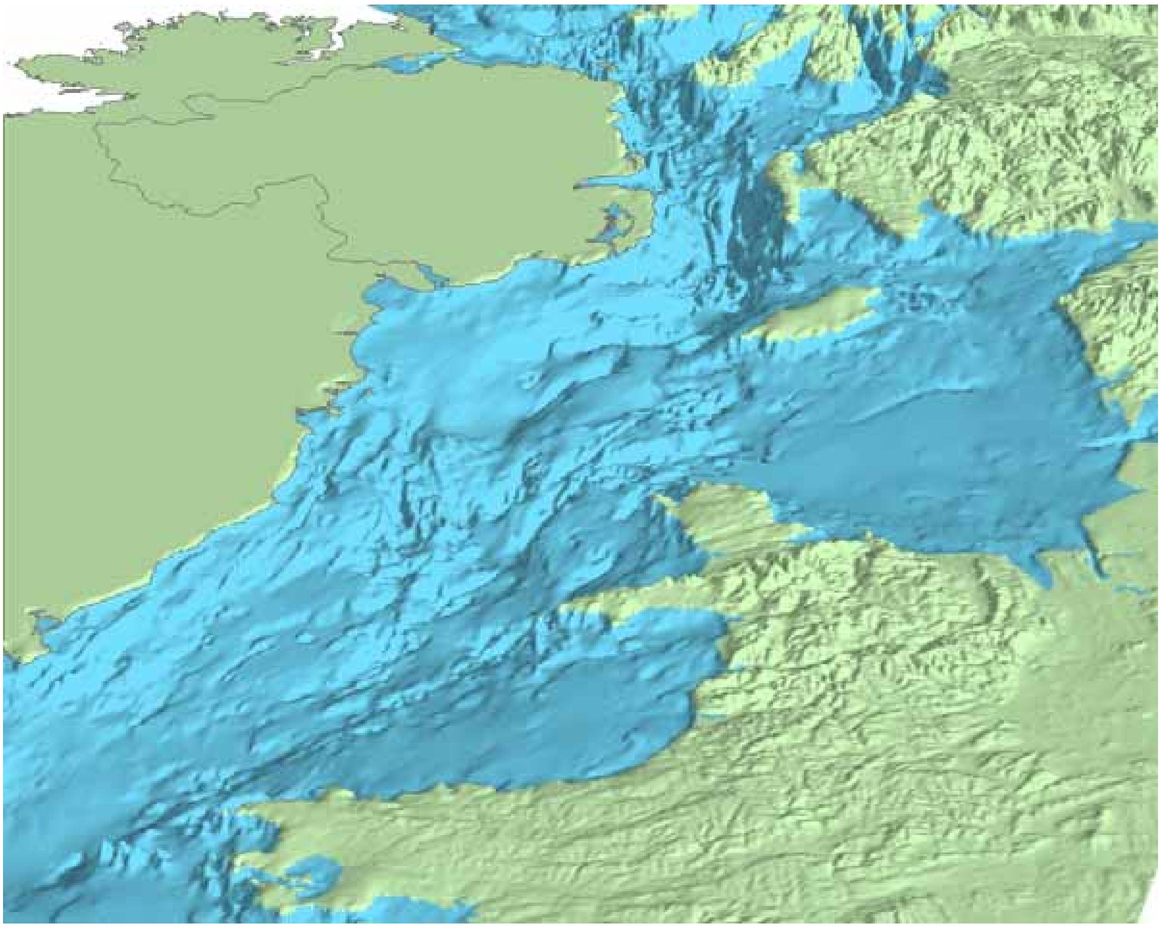
DTI Strategic Environmental Assessment Area 6, Irish Sea, seabed and surficial geology and processes

Continental Shelf and Margins

Commissioned Report CR/05/057



May 2005

BRITISH GEOLOGICAL SURVEY

CONTINENTAL SHELF AND MARGINS

COMMISSIONED REPORT CR/05/057

DTI Strategic Environmental Assessment Area 6, Irish Sea, seabed and surficial geology and processes

Keywords

Irish Sea, hydrocarbons prospectivity, strategic environmental assessment, seabed processes, seabed habitats, bathymetric charts, seabed stress, seabed sediments, seabed bedforms, sandwaves, sandbanks, sand transport, deeps, bathymetry, seafloor mapping.

Front cover

Terrain model of the submarine study area and adjacent England, Wales and Scotland. Submarine vertical topography has been exaggerated by 50 times and the mainland topography has been exaggerated by 10 times. Topographic data for the mainland of Ireland were not available at the time of this report.

Bibliographical reference

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British Geological Survey

NATURAL ENVIRONMENT RESEARCH COUNCIL Edinburgh 2005

Foreword

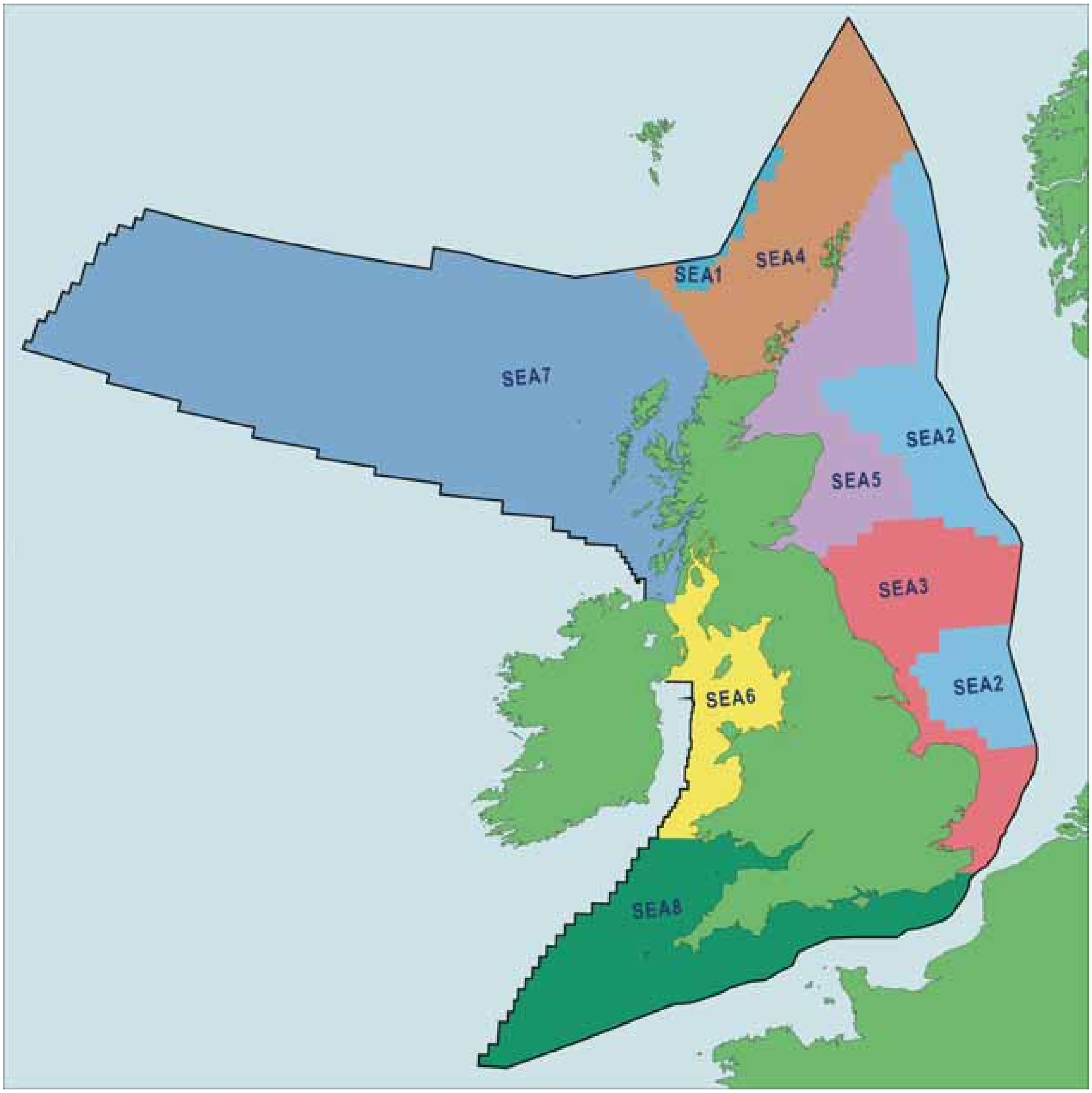
As part of an ongoing programme, the Department of Trade and Industry is undertaking Strategic Environmental Assessments prior to United Kingdom Continental Shelf licence rounds for oil and gas exploration and production and consents for wind-farm renewable energy developments. Before regional development proceeds, the Department of Trade and Industry (DTI) consults with the full range of stakeholders in order to identify areas of concern and establish best environmental practice. Stakeholders in a Strategic Environmental Assessment (SEA) include the DTI, the general public, Non Governmental Organisations (NGOs) (such as the Royal Society for the Protection of Birds and the Worldwide Fund for Nature), local authorities, government agencies (e.g. the Joint Nature Conservation Committee), experts in the field (universities, commercial consultants etc.), the industries wishing to undertake the development and other marine industries. The SEA process is used for predicting and evaluating the environmental implications of a policy, plan or programme and provides a key input to decision making. An SEA is conducted at a strategic level by the DTI - this contrasts with Environmental Impact Assessment (EIA), which is carried out for a specific development or activity by an operator.

An early step is an SEA scoping exercise to obtain external input to help define:

• the issues and concerns that the SEA should address
• key information sources and the current understanding of the natural environment and how it functions
• perceived gaps in understanding of the effects of the activities that would result from oil and gas licensing.

This technical report provides a summary of the hydrocarbons prospectivity of SEA6. This is followed by a synthesis of the seabed and superficial geology of SEA6. Natural historical and modern seabed processes are then summarized in relation to variations in the seabed and superficial geology. These are directly related to variations in the substrate properties of the seabed habitat.

In 1999 / 2000 the DTI conducted their first SEA of an area to the Northwest of Shetland (formerly referred to as the "White Zone"). The figure below shows the general plan for the SEA process where the numbering of the SEA areas indicates an initial order of consultation for the SEA areas.



Setting of SEA6 in relation to other SEA areas

Contents

TABLES

Executive summary

Hydrocarbons prospectivity

- The East Irish Sea Basin is at a mature exploration phase.

- The hydrocarbons-prospective sedimentary basins are characterised by source rocks, an abundance of structured regional petroleum reservoir and seal rocks and by suitable timing of geothermal events for generation and transfer of petroleum products from the source rocks to the reservoir rocks.

- SEA6 has regionally diverse seabed habitats which vary significantly from area to area in currently licensed acreages in the eastern Irish Sea. The variations in seabed habitats have been systematically related to the sedimentary processes driven by quantifiable patterns of mean seabed stress.

Sedimentary Processes

- Open shelf seabed sedimentary processes are driven by seabed stress originating from interaction of the seabed with strong currents generated by tidal streams and by waves.
- The scale of the stress imposed on the seabed and the related seabed habitat variability varies from regional (between mainlands, varying shelter around headlands) to macroscopic (around boulders and pebbles).
- During the fair to moderate weather conditions characteristic of the late spring, summer and early autumn seasons, the seabed sediment types on the open continental shelf are dominated by the stress imposed on the seabed by the strengths and flow directions of the peak tidal currents. In this setting most of the regional variations in seabed sediment types are dominated by the effects of the coastal configurations on the tidal streams.
- In areas where the seabed stress from waves is dominant, the seabed sediments coarsen with exposure to the increasing seabed stress generated when the waves interact with the seabed. Seabed stress from waves is dependent on wave power that varies with weather, wave fetch, seabed slope, wave direction and water depth.
- There are knowledge gaps on possible regional variations of seabed properties when the seabed is stressed during extreme weather events associated with storm surge and storm waves.
- In the most highly stressed seabed environments, exposed bedrock and strongly cohesive unsorted gravelly, sandy and muddy sediments are often swept clean of unconsolidated muds, sands, granular gravel and pebbles. Parts of the seabed in these areas may consist of cobbles and boulders. Environments of least seabed

stress are characterised by fine-grained muddy sediments. Mobile sandwaves are characteristic of areas where sediments are being transported along the seabed in environments that are situated between the areas of extremely high seabed stress and very low seabed stress. The sense of regional seabed sediment transfer is from and across areas of high seabed stress to areas of lower seabed stress.

The observations summarised above indicate that if large-scale disruptions to the natural seabed habitat are to be avoided, new development scenarios should avoid barriers that could have a significant effect on the regional patterns of seabed stress.

- As elsewhere on the UKCS, glacigenic sediments and relict static glacigenic bedforms have had significant regional and local effects on the patchiness of the distribution patterns of seabed sediments and seabed habitats.
- There is a knowledge gap in the research evidence required to securely link sub-regional increases in the percentage of biogenic carbonate in the sand fraction of the Irish Sea Mud Belt with increased biological productivity of surface waters, with methane expulsion from shallow and seabed sediments or with processes of bedload carbonate transport.
- Investigations of shipwrecks and artificial continuous barriers indicate that the amount of seabed scour is much larger than the profile of large seabed obstacles presented to near-bed current flow. The observations reveal patterns of scour asymmetry consistent with model predictions of mean peak tidal current speeds and the interpretations of the directions of regional sediment transport based on the geometries of seabed bedforms. Wreck studies could therefore be used to calibrate modelling on the likely long term effects of future seabed development scenarios. Shipwrecks have also contributed to seabed diversity.
- Active pockmarks, bioherms, banks in less than 20m water depth and some shipwrecks are already regulated by conservation measures. The following geological features are also worthy of consideration for preservation because they are irreplaceable:

Static bedforms	—	sarns, pingos, upstanding rock outcrops in mud belts
Mobile bedforms	—	banner banks, estuary banks and spits

- A gateway for sand exchange between the open shelf and the eastern Irish Sea coast off England appears to be defined by a zone situated between North Wales and the southern limit of the Eastern Irish Sea Mudbelt. Although the current prospects for large oil and gas developments in this area are very small, any developments that could the patterns of sand exchange through this environmentally sensitive area should be avoided.

1 Introduction

The Strategic Environmental Assessments (SEA) are designed to consider all of the marine environment with the main focus on areas that may be affected by the activities of the oil and gas or renewable energy industries. Parts of the SEA6, for example inshore areas, bays and inlets, are not currently considered prospective for non-renewable or renewable energy developments or for other reasons may be prohibited from future energy developments. Although such areas may not attract much attention from the oil and gas or renewable energy industries, they are included in this report in order to consider the marine environment as a whole.

SEA6 covers 10 oil and gas commercial quadrants and 13 named developed gas and oil fields in the Irish Sea (Figure 1). Some of the blocks within those commercial quadrants are unlicensed at present, but may be offered for licensing within the 23rd Oil and Gas Round to take place during 2005. With regard to windfarm development, licencing under Round 1 has resulted in seven named windfarm sites. Under Rounds 2 and 3, sites are at present under consideration (Figure 2).

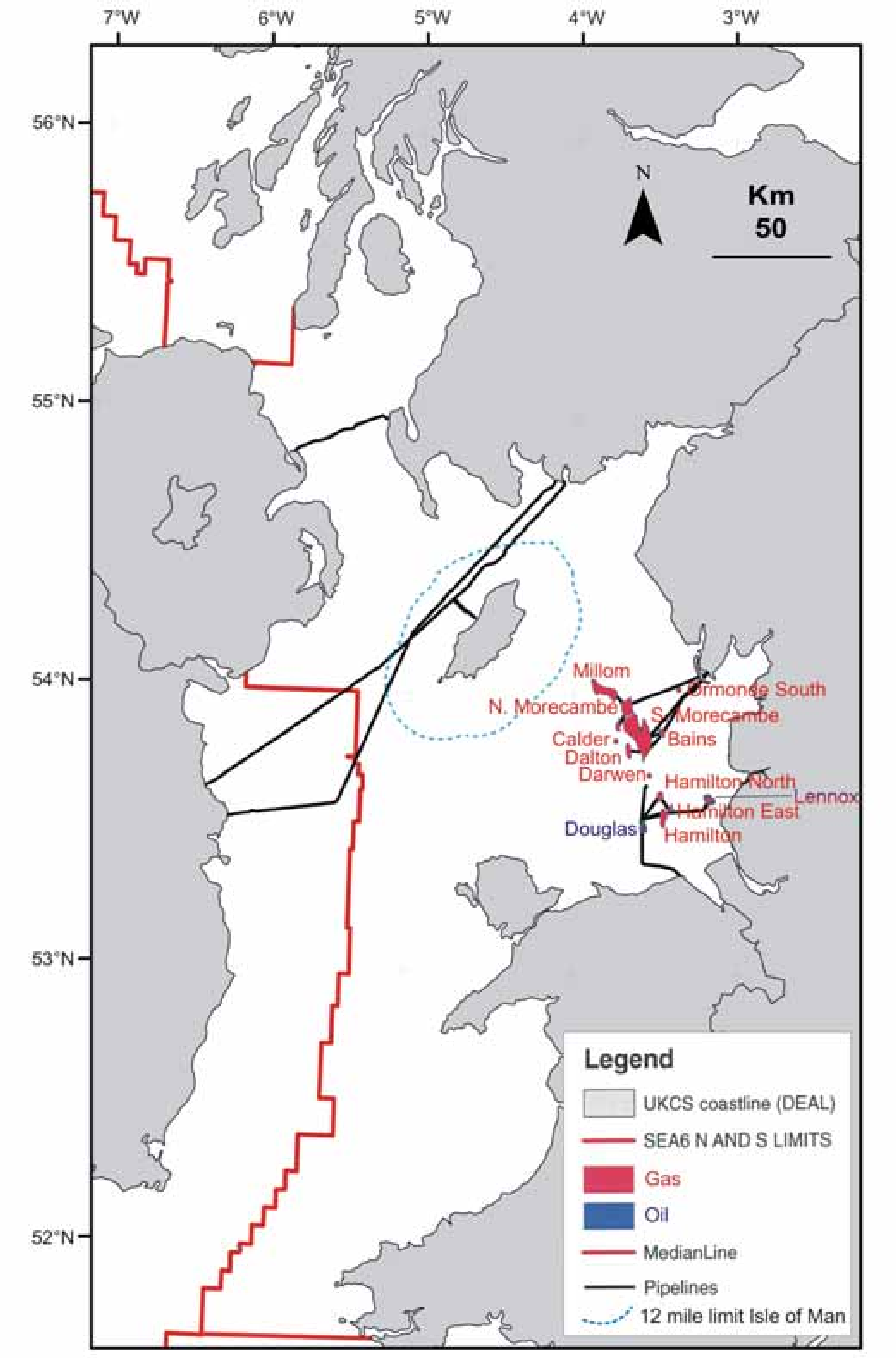


Figure 1 Location and infrastructure of producing gas and oil fields.

