paths near the Humber are complex and some sand probably follows the suspended material path into the estuary (Dyer et al 2001). Sand enters the Wash, especially in the Lynn Deeps. There may be some transport out of the Wash along the margins, following the tidal residual current (Ke et al 1996) but this is not as yet supported by observations of bedform asymmetry or otherwise proven. Sand transport is southeasterly on Docking Shoal (new swath mapping data, SEA5 2004). The coastal stream is thought to run the whole length of the Norfolk coast and thus the bedload parting off Cromer (Johnson et al 1982) is rejected.

The parting is of the lateral type (Grochowski et al 1993) and is taken to run through the sinuous sand banks such as Haisborough Sand//Hammond Knoll and Race Bank/Dudgeon Shoal, which, as argued in section 3.1.3, indicate no net sand transport.

The northerly offshore stream is based both on isolated patches of asymmetrical large sand waves and on the principle (Kenyon et al 1981) that asymmetrical linear banks can also be used to determine net sand transport paths. North of the Norfolk banks the stream is weakly defined. The pattern is largely supported by the results of modelling of maximum bottom stress for the whole area (Pingree and Griffiths 1979) and for the area around the Inner Silver Pit (Proctor et al 2001). Both of these models fit the bedform data well but both cast doubt on the northerly direction for the area north of the Norfolk banks.

The longshore drift directions (Fig. 15) are from Motyka and Brampton (1993) and McCave (1979).

6.2.1.3. Suspended load transport

There has been much work on mean flows in the southern North Sea (e.g. Lee and Ramster 1979, Eisma 1981). The main source of new sediments, both suspended and bed load, are the eroding cliffs of Holderness, which consist of 67% mud. Rivers supply very little suspended material. Transport through this area is mainly southerly and muds are supplied to the Wash and the north Norfolk coast (McCave 1987). Detailed measurements have been made in the mouth of the Humber estuary, where a ‘flux curtain’ of in situ stations has been established, supplemented by shipborne measurements. This shows that the main input is marine material, moving into the estuary and derived from the cliffs near Holderness (Dyer et al 2001). Current measurements in the Wash show that the mean flow is onshore in the Lynn Deeps and out along both flanks (Ke et al 1996).

6.2.2. Thames

This is a macrotidal estuary with a broad mouth and a high tidal range (up to 6.8 m). Sand has filled the Thames Estuary to a great degree. Much of this sand has accumulated before and during the last rise of sea level and been reworked during and after the rise of sea level. Some sand is supplied today by transport into the embayment and by the breakdown of shelly faunas. The shores of the Thames Estuary are flanked by intertidal flats that reach their maximum extent in the 8 km wide Maplin Sands. The inner and outer estuary are largely filled with sand banks. Long, wide sand banks are best developed in the northern part of the outer estuary (Fig. 17).

6.2.2.1. Currents

The peak tidal speeds in the channels between the banks are generally about 100-110 cm/sec (Sager and Sammler 1975) but reach about 200 cm/sec in some channels (Cloet 1972). Storm surge induced currents will be high but only occur rarely. The surge height in the floods of 1953 reached over 60 cm higher than previously recorded and the predicted maximum surge elevation over a return period of 50 years is about 2.75 m (Flather 1987). The maximum predicted surge current speed is about 40 cm/sec.

Waves are not especially high because of the shelter from the west and south but will nevertheless be particularly effective in moving sediment because of the shallowness of much of the seabed.

6.2.2.2. Sand transport

Asymmetric bedforms clearly show transport of sand into the estuary (Kenyon et al 1981) (Fig. 17). As well as sand waves there are asymmetric scours around wrecks (Caston 1979) that confirm the SSW path towards the outermost estuary. Robinson (1960) has proposed that the outer channels are flood dominant and the inner channels are ebb dominant. However the asymmetry of sand on the flanks of the banks shows that the outermost channels are not entirely flood dominant as they consistently have ebb oriented sand waves on their southern sides. Large sand waves are present on both flanks of the banks but are absent from the flat tops. In all known cases these large sand waves are indicative of sand transport in a clockwise sense around the banks (Langhorne 1973; Caston 1979), as found for most en echelon linear sand banks in this region (Kenyon et al 1981). The banks have steeper flanks on their northern side than on their southern side, this lead Kenyon et al (1981) to propose that the outermost banks should be considered as asymmetric bedforms in their own right and confirm the transport path of sand into the estuary determined from asymmetry of smaller bedforms and tidal current measurements. Because the sand has nowhere else to go the banks should be widening after building up to sea level (Stride et al 1982) and possibly migrating to the northwest.

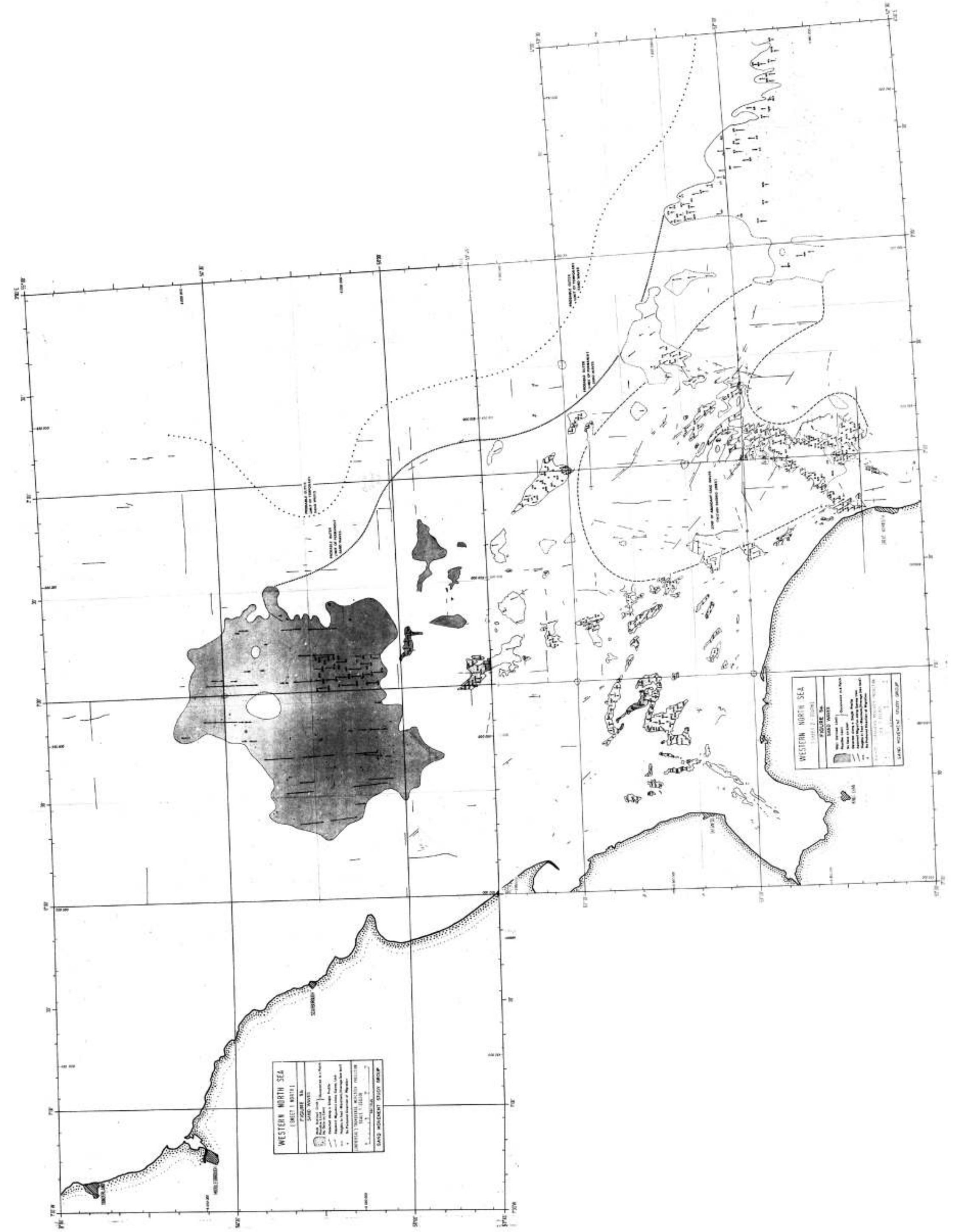


Fig. 31 Distribution of large sand waves in the Greater Wash area from an unpublished analysis (Marine Geology Group, IOS, now NOC).

The outermost banks do not appear to have moved significantly over the period of chart making and it has been suggested that they have cores of older material which may tie them in position (D'Olier 1981). However this is not the case for the Inner Gabbard and the Galloper banks from just outside the estuary which are free to move, though being fairly symmetrical are not likely to be highly mobile (Figs. 12 and 13). Some of the inner banks however have very dynamic movement. A study of the North and South Edinburgh Channels, shipping routes which traverse the 10 km wide Long Sand, shows changes over about 120 years (Cloet 1972). A sequence of charts from 1839 to 1962 show a new bank, about 6 km by 1 km, growing in about 60 years. Another bank (the Shingles Patch) grows from nothing to about 5 km by 4 km within 100 years (Fig. 24). There appears to be a pseudo-cyclical change taking place.

Stride (1988) argues for a movement of sand to the right of the peak current direction because the tidal currents in the Thames Estuary rotate clockwise, and there is a lag time for sand transport that causes sand to be in motion a short time after the time of the peak current. This will only be valid for places where the current is particularly strong as it only applies to sand in suspension. The net result would be to move sand towards the northern side of the estuary, which is indeed where there is most sand.

6.2.2.3. Suspended load transport

The net drift of water is south west in the northern part of the estuary and east in the southern part, which is close to the bed load transport directions of Fig. 17. Much of the supply of new suspended material comes from shoreline erosion. For instance, cliffs of the London Clay Formation on the Isle of Sheppey are retreating by up to 1.9 m/year (Nicholls et al 2000). This supplies silt to the estuary system, especially to the estuaries and marshes of the Essex and Kent coast. These coastal areas are under threat from rising sea level and so any supply of new sediment is welcome. Towards the head of the estuary there are dense clouds of fluid mud flowing in the channels near to the sea floor.

6.2.3. Eastern Irish Sea

The eastern Irish Sea is also called the Liverpool Bay strategic area or North West strategic area in considerations about wind farm planning and legislation. A prominent sedimentary feature of the offshore region is the Eastern Irish Sea mud belt which divides it into an open sea area to the west, where bedload transport dominates, and to the east a coastal area with many estuaries, where complex coastal processes take place. The mud belt is filled with up to 40 m of Holocene sediments, mapped as a well stratified unit by a seismic survey (Williams et al 1981) and sampled by a borehole (Pantin 1977). Details on the complex glacial and early post glacial sediments in the area are provided in Pantin (1978). In places there are ridges and knolls that consist of glacial sediments. A probable glacial pingo, similar to those mapped in the north of the Isle of Man, is seen on the SEA6 survey in the Central area (Fig. 32). These ridges and knolls will not be mobile, in contrast to the sand waves and sand banks.

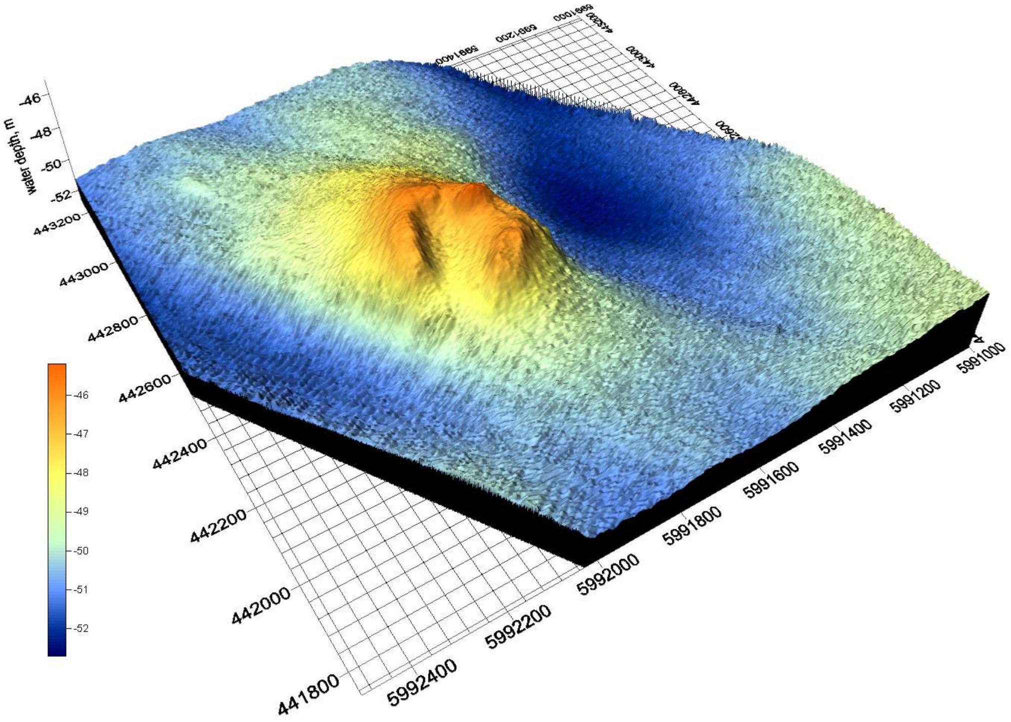


Fig. 32 Probable relict pingo, now up to 5 m high, that has collapsed on one side following the expansion and melting of the original ice core (Mackay 1998). Small sand waves surround the glacial feature.

The understanding of the active sedimentary processes in this area is based on data sets that are mainly 30 to 40 years old as this was one of the first offshore areas mapped by the British Geological Survey and the data was acquired through technologies that are now largely obsolete. Following a scoping study undertaken by the BGS (Tappin 2004) it was noted that there are large areas where geophysical data is absent, especially in the central area between the Isle of Man and the Cumbrian coast. Additionally there is a data gap in shallower waters adjacent to the coasts as well as in the major estuaries of the Solway Firth and Morecambe Bay. Seismic profiles are not of sufficient resolution to map the sand bodies and their internal structure and were rarely run across the sand banks due to navigational worries. The BGS have an extensive grid of samples, mainly Shipek Grab samples and vibrocores. For the most part these were taken at the same stations and are approximately 8 km apart, which is not close enough to confirm all of the mapped categories from the new survey. The navigational accuracy of the sampling stations (approximately 50 m) is also too low as they were based on Decca Navigator radio networks rather than GPS.

As a result of the Scoping Study a survey was undertaken by OSAE from the RV Meridian of selected areas in the Liverpool Bay/North West strategic area (Fig. 33). The areas chosen and studied are here called:

Area 1. Northern Area
    1a-d. Ayre sand system. Isle of Man

1e. Outer Solway Firth
Area 2. Central Area
Area 3. Southern Area, Constable Bank
Area 4. Outer Morecambe Bay
There was also a Cumbrian coast transit.

The Outer Mersey and Dee Estuaries were chosen as a lower priority by the Scoping Study (Tappin 2004) and were eventually dropped from the survey as they had been better studied in recent times than the other areas.