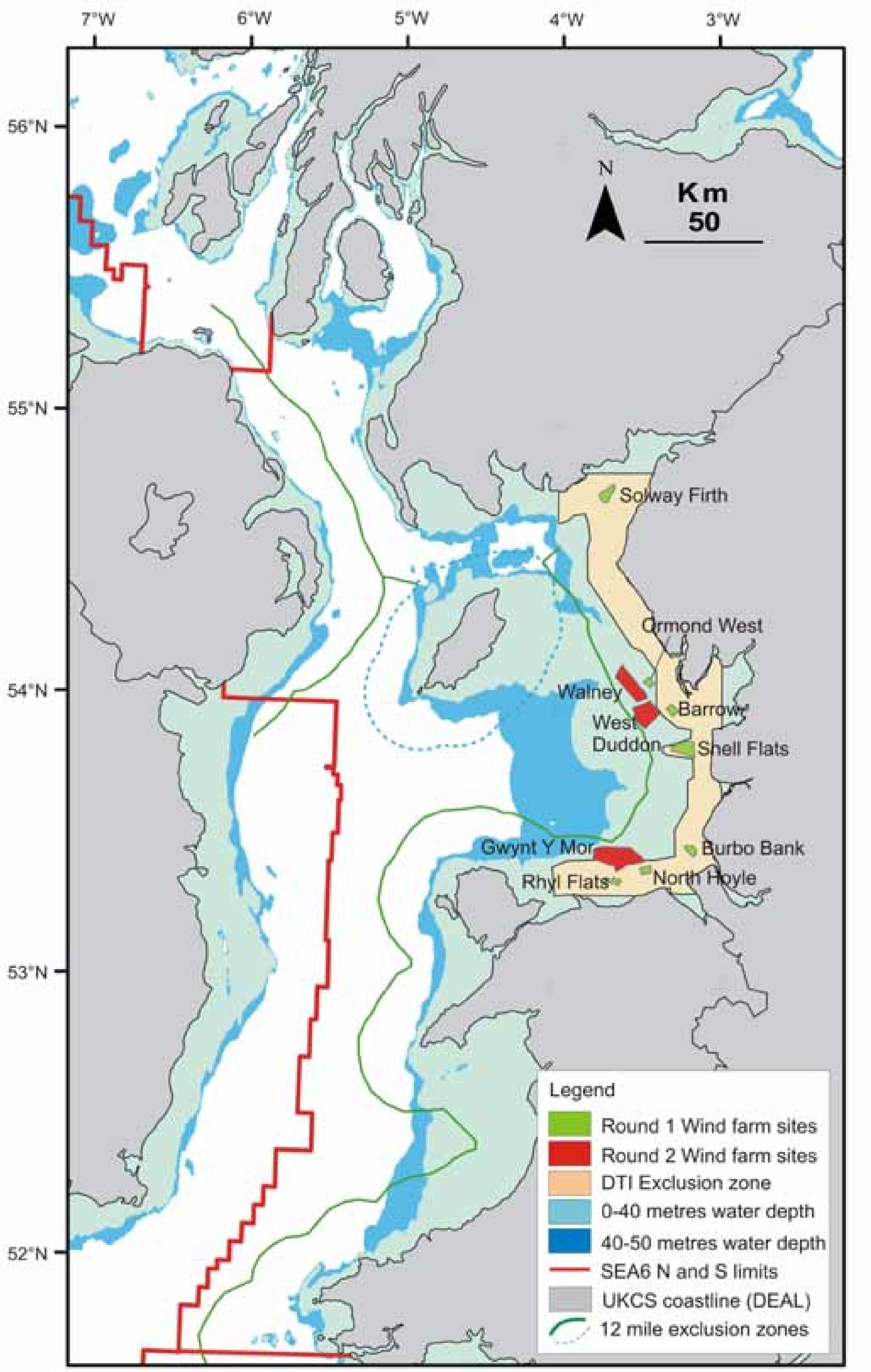


Figure 2 Location and infrastructure of windfarm development sites.

In 2002, the British Geological Survey under a commission from the Department of Trade and Industry (DTI) carried out an inventory of geological metadata for SEA6 (Tappin et al., 2002). The location of existing and proposed energy developments in the shallow water of the eastern Irish Sea supported a case for new seabed surveys to improve our understanding of the active sedimentary processes and their likely impact on windfarm development infrastructure.

A Scoping Study in 2004 (Tappin et al., 2004) was completed with the objective of determining the primary sites for the marine surveys. It was based on a combination of the existing regional knowledge of sedimentary processes operating in the area, and on a new report (Kenyon and Cooper, 2004) that reviewed the understanding of sand banks, sand transport and relationships to offshore windfarm development on the UK Continental Shelf. As a result of the study, five primary areas were identified for survey in the East Irish Sea area: Outer Solway Firth, Northeast Isle of Man, Morecambe Bay, outer Liverpool Bay and North Wales coast. The objective of the surveys was to provide data to test models of sediment movement in the East Irish Sea area.

The format defined by the contract for this report is:

- Executive Summary
- Introduction
- Hydrocarbon prospectivity
- Distribution of seabed sediments and a description of seabed sedimentary processes
- Strategic overview
- References
- Glossary of terms used in the text

The report data have been compiled and presented in the figures using the Arc9 geographical information system (GIS) based on spheroid and datum WGS 84, UTM zone 30 projection and origin 3 degrees west. The data incorporated into the BGS series of published 1:250,000 maps provide much of the seabed information presented in the GIS. This report also incorporates the data generated from the new seabed surveys completed in August 2004 during Survey Vessel *Meridian* Cruise A (Holmes et al., 2004). A glossary has been compiled of the technical terms used in this report (section 6).

2 Hydrocarbons prospectivity

The following account is largely based on data published by the Department of Trade and Industry (Dti, 2004) .

REGIONAL GEOLOGICAL AND INFRASTRUCTURAL SETTING

The main sedimentary basins within the United Kingdom Continental Shelf (UKCS) are divided into separate provinces on the basis of their petroleum geology and location. SEA6 encompasses the Irish Sea province, which can be subdivided on the basis of regional geological structure into seven major sedimentary basins (Figure 3). To date, discoveries of hydrocarbons have been gas in the East Irish Sea Basin and Cardigan Bay Basin / North Celtic Sea Basin and oil in the East Irish Sea basin. Commercial quantities of oil and gas are currently produced only from the East Irish Sea Basin (Table 1).

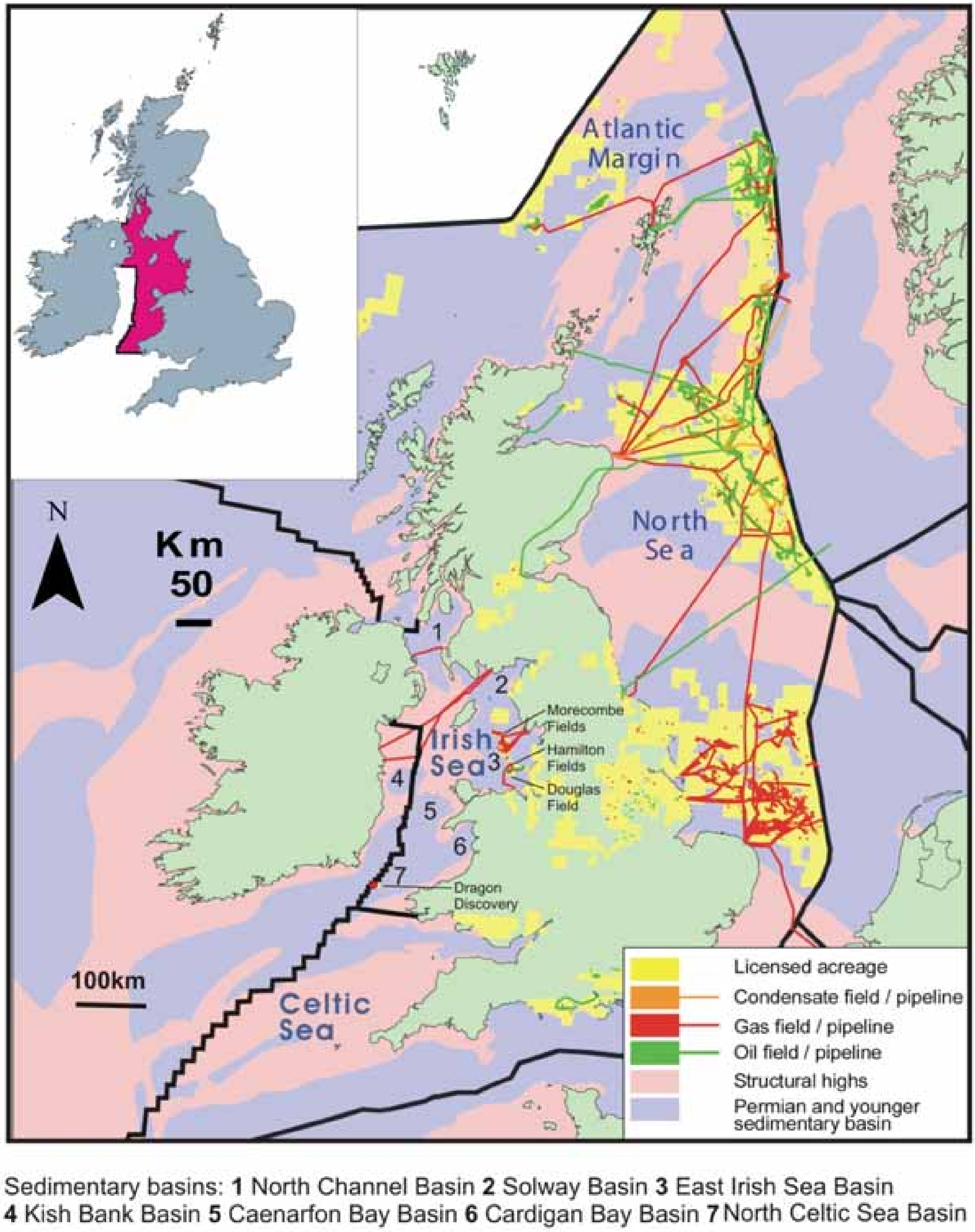


Figure 3 Regional geological setting and hydrocarbons infrastructure.

Figure 3: see Figure 2 for details of oil and gas field locations.

HISTORY OF DEVELOPMENT

Exploration of the UKCS has proceeded at a rapid rate, stimulated by the frequency and regularity of licensing rounds. Since 2000 these have been preceded by DTI Strategic Environmental Assessments (SEAs). A history of some of the developments of the producing oil and gas fields in SEA6 is summarized in Table 1.

Table 1 Development of oil and gas producing fields.

Field name	Main type of production	Discovery date	Production start	Original estimate of recoverable reserves
North Morecambe	Gas	1976	1994	27.90 billion cu m
South Morecambe	Gas	1974	1985	144.40 billion cu m
Hamilton North	Gas	1991	1995	5.34 billion cu m
Hamilton	Gas	1990	1997	14.33 billion cu m
Douglas	Oil	1990	1996	13.31 million tonnes
Bains	Gas	1974	1985	144.40 billion cu m
Calder	Gas	No information		
Dalton	Gas	1990	1999	2.87 billion cu m
Darwen	Gas	No information		
Lennox	Gas Oil	1992 1992	1996 1996	10.31 billion cu m 10.11 million tonnes
Millom	Gas	1982	1999	6.07 billion cu m
Ormonde South	Gas	No information		

Table 1 has been compiled from information from the DTI released in hardcopy up to 2001 and from the DTI website to 2005.

HYDROCARBONS GEOLOGY

Commercial oil and gas accumulations are generated when petroleum source rocks and seal reservoir rocks are configured adjacent to reservoir rocks with structural and/or stratigraphical closure. Source rocks have then to be matured by geothermal heat at suitable times for the petroleum to be generated and transferred into the sealed reservoir rocks. Areas with Jurassic mudstones with world-class oil potential, Carboniferous oil-prone basinal mudstones and Carboniferous gas-prone coal measures in the North Channel and Solway Basins possibly indicate some of the best scenarios for future commercial petroleum discoveries (Figures 4, 5).

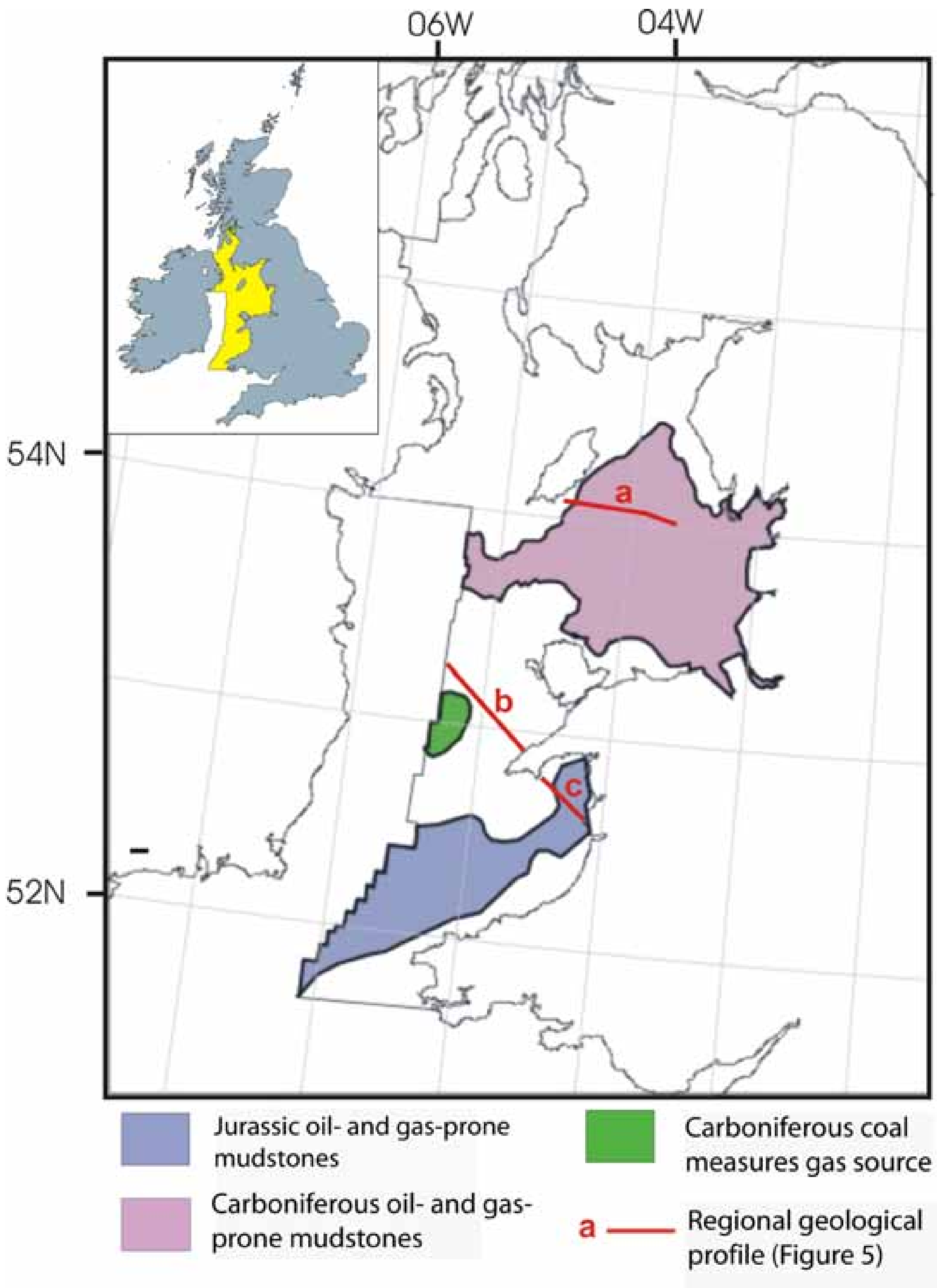


Figure 4 Distribution of petroleum source rocks.

Hydrocarbons-prospective sedimentary basins in SEA6 are characterised by source rocks and an abundance of regional petroleum reservoir and seal rocks (Figures 4, 5). The timing of geothermal and structural events has also been suitable for generation, transfer and trapping of petroleum products from source rocks to the reservoir rocks.

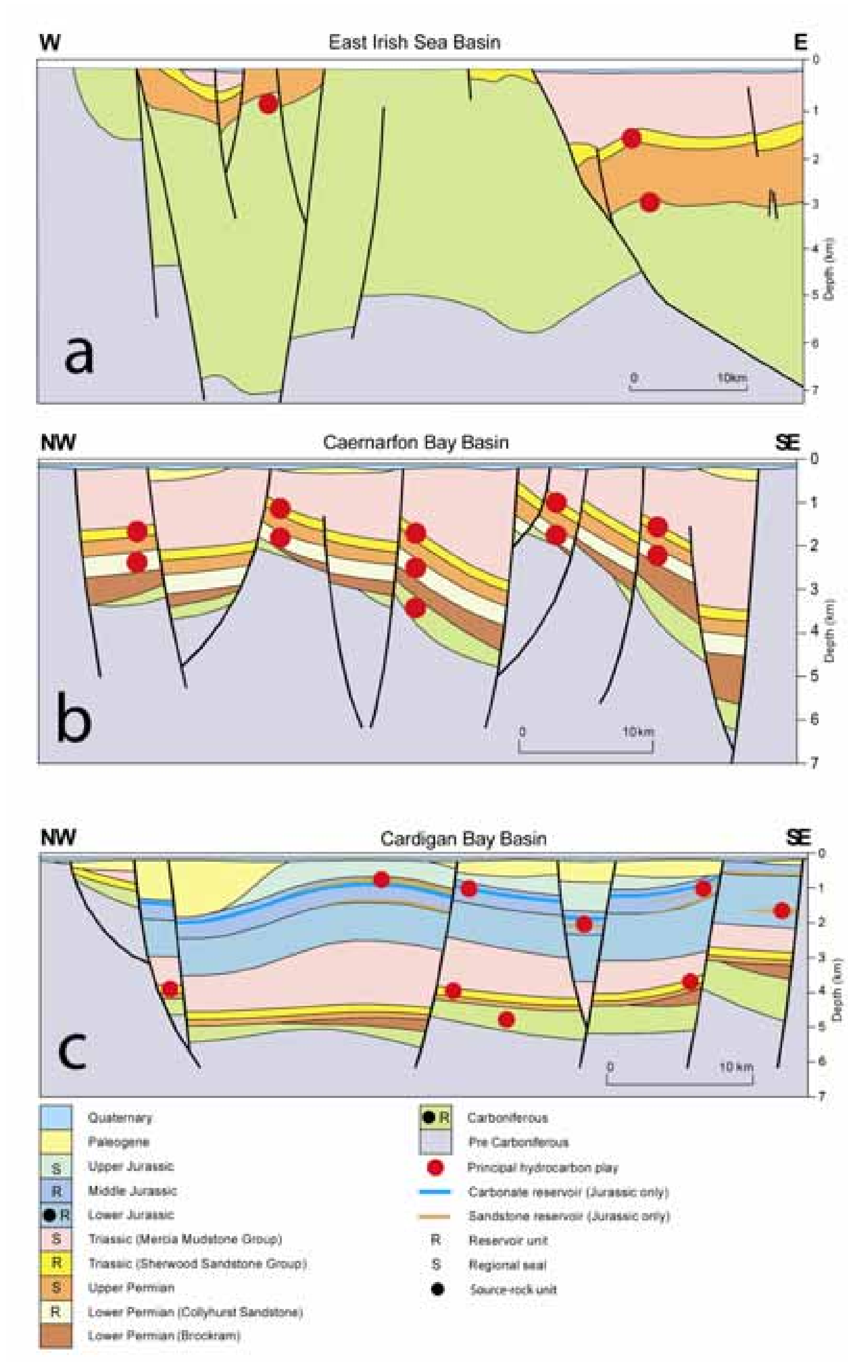


Figure 5 Generalised geological profiles and petroleum prospectivity.