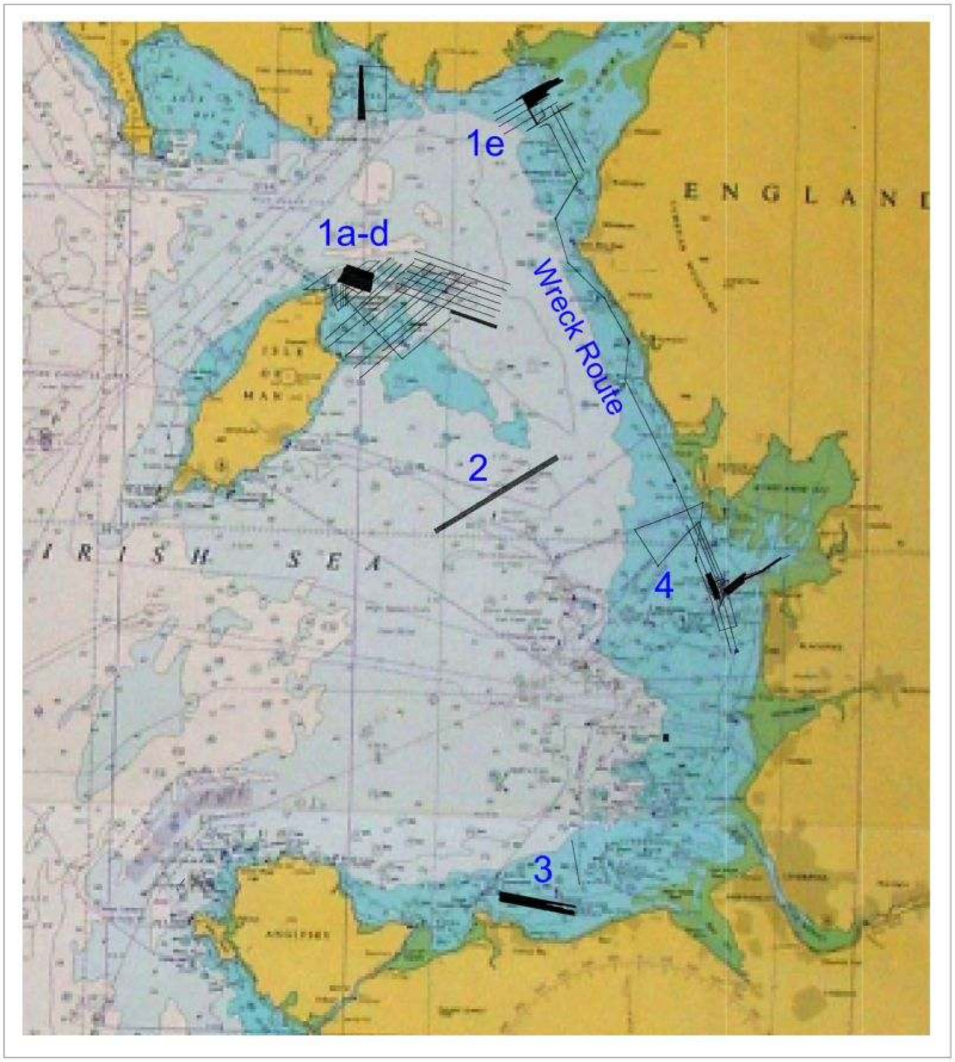


Fig. 33 Geophysical coverage from the 2004 SEA6 survey by RV Meridian in Liverpool Bay/Northwest strategic area

6.2.3.1. Currents

Bedload transport is controlled by peak currents. The direction is determined by the asymmetry of the tidal current ellipse, together with any input from surge induced currents. The peak tidal currents for the eastern Irish Sea are shown by Sager and Sammler (1975) to decrease to the east, away from the narrows between the northern Isle of Man and the Scottish coast and between the southern

Isle of Man and the coast of Anglesey. Peak tidal currents are at a minimum east of the Isle of Man, in an area corresponding to the Eastern Irish Sea mud belt. There is much additional current meter data, including measurements from meter arrays at various heights above the sea bed, because of the work of the Bidston Observatory (POL) and of CEFAS, Lowestoft and Burnham, in this area. Current meter data for the wider area is reported in Robinson (1979) and for the approaches to Morecambe Bay by Aldridge (1997). This data largely confirms the charts of Sager and Sammler (1975). Modelling of tidal currents (Pingree and Griffiths 1979) fits well with the observations of current, bedforms and seabed sediment type. An even better fit is with the bed stress maps of Davies and Jones (1996) (Fig. 34). As well as predicting the belt of weak current in the middle of the shelf, the models add some detail where measurements are sparse such as near to the English coast, where they show a large increase in peak current speed/bed stress in the approaches to the estuaries. This increase in peak speeds in the estuaries and near headlands would be expected because of the relatively high tidal range (up to about 8 m). Storm surge elevations are predicted to be quite high (Flather 1987), up to about 2 m, which should give significant sand transport in shallow water, but peak surge current speeds in offshore areas are only moderate, about 20-40 cm/sec, and should play relatively little part in bedload transport.

Waves have been much studied in the eastern Irish Sea. Being a nearly enclosed basin there is little effect from Atlantic swell waves, however the 50 year maximum wave heights are still 14 to 17 m (Draper 1991), similar to those in the Southern Bight of the North Sea. Wave heights in shallow water will be lower than these values. Motyka and Brampton (2001) quote up to 4.7 m heights for the 1 year wave. Where banks are present there will be higher values on the seaward side of the banks. This effect may account for some of the differences between the northern, exposed side of Constable Bank and the southern, sheltered side. On the northern side and on the top of the bank the sand waves are lower in places than on the southern side (Fig. 44) as well as being rounded crested at the time of the survey. Long period storm waves will be dominant in shallow areas, such as the tops of sand banks and coastal shallows and also where tidal currents are weak, such as in the east Irish Sea mud belt, east of the mud belt along the coast of the Lake District and east of the Isle of Man north of about the latitude of Douglas.

Suspended load transport is in the direction of the mean flow. For this area the mean flow is complex, as shown by the different versions of Lee and Ramster (1979), Bowden (1980) and Pantin (1978), and changes with wind direction. Several workers suggest a two layered circulation. An overall path that is weakly to the north is confirmed by transport of radionuclide material out through the North Channel (e.g. Leonard et al 1997). Much of this radionuclide material is transported to the mud belts, west and east of the Isle of Man, where it accumulates. Suspended materials can move rapidly. Elevated levels of discharge from Sellafield can be traced in the North Channel after approximately 3 months and in the North Sea after approximately 9 months (Leonard et al 1997).

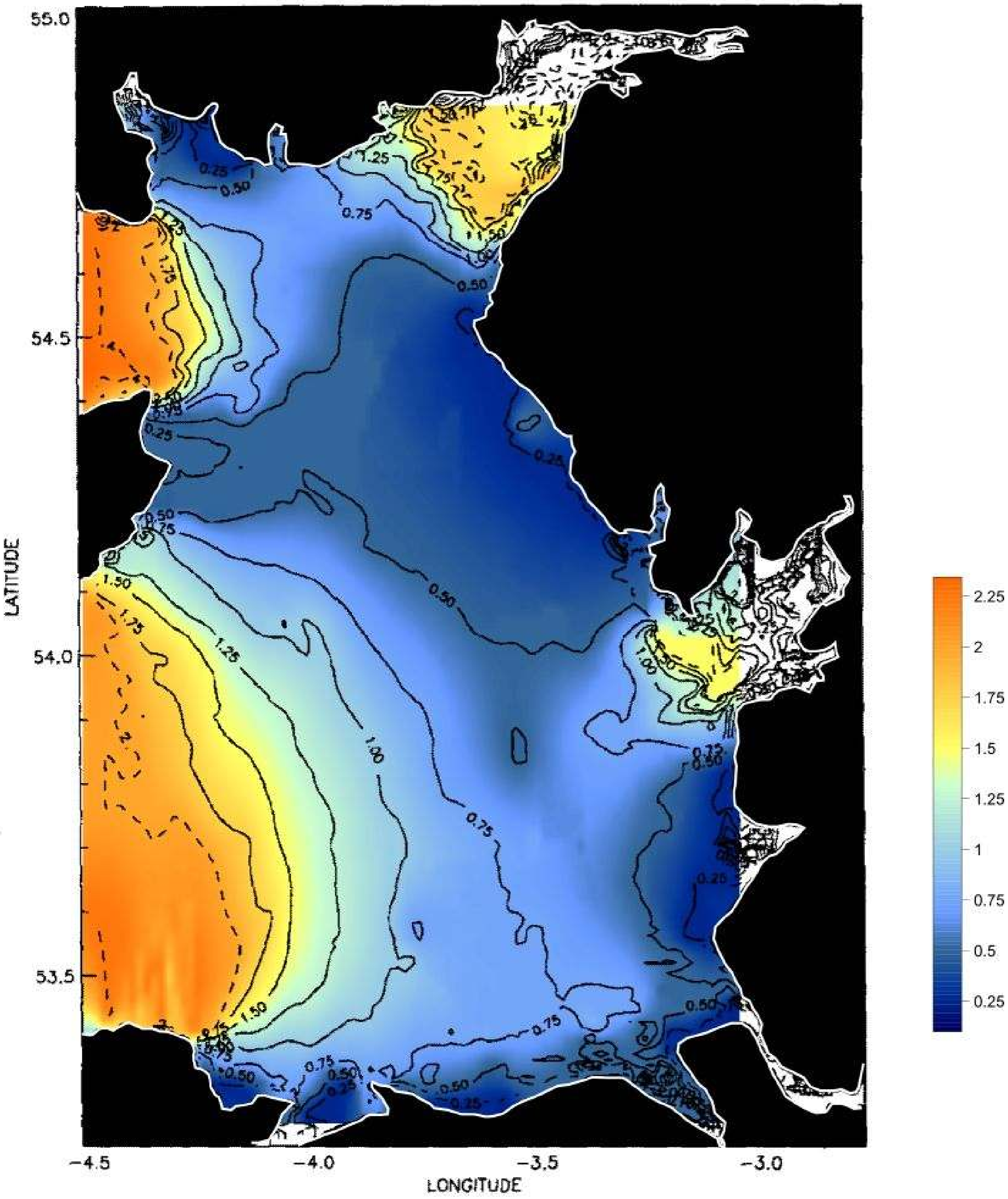


Fig. 34 Maximum bed stress from modelling by Davies and Jones (1996)

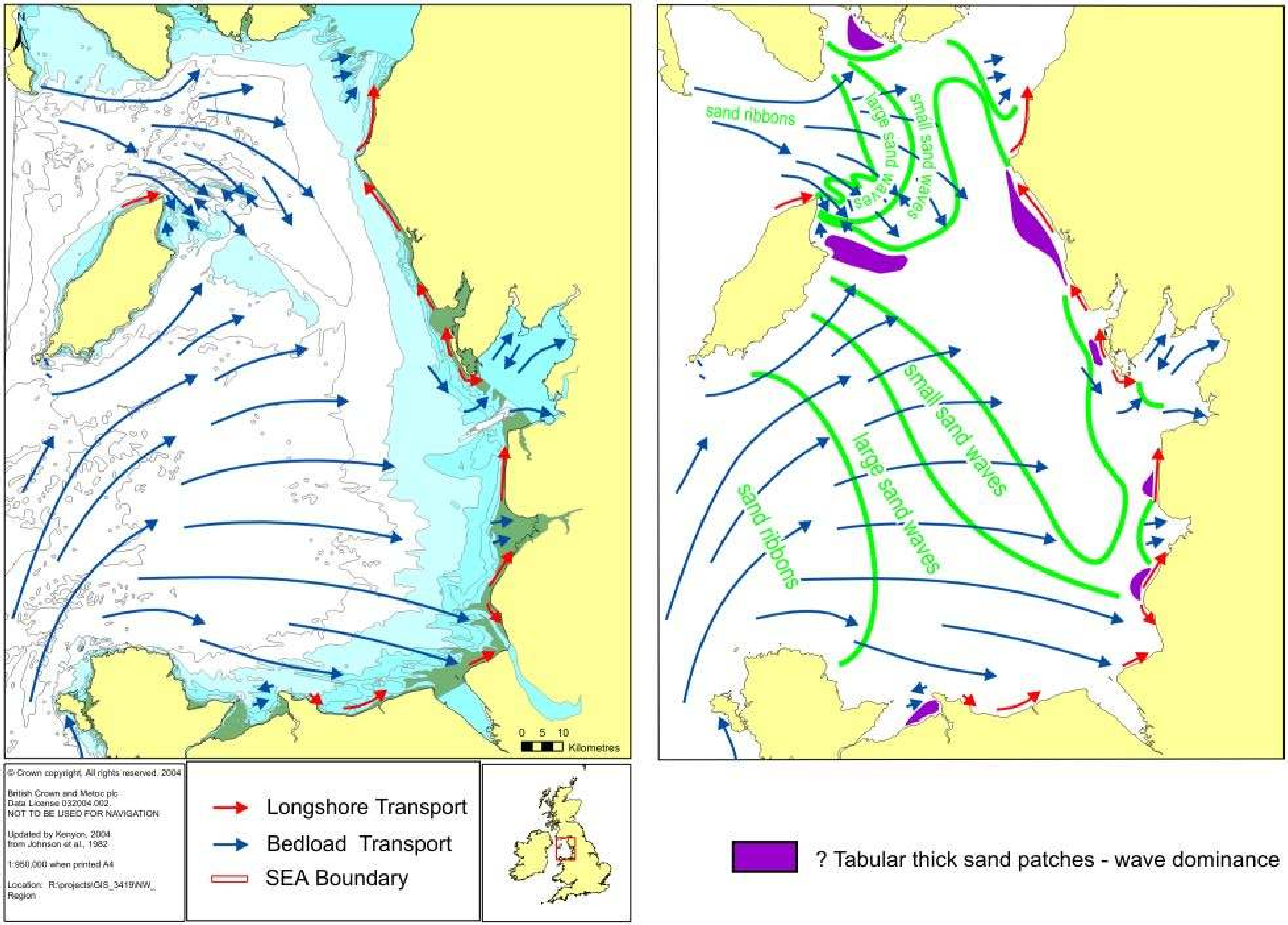


Fig. 35 Sand transport paths and bedform zones in the North West (Liverpool Bay) strategic area.

6.2.3.2. Introduction to sand transport in the eastern Irish Sea

The seabed sediments and bedform zones are compatible with knowledge of currents and waves (Fig. 35). Transport paths of bedload are into the eastern Irish Sea from the west as shown by observations of sand wave asymmetry (Belderson and Stride 1969; Jackson et al 1995) and tidal current asymmetry (Fig. 35). Sand moves eastwards towards the English coast along a decreasing gradient of peak currents. It is unable to cross the Eastern Irish Sea mud belt because the peak currents are too weak. Thus the only region where there is long distance transport of offshore sand to the nearshore is in the south where the mud belt is absent. (It is possible that there is a “weak” sand transport path towards the Solway Firth along the seafloor south of Scotland, an area that has not been surveyed to check for the presence of small asymmetrical sand waves and/or a rippled sand sheet). The inshore areas of Liverpool Bay (sensu stricto) have extensive banks and tidal flats that are at or near to sea level. Mapping on the Wirral coast indicates that foreshore levels are increasing at a relatively rapid rate (reported in Motyka and Brampton 2001). Transport of sand into an embayment such as Liverpool Bay is the norm, as is seen on the map of bedload transport paths for the shelves of northwest Europe (Fig. 25).

Sand banks are found north and northeast of the Isle of Man. On either side of the Point of Ayre there are several banks. Little was known about them prior to the SEA6 survey of 2004 (see below). Because the headland consists of loose sediment the innermost banks were thought to be possibly of the moving headland banner bank type. The three long outer banks, found to the east of the Point of Ayre (Bahama, Ballacash and King William banks) were thought to be possibly of the open shelf linear type, though they may have once been formed as banks tied to an earlier position of the headland. That they are currently active sand banks seemed likely as they are built up to near the sea surface, in an area where peak current speeds are about 120 cm/sec. It was not known whether they were oriented anticlockwise with respect to the current (as usual for the northern hemisphere) but this was expected as they are steeper on the south side. The sand transport path south eastwards of the sand banks, that runs towards the Eastern Irish Sea mud belt, was also poorly known prior to the 2004 survey.

Apart from small banner banks tied to the headlands of Anglesey there are many banks in the wide embayment of the approaches to Liverpool and filling a large proportion of the many wide-mouthed estuaries. Little is known about the banks in the southern approaches to the Dee and Mersey estuaries. They are unusual in that, unlike banner banks, they do not have a gap at the coast and some are without a steeper side and are not built up to near sea level, though the long Constable Bank is steeper to the south. It was proposed, prior to the new survey, that some could be banks formed at lower sea level that are now being reworked rather than maintained by active bank building processes. The inner banks are typical of the wide banks of estuary mouths and have moved dramatically since long retaining walls were placed at the entrance to the channel leading into the Mersey in the 1920s and 1930s. A very thorough study of a small area, 30 km west of the Mersey, where sewage sludge is dumped, indicates that sand movement is towards the east (Norton et al 1984). A numerical model for sand transport, using HR Wallingford’s SANDFLOW-2D model, produces the known easterly transport due to flood tidal dominance in the offshore areas but does not take account of the enhanced transport expected in inshore areas due to the addition of wave induced currents. The directions of transport in these nearshore areas should be nearer to shore parallel and should be easterly along the north Wales coast and northerly along the Wirral and Sefton coasts (Motyka and Brampton 2001). This agrees with the observations of asymmetrical bedforms (Sly 1966, Belderson and Stride 1969, Jackson et al 1995). The application of sediment trend analysis also shows this easterly sand transport (Williams 2001).