Figure 5: **a** *is adapted after Tappin et al (1994),* **b** *and* **c** *are adapted after DTI (2004). For profile locations* ***a***, ***b***, ***c*** *see Figure 4.*

PROSPECTIVITY PLAYS

East Irish Sea Basin

The East Irish Sea Basin (Figure 3) is at a mature exploration phase, having produced oil and gas since 1985 (Table 1).

Early Namurian basinal mudstones are the source rocks for the hydrocarbons. Production from all fields is from fault-bounded traps of Lower Triassic, principally aeolian Sherwood Sandstone reservoir, sealed by younger Triassic continental mudstones and evaporites. Future exploration will initially concentrate on extending this play, but there remains largely untested potential also for gas and oil within widespread Carboniferous fluvial sandstone reservoirs. This play requires mudstone seal units to be present, as there is no top-seal for reservoirs subcropping the regional base-Permian unconformity in the east of the basin, and Carboniferous strata crop out at the seabed in the west.

Caernarfon Bay Basin

The Caernarfon Bay Basin (Figure 3) contains up to 7 km of Permian and Triassic sediments in an asymmetrical faulted basin that is bounded to the north and south by Lower Palaeozoic basement with no reservoir or source potential.

Only two exploration wells have been drilled so far, and there remain numerous undrilled targets in the tilted fault block plays that are characteristic of this basin (Figure 5). As in the East Irish Sea Basin, the principal target reservoir is the Lower Triassic, Sherwood Sandstone, which is top-sealed by younger Triassic mudstones and evaporites. Wells in the Irish Sector to the west have demonstrated that pre-rift, Westphalian coal measures are excellent hydrocarbon source rocks. These are at peak maturity for gas generation (Maddox et al., 1997). Seismic profiles clearly image these strata continuing beneath a basal Permian unconformity into at least the western part of the Caernarfon Bay Basin. The timing of gas generation presents the greatest exploration risk. Maximum burial of source rocks, and primary gas migration from the source rocks could have terminated as early as the Jurassic. Many of the tilted fault blocks were reactivated or created during Palaeogene inversion of the basin. It is also possible that a gas charge occurred during regional heating associated with intrusion of Palaeogene dykes, such as those that crop out nearby on the coastline of North Wales. This second phase of hydrocarbon generation has been invoked as an important factor in the charging of the East Irish Sea Basin's oil and gas fields (Floodpage et al., 2001). Fault block traps could also have been recharged by exsolution of methane from formation brines as a direct result of the Cainozoic uplift (Doré and Jensen, 1996) .

Cardigan Bay Basin

The Cardigan Bay Basin forms a continuation into UK waters of Ireland's North Celtic Sea Basin (Figure 3). The Cardigan Bay Basin comprises a south-easterly deepening half-graben near the Welsh coastline, with an internal structure that becomes increasingly complex towards the south-west. Permian to Triassic, syn-rift sedimentary rocks within the basin are less than 3 km thick and are overlain by up to 4 km of Jurassic strata, and locally also by up to 2 km of Palaeogene fluviodeltaic sediments. The basin has a proven petroleum system, with potentially producible gas reserves at the Dragon discovery near the UK/Ireland median line (Figure 3). There are oil shows in a further three wells.

The Cardigan Bay Basin contains multiple reservoir targets (Figure 4), which include the Lower Triassic (Sherwood Sandstone), Middle Jurassic shallow-marine sandstones and limestone (Great Oolite), and Upper Jurassic fluvial sandstone, the reservoir for the Dragon discovery. The most likely hydrocarbon source rocks are early Jurassic marine mudstones (Lias Group). These are fully mature for oil generation in the west of the UK sector, and are mature for gas generation nearby in the Irish sector. Gas-prone, Westphalian pre-rift coal measures may also be present at depth locally. The Cardigan Bay Basin underwent two Cainozoic phases of compressive uplift, whereas maximum burial that terminated primary hydrocarbon generation was probably around the end of the Cretaceous, or earlier if Cretaceous strata, now missing, were never deposited in the basin. Despite the Cainozoic deformation, the Dragon discovery has proved that potentially commercial volumes of hydrocarbons were retained at least locally in Cardigan Bay. In addition to undrilled structural traps, the basin contains untested potential for stratigraphical entrapment of hydrocarbons near syn-sedimentary faults, especially in the Middle Jurassic section.

3 Seabed sediments, seabed habitats and sedimentary processes

The method adopted for description of seabed habitats in this report broadly follows the approach adopted by the Joint Nature Conservancy Council: in the absence of detailed biological data, marine habitat types can be identified from variations in seabed physiography and seabed-sediment properties (Golding et al., 2004). In turn, these are derived from interpretations of seabed-sample data, geophysical data and hydrographical data. Maps of seabed physiography and seabed-sediment properties are separated for clarity of presentation in this report. A summary of some of the procedures and classification schemes used for acquiring and processing seabed samples for seabed-sediment mapping is in Appendix 1. Figure 6 summarises the regional physiographical and cultural setting of the seabed in SEA6.

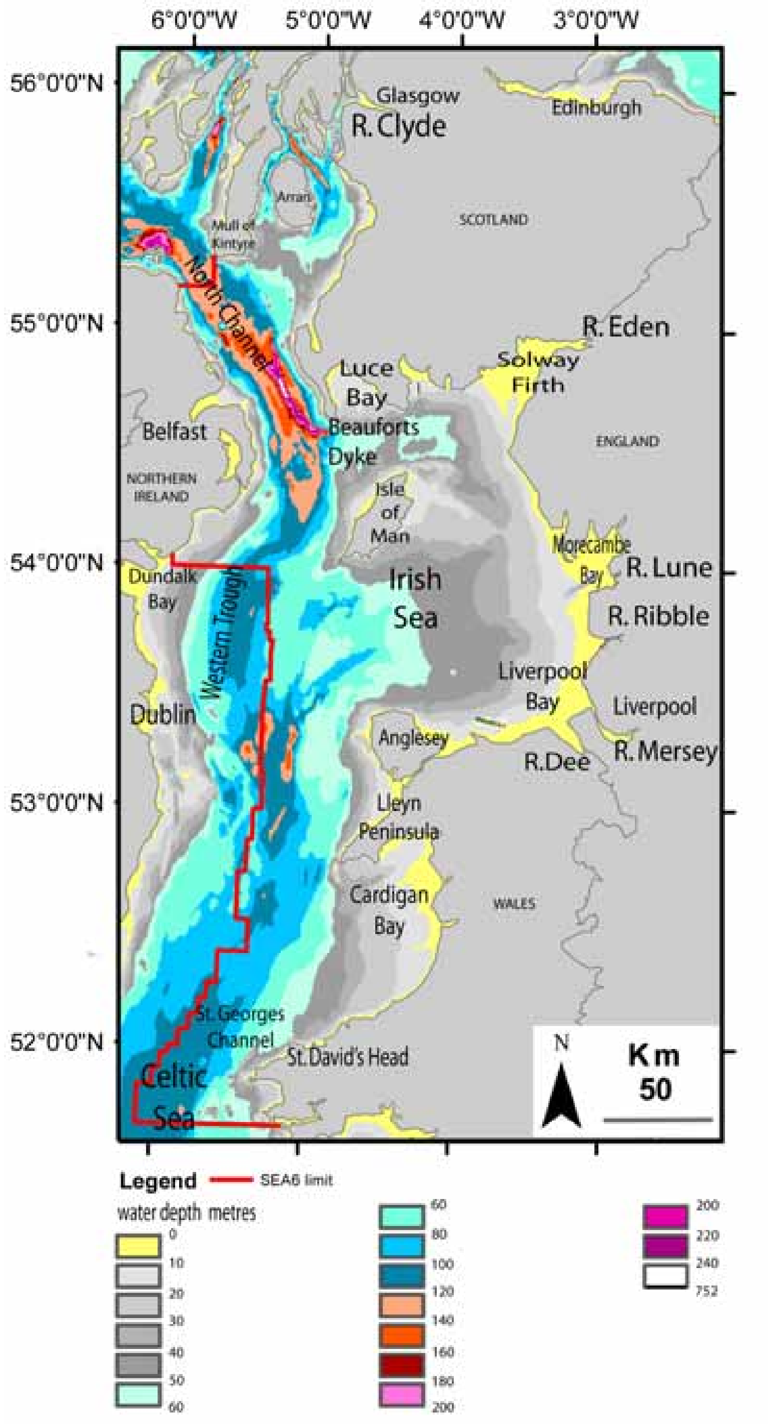


Figure 6 Regional seabed physiographical and cultural setting.

Figure 6: Physiographical data are adapted from the BGS digBATH dataset. See Frontispiece for an illustration of a digital terrain model that links the physiography of mainland Wales, England and Scotland with the seabed physiography.

SEABED SEDIMENTS

Sediment grains are winnowed on the seabed depending on how strong the near-bed currents are in relation to the threshold speeds of near-bed currents required for grain suspension into seawater and grain bedload transport. The seabed-sediment grain-size distribution patterns reflect the exposure of the seabed to winnowing processes, which are driven by the stress put on the seabed by directional ocean, wind, storm surge and tidal currents and by non-directional currents from wind and swell waves. The regional trend is for sediment grains to move across or away from seabed with higher stress towards the seabed with a lower stress. The amount of stress imposed on the seabed and thus the amount and type of sediment imported into, deposited, or exported out of the study area varies with position and time. As a result, in areas of seabed scour and grain bedload transport, there are continuous processes of sediment reworking and redistribution resulting in ‘ seabed polishing’. The end-members of the processes driving sediment transport and deposition are large areas of (a) exposed bedrock and exposed strongly cohesive unsorted gravel, sand and mud (collectively termed diamicton: explanation Section 6, Glossary) and (b) muddy sediment (see Figure 27 for a definition of the range of grain sizes commonly found in mud). Large areas of exposed rock and diamicton are swept clean of unconsolidated sand in the most highly stressed seabed environments, perhaps leaving some pebbles, cobbles and boulders (collectively termed gravel, see Figure 27). Areas of least seabed stress are characterised by more or less stable fine-grained muddy sediments, significant proportions of which have been deposited from suspension in conditions where there are very low seabed currents (Figure 7).

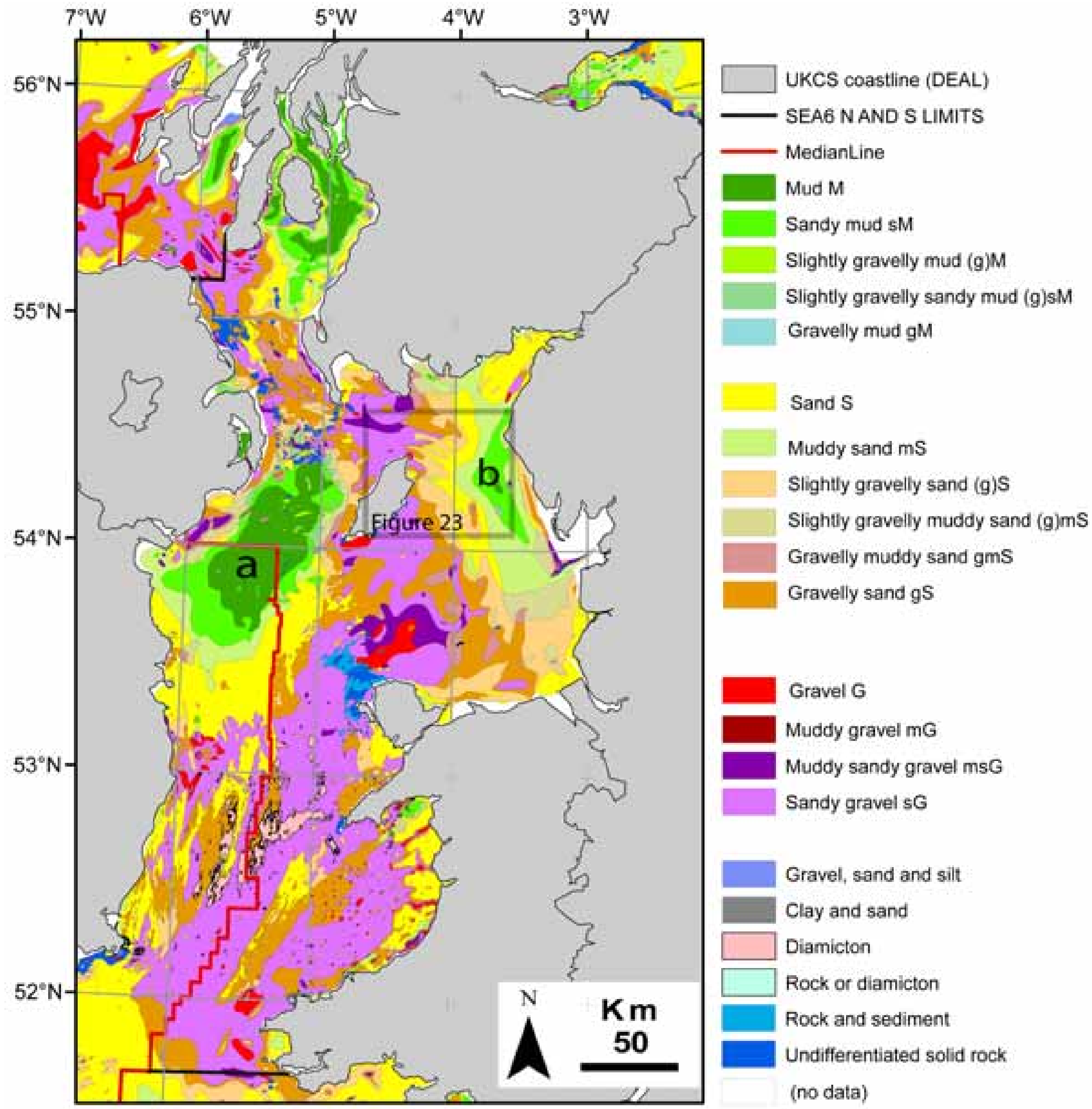


Figure 7 Seabed sediments.

Figure 7: Data sourced from the BGS series regional 1:250 000 scale maps of seabed sediments. The large areas of mud, sandy mud, muddy sand and slightly gravelly muddy sand characterised by a smooth and relatively featureless seabed in the Irish Sea are referred to as the **a** *Western Irish Sea Mudbelt and* **b** *Eastern Irish Sea Mudbelt. See Appendix 1 for an explanation of the methodology and terms used to describe variations in seabed sediment types.*

PROCESSES INFLUENCING SEABED SEDIMENT GRAIN SIZE AND BULK COMPOSITION

An analysis of the oceanography of the study area is presented by Proudman Oceanograpic Laboratory in this 2005 DTI SEA6 technical report series (Howarth, 2005). The purpose of the following account is to tie variation in the hydrography with regional variations in seabed sediment properties and processes.

3.1.1 Tides

The tides propagate from the Atlantic Ocean to the north through from the Celtic Sea and to the south through the North Channel. The areas where the tidal fronts meet adjacent to the Isle of Man are characterised by relatively weak peak tidal currents. There is an overall very strong correlation between the annual mean peak tidal currents and annual mean seabed stress (Figure 8). The strong correlation between the distribution patterns of coarser sediments and the stronger mean peak spring tidal currents establishes that the stress put on the seabed by the tidal currents is a major influence on sediment composition. The positive correlation between the stronger mean peak tidal currents and seabed stress with constrictions to tidal flow by coastal configuration also means that on the open continental shelves of the north Celtic and Irish Sea and the North Channel there is little regional correlation between the water depth and sediment composition (Figures 6,7,8).

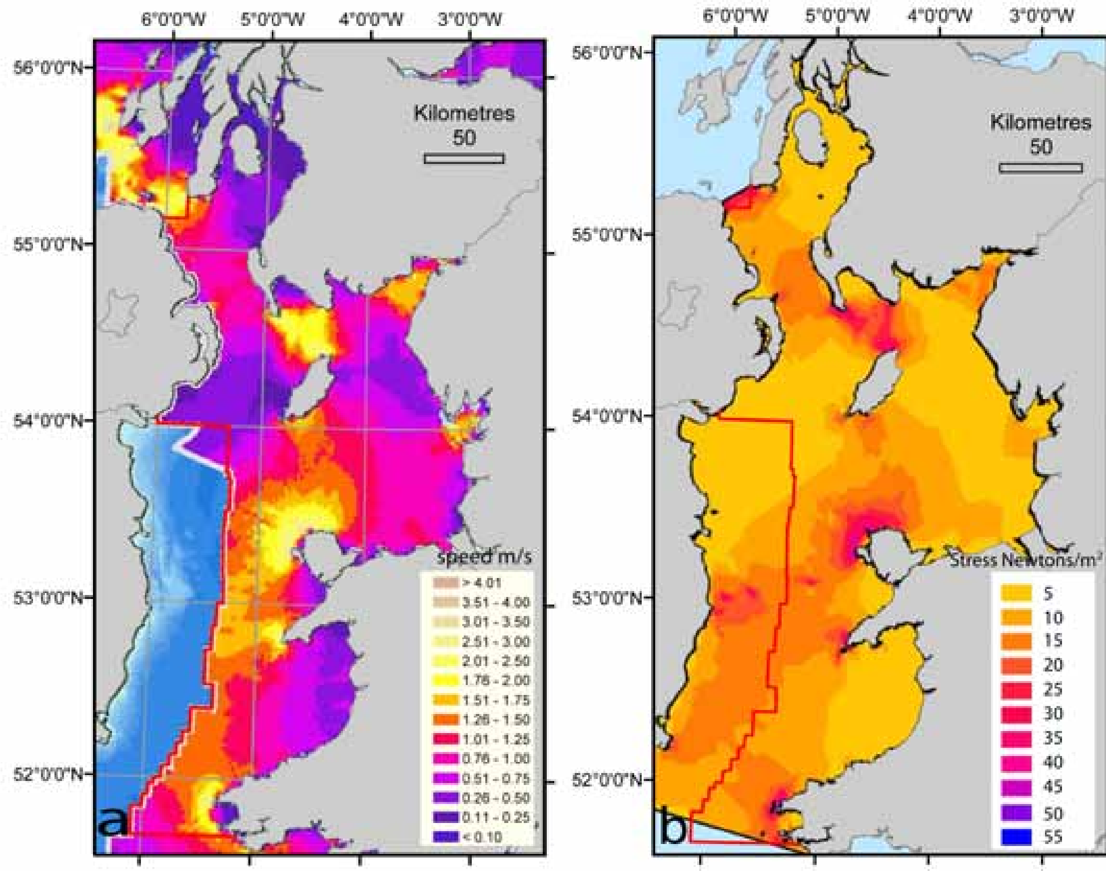


Figure 8 a Mean peak spring tidal currents **b** Mean seabed stress.

Figure 8: **a***: sourced from the DTI Atlas of Renewable Energy (2004), and modelled for mid-water currents averaged over 1 year.* **b***: modelled by Proudman Oceanographic Laboratory for seabed stress forced by tides and winds averaged over 1995-1997 (J.N.C.C., 2004); Figure 7 in(Howarth, 2005).*

Mid-water mean peak spring tidal currents of <0.5 m/s encompass the mud belts, >1m/s encompasses most areas of sandy gravel, and >1.25m/s encompasses the distribution of gravel and exposed rock and diamicton at seabed.

3.1.2 Climate

Wind drives directional sea-surface wind currents and storm surge currents. Wind also drives non-directional rotational near-bed currents. These are generated when wind waves and swell waves interact with the seabed to stir it up. The effects of swell and wind waves on processes of seabed erosion and seabed sediment transport varies with the wave fetch, seabed gradient and tidal range. The Solway Firth, Morecambe Bay and Liverpool Bay, with the highest mean spring tidal range (>6m) and <0.02˚average seabed gradient, include the largest areas of mud and sand tidal flats in SEA6. Exposure of seabed in these areas to waves and wind-driven currents shifts with the changes in the wind patterns and the shelter provided by land and offshore banks and ridges. In contrast, the seabed exposure to stresses from tidal currents varies more predictably with constrictions to the cyclical flood and ebb tidal streams.

One effect of wave interaction with seabed in shallow water is a tendency to flatten sandwaves and other mobile seabed bedforms that may have been previously built up by the tidal currents (Appendix 2: Figure 27 b). This process re-distributes sediments laterally and contributes to widening of banks and ridges on the open shelf and flats in estuaries. If the stresses imposed on the seabed by wind-driven currents and waves prevail from one direction, the stress asymmetry also imparts geometrical asymmetries to seabed banks and ridges. Such effects are illustrated on Constable Bank, the crest of which defines a submarine sand spit that extends to the west from the Rhyl Flats on the approaches to the River Dee Estuary (Figure 9). The bank was surveyed during the DTI SEA6 surveys in August 2004 immediately following northerly gales. The waves that were generated during the gales appear to have flattened the crests of east-migrating, very large sandwaves formed on the north flanks of Constable Bank and, consistent with the interactions between the tidal and wind-driven processes summarised above, the steeper south flank faces away from the direction of waves with historically the longest fetch. The large-scale asymmetry of the bank facing direction appears to be long standing as it is also registered on Admiralty Chart number 1971 (Constable Bank surveyed 1927-1929). Because of this asymmetry, it is expected that over the long term the Constable Bank is migrating towards the North Wales coast. The overall shape of Constable Bank also widens and flattens to the east where the bank shallows and merges with the Rhyl Flats (Figure 9).

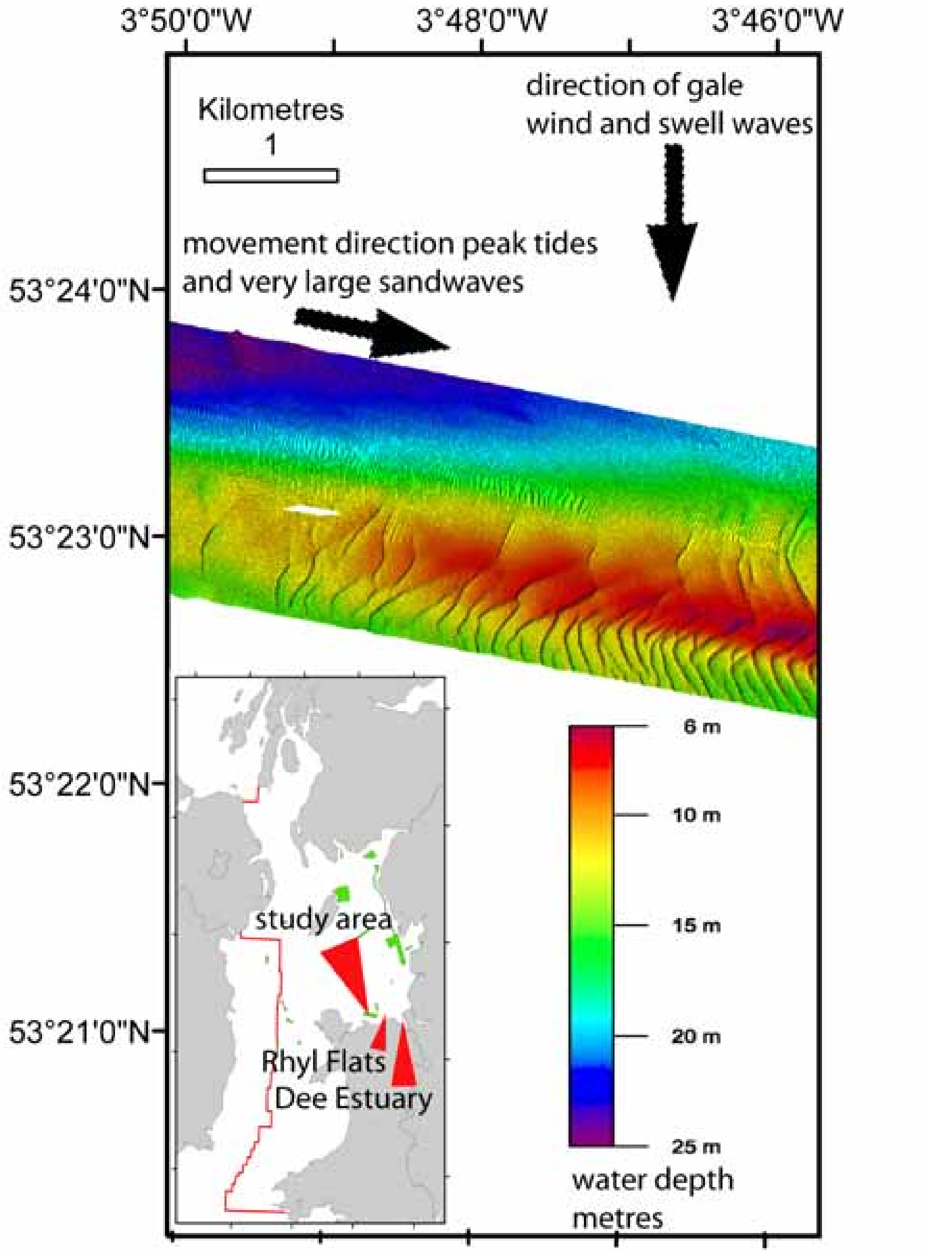


Figure 9 Constable Bank: physiography and environmental setting, August 2004.

Figure 9: Image extracted from the DTI 2004 SEA6 survey dataset. BGS regional sample data indicate that the bank is composed of sand, and the surrounding seabed in more than approximately 20 m water depth is composed of slightly gravelly sand.

A plot of the areas of seabed in less than 15m water depth imposed on areas with low peak tidal speeds gives a nominal indication of the shallow water areas with potential for wave interaction with the seabed in fair-weather conditions (Jackson et al., 1995) (Figure 10). These are areas where the wind-driven surface currents, or wind and waves driving longshore drift are likely to have a significant effect on seabed composition and near-bed sediment transport. Such areas vary from very narrow bands around the sheltered margins of the Scottish sea lochs to wider ramps of wave dominance in the eastern Irish Sea, including Cardigan Bay. A prediction for the effect of swell and wind-wave dominance in part of Cardigan Bay goes towards explaining why the seabed there is characterised by sands and gravels, and the sarns by gravels, even though the water depths and (relatively low) mean peak spring tidal currents are comparable to those associated with the Eastern Irish Sea Mudbelt (Figures 8, 10).

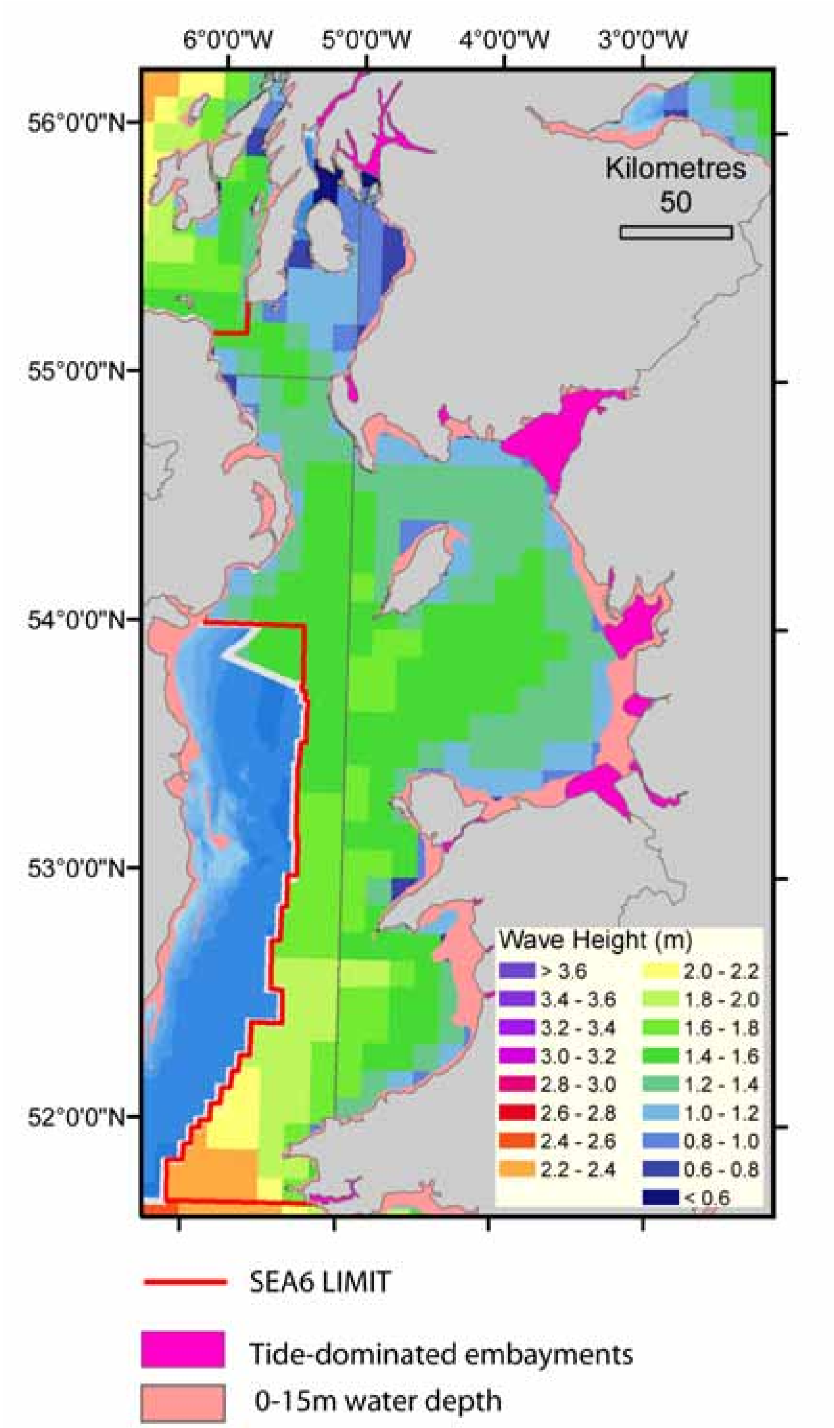


Figure 10 Annual mean significant wave height.

Figure 10: Data sourced from the DTI Atlas of Renewable Energy (2004).See Glossary Section 6 for a definition of significant wave height.

Regional trends of changes in annual mean significant wave height occur where the open shelf areas are exposed to prevailing wind and swell waves originating from the south-west and from the north-west (Figure 10). Exposure to the largest waves is most pronounced on coasts and submarine shoals facing the longest fetches and in environments where the wave energy has been least dissipated by the interaction of the waves with shoaling seabed. Such areas occur off southern Wales, the Lleyn Peninsula, Anglesey and the Isle of Man. These areas are also characterised by very high stress imposed on the seabed by strong tidal currents (Figure 8) so that the waves are only expected to have a dominant effect on the seabed when mean significant wave height is enhanced during the more severe weather conditions.

Observations off the Isle of Man from gravel waves in 50 m water depth where the wave orientations were unrelated to the tidal streams, indicate that gravel may be occasionally mobilised at such depths by long-period storm waves (Jackson et al., 1995). In the Irish Sea, winds of storm force and higher are recorded on average for 35 to 45 days a year (Hydrographic Department, 1960). The lack of observations of the regional changes forced on the seabed composition during storm conditions are a significant gap in our knowledge. This is because most of the data collected during sampling and geophysical surveys used for the BGS interpretations of variation in seabed sediments have been acquired in fair weather during the spring, summer and early autumn months over a total survey period of approximately 20 years since 1972. The possible impact of seasonal climate change on the regional pattern of sediment distribution has not been investigated during the BGS regional sampling programme. However, the strong correlations between annual mean tidal current strength and the regional sediment distribution patterns appear to show that the local effects of storms on seabed composition and bedforms are repaired during the relatively long periods of fair to moderate weather.

In areas of high seabed stress the environment will rapidly respond to changes. Thus, for example, drill cuttings released to the seabed will be rapidly dispersed from their origin. The seabed will also rapidly change both shape and sediment grain-size composition in response to stress patterns generated when near-bed currents are diverted around permanent seabed fixtures.

3.1.3 Historical seabed evolution

The seabed is composed of outcrops of bedrock and glacigenic sediments that form relict seabed features covering approximately 10% of the area of SEA6. In the other areas, relatively thin mobile seabed sediments transit across an variety of thick relict sediments. The influence of historical processes on the properties of relict seabed and relict superficial features are therefore summarised in this section.

Historical coastline shifts around the British Isles have occurred with adjustments to large-scale vertical movements of the Earth's crust, the largest of which was more than 500 m uplift and then long-term subsidence since approximately five million years ago (Japsen, 1997). On these movements were imprinted global sea-level changes and regional differences of vertical crustal movements. These changes were due to unloading and loading of crust by ice and sediments, particularly after approximately 760 000 years ago, when there was a shift to larger polar ice volumes (Funnel, 1995). This period included seven major glacial periods of approximately 80 000 to 120 000 years duration, when global sea level fell to 100 m or less below present level. The geological evidence is that at least three regional glaciations have profoundly moulded the seabed physiography and shallow sub-seabed sediments in SEA6 (Wingfield, 1989) .

During the maximum of the last major glacial period, approximately 21 000 to 17 000 years ago, sea level in the Celtic Sea was possibly 135 m below present (P Bouysse, 1976) and a land bridge linked Ireland with England and Wales (Lambeck, 1996). Between the major glacial and interglacial periods there were other significant climate and global sea-level changes of 1000 to 3000, sometimes 5000 years or more average periodicity (e.g.(Clapperton, 1997). During these times the sea level probably fluctuated in SEA6 over a range of less than 10m to 50 m or more.

At the maximum of the last glaciation, the regional ice sheets had merged across much of the northern British Isles and flowed south (Lambeck, 1995). In areas where the main stream of ice flow was accelerated, it gouged major north–south and north-west–south-east elongated basins into the rock. The largest and deepest of these occur in the northern SEA6 and have contributed significantly to seabed habitat diversity (Frontispiece, Figure 6).

By cutting through regional variations in hardness and composition of rockhead and unlithified strata, the ice reworked and then redeposited a wide variety of sediments (Figure 11). During the waning stages of the last glaciation and as the ice retreated, it deposited fluvial outwash and also left behind unsorted gravelly, sandy and muddy sediments (diamicton, definition Section 6) over the areas that it had previously eroded. The diamicton was subsequently resistant to marine erosion and is the main sediment type underpinning the seabed sediments (Figure 11).

The sea rose to reconnect the North Channel with the Celtic Sea after approximately 16 000 years ago (Lambeck, 1995; Lambeck and Purcell, 2001). By the early part of the present interglacial, approximately 8 300 years ago, much of SEA6 was submarine, by which time a fully marine connection had also been re-established between the North Sea and the English Channel (Jelgersma, 1979) and the currents from wind and swell waves and strong tidal streams once again shaped the seabed.

There continue to be predictable modern net vertical coastal and offshore movements. These are driven by the interactions between postglacial global sea-level rise and crustal movements that are part of a continuing gradual response to historical changes in crustal loading due to former ice melt and the transfer of rock and unconsolidated sediments. Such adjustments are reflected in a modern maximum net rate of vertical land and seabed uplift of approximately 1.1 mm/yr in the northern SEA6 compared to a fall in the southern SEA6 of approximately 0.5 mm/yr (Shennan and Horton, 2002). The adjustments are unrelated to natural seismicity and they do not pose a significant safety risk to future seabed developments related to oil and gas.