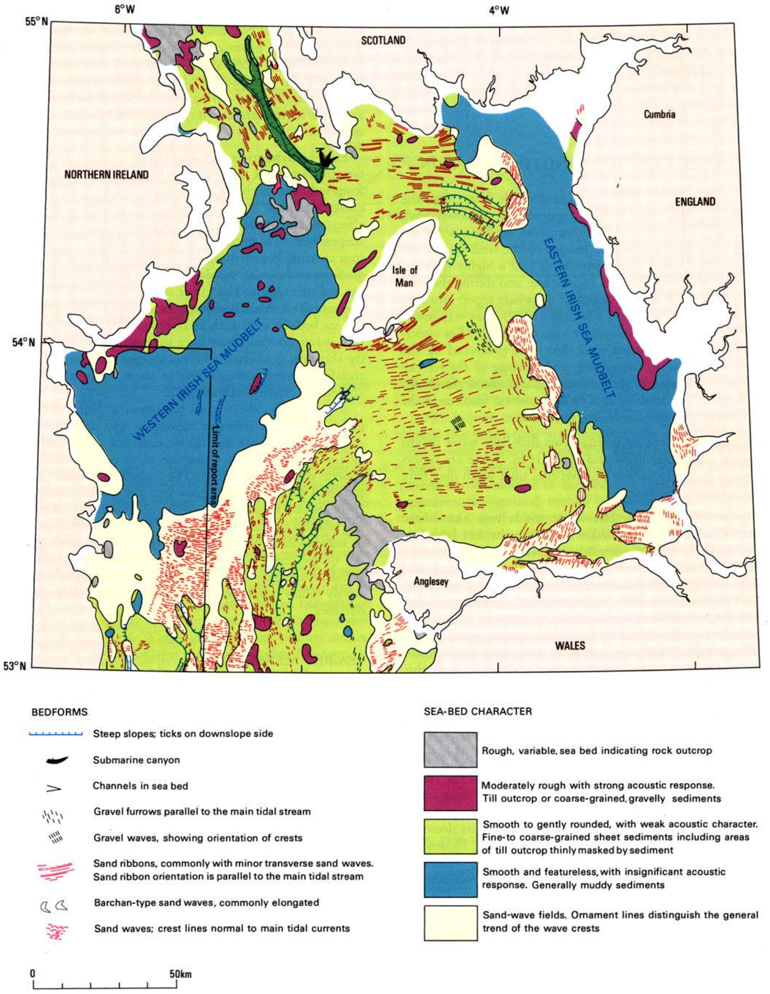


Fig. 36 The character of the seabed and the distribution of bedforms in the eastern Irish Sea (Jackson et al 1995). This map is largely from the thorough and careful work of the late Robin Wingfield of the BGS.

The banks in the wide-mouthed estuaries are themselves wide and built up to sea level, resulting in extensive tidal flats. The main channels, for instance that on the south side of the Solway Firth and the Lune Deep in the centre of Morecambe Bay, are sites of strong current and gravel floors. The movement of sand east of the mud belt is poorly known apart from observations on beaches and tidal flats. It would be expected, from modelling studies (e.g. Pingree and Griffiths 1979) and from tidal theory of wide-mouthed estuaries (e.g. Dyer and Huntley 1999) that overall bedload transport would be into these estuaries. A detailed model of Morecambe Bay (Mason and Garg 2001) shows that tidal asymmetry is the dominant agent and that flood paths dominate except in parts of the outer estuary. Their model is tested by study of repeat Synthetic Aperture Radar images of the changes to the waterline over a period of 5 years. No bedform asymmetry or other morphological evidence of the sediment transport paths in these estuaries has been presented in the open literature e.g. by McLaren (1989) for Morecambe Bay, reported in Mason and Garg (2001). McLaren (1989) uses a method based on analysis of grain size trends that is useful but has some limitations unless backed up by other evidence (see section 9). He has also done an analysis of bed stress (Fig. 50) that is more detailed than that of Pingree and Griffiths (1979). Study of 150 years of bathymetric charts of the Ribble Estuary show a clear history of accretion (van der Wal and Pye 2003, van der Wal et al 2002).

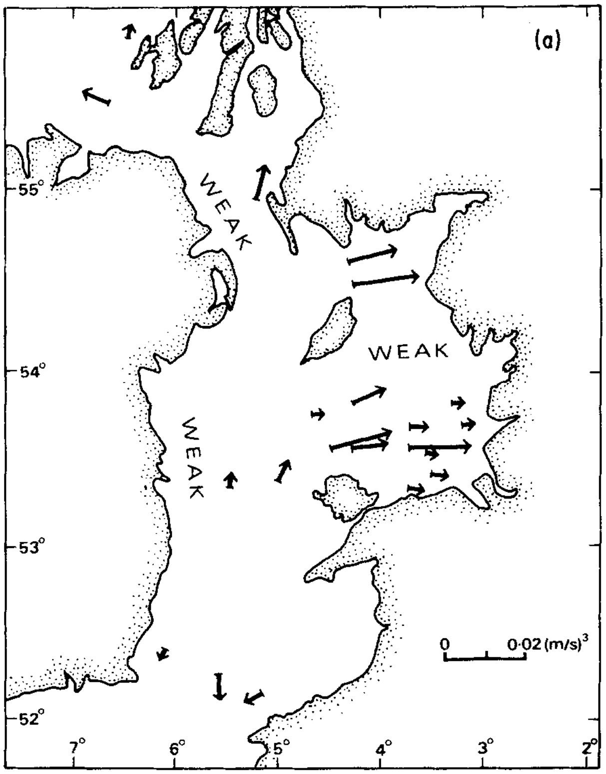


Fig. 37 Net directions and relative magnitudes of sand transport in the eastern Irish Sea, computed from current observations for approximate mid depth (analysis by M.J. Howarth in Johnson et al 1982).

The pattern of longshore drift on Fig. 35, taken mainly from Motyka and Brampton (1993), is in towards the Mersey, Ribble, Morecambe Bay and Solway Firth.

6.2.3.2.1. The SEA6 survey by RV Meridian

The survey was carried out between 4th and 24th August, 2004. The tides at that time were in a neap cycle (Fig. 38) and so it would be expected that there was little sand transport during the cruise.

The swath bathymetry system used, a RESON 8101, was of high resolution. One of the valuable aspects of the swath maps is that they were not heavily filtered to remove some of the smaller mobile bedforms such as small sand waves (the dunes or megaripples of some authors). The swath map of the Sandy Riddle for instance (Fig. 7) does not show these small sand waves though they will have been present. At the time that the RV Meridian survey was carried out there was little movement of these small sand waves as crest lines on adjacent swaths could always be perfectly matched even though there were some lines that were surveyed up to about two days apart. It would seem advisable to do swath bathymetry surveys designed to study sediment transport processes near to neap tides, and preferably in a period without the storms that greatly enhance sand transport, if the valuable data from the smaller bedforms is to be included on swath mosaics.

It is acknowledge that small sand waves can change asymmetry direction over a tidal cycle at times of especially high current speed. However in all areas surveyed small sand waves had the same sense of asymmetry as the large bedforms and as the measured and modelled currents. Thus they seem here to be useful indicators of longer term sand transport paths.

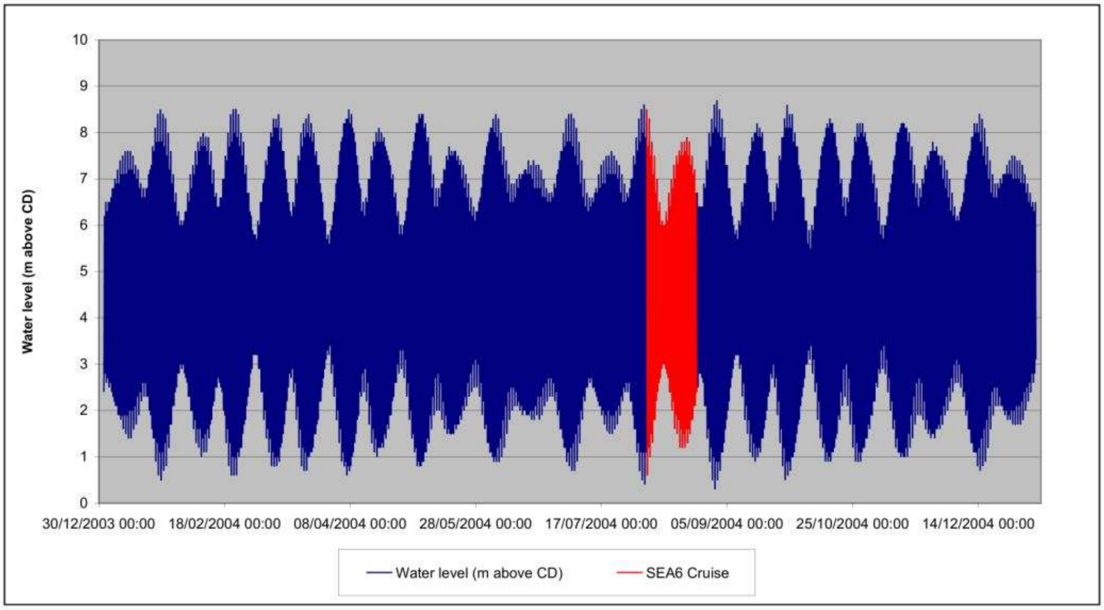


Fig. 38 Position of the first leg of the RV Meridian cruise in relation to the tidal cycle for 2004.

6.2.3.2.2. Area 1a-d. Northern Area, Ayre sand system, Isle of Man

Little is known about the sedimentary processes on the transport path that runs eastwards from the area of strong current north of the Isle of Man towards the area of weak currents where the Eastern Irish Sea mud belt is located. On land there is a plain of soft Quaternary sediments extending for 12 km from the foot of the hills of Palaeozoic rocks to the Point of Ayre. There are 25 km of cliffs along this northern plain with diverse glacial sequences (Chadwick et al 2001). Active beach processes here are a part of the circulation of bedload and may supply some of the extensive tidal sand deposits that are found offshore (Rouse 1991) (Fig. 39). Along the northwestern coast in the low lying region called the Ayres there are accreting beach ridges. Thirty metres is said to have been added in 50 years near Rue Point (www.gov.im/daff/countryside/wildlife/ayres.xml). Most of this material has been eroded from the low cliffs to the south and moved northwards as longshore drift forced by the prevailing southwesterly winds. For example during a single storm in 1946 a 2 m wide strip was eroded from 2 km of the cliffs (Chiverrell and Thomas 2005). Along the northeast coast the sands, gravels and clays of the terminal moraine that form the Bride Hills have been eroded to form an up to 80 m high cliff. The Bride Moraine is one of the largest moraines in Britain (Thomas 1984). Other glacial formations form low cliffs that are also being eroded. The rate of this erosion is reported to be as much as 1.2 m per year in places and transport is north towards the Point of Ayre. The eastern end of the beach ridges that form the Ayres are also being eroded. It seems likely that during the rise of sea level since the formation of the Bride moraine that very large amounts of coarse sediment were redistributed and that a high proportion of this material went into the offshore tidal sand system and continues to do so.

A grid of reconnaissance lines was run between the Point of Ayre and a line extending east from Maughold Head, which forms the southern limit of Ramsey Bay. The intention was to understand the extent of tidal sand bodies and to further detail the bedload transport paths. There is the usual complexity of sedimentary pattern but nevertheless bedform/bottom type zones were mappable (Fig. 39).

Sand banks

There is a small bank, the Strunakill Bank, west of the Point of Ayre, that is 2 km long. It seems from the single crossing to be an active sand bank as it is covered by sand waves. The 2.5 km long Whitestone Bank, which is the innermost bank east of the Point of Ayre, is more problematical. Although coverage is only partial, no sand waves are identified on the bank. The bank is rounded in profile in contrast to the Ballacash and King William banks. The current speed is high and the sediments appear from the high backscatter to be coarse. No penetration was seen on the profiler, though the profiler was not really suited to mapping thick sands. It is supposed from this limited evidence that this is a composite body including some reworked coarse glacial material and is not a proper tidal sand bank.

The 8 km long Bahama Bank extends from the sand ribbon/erosion zone, through the zone of large sand waves and into the zone of small sand waves. The southern end of the bank is unlikely to be maintained by currents active at the present day as they are too weak and so this bank is thought to be in part a relict of lower sea level and stronger currents than are present today. However there is no supporting seismic data.

The 11 km long Ballacash Bank appears to be a fairly typical active tidal sand bank (Fig. 40). It is surrounded by gravel floors across which sand ribbons are moving and thus falls mainly within the sand ribbon zone. The zone of large sand waves is identified at its easternmost end. The bank is covered by large sand waves, which in turn are covered by small sand waves. It is asymmetrical and steep towards the south. The asymmetry of the sand waves, both large and small, shows it to be maintained by bedload convergence towards the bank crest. The bank is rotated anticlockwise with respect to the southeasterly sand transport path.

King William Bank is similar to Ballacash Bank. It is 11 km long, steep to the south and has converging transport towards the crest. Both of these banks have smaller longitudinal bodies, covered by sand waves, extending east of them. They may be equivalent to the sand shoals that Bastos et al (2003) map beyond the banks tied to Portland Bill but unlike those Fixed headland banner banks the Ballacash and King William banks are over 5 km from the Point of Ayre, which is in any case a headland that is changing shape throughout the Holocene.

Sand ribbon/erosion zone

This zone extends from near to the Scottish coast to near to the southern end of the sand banks. Backscatter is high due to a basal bed of gravel and sediments of coarser grade. In places it is probable that there are well sorted sheets of coarse sediment that are in equilibrium with the peak current prevailing at that point (Stride et al 1999). Across the basal bed, sand that is out of equilibrium is moving eastwards towards a point where it will become in equilibrium. The characteristic bedform here is the longitudinal sand ribbon. The sands are mainly shelly material, carbonate content of the sand fraction being typically 40 to 60 % (BGS sea bed sediments and Quaternary geology map).

Extensive areas of very low wavy bedforms (Fig. 41) with a wavelength of about 8 m and a characteristically irregular shaped crest line (Fig. 42) correspond to areas that have been mapped as beds of *Modiolus modiolus* (Mosley, pers. comm.). Reefs of *Modiolus* occur in strong currents north of the Lleyn Peninsular and Anglesey and south of Langness, Isle of Man. The mussels form a dense mat that can incorporate the pebbles of the substrate and are sites of rich biological diversity (see chapters in Sanderson et al 2001). This acoustic facies type has a patchy distribution. The small sand waves that occur nearby at the foot of Ballacash Bank have crest lines that are distinguishable by being straighter (Fig. 42), having a lower value of acoustic backscatter and also forming more elongate patches or more extensive areas. The waves in the area of *Modiolus* were the most difficult to see on the three dimensional figure of small wave types (Fig. 42) in which all types were plotted at the same vertical and horizontal scales. Trains of gravel waves also have high backscatter but it is usually possible to distinguish them by their straight crests (Belderson et al 1982). There was one area where the origin of the seabed waves was not clear from their appearance on the geophysical survey alone (Fig. 41).

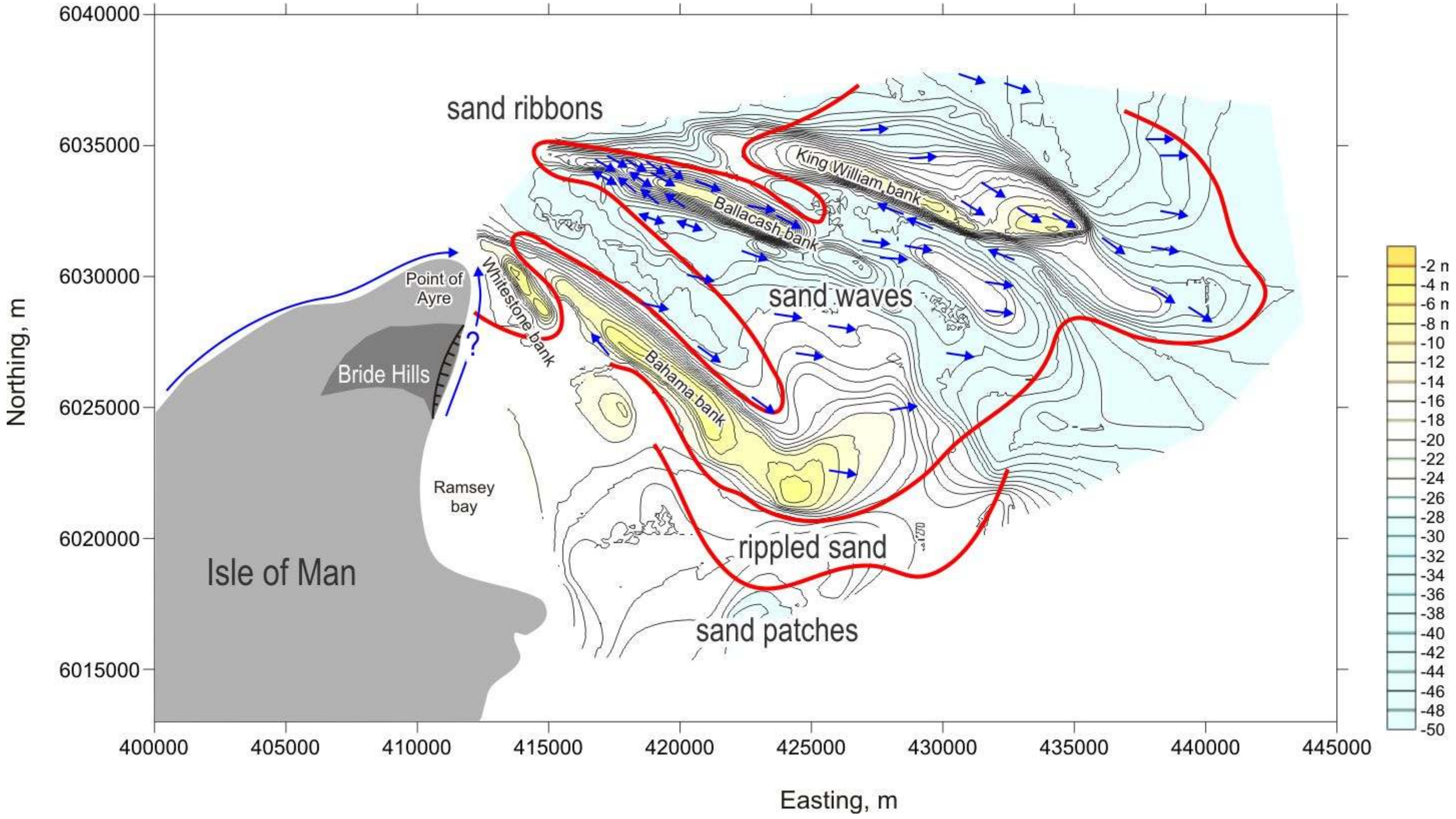


Fig. 39 Bedform zones and bedload transport paths in the area of tidal sands northeast of the Isle of Man.

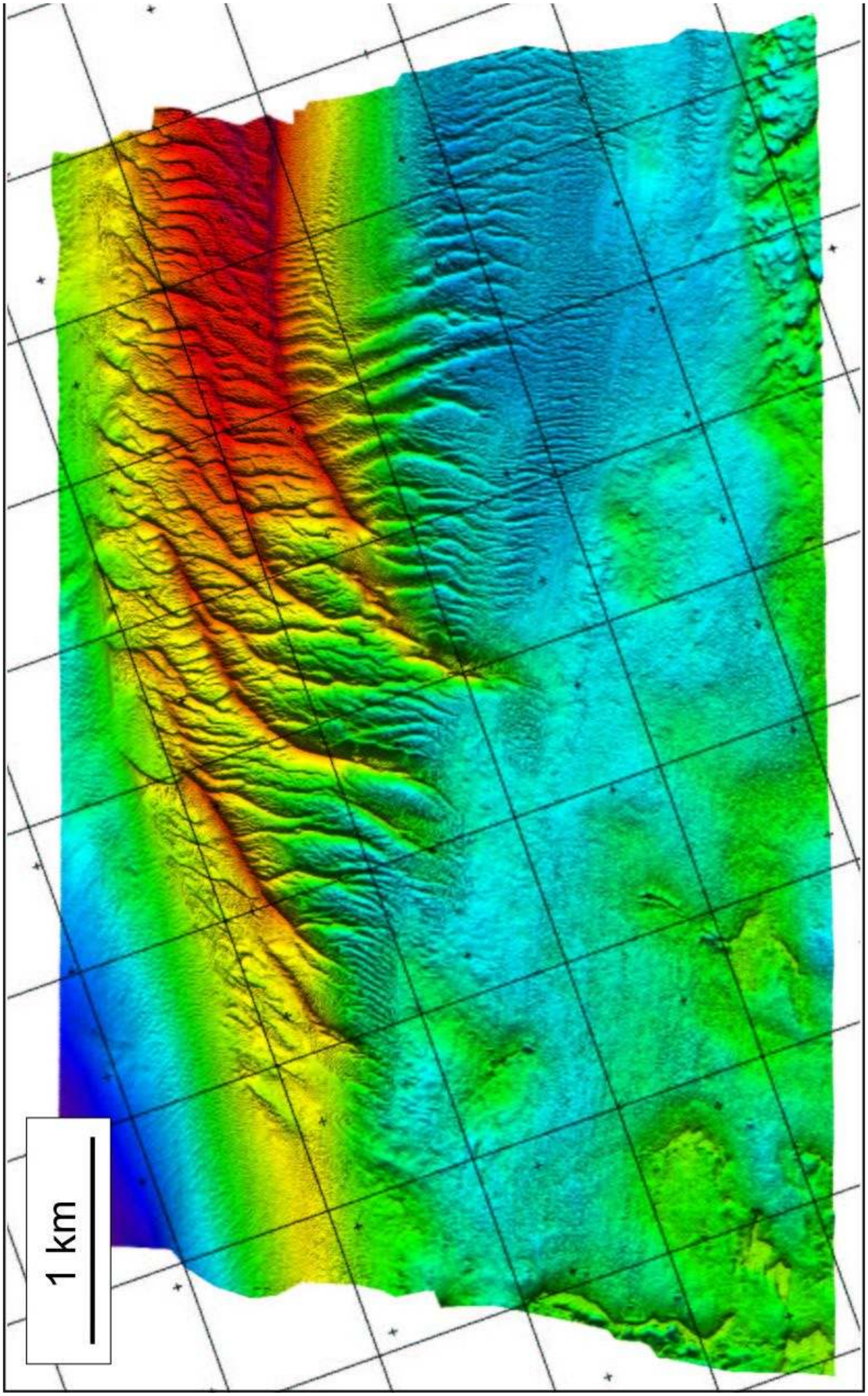


Fig.40 Swath bathymetry of the western end of the Ballacash Bank. Intrepretation in Fig. 38.

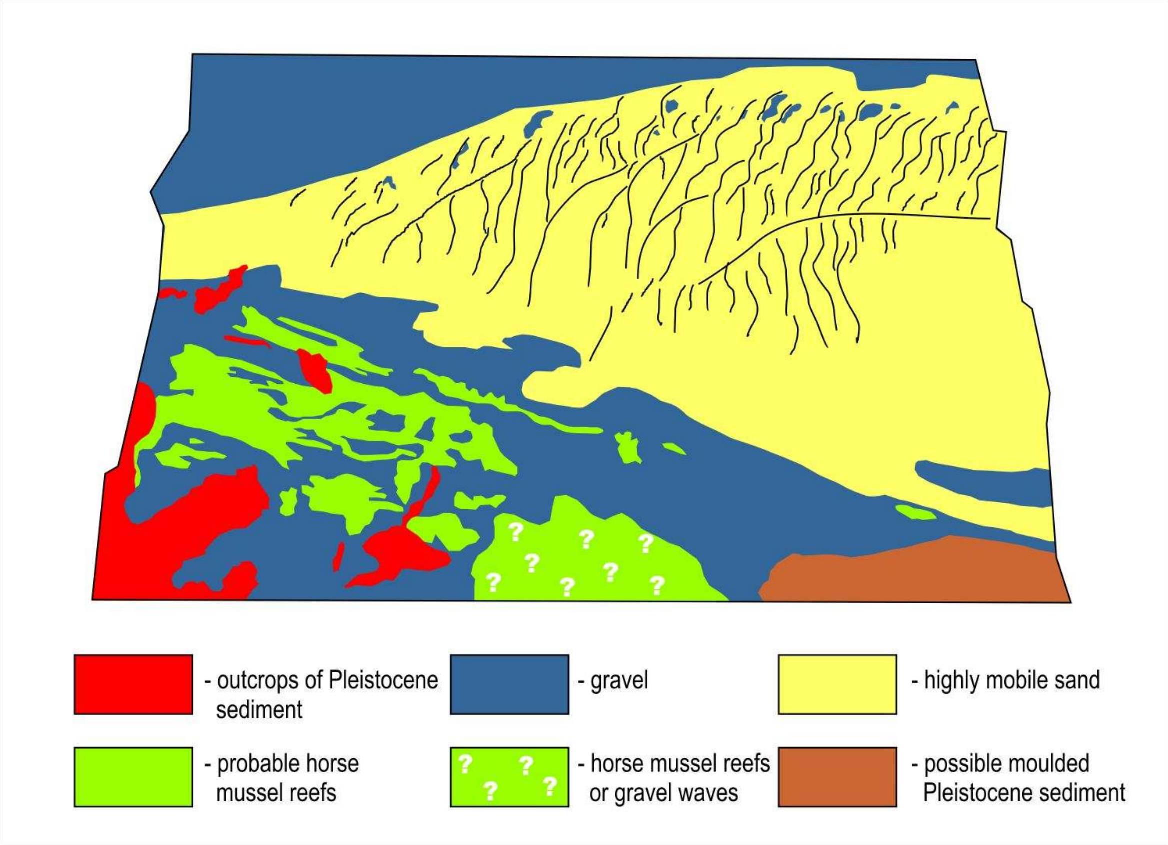


Fig. 41 Provisional interpretation of bedform zones near the western end of Ballacash Bank, Isle of Man.

Large sand wave zone

There is an extensive zone of large sand waves extending from the eastern end of the sand banks. It has a width of up to 10 km. All of the sand waves are steeper on their eastern side apart from in a narrow band on the southern flanks of the sand banks, where they are steeper on the western side, as would be expected for active sand banks. The waves south of King William Bank are of a different shape from the others (Fig. 42). They are not parallel crested but form a regular linguoid pattern. This may be due to some variation in current direction though it is not obvious why it does not also occur on the north side of the bank.

The thickness of the sands in this zone is probably variable as there are shallower areas lying within it that may be sand bodies. Three are mapped from the bathymetry that was hand drawn from the open grid of reconnaissance lines (Fig. 39). All three are elongate in approximately the direction of the sand banks and are about 2 km wide. The shoal connected to the southeastern end of Bahama Bank, is about 5 m high and bends northwards. The longest one extends east of Ballacash Bank, is about 10 m high but is not connected to it. One extends from the eastern end of King William Bank and is up to 30 m high on its north side. They may be relict sand banks from a time of lower sea level in the present cycle or from a previous sea level cycle.

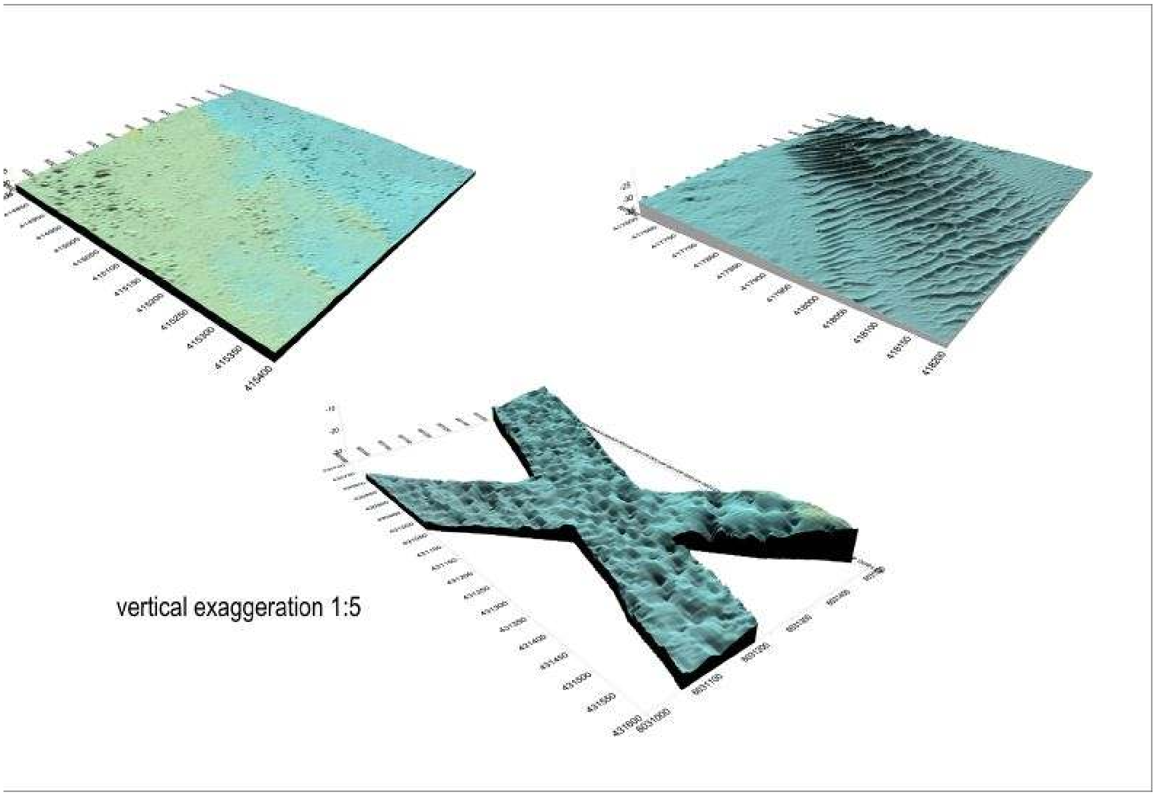


Fig. 42 Types of wavy bedform in the northern area. Top left, possible Modiolus reefs. Top right, typical small sand waves. Bottom, linguoid sand waves south of King William bank.

Small sand wave zone

This zone lies in a belt of weaker bottom stress than the large sand wave zone. Its outer limit is clearly mapped by the high resolution swath survey and is probably better mapped here than has ever been reported for a small sand wave zone in tidal seas. It is variable in width as the large sand waves tend to occur on the elongate shoals. The greatest width seen is 11 km. As for the Area 2, Central Area (reported below) there is a tendency for there to be a longitudinal fabric to the small sand waves (with some similarity to the long bedwaves of Knaapen 2001) in places and for the sand wave wavelength to be slightly smaller near the outer limit. All of the small sand waves were steeper on their southeastern side. Such small bedforms can be reversed in direction during times of peak springs or when tidal currents are enhanced by storm surges and waves but throughout this survey all directions of large and small sand waves were consistent.

Rippled sand sheet zone

This zone is mapped by its low backscatter on the sidescan data and by its absence of bedforms on the swath data. It is known to occur elsewhere, such as in the southern North Sea (Stride et al 1982), and fits with the extent of sand mapped on the British Geological Survey (1:250,000 series, Seabed sediments and Quaternary Geology). There will be limited sand transport within the zone, probably in the same southeasterly direction as shown by asymmetrical bedforms and measured and modelled currents.

Thick tabular sand patch zone

As discussed in section 5.4. this bedform is an indicator of seabed sediments where transport is dominated by waves. Tidal currents are too weak to transport sand except when they are enhanced during storms. The transport will be by a sweeping action from the gravel floors between the sand patches and up onto the patches and there should be no net sand transport. The changes to shape of the patches are expected to be minor except on the rarest of occasions.

The sand patch zone was only found in the southwest of the mapped area, east of Maughold Head.

Conclusions

The reconnaissance approach taken seems justified by the results. Almost the whole of the offshore part of the Ayre bedload transport system was covered by the grid of lines, though a more conclusive result would have been obtained if there had been more coverage of the area nearest to the coast both to the west and east of the Point of Ayre. It was unfortunate that the seismic system was unable to penetrate into the larger sediment bodies.

There is an active sand transport system with links between the beaches and the offshore banks and sand sheets. There are possible relict ridges including the innermost banks, Whitestone Bank and perhaps Bahamas Bank, both of which seem to have little sand grade material. The three elongate shoals beyond Bahama, Ballacash and King William Banks are possible relict sand banks and there may be cores of older tidal sand deposits underlying the very active Ballacash and King William Banks. However these two banks could be free to migrate in a southerly direction as described in section 4.3. The latter two banks could be classified as open shelf linear banks that originated as moving headland banner banks. They are oriented anticlockwise with respect to the net sand transport path. The offshore sand transport path is to the southeast. Sand will not be able to be transported in the zone of wave dominated bedforms east of Maughold Head. The main conclusion of this work is that it has been possible to demonstrate from a brief geophysical survey that this sand circulation system goes from onshore to offshore but cannot go from offshore to onshore, unless it does so west of the Point of Ayre.

The budget of sand in the system can only be surmised. It is probable that very large amounts of sand and gravel were derived from the Bride Hills moraine during the last sea level rise. It is certain that it is still being supplied from the erosion of cliffs and beach ridges as erosion is very much greater than deposition along the coasts of the northern plain. The present day supply of sand will also include broken down shelly material coming mainly from the sand ribbon zone, although this is not a great amount as the carbonate content of the sand fraction, derived from the few samples, is less than 10 % (Wingfield 1985).

6.2.3.2.3. Area 1e. Northern Area, Outer Solway Firth

The Solway Firth is an area of very high bedstress directed into the confined estuary (Davies and Jones 1996). Little is known about the sand body geometry or the bedload transport paths. Sand banks fill most of the estuary apart from the channel in the south along the coast of Cumbria. As in typical confined (estuary) sand banks the banks are wide and have built up to form extensive tidal flats at low tide.

Several reconnaissance lines were run to establish the outer limits of mappable bedforms and to get an overall view of the outer part of the outermost banks. As a result the north side of the Two Feet Bank was chosen for a complete coverage together with the channel to the north of Two Feet Bank. The Two Feet Bank is very wide, 8 km, and low, about 10-12 m high/thick. Seismic profiles revealed that the bank sits on an underlying horizon which implies that there has been outward growth across a seafloor that is presently about 15 m deep. The bank shape is very smooth and streamlined with no marked asymmetry in cross section. Unusually there is an almost total absence of large sand waves whereas small sand waves are near ubiquitous. These small sand waves are very small, wavelength of less than 10 m, except for in the deeper water around the foot of the bank where they have a wavelength of up to 60 m. Nearly all of the sand waves on Two Feet Bank were asymmetric and steeper on the northeast side. A few small sand waves on the south side of the next bank to the north were steeper on the southwest side. There are several shoal patches on top of the bank and it was noted that there were considerable changes in the location of these shoals since the last survey that we are aware of in 1936-1938 (Admiralty Chart 1346). Deeps occur between banks that are floored with sand for the most part, as indicated by the sand waves and the low backscatter on the sidescan records. Only the major channel to the south has a coarser floor.