The overall geological perspective is for rapid 1000 to 100 000 year or more cyclical changes in subglacial and submarine processes of erosion and deposition. As summarised above, these changes have played a pivotal part in shaping the large-scale physiography of the modern seabed. Another lasting impact of the rapid evolution of the seabed has been that the superficial strata below the seabed sediments vary on a sub-regional basis and have significantly different properties to those of the seabed sediments (Figures 7, 11). As a result, new developments which require foundations set below the seabed are likely to encounter geohazards that could affect the safety and cost of seabed and shallow sub-seabed development operations.

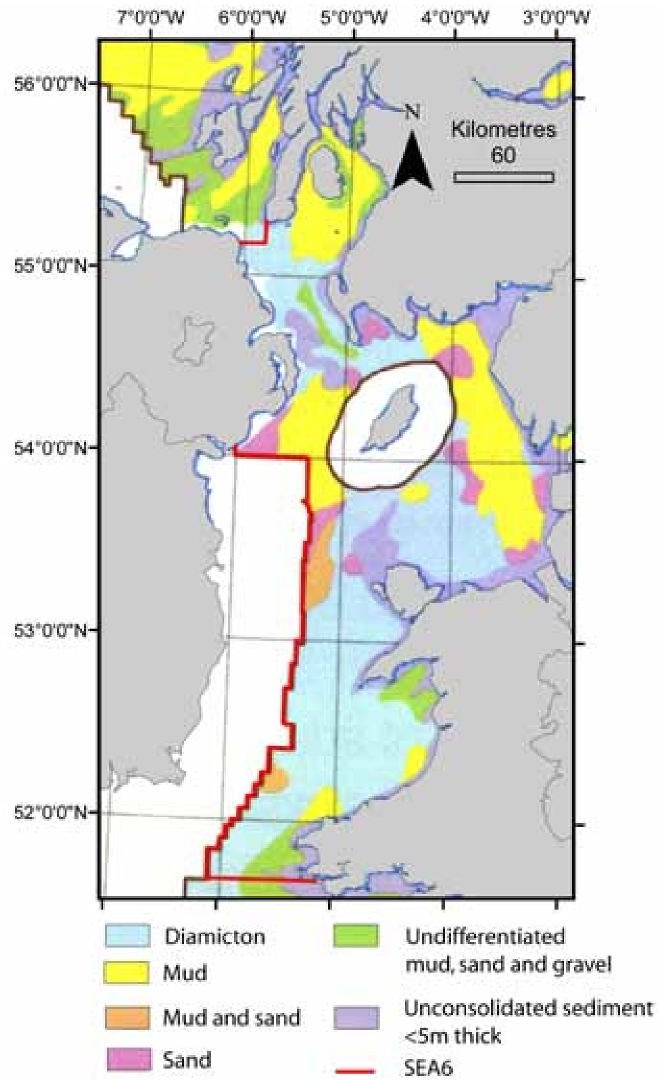


Figure 11 Generalised distribution patterns of sub-seabed sediments.

Figure 11: based on interpretations of high-resolution seismic reflection-records integrated with core samples in the range of 1 to 5 m or more below seabed. Nominal distribution patterns are simplified from the BGS 1:1 million and 1:250 000 scale regional maps (Holmes et al., 1993, 1994).

The minerological composition of the seabed sediments has also evolved with time and climate change. For example, former sub-ice and ice-proximal diamictons and fluvial muds, sands and gravelly sediments on the open continental shelf originally consisted of rock and silica-rich grains with no carbonate biota or few carbonate biota with little biodiversity. Modern submarine sediments consist typically of a mixture of reworked glacigenic and fluvial sediment grains and 5 to 20 weight % or more biogenic carbonate fragments that have mainly originated from fossil biota living in post-glacial times. There is a strong overall correlation between high concentrations of seabed biogenic carbonate in sands associated with strong tidal currents. Thus, the proportion of carbonate grains in the sand fraction of the modern seabed sediments increases with the mean grain size. With the exception noted for areas of pockmarks (page 31), the proportion of biogenic carbonate is highest in the sand fractions of the coarsest seabed sediments. A bias is for preservation of fragments of many of the modern shelly biota in sandy seabed sediments exposed to relatively high average seabed stress (Figures 7, 8 12). These observations suggest that modern physical processes have a strong influence on the chemical composition of the seabed sediments.

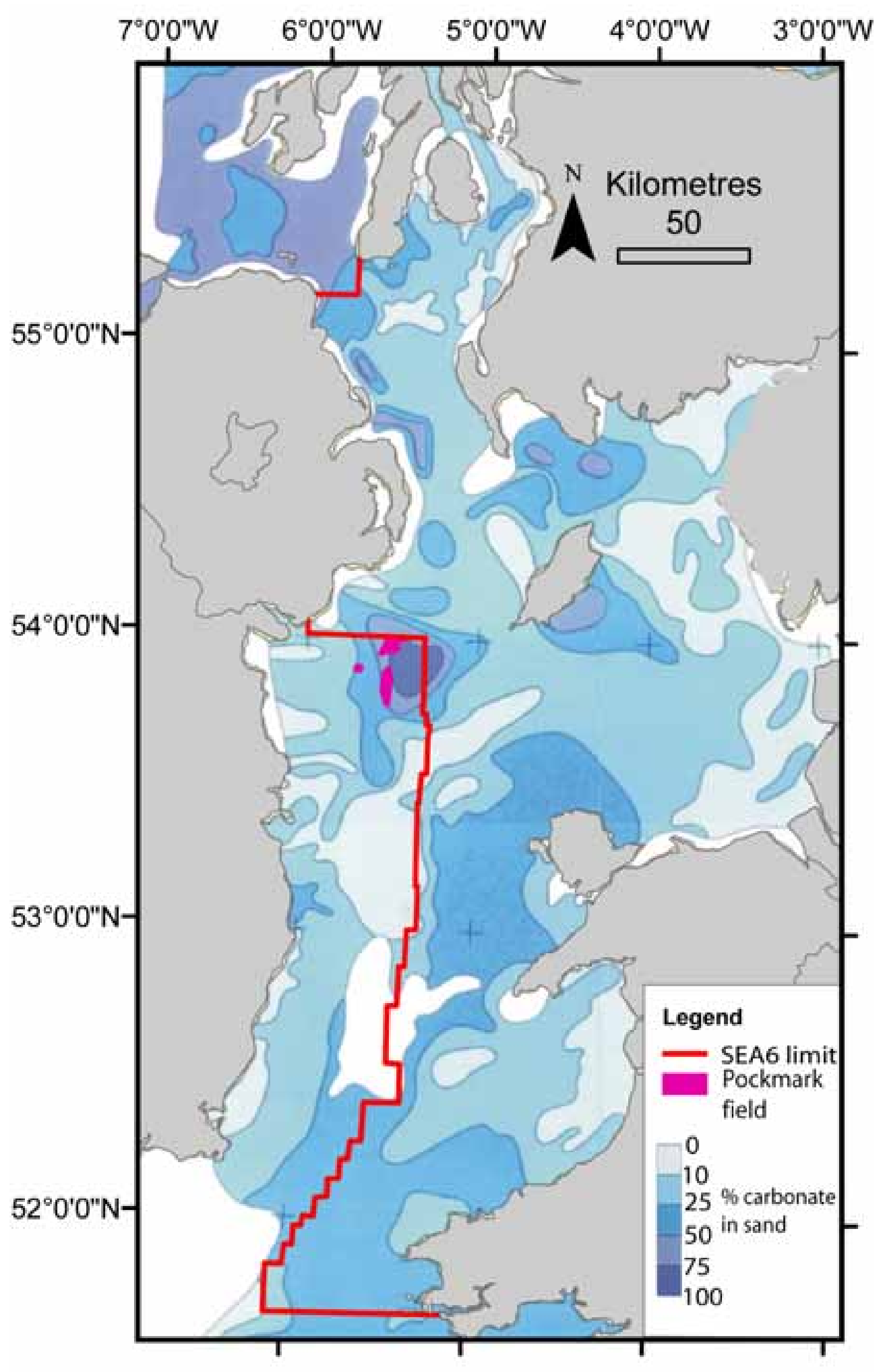


Figure 12 Percentage carbonate in the seabed-sediment sand fraction, and locations of pockmark fields.

Figure 12: Locations of pockmark fields updated using the DTI 2004 SEA6 survey dataset. Adapted from the BGS regional mapping (Pantin, 1991).

SEABED BEDFORMS

Seabed bedforms can be broadly classified into static and dynamic bedforms.

Static bedforms

Static bedforms are important because they provide stable sites for distinctive biota and, where occurring in isolation, they contribute to the local diversity and patchiness of the seabed habitat. By redirecting the stress imposed on the seabed by the directed currents, the static bedforms also generate useful indicators of the direction of bedload sediment transport. Excepting shipwrecks, pipelines, power cables, telephone cables and the static bedforms built up by living biota (bioherms or reefs), the static bedforms provide snapshots of former terrestrial, submarine, glacial, periglacial and early postglacial features and processes (Figure 13).

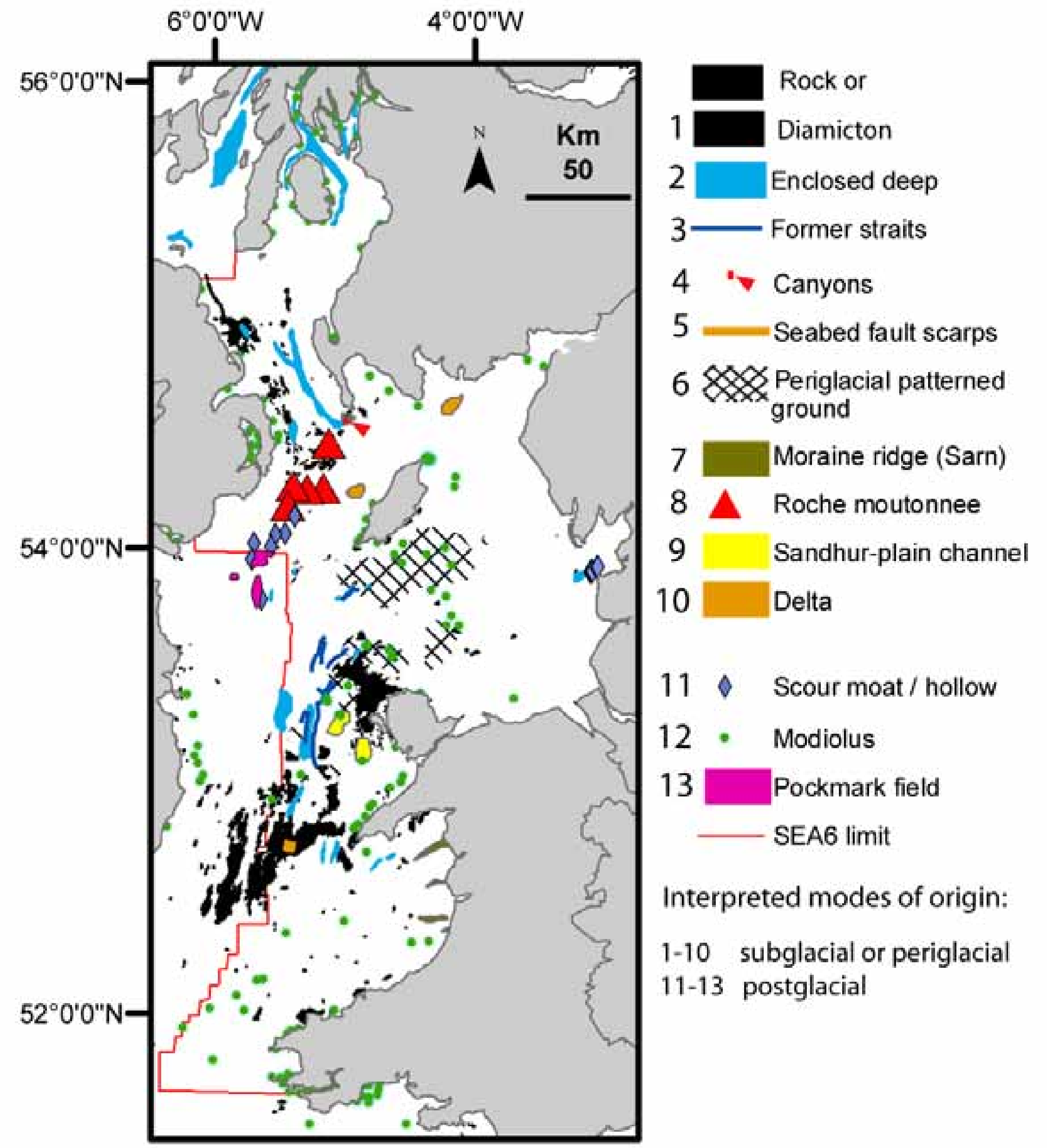


Figure 13 Static bedforms

Figure 13: See Figure 16 for the distribution of shipwrecks surveyed by the DTI in 2004. Adapted after BGS regional reports (Fyfe et al., 1993; Tappin et al., 1994; Jackson et al., 1995), the Joint Nature Conservation Committee (2004) database for Modiolus and modified by results from the DTI 2004 SEA surveys.

Rock and diamicton

The largest areas of outcrops of rock, rock and sediment and diamicton occur with rough and very varied seabed topography, usually with seabed gravels, in areas of very high seabed stress and seabed scour (Figures 7, 8). Some rock outcrops, such as the *roche moutonnée*, were formed subglacially and have an elongated form with a tail pointing south indicating the direction of former ice movement. Off Anglesey, steep slopes of 20° to 30° or more and 10 to 40 km or more in length form prominent scarps composed of glacigenic and rock strata (Figure 13). The scarps are subparallel to regional fault patterns in the underlying solid rock. They are locally aligned to the modern Anglesey coast and may have been partly eroded by ice. They are also thought to align with former tidal straits (Figure 13) (Jackson et al, 1995). They are important because the areas in which they occur are characterised by some of the strongest modern peak mean spring tides, the diversion of which is likely to lead to near-bed current acceleration and distinctive seabed habitats. Gas seepage has also been mapped by the BGS as being coincident off Anglesey with a major fault. The fault separates Mesozoic sedimentary rocks to the west from basement rock that forms the bulk of the Anglesey Platform. This fault may act as a gas migration route. Such seepage has been identified from seismic-reflection records but it has not been verified by sampling. (Judd, 2005) (this technical report series) has identified other areas with a possible connection between former straits and methane-derived authigenic carbonate.

Where rock outcrops in the Western Irish Sea Mudbelt, an unusual environment is found where thin seabed sediments sit directly on the upstanding rock. In this case, the rock outcrop is not an indication of a very high energy environment, rather it is isolated because it has not yet been buried by mud deposited from suspension. The exposed rock faces are swept clean of fine-grained muddy sediments because of acceleration of weak near-bed currents around an upstanding obstacle. The Pisces Reef provides an example of such an environment (Figure 14). The feature provides a refuge habitat, partly because the upstanding rock is hazardous to near-bed commercial fishing operations. Ledges and pinnacles formed on jointed rock and steeply dipping strata also provide habitat niches of very hard and very soft substrates. A north-extended scour moat around the east margin of the Pisces Reef was probably eroded by tidal flow. Other isolated and upstanding seabed crops of rock and diamicton that are set in unconsolidated sediments also provide discrete patches of diverse habitats set in otherwise relatively uniform seabed (Figure 21).

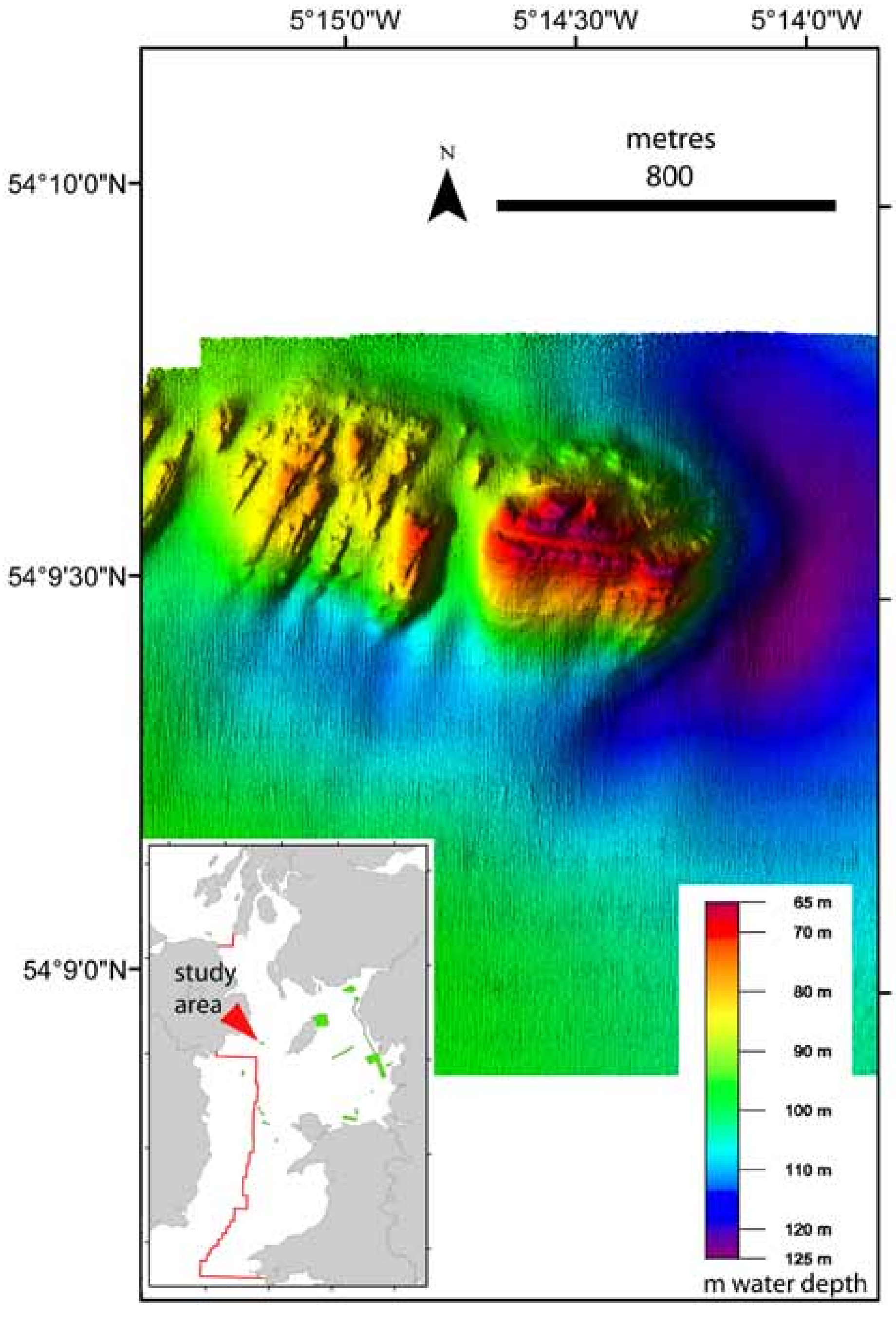


Figure 14 Example of seabed scour formed in mud around the Pisces Reef, an upstanding area of bedrock exposed at seabed

Figure 14: Image extracted from the DTI 2004 SEA6 survey dataset.