In conclusion these banks of the outer Solway Firth represent extreme examples of the confined (estuary) sand bank type in that the estuary is especially choked with sand. The ratio of width to height is about 700: 1 compared with less than 250:1 for the confined sand banks of the Thames Estuary and 50:1 for the open shelf banks outside the Thames Estuary. There is an absence of large sand waves and little sign of asymmetry or obliquity of banks to overall transport paths. The development of channels is more in keeping with their being ebb or flood dominated channels than is seen in the Thames Estuary where obliquity to the overall transport path is seen (Fig. 17).The net transport path is clearly in toward the embayment. If one applies the argument of Stride (1988), that sand in suspension may be transported in the direction of the rotation of the tidal currents, then the sand here should move anticlockwise of the peak current direction as the currents here rotate anticlockwise (Sager and Sammler 1975). This is in agreement with more sand being present on the north side of the Solway Firth.

6.2.3.2.4. Area 2. Central Area

The area between the Isle of Man and the coast of southern Cumbria was chosen because there is little geophysics coverage here and it also offers a relatively straight forward example of a typical bedform sequence along a bedload transport path that runs down a velocity gradient (Fig. 44), as in the outer Bristol Channel (Belderson and Stride 196), the western English Channel (Belderson et al 1982) or the southern North Sea. Study of this traverse was expected to provide evidence for the limit of bedload transport even though it should be a complex boundary, varying with depth, and lying somewhere close to the edge of the Eastern Irish Sea mud belt.

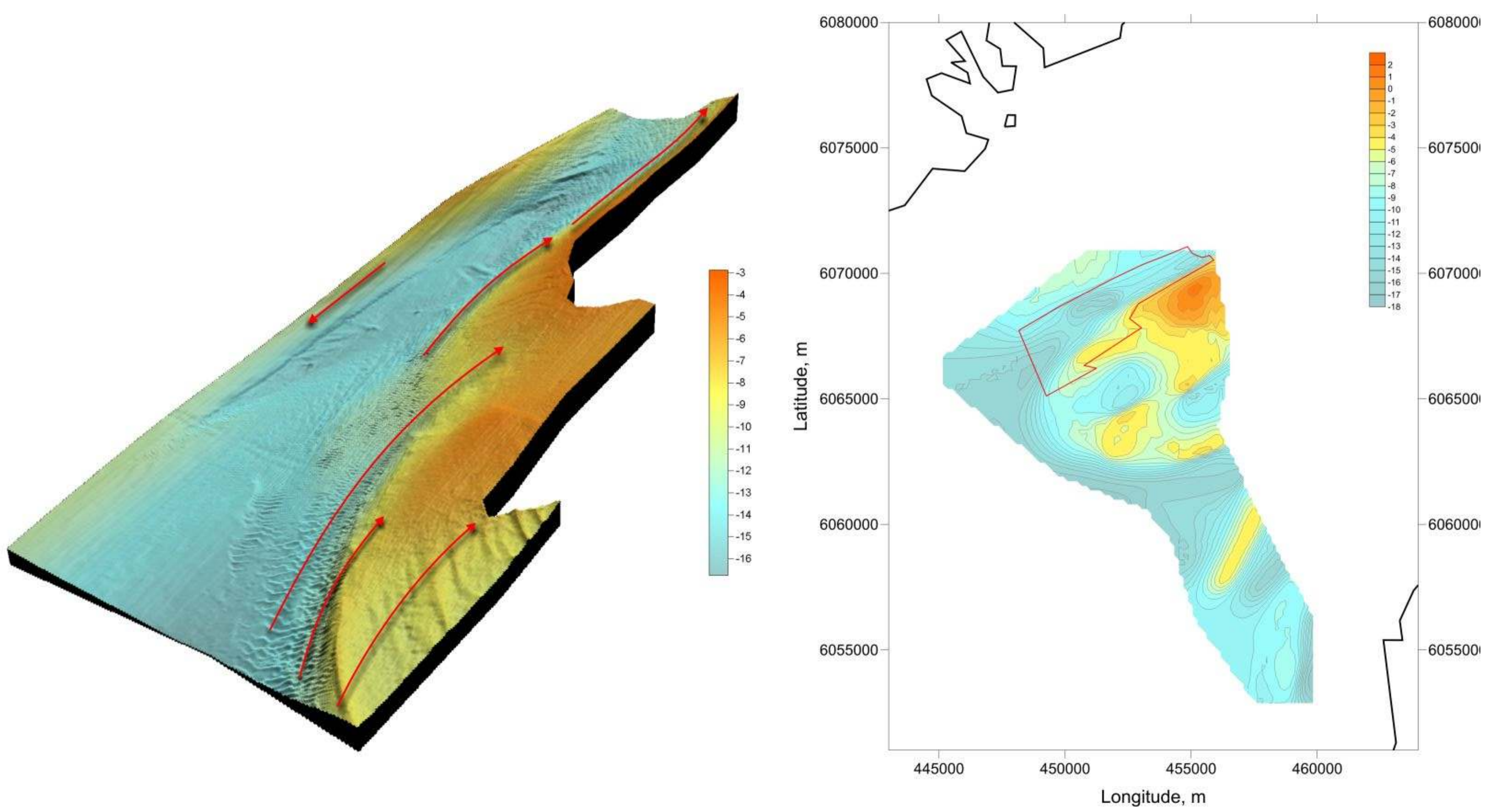


Fig. 43 Swath bathymetry of the Two Feet Bank, Solway Firth and the channel to the north and transport paths of sand, determined from asymmetry of small sand waves.

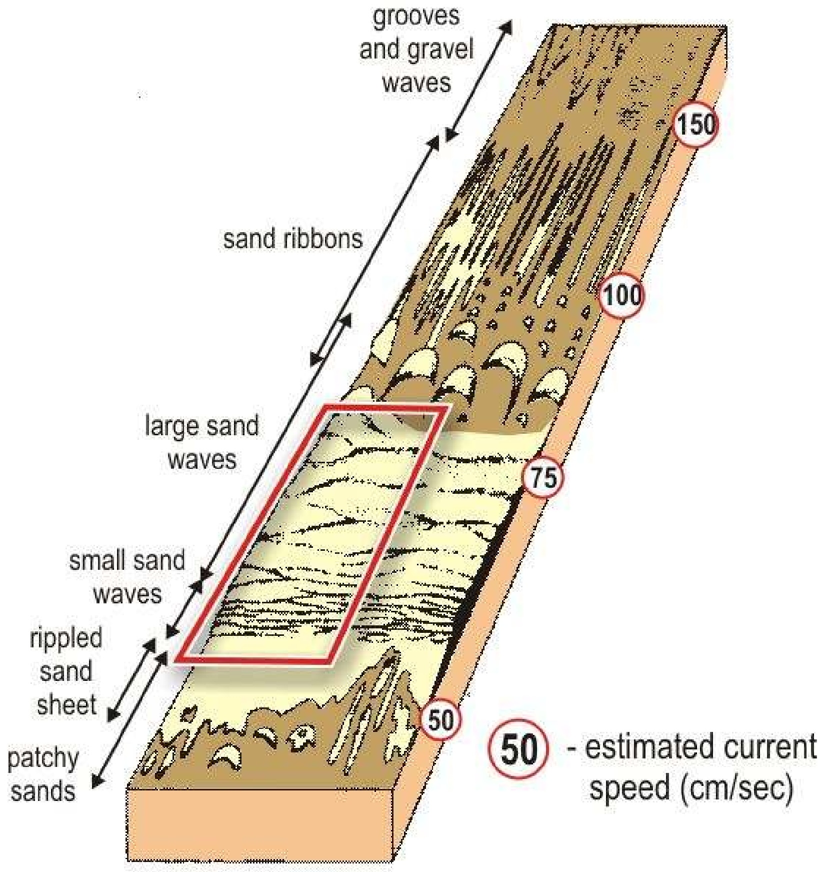


Fig. 44 Bedforms found along a transport path down the gradient of tidal velocity in areas of medium sand supply (Belderson et al 1982).

The bedform zones follow the scheme given by Belderson et al (1982) for a medium sand supply. Beyond the western end of the survey there will be a zone of sand ribbons/scour as shown by Belderson (1964) and Kenyon (1971). This will be an area of gravel and stones in which there should be some sorting of the coarse basal bed material as the current speed decreases along the velocity gradient (Stride et al 1999). The sand ribbons will be a very thin cover of sand that barely covers the underlying basal bed. The large asymmetrical sand waves have a wavelength of 300 m and a height of up to 3.5 m (Fig. 45). The sand size is probably medium to coarse. The sand waves are steeper on the northeastern side and do not form a continuous cover over the underlying basal bed, which is mapped on the sidescan sonar records as higher acoustic backscatter between the sand waves. This basal bed consists of both gravels and outcrops of presumed glacial sediments, seen as subcircular knolls up to 3 m high (at least one of which is interpreted as a glacial pingo (Fig. 32)). Unexpectedly the small sand waves do not entirely cover the large sand waves. They are seen on only a part of both the steep slope and the gentle slope of the large waves. This may be because the seafloor has been inactive for some time before the time of the survey or it may be because the large sand wave surfaces were close to the threshold of behaving like an upper flow regime plane bed. In support of the latter the first few days of the cruise, when this data was obtained, were the time when the currents should have been strongest (Fig.38).

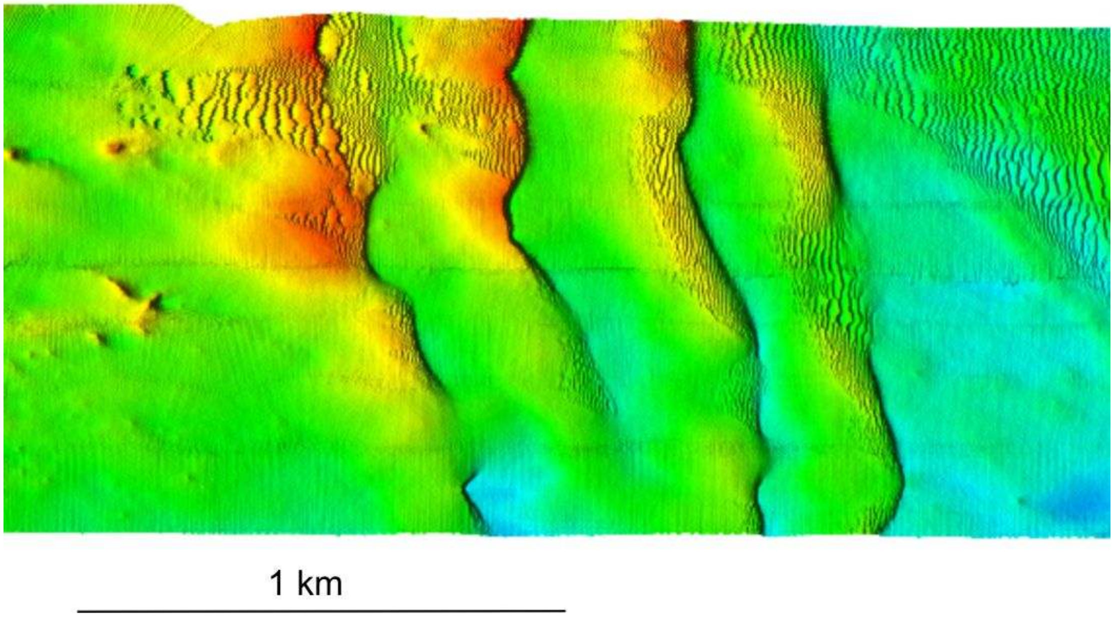


Fig. 45 Large sand waves with partial cover of small sand waves.

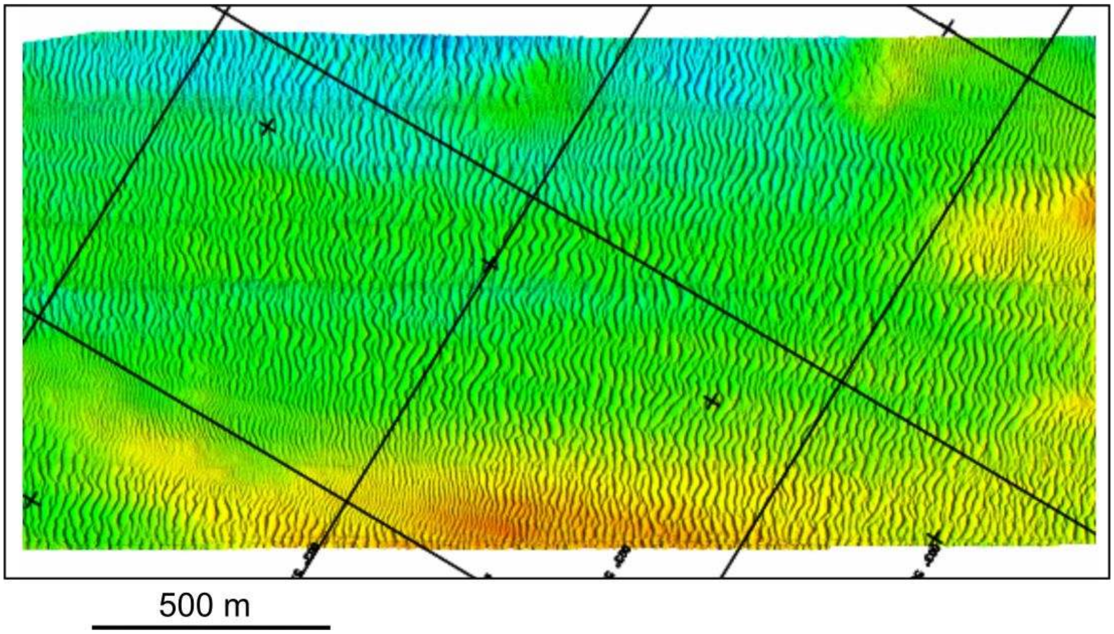


Fig. 46 Small sand waves with some longitudinal fabric.

Beyond the large sand wave zone is a zone of small sand waves that forms a near continuous cover of well sorted medium to fine sand. The high resolution of the swath data allowed new insights into the small sand wave zone. This small sand wave zone is about 12 km wide. The average wavelength of the small sand waves decreases down the velocity gradient from about 17 m to about 12 m. There is some longitudinal fabric at the higher velocity end of the zone due to trains of small waves that have a similar wavelength but a different wavelength from that of their neighbours. Beyond the zone of small sand waves is a zone of rippled sand sheet. The transport of bedload is still to the northeast as shown by an asymmetrical scour behind a small wreck.

The thickness of the sand sheet is variable and up to about 4 m (Fig. 47). It reaches a maximum in the large sand wave zone according to the seismic profiles. The outer limit of sand mobility will move according to several factors of which the main one is the situation of the tides. When peak spring tides coincide with major storms then the outer limit of bedload transport will be furthest to the east. This should be during the winter, which is the stormiest period. However the limit will otherwise be furthest east in the summer as the water is warmer and consequently the water viscosity is less (Johnson et al 1981). The limit of bedload movement can thus vary widely and there may be some history of the changes to this limit detectable from the stratigraphy in the BGS vibrocores which are available along the length of the traverse.