PERIGLACIAL FEATURES

Evidence on the seabed of former periglacial terrestrial environments includes fossil ice-wedge polygons that are 15 to over 80 m in diameter (Wingfield, 1987) and former pingos. Examples of patterned seabed formed on fossil ice-wedge polygons were not observed during the DTI 2004 surveys.

Pingos are formed in modern arctic permafrost conditions in terrestrial, lacustrine and submarine environments when an ice core, usually in poorly drained or flooded soils, has expanded to push up sediments into domes. The domes typically vary from 10-500m diameter, larger if the pingos have formed under lake beds. The surface sediments on the pingos move downslope and collapse as the ice melts, leaving a crater and rim, the form of which may or may not be enclosed. In the example shown (Figure 15) a horseshoe-like raised rim of approximately 200 to 300 m diameter has formed. The rim is interpreted as the perimeter of a pingo that originated in former permafrost conditions. The BGS regional data indicate that the pingo is set over an area of sub-seabed diamicton. It is preserved with relatively smooth flanks that is set in a field of modern active submarine sandwaves (Figure 9) composed of slightly gravelly sand. The pingo flanks have not been sampled, but the patches of low sonar backscatter around the pingo (not illustrated) are interpreted as areas with gravel-free seabed sand or muddy sand that have added to the natural seabed diversity.

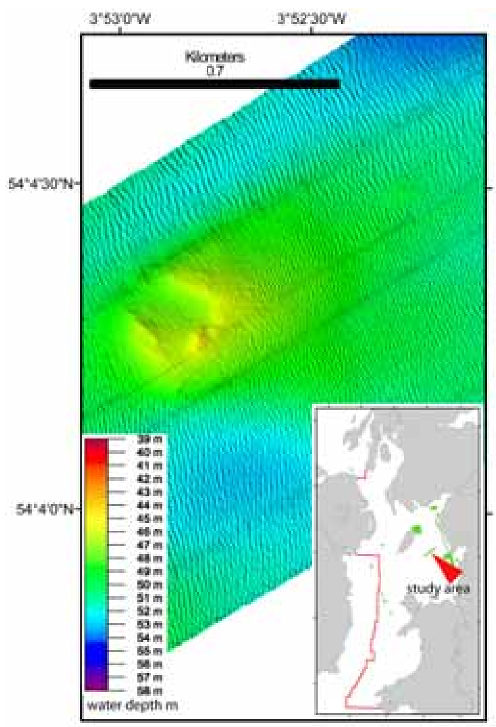


Figure 15 Former pingo, a contributor to periglacial patterned ground.

Figure 15: Image extracted from the DTI 2004 SEA6 survey dataset.

Habitat diversity has also been generated over varied topography on drowned former river channels (rias), estuaries, deltas and braided sandhur plain channels, many of which were probably sited adjacent to former ice margins (Jackson et al., 1995). The sarns are composed of ridges of boulder to pebble-size gravel, and are thought to be relicts of lateral moraines of glaciers that formerly extended to the west from the mainland of North Wales into the Irish Sea. In Cardigan Bay, the sarns appear to be truncated at their west ends (Figure 13), which is thought to have occurred at times during the last glaciation when the dominant ice stream was moving south. Former subaerial channels extend into some enclosed basins, for example, the Beaufort's Dyke which at times of severe climate and very low sea level were likely to have been freshwater lochs (Figure 13). The pingos and sarns provide examples of unusual features which have no short-term potential for regeneration. For these reasons they may be suitable for preservation from damage during future seabed developments.

NARROW ENCLOSED DEEPS

Narrow enclosed deeps are static bedforms relict from subglacial ice gouging (Frontispiece). Modern Scottish sea lochs provide some of the most spectacular examples of these features. Lune Deep (Figure 16) is also relict from ice scour from former ice sheets that have flowed at various times to the south and west from mountain sources in the Lake District. The northern flanks of Lune Deep are composed of exposed bedrock with a rugged seabed physiography. This observation suggests that the northern flanks of Lune Deep are set in an area of modern sediment bypass. In contrast, the southern flank consists of a smooth seabed which is a sink for muddy sands (Figure 68 in Jackson et al, 1995; BGS DigSED database). The asymmetry of the sedimentary infill in the deep indicates that the sediments have probably been transported into the deep by a process of sediment input from the south. To the east, patterns of seabed scour around seabed obstacles situated at the eastern end of the Lune Deep indicate that the prevailing transport direction of the muddy sand in the deep is towards the east and sub parallel to the coast (Figure 16). It is not known if the seabed obstacles illustrated on Figure 16 are natural or man-made features.

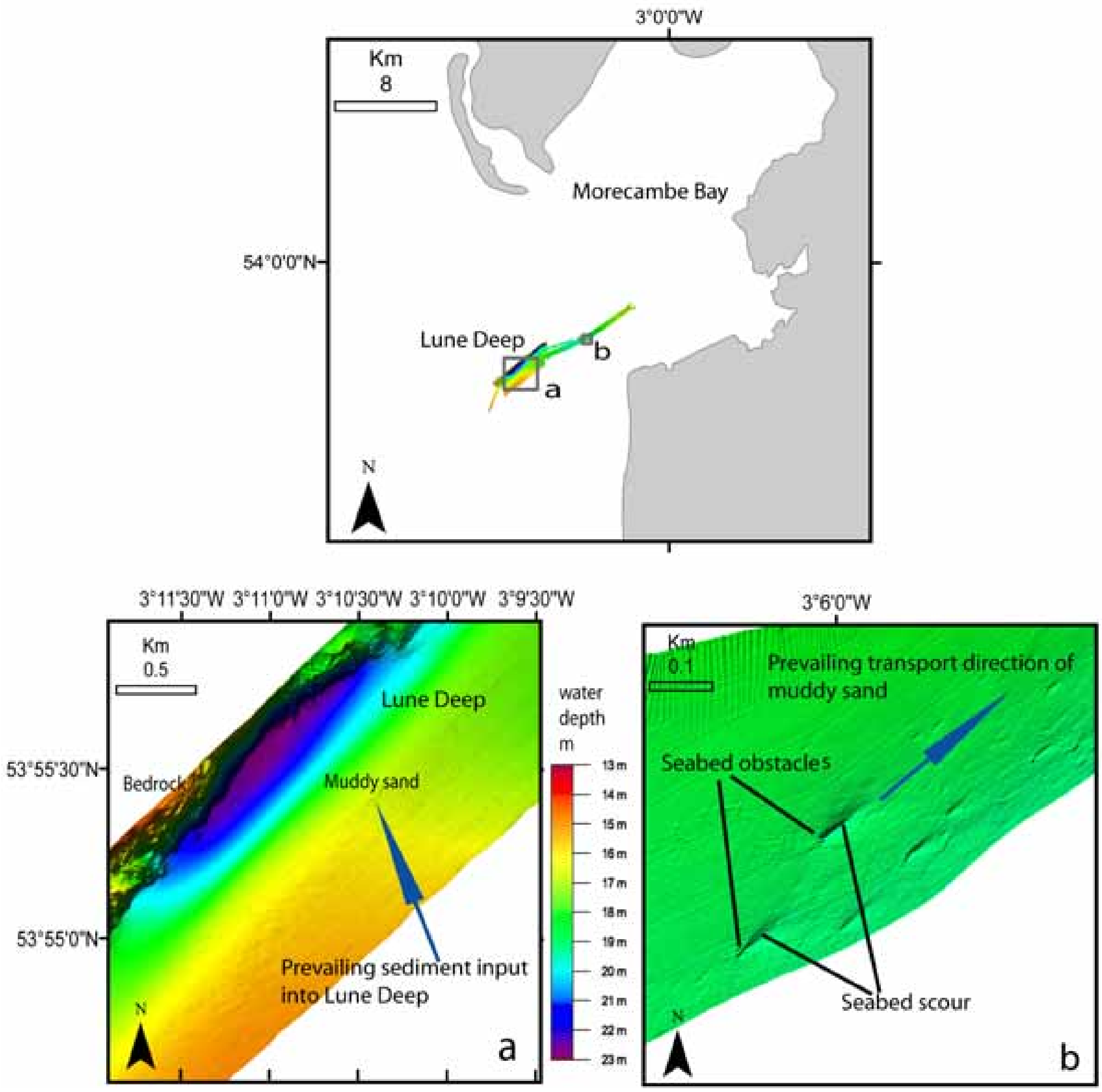


Figure 16 Examples from static bedforms for asymmetry of sediment infill and sediment transport directions.

Figure 16: Images extracted from the DTI 2004 SEA6 survey dataset. **a** *Prevailing direction of sediment input into Lune Deep* **b** *Obstacle scour marks, southern approaches to Morecambe Bay, and prevailing transport direction of muddy sand. Scour marks which do not appear to be associated with seabed obstacles are underlain by acoustic scatter, possibly caused by shallow gas trapped below the seabed. Some of these scour marks may therefore be pockmarks that have been excavated by the release of gas from seabed and elongated in the direction of prevailing near-bed current flow.*

MAN-MADE OBSTACLES

Near-bed currents are diverted and accelerated around shipwrecks and generate seabed scour, seabed hollows and ribbon-like bedforms. The orientation and asymmetry of the scour is a particularly useful indicator of prevailing currents in areas that may otherwise have a relatively featureless seabed. Features generated by shipwrecks and cables and pipelines can also be used as models for monitoring the possible long-term effects of future permanent or semi-permanent seabed installations (Figure 17).

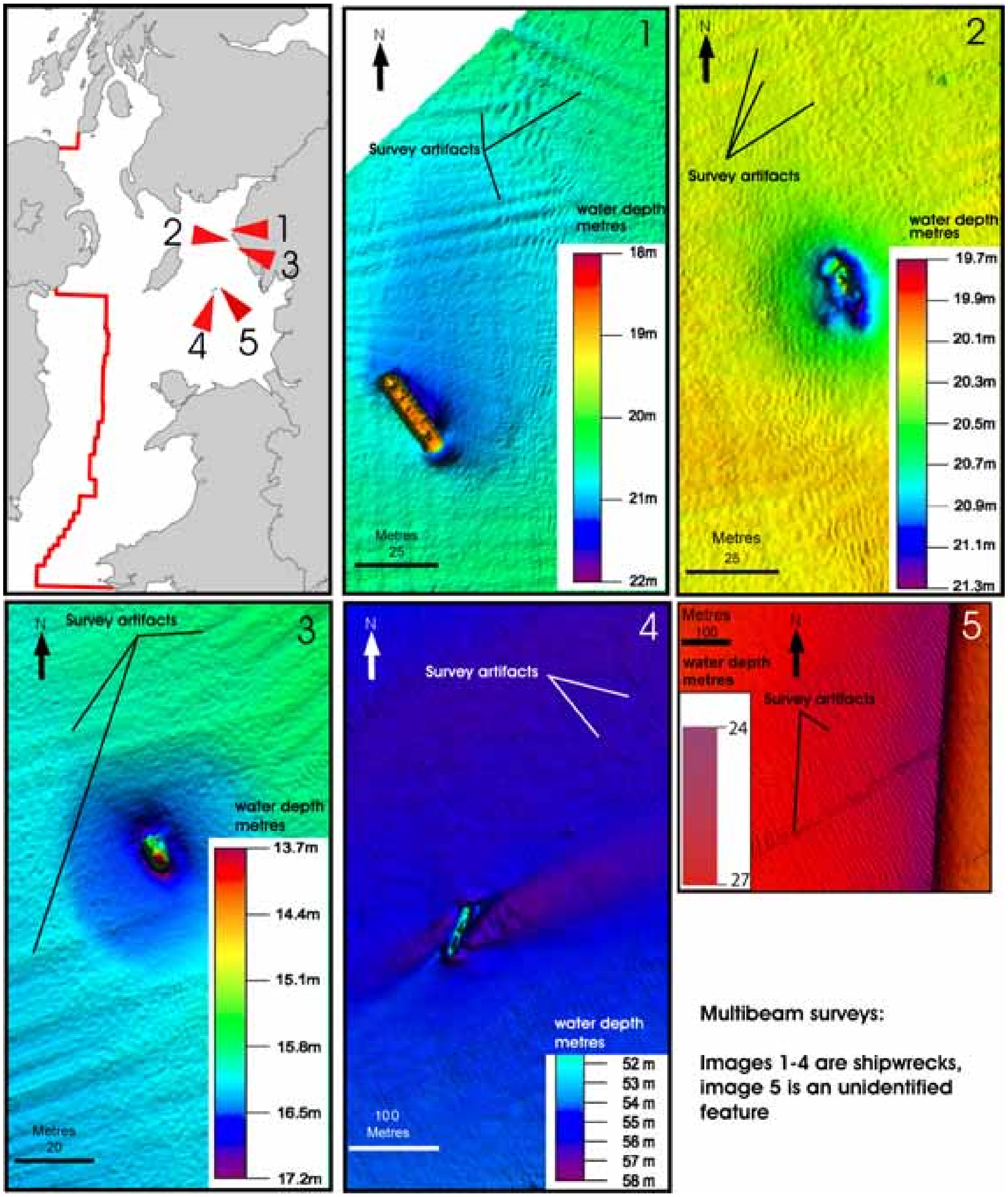


Figure 17 DTI 2004 surveys of shipwrecks and other man-made features

Figure 17: Images extracted from the DTI 2004 SEA6 survey dataset. Examples of the survey artefacts noted on the recorded images result from the method of data collection and are not real seabed features.

The BGS regional sample datasets show that shipwrecks 1 and 3 (Figure 17) are set in slightly gravelly mud, 2 in sandy mud and 4 in slightly gravelly (shelly) sand. High backscatter recorded on the sidescan sonar records indicates that the seabed in the scour hollows around shipwrecks 1, 3 and 4 have coarser sediments than the seabed outside the hollows. This observation suggests that the scour has generated a lag deposit or that the scour may have penetrated into early Holocene gravels underlying the seabed sediments. Shipwrecks 2 and 3 are set in the low tidal current speeds, the plan shape of seabed scour indicating that there has been an overall lack of preference in the direction of the near-bed tidal currents. In contrast, shipwrecks 1 and 4 clearly show stronger scour to the east, which is the travel direction of the stronger near-bed flood tidal currents. The seabed scour extends for significant distances beyond the wrecks. For example, shipwreck 4, which presents a profile of approximately 50 m length and 6 m height, has generated seabed scour of approximately 4 m maximum depth which tails into shallower scour for a distance of at least 200 m in a north-east direction from the wreck.

In areas of relatively weak currents, sediments accumulate against continuous barriers that are upstanding from the seabed. Examples of such barriers include those occurring naturally where former igneous intrusions (dykes) crop out at seabed, or those placed as a result of man-made seabed developments such as pipelines, cables and beach groynes. In the example shown in Figure 17.5 a sediment ramp has formed as fine-grained sandy sediments have banked up on the upstream side of prevailing currents to a linear barrier to sediment movement. The barrier is approximately 3 m height above the surrounding seabed (Figure 17.5). The crest of the obstacle more or less coincides with a local sedimentary boundary mapped by the BGS, which separates sand to the west from muddy sand to the east. The origin of the linear feature is unclear. It has not been recorded on the Admiralty Charts or the United Kingdom Hydrographic Office database of man-made seabed features (UKHO Wrecks Officer, written communication, 2004). Searches of the BGS maps and interpretations of the seismic reflection records (predating 1975) indicate that it is probably not a natural feature.

POCKMARKS

The seabed is eroded when methane gas or other fluids are expelled from point sources on the seabed and when sediment particles are also vertically entrained by the fluids into suspension by seawater. The suspended particles are then be carried away laterally by near-bed currents. Over a period of time this process erodes the seabed into hollows or ‘pockmarks’. Although they are commonly elongated in the direction of dominant tidal current flow, the pockmarks are essentially static bedforms. Pockmarks are typically identified in areas with an overall smooth seabed consisting of Holocene very soft mud or silty very fine-grained sand. Fields of such pockmarks occur in the Western Irish Sea Mudbelt. At least one of these fields extends for a short distance into the UKCS (Figures 12, 13). It has been observed in the North Sea (Hovland and Judd, 1988) and in the Irish Sea (Judd, 2005) that high values of methane-derived authigenic carbonate and other forms of biogenic carbonate production occur with locally increased biological activity tied to the expulsion of methane gas from ‘active’ pockmarks. Most of the pockmarks are currently inactive and relict. In the active pockmarks an increase in the biological production of carbonate occurs in the gas conduits buried in shallow sediments below seabed and at the locations of gas expulsion from seabed into seawater.

A brief review of pockmarks is important to understanding sedimentary processes in the mudbelts because a regional synthesis shows that anomalously high values (>75%) of carbonate in the sand fraction of seabed sediments occur over and adjacent to the pockmark fields in the Western Irish Sea Mudbelt. These values can be compared to an average of <25% carbonate in the sand fraction of seabed sediments in the Eastern Irish Sea Mud Belt where there are no recorded pockmarks (Figure 12). The high values of carbonate in the sand fraction of the seabed sediments are isolated at a location that is approximately mid-point in the Western Irish Sea Mudbelt between convergent pathways of sand transport (Figures 12, 26). Sediments in the Western Irish Sea Mudbelt have high sediment pigment concentrations and respiration, possibly because they are below areas of high surface-water productivity or they are a sink for organic material swept in from other parts of the western Irish Sea (Wilding et al., 2005). The observations summarised above suggest that the patterns of high carbonate concentration in the sand fraction of the Western Irish Sea Mudbelt could possibly originate by several processes. These are, decreased input from sand-size clastic sediment grains, convergence of sand-size carbonate grains (mobilised because of different shapes, densities and hydrodynamic properties compared to sand-size clastic grains) and enhanced biogenic carbonate production sourced directly or indirectly from the sea-surface or during processes of methane expulsion from shallow and seabed sediments.