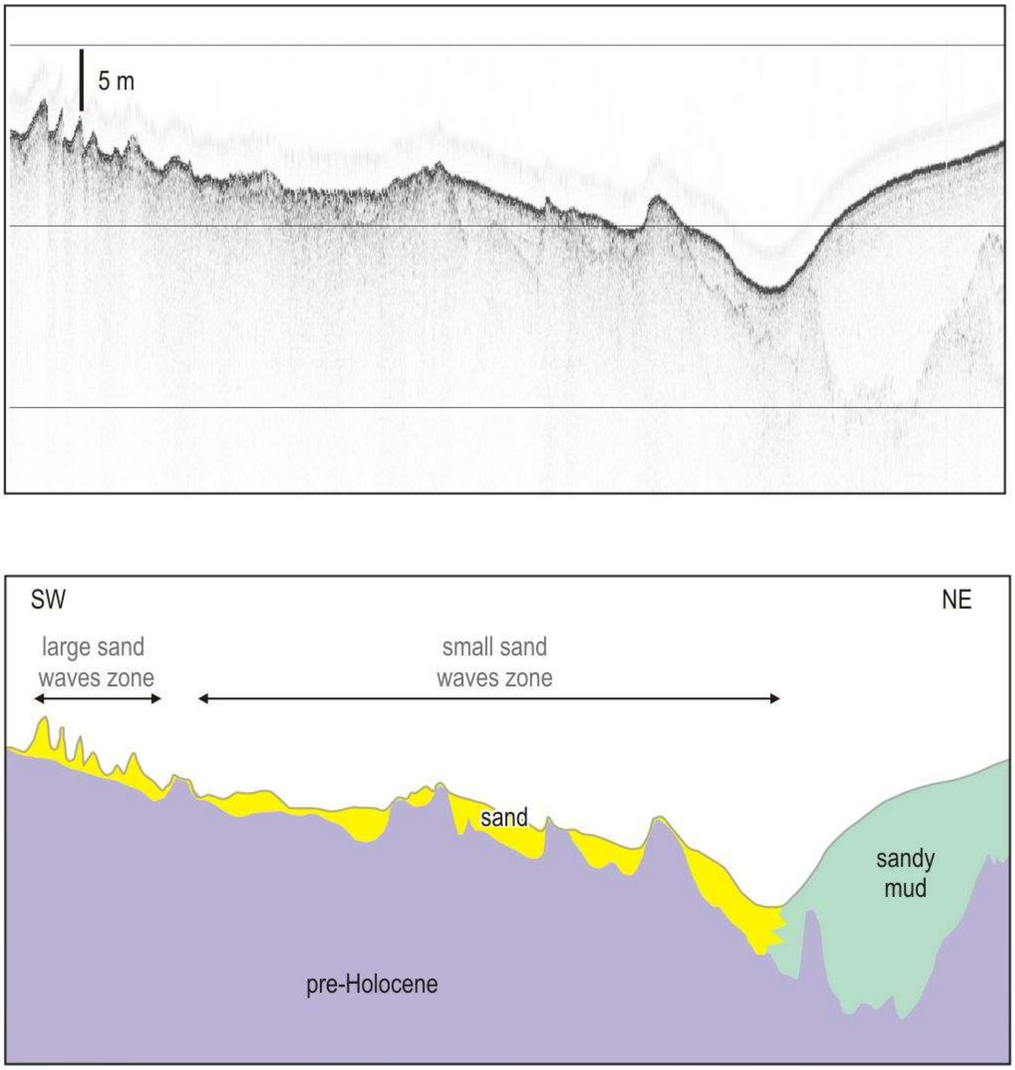


Fig. 47 Interpretation of the seismic profile down a velocity gradient and transport path running from right to left. Showing the variable thickness of sand and the considerable thickness of the muddy sediments of the Eastern Irish Sea mud belt.

6.2.3.2.5. Area 3. Constable Bank

Constable Bank, in the outermost part of the embayment that forms the approaches to Liverpool, was chosen for a detailed survey rather than the banks of the innermost part of the Liverpool Bay where there have been recent studies. Constable Bank was recognised as unusual prior to the study, something of a hybrid type. It extends right to the coast and has no gap between it and the beach. In this respect it resembles a confined (estuary) sand bank rather than a banner bank but it is located outside the embayment and is not broad and is not built up so as to become exposed at low tides. It has some resemblance to a storm generated ridge in that it is long and narrow and extends to the coast through the Rhyl Flats and makes an angle with the coast of about 20 degrees. There is an existing wind farm at North Hoyle on the eastern part of the bank and another planned for Round 2 in the area seaward of our survey.

A 15 km length of the outermost part of the bank was covered by the survey. Unfortunately there was not enough time to do any reconnaissance lines apart from one to the north through the area of the planned wind farm. The line to the north showed very clearly that the part of the bank that we surveyed lies within a zone of active sand waves that are being transported to the east across a floor of underlying basal conglomerate. It would be very useful to add data on the area inshore of the bank where wreck marks should be able to give reliable directions of bedload transport. The peak current in this area, from Admiralty chart tidal observations, is about 120 cm/sec.

The bank is over 20 km long, up to 2 km wide in its outer part, but widens progressively towards the coast, and is up to 10 m high. The ratio of width to height is about 200:1. It is straight and consistently steeper towards the south. Only in the north western corner of the survey area were there the coarser sediments that are usually found between linear open shelf sand banks. All of the rest of the seafloor is covered with sand. Small sand waves are ubiquitous apart from a few very small areas in the lee of the steep slopes of some large sand waves. They have wavelengths that are mainly between 7 and 10 m with a few trains of small waves up to 50 m in wavelength, found in the deeper water on the north side. Large sand waves cover all of the steeper southern side of the bank. They are very regular and have a wavelength of about 120 m. On the north side of the bank the large sand waves are not everywhere present and vary in wavelength from 120 m to 600 m. Most of those on the south side have sharp crested profiles whereas those on the north side have rounded profiles (Fig. 48). All sand waves, both large and small, are asymmetric in profile and steeper to the east. The large sand waves south of the bank are less asymmetric than those on the north side. The larger waves are crescentic in plan view and their tips point to the east. Where crescentic crests from north and south of the bank meet at the bank top there is an intersecting pattern.

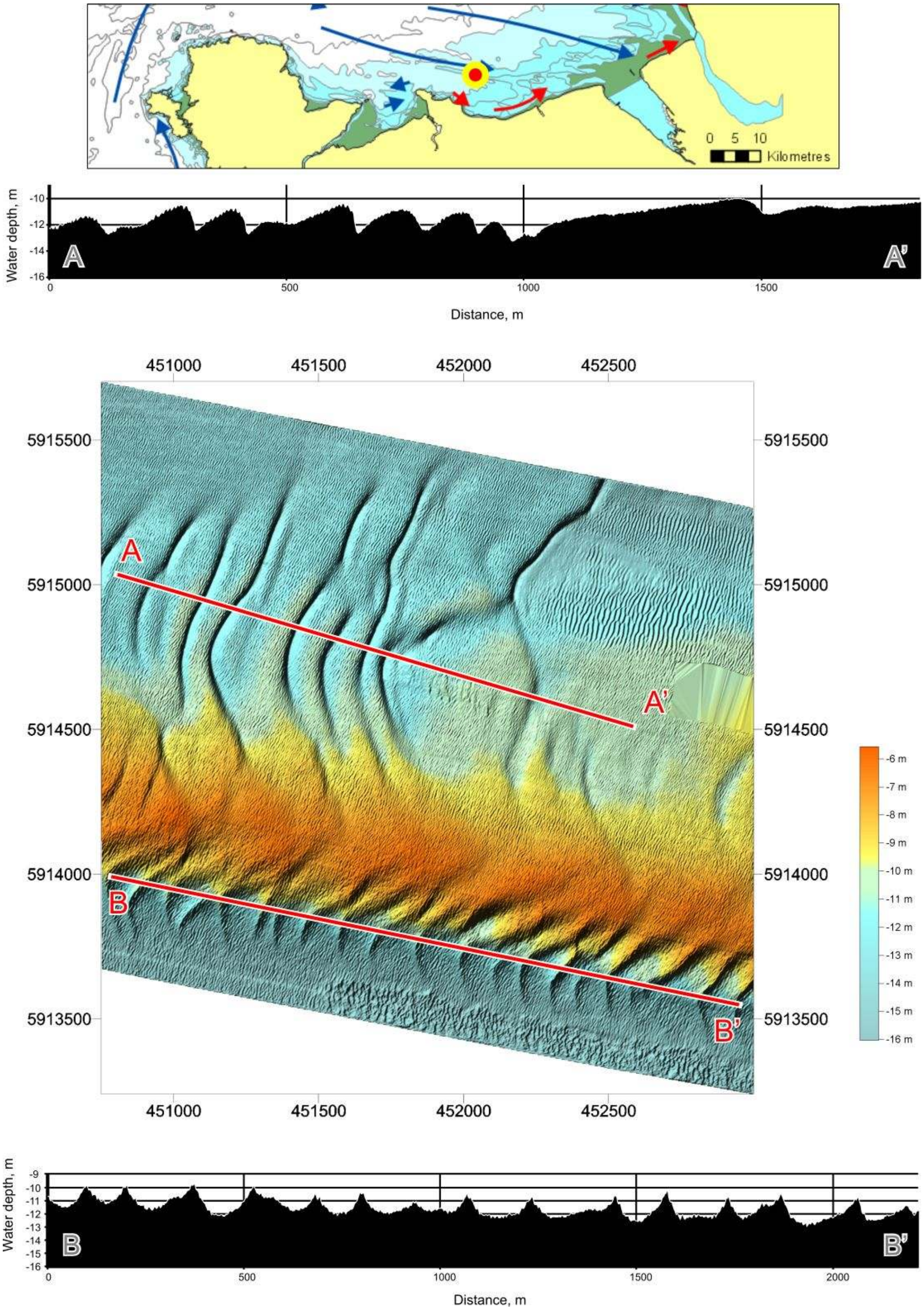


Fig. 48 Swath bathymetry of a portion of the outer part of Constable Bank. Profiles show rounded sand waves north of the bank and sharp crested sand waves south of the bank. Eastings and northings are in metres.

It is very unusual that there is the same direction of bedload on both sides of a tidal sand bank. If this pattern is maintained then the bank should be shortening and should eventually disappear. As this is an area of active sand transport it is anticipated that a sand body without an opposing transport path to maintain it should not survive for more than a few hundred years. It is not known whether there will be a change in transport direction at other states of the tide or in other seasons. It is recommended that an echo sounder profile be obtained along a line on either side of the bank at the end of winter. The rounded crests of the large sand waves on the north side may be a transition phase from sharp crested waves that are steep to the west or they may be due to modification by storm waves as this northern side will be more exposed than the coastwards side.

A seismic profile, carried out by BGS, shows a flat and horizontal reflector underlying the bank which supports a tidal sand bank origin. However there is the possibility that this is a sedimentary body of another origin that is being reworked. Several seismic profiles should be enough to solve this problem.

6.2.3.2.6. Area 4. Outer Morecambe Bay

This area was chosen to check for sand transport paths in an area were the only data was from modelling and sediment trend analysis (section 6.2.3.2. and section 9). The sand banks within Morecambe Bay were too shallow to survey from the RV Meridian. A reconnaissance grid showed that there were uniform, low backscattering sediments in water deeper than about 20 m in the outer part of the area, indicative of fine grained sands and muddy sands at the southern end of the Eastern Irish Sea mud belt. In shallower water to the north of the survey area there were strong backscattering sediments with patches of low backscatter on top, usually in this context meaning low amounts of sand transport. The shallow Shell Flat area to the south of the Lune Deep had no features of interest, but the survey there was very limited in coverage and bad weather had lowered data quality.

The main area of coverage was to the north of the Lune Deep where bedforms had been noticed on the reconnaissance lines. It was hoped that these could be used to “ground truth” the results from Sediment Trend Analysis. There is an area of very strong acoustic backscatter in water depths of about 20 m that is attributed to outcrops of till, winnowed to produce pebbles and gravel at the seabed (Wingfield 1985). Offshore from this winnowed till there are extensive fields of small sand waves. The sand waves have a wavelength of between 10 and 12 m and are consistently steeper to the east. This eastwards direction towards Morecambe Bay may be the long term sand transport path because:

1. sand is clearly being trapped in Morecambe Bay as it is nearly full of confined sand banks that are exposed at low water.
2. there seem to be thin sheets of low backscattering sand advancing from the west onto the high backscattering seafloor, which shows through in the troughs between the sand waves (Fig. 49).

Wherever seen throughout this survey the asymmetry of small sand waves has been consistent with longer term trends such as large bedforms and current measurements. However further work is needed as such small bedforms can change dramatically, for instance after storms (Langhorne 1976).

This possible easterly sand transport path is in the opposite direction to that given by Sediment Trend Analysis (McLaren 1989, Williams 2001, Mason and Garg 2001).

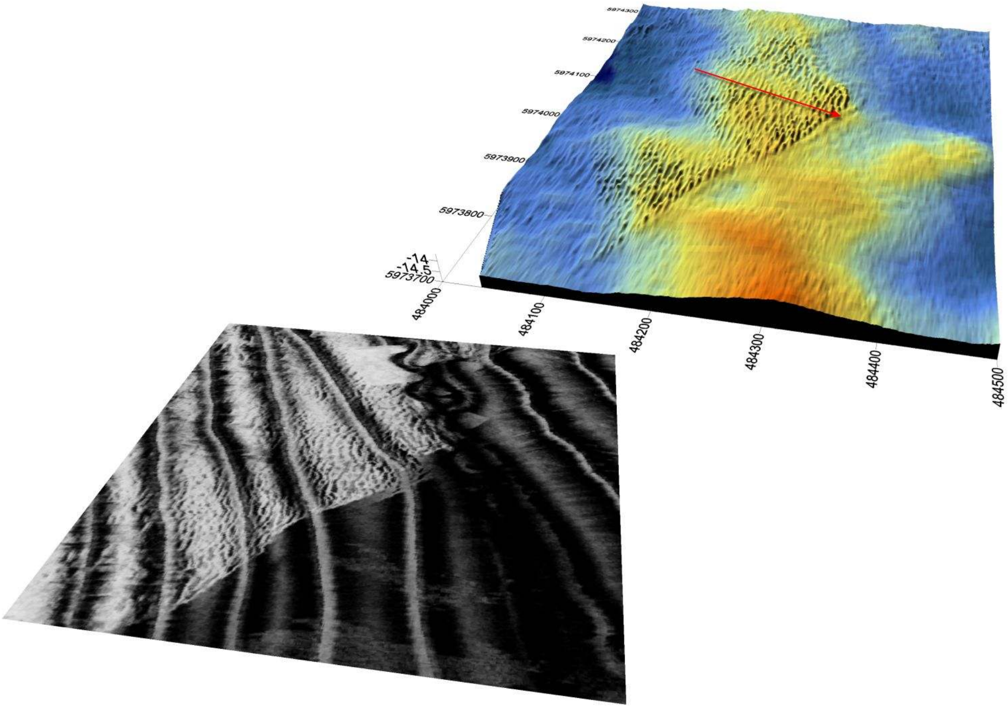


Fig 49 Thin sheet of sand advancing eastwards across coarse lag of winnowed till surface. West of Morecambe Bay.

6.2.3.2.7. Cumbrian coast transit.

A single line, supplemented by data from some small survey boxes, was run near to the coast in order to get new insights into sedimentary processes east of the Eastern Irish Sea mud belt. This area is poorly known, currents are weak apart from in the estuaries, where they increase rapidly. Study of sedimentary processes in areas of weak currents, beyond the area of small sand waves, is neglected because the geophysical data from such areas appears dull. Sonographs usually show uniform low backscatter. Typically there are sheets of well sorted fine sand or muddy sand. Photographs show that the sands are often rippled. Although directional currents are weak there should be transport of sandy materials during the largest storms. In order to get indications of sediment transport directions one needs to find directional bedforms.

Wreck marks

In the absence of other directional bedforms it was proposed that a survey through sites of known wrecks may provide evidence of scour. Sidescan sonar had been used to demonstrate the value of wreck marks to sand transport studies (Caston 1979) but this has not been done with swath bathymetry systems. No ice transported boulders with obstacle marks were noticed on any of the survey lines though they should be common in this glaciated area.

Four wreck marks were surveyed east of the Eastern Irish Sea mud belt and another was found in the Central Area (section 6.2.3.2.3.). Three of them are shown together with the modelled tidal ellipses from Davies and Smith (1996) in Fig. 50.

Wreck mark 1. An asymmetrical mark from the Central Area in the zone of rippled sand sheet, about 1 km beyond the limit of small sand waves. The depth of the scour is about 1 m. Assuming an elliptical envelope around the outer limits of the mark the ratio of the long axis to the short axis is 4. A suggested asymmetry index, measured as the distance from obstacle to furthest limit divided by the distance from obstacle to the limit in the opposite direction, is 2.5 (A symmetrical mark will have an index of 1). The direction of the scour is 050 degrees.

Wreck mark 2. 5 km NNW of St Bees Head is about 1.2 m deep. It has a ratio of long to short axis of 1.6 and an asymmetry index of 6. The direction is 020 degrees.

Wreck mark 3. 5 km southwest of St Bees Head is about 0.5 m deep. It has a ratio of long axis to short axis of 1.25 and an asymmetry index of 1. It is slightly elongate parallel to the coast.

Wreck mark 4. 12 km southeast from St. Bees Head is about 1.0 m deep. It has a ratio of long axis to short axis of 1.1 and an asymmetry index of 1.

These wreck marks give useful information on sediment transport. They show that there is potential for transport even in weak currents. They act as proxies for tidal ellipses and may give insight into the scour to be expected around engineering structures. How accurate a proxy this is requires further study.

Wave dominated bedload transport indicators

Two areas of the thick tabular sand patch/gravel association, believed to be an indicator of wave dominance (section 5.4.), are mapped west of Cumbria. They are both about 3 to 4 km from the coast in depths of about 15 m. The low backscatter patches of fine sand are only up to 0.6.m higher than the underlying gravel areas, which is less than usual for such bedforms. They have the usual sharp boundaries with steep edges. Small ripples, less than 2 m in wavelength, are seen at the edge of one gravel patch (Fig. 28). Similar but more shore normal features, found in similar settings, such as those from 3.5 to 4 m depths on an Arctic shoreface (Hequette and Hill 1995), are ascribed to shore normal currents generated during storms.