The large areas of pockmarks and mud in the central and northern North Sea also have relatively high carbonate in the sand fraction of the seabed sediments (25-50%) compared to the values the seabed sediments outside the areas with mud and pockmarks (0-10%) (Figure 10 in Pantin, 1991). The enhanced carbonate values in the sand fraction of the North Sea mudbelt cover the whole of the mudbelt and they are empirically related to the reduced input of sand-size grains of clastic sediments to the muds. Sampling and photographs from the areas of three large active pockmarks in the Fladen Ground of the North Sea, for example, at approximately 58^0 20’N 01^0E, show that the craters of large active pockmarks are associated with local concentrates of seabed methane-derived biogenic carbonate(Judd, 2001) that are fed by conduits of methane gas rising from at least 60m below seabed (Holmes and Stoker, 2005). The seabed sediments surrounding the active pockmarks in the North Sea are, however, not associated with higher values of carbonate in the sand fraction of the muds compared to the seabed sediments surrounding the inactive pockmarks (Figure 10 in Pantin, 1991).

These observations throw into doubt the possibility that fields of active pockmarks in the Western Irish Sea Mudbelt could have had a significant influence on the anomalously high percentages carbonate in the sand fraction. However, the Western Irish Sea Mudbelt has not been fully explored for active pockmarks and the source components of the carbonate anomaly in the sand fraction of the mudbelt have not been investigated. These are knowledge gaps which prevent an understanding of possible links between active pockmarks, sea surface productivity and carbonate grain transfer and biogenic carbonate concentrates in the sand fraction of the Western Irish Sea Mudbelt.

MODIOLUS REEFS

The study area has living reefs, bioherms, of the bivalve *Modiolus modiolus* (Horse Mussel). The bioherms form imbricated stacks of pebble-size bivalves, the ridge-axes of which are aligned transversely to the near-bed currents. Comparison of Figures 13 and 19 shows that *Modiolus* bioherms do not occur in the extremely high-energy scour environments. In these environments the fine-grained sediment is mostly swept clear of the seabed into suspension so there may be a high risk of abrasion, or perhaps suspended mineral grains may interfere with normal feeding patterns. Also, *Modiolus* is excluded from areas of relatively low seabed stress where there is a high risk of the biota being covered by sandwaves or muds deposited from suspension. The larger bioherms build up above the level of the surrounding seabed as static bedforms with ridges of 0.5 to 1.0 m relief formed transversely to prevailing current directions. The geological interest in them is because of their geometrical similarity to the mobile sandwaves that are also formed transversely to prevailing currents. Areas with bioherms and sandwaves are readily distinguished on the basis of their sedimentary settings and the detailed data available from multi-beam surveys the (Figure 18).

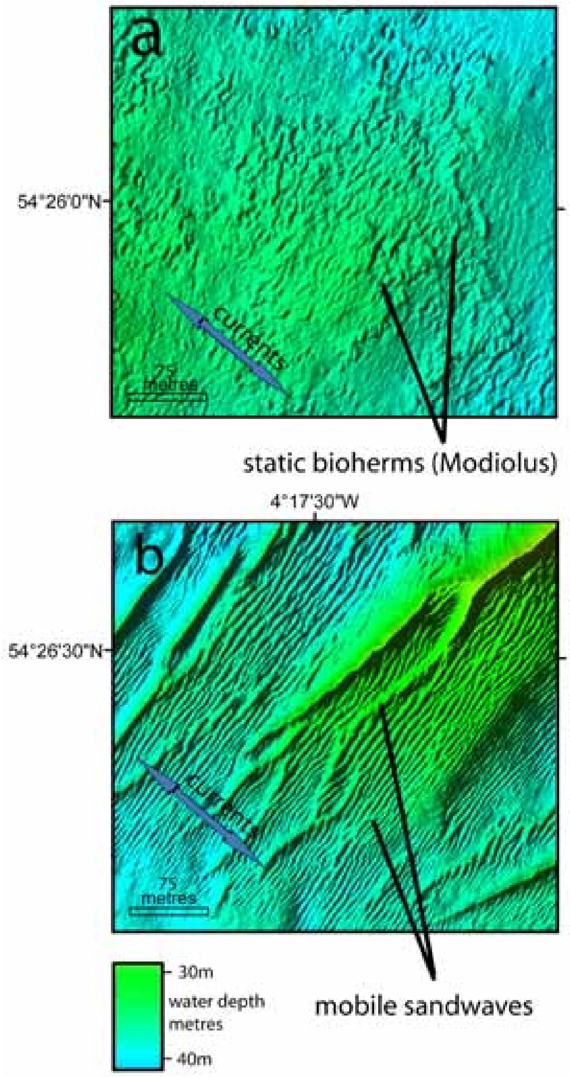


Figure 18 Contrast in the geometry of small- to medium-sized **a.** biogenic and **b.** non-biogenic transverse bedforms

Figure 18: For locations of **a** *and* **b** *in Figure 18, see Figure 24. The images have been extracted from the DTI 2004 SEA6 survey datasetof multibeam images.*

The static carbonate bioherms illustrated in Figure 18a are mainly composed of stacked pebble-size bivalves of living *Modiolus modiolus*, and are set in an environment of sand bypass. The mobile sandwaves illustrated in Figure 18b are mostly composed of sand-size rock mineral grains (clastic sediments) and are set in an environment of rapid transient sand deposition.

The seabed images illustrated in Figures 18a and b are from adjacent locations, they are set to the same horizontal and vertical scales and they illustrate the sensitivity of the distributions of seabed biota to seabed substrates.

Mobile bedforms

Mobile bedforms mainly occur between extremes of high seabed stress typified by static bedforms of rock and diamicton outcrop at seabed and the lowest seabed stress associated with a smooth seabed, typically consisting of large areas of essentially static seabed in the mudbelts (Figure 19).

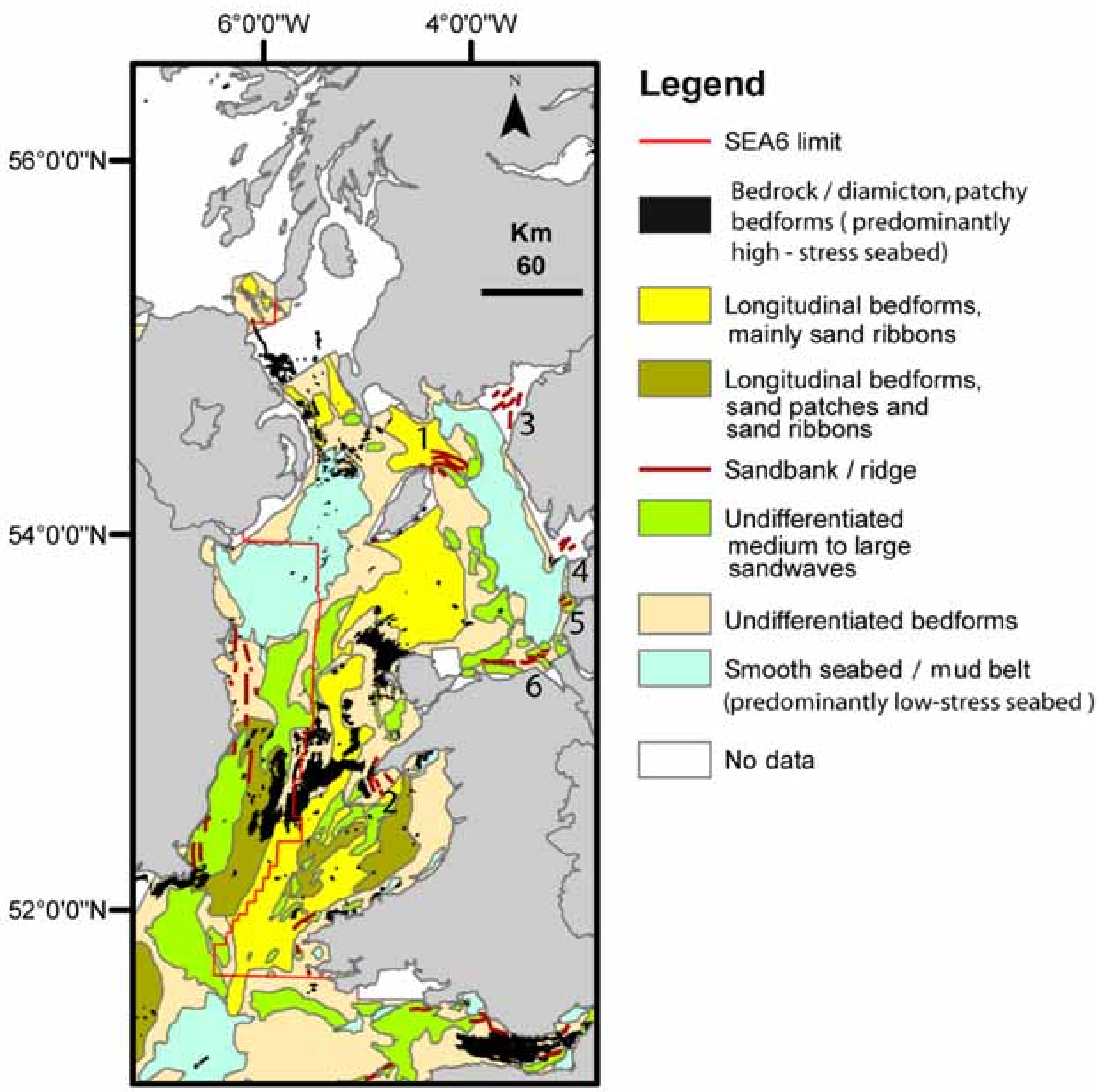


Figure 19 Generalised distribution patterns of mobile bedforms set between high seabed stress (bedrock/diamicton) and low seabed stress (smooth seabed / mudbelt) static bedforms.

Figure 19: adapted from BGS regional reports (Fyfe et al., 1993; Tappin et al., 1994; Jackson et al., 1995). Sandbanks/ridges shown in SEA6 are banner banks off: 1 Isle of Man; 2 Lleyn Peninsula; and wide estuary banks in 3 Solway Firth; 4 Morecambe Bay banks; 5 Ribble; 6 Mersey and Dee estuaries. Smaller banks in the inner estuary environments and other banks on the smaller estuaries are not shown.

Observations on the distribution patterns of the end-member static bedforms and the mobile sandy bedforms observed in SEA6 show that they can be related in a generalised manner to the patterns of long-term stress imposed by tides and waves on the seabed (Figure 20).

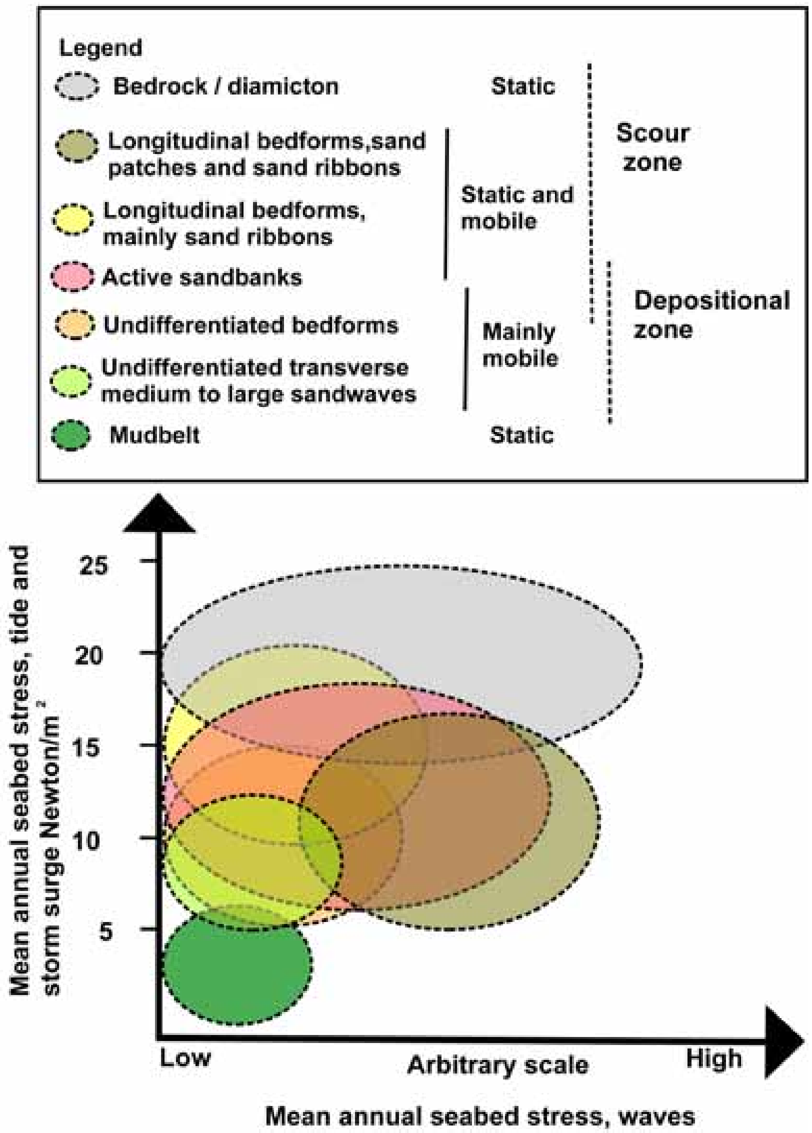


Figure 20 Schematic summary of the observed relationships between mean seabed stress and mobile and static bedforms, Irish Sea.

Sand ribbons

Sand ribbons are sometimes connected to the downstream side of static seabed obstacles such as pebbles, cobbles, boulders, upstanding rock outcrop, and commonly feature in areas of seabed scour and very high seabed stress. In this environment they usually align parallel to the peak tidal streams. Thus the smaller sand ribbons are mobile in the sense that they may change positions in response to changes in the amount and direction of seabed stress with the cycles of flood and ebb tides.

Transverse sandwaves and sandbanks

The bedforms that are formed transversely to tidal streams include sand ripples and sandwaves. Sandbanks are commonly formed sub-parallel to the prevailing tidal streams (Appendix 2a) and in wave dominated areas sub-parallel to longshore drift. Observations of external and internal geometries of these bedforms can be interpreted to infer their processes of formation. These interpretations have resulted in an ability to qualitatively predict the direction and rates of bulk sand transfer during sandwave and sandbank movement (Appendix 2a). Because of their relative stability, it has been possible to make observations of the development of large transverse sandwaves and sandbanks over relatively long periods of time. Such studies have resulted in an increasing awareness of the shaping effects of wave stress on the seabed in tidally-dominated environments (Appendix 2b).

Detailed survey data have provided a basis for a better understanding of the distribution patterns of sandwaves and the shaping of sand patches and sand sheets formed from them. These data have therefore made a significant contribution to predictions of the processes that generate small-to-medium scale seabed habitat patchiness in areas of sandwaves (Figure 21).

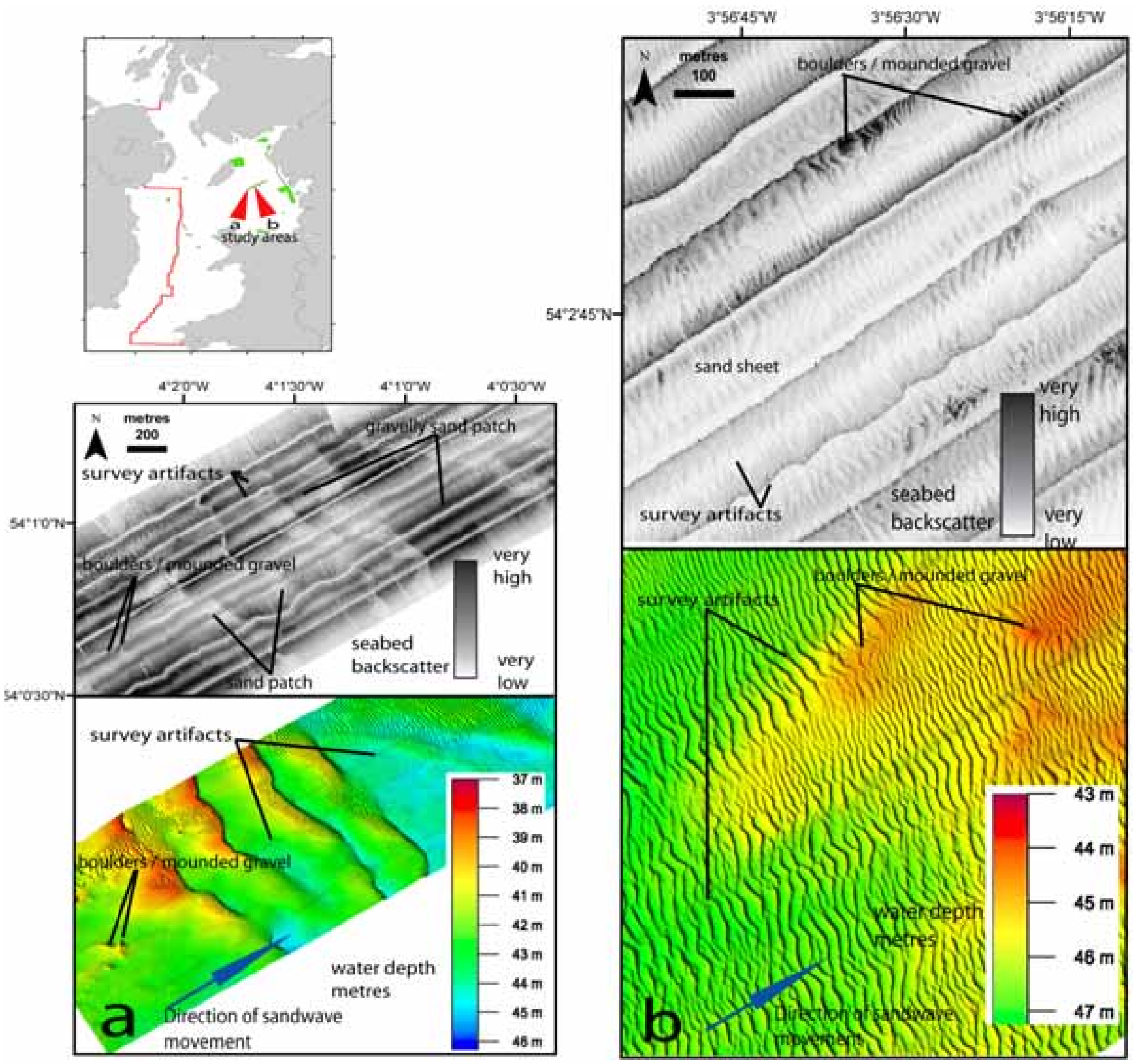


Figure 21 Examples of fields of transverse small to very large sandwaves (a,b), boulders / mounded gravel (a, b), sand patches and gravelly sand patches (a) and a sand sheet (b), Liverpool Bay

Figure 21: The images have been extracted from the DTI 2004 SEA6 survey dataset. The upper greyscale images are records of seabed sonic backscatter collected during sidescan-sonar surveys, interpretations of which yield indirect information on seabed sediment grain size and areas of rock outcrop. In this case, the areas of highest seabed sonic backscatter are interpreted as areas of upstanding boulders and other gravel. The lower coloured images are been derived from multibeam data over the same area and set to the same horizontal scale. These coloured images yield information on seabed topography. The data from images such as these are combined with further data derived from seabed photography and seabed sediment sample analyses so that the characteristics of the seabed habitats can be further refined.