In conclusion the two indicators found, wreck marks and thick tabular sand patches, point to no overall transport in the shallow sea between the Eastern Irish Sea mud belt and the Cumbrian coast. There is some transport into the Solway Firth but it is only significant very close to the foot of the sand banks, where the outermost small sand waves are seen. The transport seaward of Morecambe Bay is dealt with in section 6.2.3.2.5. It also seems to be in towards the estuary.

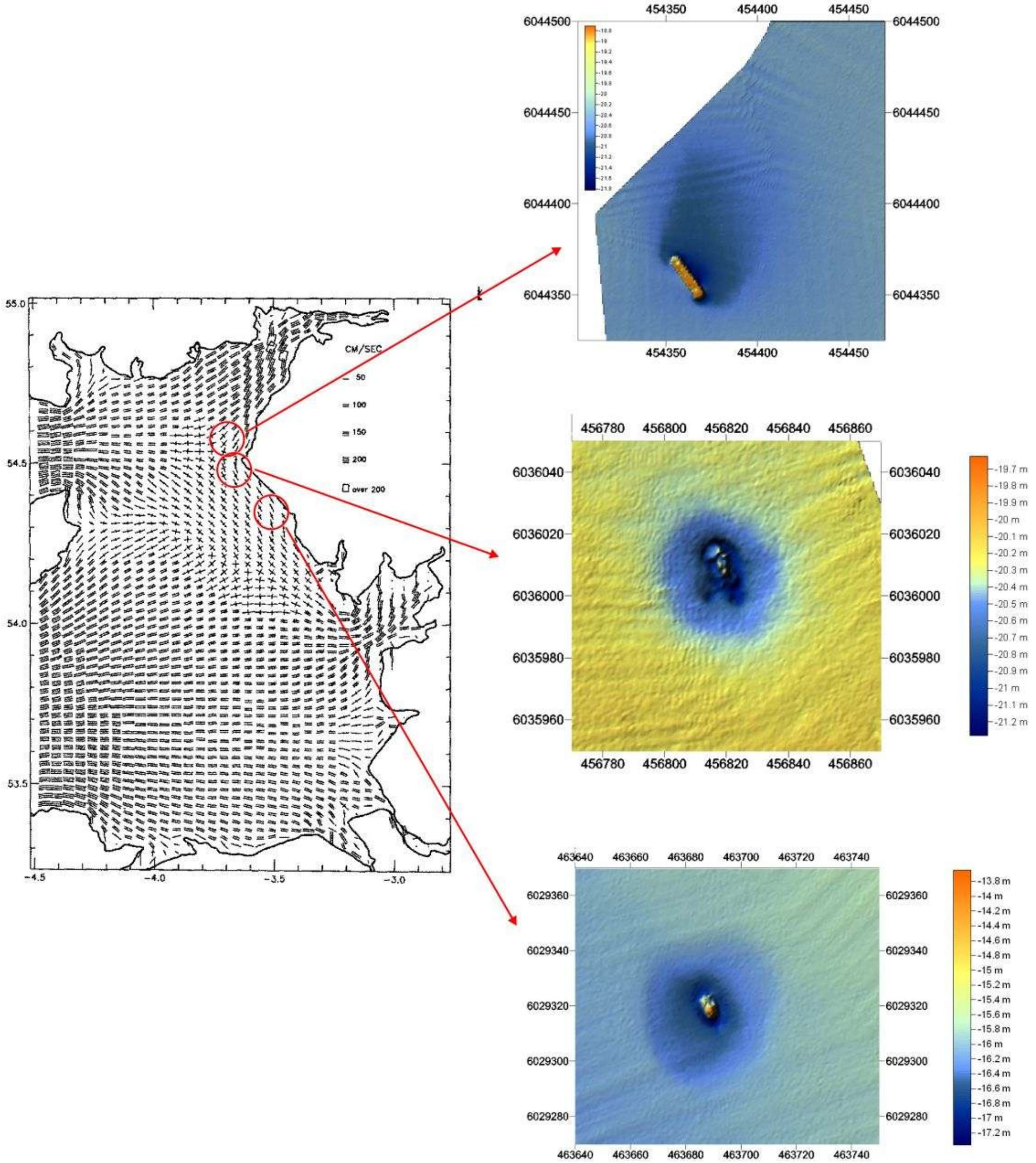


Fig. 50 Wreck marks along in area of weak currents off Cumbrian coast and their relation to modelled M4 tidal ellipses (Davies and Jones 1996). Wreck marks 2, 3, and 4 of the text (from north to south)

6.2.3.3. Suspended load transport

Muds are transported in suspension to the offshore mud belt both from the coast, as confirmed by accumulating radionuclides, and from the west as postulated by Pantin (1978). There has been considerable effort to study the radionuclides in sediments in the Irish Sea, a task made difficult by the extensive bioturbation which carries radioactive materials down to depths below the seabed of up to 140 cm e.g. McCartney et al (1994). Muds should also be transported to the estuaries (Kirby 1987). How much mud is accumulating in the estuaries is less clear. Much of the suspended sewage sludge in the approaches to Liverpool moves inshore towards the Mersey with some being widely dispersed and accumulating in shallow muddy sediments around the coast (Norton et al 1984). Sample sites in the outer estuaries appear, from available literature, to be few and most of the sediment of the intertidal area consists of fine sand and very fine sand (McLaren 1989). The Sellafield derived radionuclide levels in the estuarine sediments are low. However some Sellafield derived radionuclides do accumulate in salt marshes at the head of the Solway Firth and so some suspended materials are being transported through the estuary system (Fridlington et al 1997). Perhaps muds are flushed out by tide and surge currents from the sand banks, leaving the sediments relatively “clean”. By 2000 the radionuclides being put out into the seawater were at about 1% of the levels of the 1970’s.

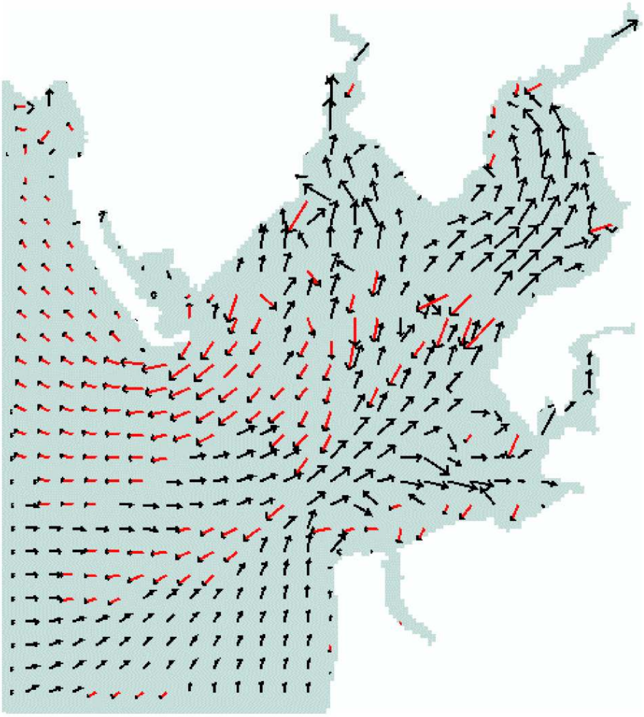


Fig. 51 Modelled bed stress in Morecambe Bay, by P. McLaren and reported in Mason and Garg (2001).

7. Changes in equilibrium resulting from human intervention

This is a difficult area of study. Approaches include observation and measurement and modelling. The wider scope of the problems is dealt with in Collins et al (1980). Of particular concern is the possibility of interchanges of sediment between the coastline and the offshore seabed.

The case of “beach draw-down”, sediments from the upper beach moving down to fill a dredged depression, is of significance for aggregate extraction (being responsible for the Hallsands disaster). The depth limit for the active beach profile on the East Anglian coast is suggested to be 7 m (below Chart Datum) and thus this problem need not be considered for windfarms on sand banks outside the coastal exclusion zone as they neither create sizeable depressions nor are close enough to shore. Hallermeier (1977) provides a depth of closure hypothesis to quantify this depth limit based on criteria of wave height, period and sediment density.

Generic research into the potential effects of offshore wind farm developments on coastal processes (Cooper and Beiboer 2002) suggests that the main influences are likely to be confined to each turbine foundation and manifested as ‘local’ scour. They state that as long as the large spacing between adjacent turbine blades is maintained at the distance that optimizes wind energy capture, and the scale of the individual foundations remains small, then the opportunity for ‘global’ scour (cumulative scour) is removed. If ‘global’ scour was allowed to occur then the equilibrium conditions of a sand bank are likely to be altered.

Fixed headland banner banks

The Swansea Bay (SKER) project investigated the sandy foreshore inside the bay and the sand banks tied to the headlands, including Sker Point, at the east end of the bay using a variety of measuring techniques (Fig. 52) and modelling. It was a major effort taking some 7 years from start to reporting (Heathershaw et al 1981, and reports and papers therein). Dredging for sand had taken place on Nash Bank and also on the foreshore and there had been major construction work on a harbour at Port Talbot. It was hoped to establish that there was some natural replacement of beach sand taking place from offshore. The study went only a small way to achieving its goals. It was established that some long term, natural erosion of the foreshore was taking place. Bedload transport paths from the banks to the beach were predicted from modelling but not proven from tracer studies etc. The importance of sand banks to the sediment budget was acknowledged, including their role in protecting coastlines from wave attack. It was recognised that biological processes may be significant in sedimentary processes. There was an acknowledged large element of uncertainty in the findings and more work, with a multidisciplinary approach, was recommended.

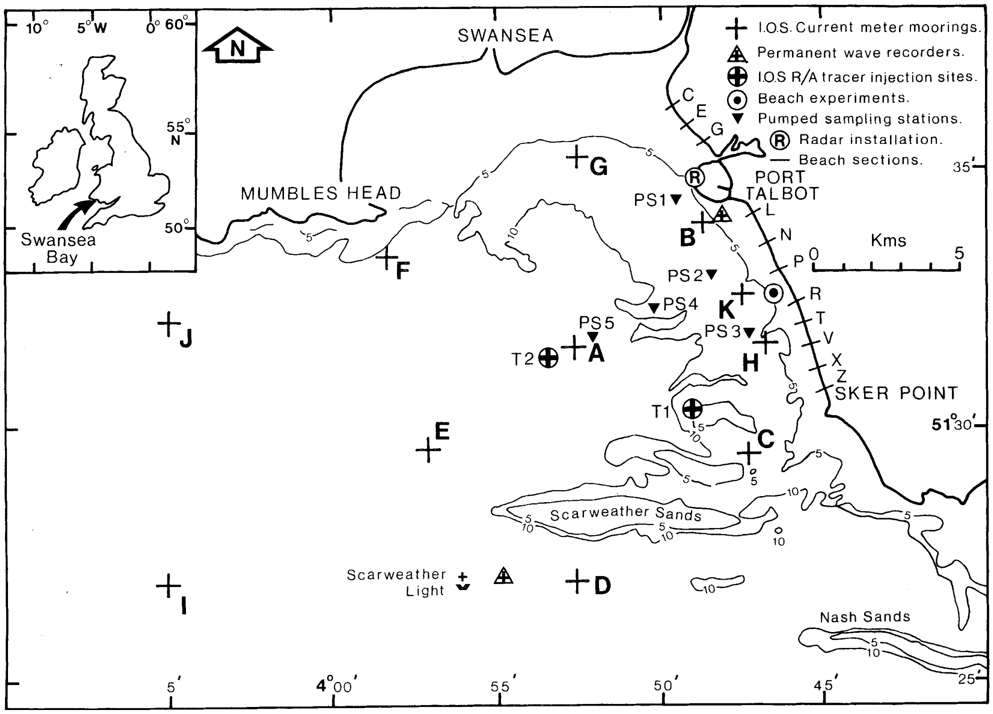


Fig. 52 The site of the SKER project, Swansea Bay, and the location of the experiments and instruments (Heathershaw et al 1981).

The sheltering effect of banks, which prevent waves from removing sand from nearby beaches, has been a factor considered in applications for dredging licences (Tucker et al 1983). Suter et al (1989) have modelled the effect of removing a small, 4 m thick, sand bank that is sheltering the eroding coast of Louisiana. Hurricanes sweep the area and the bank was being considered as a source for beach replenishment. The shoal was shown to attenuate the storm waves and removing it would only result in increased erosion.

Moving headland banner banks

The Sizewell-Dunwich Banks field study (Lees 1980, Heathershaw and Lees 1980, Carr 1979) investigated banks close to a retreating shore. The nearby cliffs are eroding at a fast but variable rate of from 0 to 18 m/year. Analysis of historical charts (Carr 1979) showed progressive northward development of one bank until it joined with another, as well as landward movement of the whole system. The sedimentary budgets were not well established. Although the volume of sediment gained by the banks was equal to that lost by the cliffs there were too many uncertainties to predict the effect of human intervention. The material of the cliffs and of the banks was different and it was not known how much sand was coming in from the southerly directed offshore bedload transport path, from the longshore drift and from seabed erosion.

The Horns Rev area is presently the site of the largest offshore windfarm (Larsen 2003). Construction of the windfarm was completed in 2002 and comprises of 80 turbines, supported on 4 m diameter mono-piles, installed 580 m apart in a regular array. It covers an area of 20 km on the southern part of the "reef" (Elsam

2003). The inner Horns Rev is an extension to the sandy coastal headland (Fig. 8). The headland has a high supply of longshore drift from the north and is building outward. Separated from the inner Horns Rev by a narrow channel is the outer Horns Rev. This is 40 km long and about 10 km wide and was thought to be a glacial morainic feature. However it was found by geological investigation to be a tidal sand bank that is becoming wider and accumulating sand. The sand is thought, from modelling and observation of bedforms, to be fed from the offshore area to the west. Because the area is considered to be one of bedload convergence, with a high sand supply, the effect of the windfarm on the nearby coastal sand supply was considered to be insignificant.

In the UK, two offshore turbines were first installed in 2000 off Blyth, Northumberland, on North Spit, a small rocky shoal around 1 km from the coast. This was followed in 2003 by the North Hoyle project, the first built Round 1 offshore windfarm, and in June 2004 by the Scroby Sands project, off Great Yarmouth. Scroby Sands itself is regarded as a moving headland banner bank and is part of a group of very dynamic sandbanks located off the coast of East Anglia. In addition to developer funded studies for consent and engineering requirements the site is also presently the focus of two DEFRA funded research projects:

- AE1227 Assessment of the significance of changes to the inshore wave regime as a consequence of an offshore wind array
- AE0262 Development of generic guidance for sediment transport monitoring programmes in response to construction of offshore windfarms

Further details of these two projects are available from:
http://www.cefas.co.uk/renewables/default.htm

The purpose of this research is to improve the understanding of offshore windfarm effects on local coastal processes and the confidence with which these effects can be predicted by modelling. Both projects are due to report in 2005.

Open shelf linear and sinuous banks

Linear banks on open shelves have been the subject of much recent study by mathematical modelling e.g. Roos and Hulscher (2003). Modelling human intervention in sand bank areas gives insight into how far and how fast the effects can spread, among other things. The banks are assumed to be regular bedforms, with height of up to 80% of the water depth and a slight cyclonic (anticlockwise offset) crest orientation with respect to the tidal current. The physics of their formation, as a morphodynamic instability of a flat seabed subject to tidal flow, follows from that of Huthnance (1982). Roos and Hulscher (2002) model the effect of a man made circular depression in a shallow tidal sea. A sand bank pattern is created that spreads horizontally away from the subsidence at a rate that may go up to 160 m/year. The area influenced by this local intervention by man is extensive (Fig. 53). They suggest that mining in a sand wave area would produce similar results, which could be tested because they would take shorter time scales to develop (typically 1-10 years). Similarly, a modelled circular sandpit in an area of asymmetric tide (Roos and Hulscher 2003) results in deepening and elongation of the pit and formation of a parallel pattern of elongate, cyclonically oriented banks that spreads away from the pit. Work is continuing to validate these results by comparing North Sea sand bank evolution over the past 100 years.

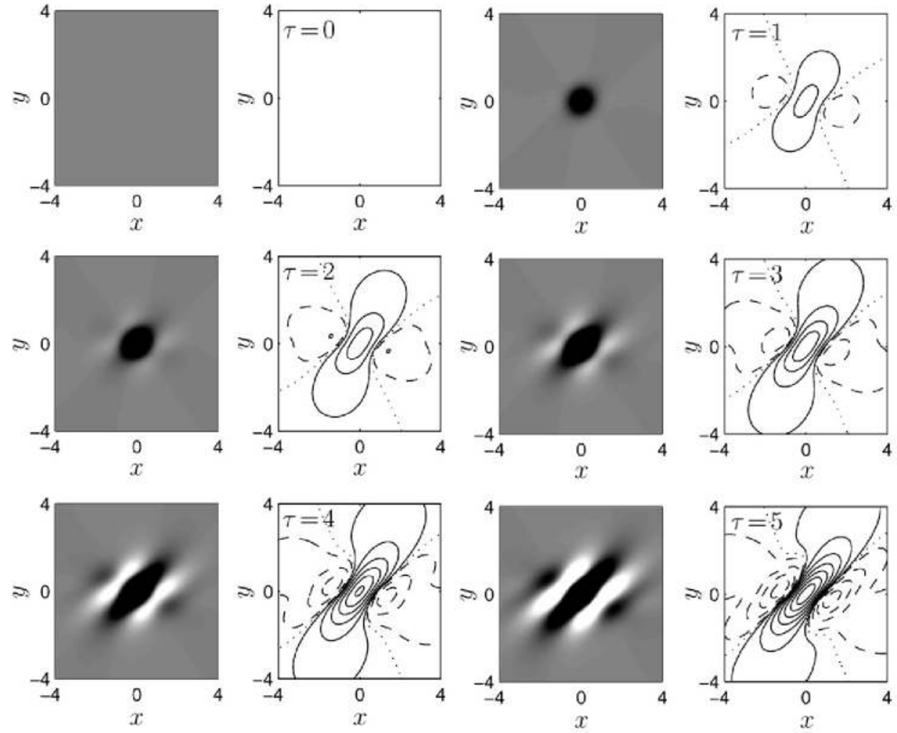


Fig. 53 Modelled evolution of a flat seabed in tidal currents, following introduction of a ("manmade") circular depression. The developing sand bank crests are white and their troughs are black. The dashed contours show clockwise circulation of residual currents (Roos and Hulscher 2002).

Middelkerke Bank off Belgium is a fairly modern bank, from 100's to 1000's of years old according to Vincent et al (1996). Thus it "may respond and evolve on a time scale of centuries to changes in equilibrium conditions." Studies of the effects of sand extraction on banks along the coasts of the Netherlands is described in reports of the KUST2005 programme such as Boers and Jacobse (2000). Numerical wave models predict that sand extraction should have only a small influence on the wave conditions along the coast.

Kwinte Bank off Belgium has had regular volumetric surveys with swath bathymetry in order to study the evolution through time of the sand budgets in an area of extraction. Following cessation of dredging, which left a 5 m scar, there is a process of regeneration. This has been studied as part of the EUMARSAND programme and the MAREBASSE programme (van Lancker et al 2004).

Confined sand banks

For estuaries there is more knowledge about the effects of human intervention e.g. Inglish and Kestner (1958). Dumped materials in the outer part of estuaries are often rapidly returned to the near shore by the headward directed asymmetry of the tidal current e.g. Liverpool Bay (Norton et al 1984). Similarly dredging of the harbour at Rosyth in the Firth of Forth kept a dredger permanently occupied. The spoil was dumped 12 km down estuary in a channel. Tracer studies showed that some of this material was back in the port by the following day (Cloet 1972). Effects on benthos in Liverpool Bay include a dramatic increase in shrimps in sands following a settlement of silt due to jetting operations to bury a sewage outfall pipe (Eagle 1973). The Ribble Estuary has had accretion of sediment over the last 150 years, including infilling of the main channels and accumulation on the sand banks and salt marshes (van der Wal et al 2002). There was probably some natural infilling because of the weaker ebb tide but the rate was increased following embankment construction and reclamation and the impact of such works has been substantial. The study in the Thames estuary by Cloet (1972), (see section 6.2.2.2.) also points to the effect of human intervention on bank changes. The changes, observed from 1839, that were taking place naturally were exacerbated by spoil dumping in 1907.

Storm-generated ridges

Baland Bank near the coast of Belgium, seems to have formed following dredging prior to the 1920’s (van Lancker, 1999, p.169). Equilibrium was gradually re-established. Dredging of the Stroombank for a navigation channel off Ostend has disrupted the equilibrium (van Lancker 1999).

8. Conclusions

1. Much recent data has been considered that is pertinent to wind farms and sand banks. This includes the experience of other countries that have placed windfarms on sand banks e.g. Denmark, (Larsen 2003, Danish Hydraulic Institute 1999a, 1999b) or intend to do so e.g. Ireland (Wheeler et al 2001, and confidential reports). The German experience (BHS 2003) is just beginning. The Belgians have done a great deal of work on the sedimentary setting (the BUDGET programme, Lanckneus et al 2001), as well as on aggregates through the MAREBASSE programme (van Lancker et al 2004), and have a report on offshore windfarms in preparation. There are also Dutch programmes including KUST2005 which includes study of the effects of sand extraction on the coast. EU funded programmes that have considered sand bank sediment dynamics include RESECUSED (De Moor and Lanckneus 1993), STARFISH (Heyse and De Moor 1996), CSTAB (O'Connor 1996), PACE, Predicting Aggregated Scale Coastal Evolution, (De Vriend 2003) and EUMARSAND (current).

2. A simple classification of sand banks is presented that includes their setting within local and regional sand transport paths. Each type of bank is considered to be a regular bedform and has some characteristic behaviour of its own. This classification includes a possible continuum from open shelf linear banks to confined (estuary) banks that can be characterised by ratio of width to height. The former end member can have a ratio of greater than 500:1 and the latter end member less than 50:1. Composite (hybrid) bank types were found during the SEA6 survey of 2004.

3. A new sand transport path map for the shelf around the British Isles adds published and unpublished data since the map of 1982. The seabed is further divided into areas of dominance of tidal, surge, wave and oceanic current. This provides information on a coarse regional scale. It ought also to be helpful to other applications of shelf management such as habitat and archaeological mapping .

4. The sand transport paths for the three strategic areas of the Greater Wash, Thames and North West (Liverpool Bay) are considered in greater detail. For North West/Liverpool Bay there is also a new map of bedform zones derived from the SEA6 survey of 2004.

5. Flux of sand, the movement of small sand waves, the movement of large sand waves and the movement of sand banks should be considered separately. Though sand banks are the largest bedform and naturally occur in higher current speeds that the zone of large sand waves, it is still surprising to find that their movement is in some cases greater than that of large sand waves. For all moribund and fixed headland banks movement will be near zero, though the flux of sand will be at or near zero for the former and very high for the latter. Moving headland banks can shift at high rates (near 50 m/year is recorded). Open shelf linear banks can move laterally at medium rates (up to 40 m/year has been recorded). They can retreat and advance longitudinally at even higher rates, implying that sand can be lost at their ends. Open shelf sinuous banks seem to move at medium rates (usually less than 10 m/year). Confined sand banks can shift at high rates, especially in inner estuaries (up to 100 m/year is recorded).

Ebb-flood delta banks and storm generated ridges can also shift at high rates (up to 120 m/year has been recorded). Rates of bank movement will be typically less than these figures but nevertheless these are greater rates than is usually assumed for sand banks (e.g. the order of 1 m per year is predicted from modelling (Roos et al 2004)).

6. The relationship of banks to the nearby coast is poorly understood, part of a complex system and difficult to study. The supply of materials to and from the coast is very considerable, for instance from the coast by erosion in Holderness, East Anglia, the Isle of Sheppey, Thames Estuary and the northern plain of the Isle of Man. This will be very much greater than any predicted changes in supply resulting from large wind farms. Some of this is in the form of bed load and some as suspended load. It is considerations of bedload that will be significant for windfarms on sand banks rather than suspended load. Bedload is moved more slowly and less widely than suspended load and so it is the local transport paths that need to be considered the most.

9. Recommendations

This report provides an overview of present understanding related to sand banks and sediment transport for the shallow waters across the UK continental shelf. A sand bank classification scheme sets an initial morphological context for the main bank types which should assist considerations as to how offshore wind developments might alter the local equilibrium conditions.

The present understanding is limited by sparsity of data in key areas, such as the Irish Sea, and a general lack of quantified rates of sediment transport. In addition field evidence on the direct effects arising from an offshore windfarm is limited by both the amount and the duration of available monitoring.

9.1. Suggestions for Round 2 developments

Recommendations as to how to assess the role of sand banks in a coastal system is provided in Whitehouse (2001), and approaches to the study of the regional context by Brampton and Evans (1998). The key to such an assessment is the availability of site specific information.

A range of baseline descriptions is readily available from navigation charts (published by UKHO) and geological maps (published by BGS). This material can provide a useful starting point for identifying the following:

- Bank type (related to the scheme provided here)
- Bank geometry (size, profile, volume, etc)
- Proximity to the coast or other large features
- Water depths
- Classification of general sediment type
- Position within regional sand transport maps

Chart archives (available mainly from the UKHO) may additionally reveal previous surveys in a local area which can be used to quantify the contemporary development (from about 1900 to present) of the seabed and to identify any major morphological trends and apparent linkages to the coast.

Geological maps are able to provide a broad scale interpretation of surficial sediments at scales down to 1:250,000 for discrete regional units around the UK coast. The published interpretation is usually based on a fairly sparse data set that is used to map sediment type at a semi-quantitative scale (using for example a Folk classification). These maps are usually unable to accurately identify local sediment types (including particle size distributions) and the presence of sedimentary bedforms.

There is generally insufficient data to determine how individual sand banks will behave in any of the three strategic areas, thus studies tailored to more local situations will be required. Such field studies for offshore windfarms are generally anticipated by developers and, in the main, will provide key baseline definitions of local seabed depth and shape, sediment type and sub-surface stratigraphy. A significant part of the transport system for the assessment of possible coastal effects is that between the bank and the coast. Attention should also focus at and beyond the ends of the banks as these are the most likely places for sand to be added or taken away from a bank. If it can be established that sand is being gained by the bank(s) from the shore, as seems to be the case for the Horns Rev and the Ballacash and King William Banks, then there should be no problem of beach erosion resulting from wind farm developments. In the opposite situation then there might be a problem. One approach is to look for asymmetrical bedforms between the bank and the shore, such as small or large sand waves, sand shadows and obstacle marks (Belderson et al 1982), including wreck marks. This is best done with high resolution sidescan sonars (systems with a frequency of 100 kHz or more should provide enough resolution) or, better still, high resolution swath bathymetry systems because the bedforms may be small. Cameras could be usefully employed here.

The geophysical survey techniques that are commonly employed include swath bathymetry, sidescan sonar, sediment samplers and towed transponders such as boomers and pingers. The careful interpretation of the data obtained using these techniques should provide the evidence to quantify the composition of the local seabed, and to map the local sand transport indicators and thus determine whether banks were mobile and gaining or losing sand. Moribund banks and banks with cores of older deposits should be readily identified from the criteria given above (Fig. 11). A few transverse and longitudinal profiles should be able to determine which way a typical asymmetrical bank was extending. Seismic profilers with the ability to see internal structure need to be chosen with care (e.g. Tessier et al 1999).

For particular areas with rapidly changing bedforms there may be a requirement for repeated surveys with swath bathymetry systems.

What is more difficult to achieve is quantification of rates and modes of transport. In part this can be investigated by a parallel campaign of metocean observations with deployment of wave, tide (both flows and water levels) and suspended sediment measuring devices. Further guidance on data and study requirements to support offshore windfarm projects is provided in CEFAS (2004).

With the addition of this type of high resolution data the local transport paths and sedimentary budget should be investigated, making use of well calibrated numerical models, as appropriate. Cooper and Dearnaley (1996) give guidelines for modelling related to engineering studies in coastal areas.

9.2. Techniques for determining regional bedload transport paths

Use of sediment grain size trends (sediment trend analysis, STA) is a promising technique for determining net transport paths in regional coastal areas. It is a technique pioneered by McLaren and Bowles (1985) and with later development by Gao and Collins (1992). It is best suited to transport paths that run down a velocity gradient and those that run up a velocity gradient. Gao and Collins (1992) show how to use a grid of samples and to use filtering to remove "noise". However there are difficulties such as the choice of sampling grid density (neither too coarse nor too fine) and uncertainties introduced by patchiness of sediments. There is usually sand moving across a basal bed as bedforms such as gravel ribbons, sand ribbons, isolated sand waves and sand patches (Fig. 44). This produces statistical "noise" that may be difficult to remove unless samples are selected on the basis of sidescan sonar or swath mapping. Hence this may not be the optimum method for determining transport paths but should be used in conjunction with bed stress modelling and bedform mapping. To date the technique has been used with some success at various sites around the UK and elsewhere. This includes several applications in the Bristol Channel, work in the Humber Estuary, off the coast of East Anglia as well as in Liverpool Bay and Morecambe Bay (Fig. 54). Where STA analysis was tested out by "ground truthing", as a part of the SEA6 survey outside Morecambe Bay, it seems to have failed.

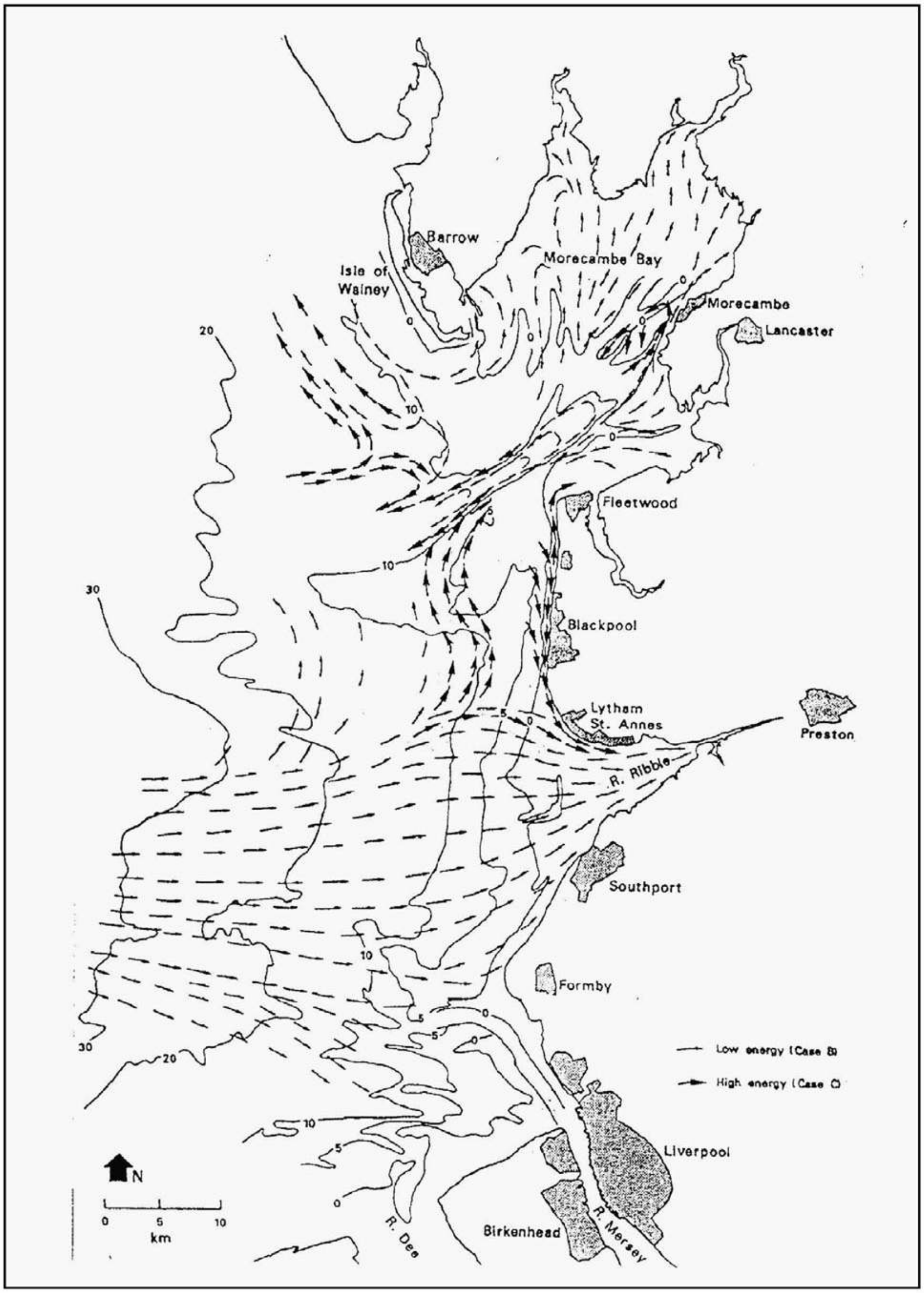


Fig. 54 Net bedload transport paths from sediment trend analysis in Liverpool Bay and Morecambe Bay (Williams 2001).

9.3. Further research

It is suggested that the strategic level review provided by this study is revised as new data and knowledge from individual Round 1 and 2 projects are published, and similarly for outputs of any surveys being commissioned directly from the SEA.

The present review provides refined strategic level sediment transport maps for the whole UK and for the three strategic areas. Should further rounds of offshore renewable development identify new strategic areas then the present work can be readily extended to address the new requirements.

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