As illustrated by Figure 21a the sandwaves return low seabed backscatter on the greyscale sidescan-sonar records. The BGS database of samples from the study area shows that the sand is composed of well-sorted and essentially gravel-free sand with less than 10-25% by weight of carbonate in the sand fraction. Gravelly sand occurs in the troughs between the sandwaves and is correlated with records of moderate to very high seabed backscatter. The BGS database shows that the gravel is composed of more than 25% by weight of biogenic shell carbonate. The detailed mapping shows a distribution pattern of sand patches on the sandwave crests that are aligned transversely to the prevailing direction of near-bed currents. The sand-patch margins have sharp boundaries pointing in the direction of long-term movement of these very large sandwaves, which is towards the northeast. The observations from the various data are interpreted to mean that that the patches of finer-grained sand are migrating over patches of biogenic and clastic gravelly sand. Upstanding small, rounded and isolated seabed features are tentatively interpreted as boulders or mounds of gravel that are rooted in the underlying diamicton. The image shows that the large sandwaves appear to have been partly destroyed by the transit of smaller sandwaves travelling in the same direction.

Figure 21b shows that small to medium sandwaves are migrating towards the northeast. The sandwaves have joined to form an almost continuous sheet of sand on a low bank of diamicton. Boulders or gravel mounds rooted in the diamicton appear to be upstanding through the sandwaves and show up as small areas of very high backscatter recorded on the greyscale sidescan sonar records.

Sandbanks are adjacent to environments of seabed scour associated with the stronger tidal currents (Figure 20). The sandbanks feature in areas of sediment convergence, mainly in the coastal areas of SEA6, where the sand is swept up from surrounding areas of seabed scour and then deposited on the banks. The banks can be subdivided into four broad categories on the basis of their physiography, geological setting, and interpretations of the processes that appear to have shaped the banks (Figure 22).

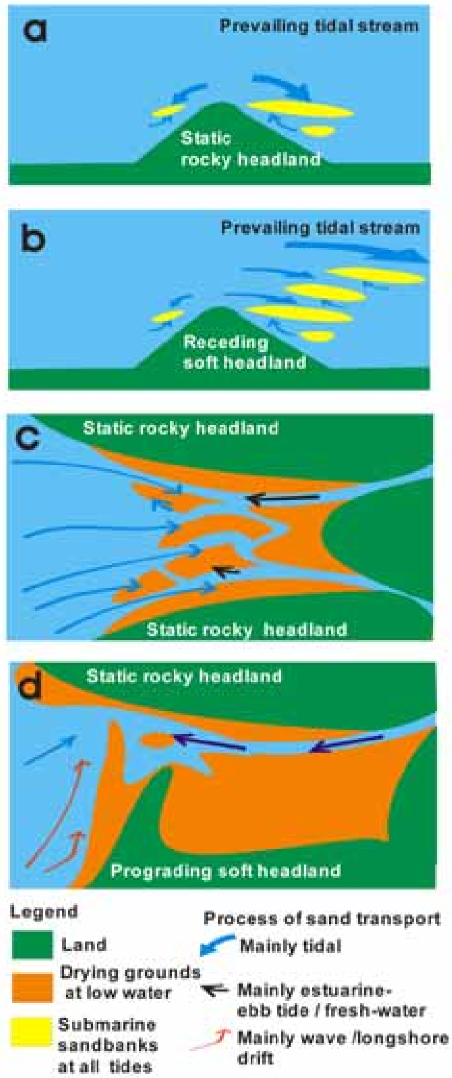


Figure 22 Schematic summary of the environmental settings and processes of formation of sandbanks, eastern Irish Sea

Figure 22: **a, b** *and* **c** *adapted after Dyer and Huntley (1999) and Kenyon and Cooper (2004).* **a** *Banner banks formed around static rock headland, e.g. Wart Bank, east of the southern end of the Isle of Man.* **b** *Banner banks formed around receding soft headland, e.g. around the northern tip of the Isle of Man, see Figures 23, 24 .* **c** *Estuary mouth banks, e.g. Solway Firth, Ribble Estuary, see Figure 25.* **d** *Sand spit and estuary mouth banks associated with prograding soft headland, e.g. Barmouth Estuary, Cardigan Bay. The River Mersey and River Dee estuaries contain mixtures of the historical and modern processes that are schematically illustrated in* **c** *and* **d.**

Although sandbanks and ridges are traversed by mobile transverse sandwaves, the overall positions of the largest banks and ridges are relatively stable. The stability derives from their large bulk volume and the relatively long time for the large banks and ridges to shift in response to prevailing near-bed currents (Appendix 2a).

Banner banks are the highest upstanding sandbanks. The active banner banks may accumulate sand from more than 30m water depth to the depth at which their crests are eroded by waves (wave base). The tops of these banks rarely dry out at the lowest astronomical tides. The locations of the largest banner banks are relatively static because their depositional heads are tied to tidal eddies that drive circulatory patterns of seabed sand movement when strong tidal streams flow past headlands (Pingree, 1978; Signell and Harris, 2000); (Bastos et al., 2002; Bastos et al., 2003; Duffy et al., 2004). However, asymmetry in the large-facing directions of some of the banner banks off the northern Isle of Man indicate that their long-term movement is possibly to the south and in the same direction of long-term headland recession (Figures 22b, 23). The sand circulation associated with banner banks, as derived from sandwave asymmetry, is from the headland along the open seaward edge of the bank and returning towards the headland on the landward side of the bank. Such an eddy process generates a depositional gap between the headland and the bank. Sediment convergence generates the banner banks and seawards of those, on a much larger scale, an extended regional bank may also form. Thus, off the northern Isle of Man, a low bank extends for more than 40 km towards the southeast beyond the principal eddy zone associated with the Bahama Bank on the eastern lee of the headland (Figure 23). The discrete zones of sediment convergence and sand deposition associated with the banner banks and with the low bank extending to the south east of Bahama Bank are marked by fingers of sand that join and coalesce into a sand sheet in the eastern Irish Sea (Figures 7 (inset rectangle), 23).

King William Bank is distal from the northern headland of the Isle of Man and is presumably partly decoupled from the strongest eddy-related processes that are now sustaining the banner banks on either side of the northern tip of the Isle of Man (Figure 22b, Figure 23). The main bank of King William Bank (western end, Figure 23) is set within the field of mean seabed stress of greater than 5-10N/m^2 that is within the stress field where the seabed on the sandbanks would be expected to show evidence for interaction with strong tidal currents (Figure 20). This prognosis is verified by the multibeam images collected during the DTI 2004 surveys showing that small to very large sandwaves are moving from west to east across the bank (not illustrated). This direction of bedform movement is in agreement with the regional direction of net sand movement compiled from other bedforms by the BGS (Figure 23).

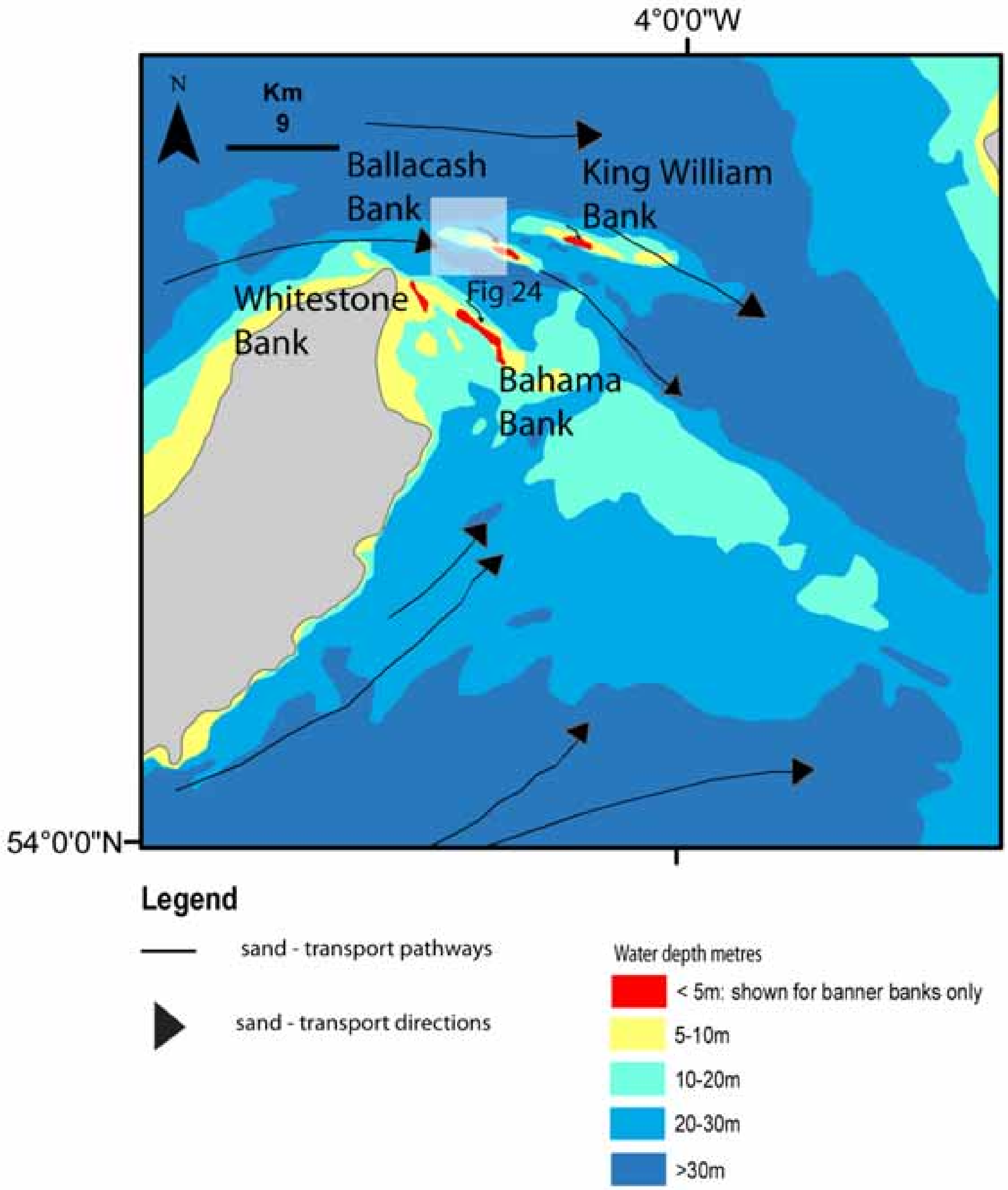


Figure 23 Regional physiographical and sand transport setting of banner banks east and west of the Isle of Man.

Figure 23: Bank names are derived from British Admiralty Chart 1826. Sand pathways and directions are compiled from the BGS regional interpretations derived from observations of sand ribbons, scour marks and the facing directions of sandwaves (Jackson et al, 1995).

Ballacash Bank was the most intensively surveyed banks of those reconnoitred during the DTI 2004 surveys and is probably one of the more active banks situated adjacent to the receding headland of the northern Isle of Man (Figures 22b, 23, 24).

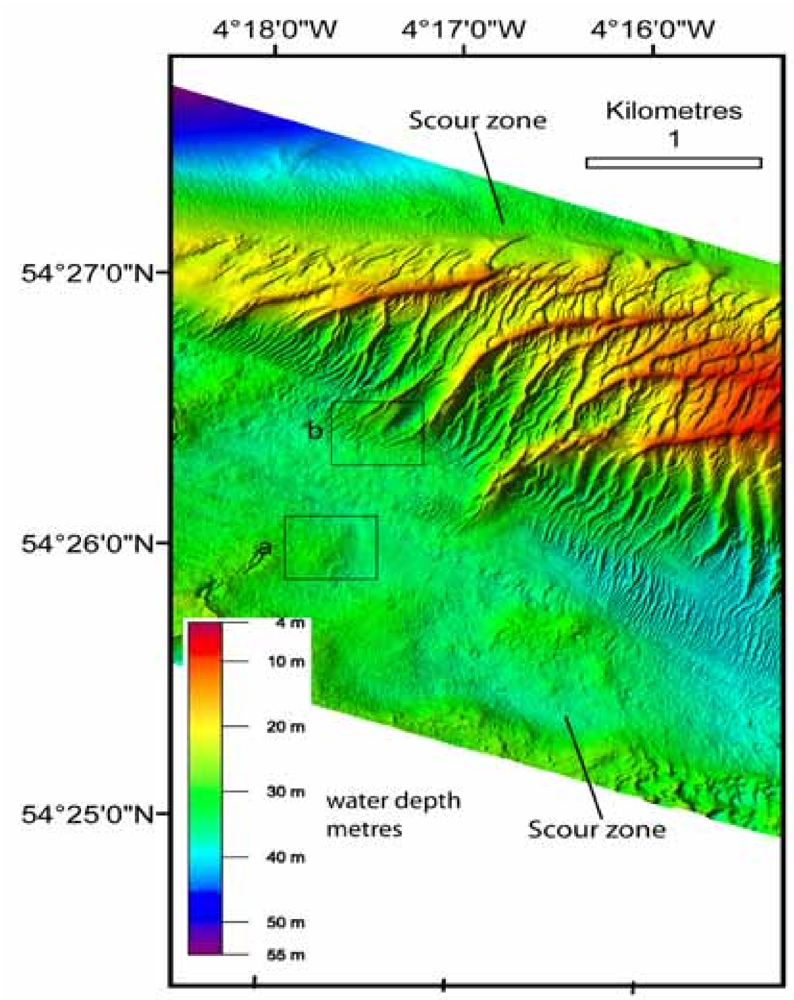


Figure 24 Ballacash Bank: extract of an image of the western (landward) head of an active banner bank.

Figure 24: The image has been extracted from the DTI 2004 SEA6 survey dataset. For location of the study area see Figure 23. For an explanation of the study areas in the inset rectangles **a** *and* **b** *see Figure 18 and accompanying text.*

The sandwave-facing directions on Ballacash Bank show that at the western end of the bank sandwaves are migrating from the northwest. They are in transit towards the east and are coalescing with east-north-east-orientated sandwaves near the bank crest. Some sandwaves on the southern flanks are migrating to the north west. The opposed bedform facing directions, the existence of the scour zones surrounding the bank and the fact that the bank has maintained its height to within the range expected of its erosion by waves in fair weather together confirm that the Ballacash Bank is being maintained by a process of sand convergence. However, the regional syntheses of seabed sediment types and sand migration pathways indicates that over the long term the banner banks on the east side of the Isle of Man are leaking sand towards the open shelf (Figures 7, 23). Because of this the banks are only temporary sinks for sand captured from the areas around the northern tip of the Isle of Man.

Wide estuary banks form in areas of strong tidal currents and areas of high sediment supply at the confluence of onshore and offshore sediment movement. The maximum overall height of the estuary banks is limited by the accommodation space generated by the tidal range. Constable Bank is an example of an outlying estuary bank, possibly a former sand spit, that has extended below lowest astronomical tide. Constable Bank is rooted in the Rhyl Flats at the mouth of the River Dee (Figure 9). The wide estuary banks of the Ribble provide examples where the banks consist of large flattened drying grounds of mud and sand at low tide (Figure 25).

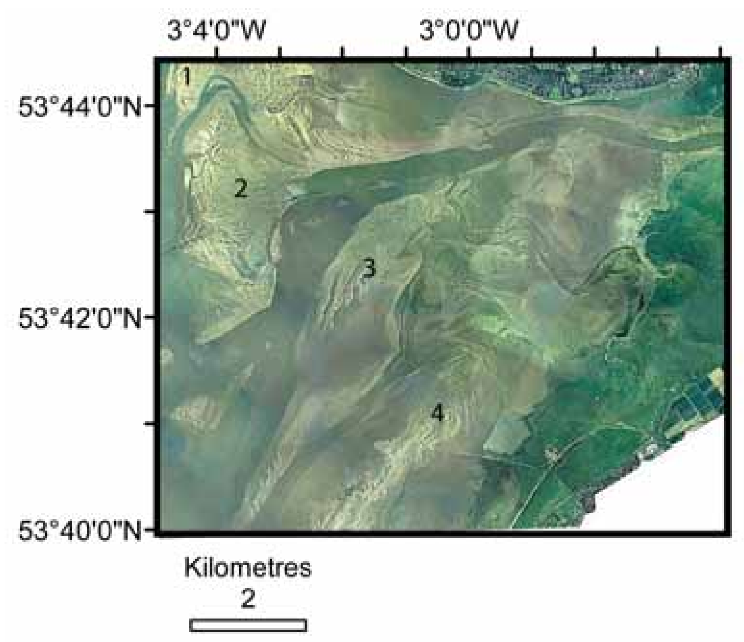


Figure 25 Wide estuary sand banks, River Ribble.

Figure 25: Image extracted from the Proudman Oceanographic Laboratory regional dataset. Examples of wide estuary banks are labelled 1 to 4. For location of the River Ribble see Figure 6. The processes of formation of the wide estuary banks are summarised in Figure 22c.

SAND PATCHES

The largest areas of sand patches are restricted to south of approximately 53ºN in areas to the east and west of the strongest mean peak spring tidal streams and in areas with relatively high mean significant wave heights (Figures 8, 10, 17). The distribution patterns of sand patches interdigitate with those of transverse sandwaves in the southern parts of SEA6 (Figures 19, 20). Because of the interdigitation of the sandwaves with sand patches it is thought possible that some sand patches may have formed by a process of sandwave flattening following the imposition of stress transmitted from seawaves to the seabed (Figure 29b). This process more or less accords with the interpretations of Kenyon (1970), who attributed the origin of sand patches on the outer continental shelf to processes whereby long-period storm waves have interacted with the seabed in areas with tidal streams.

NET SAND TRANSPORT

Although individual sand grains entrained by the near-bed currents move faster than the mobile bedforms, a useful application of observations from the geometries of the mobile bedforms and bedforms generated around static obstacles is that they can be interpreted to predict regional net sand-transport paths (Figure 26).

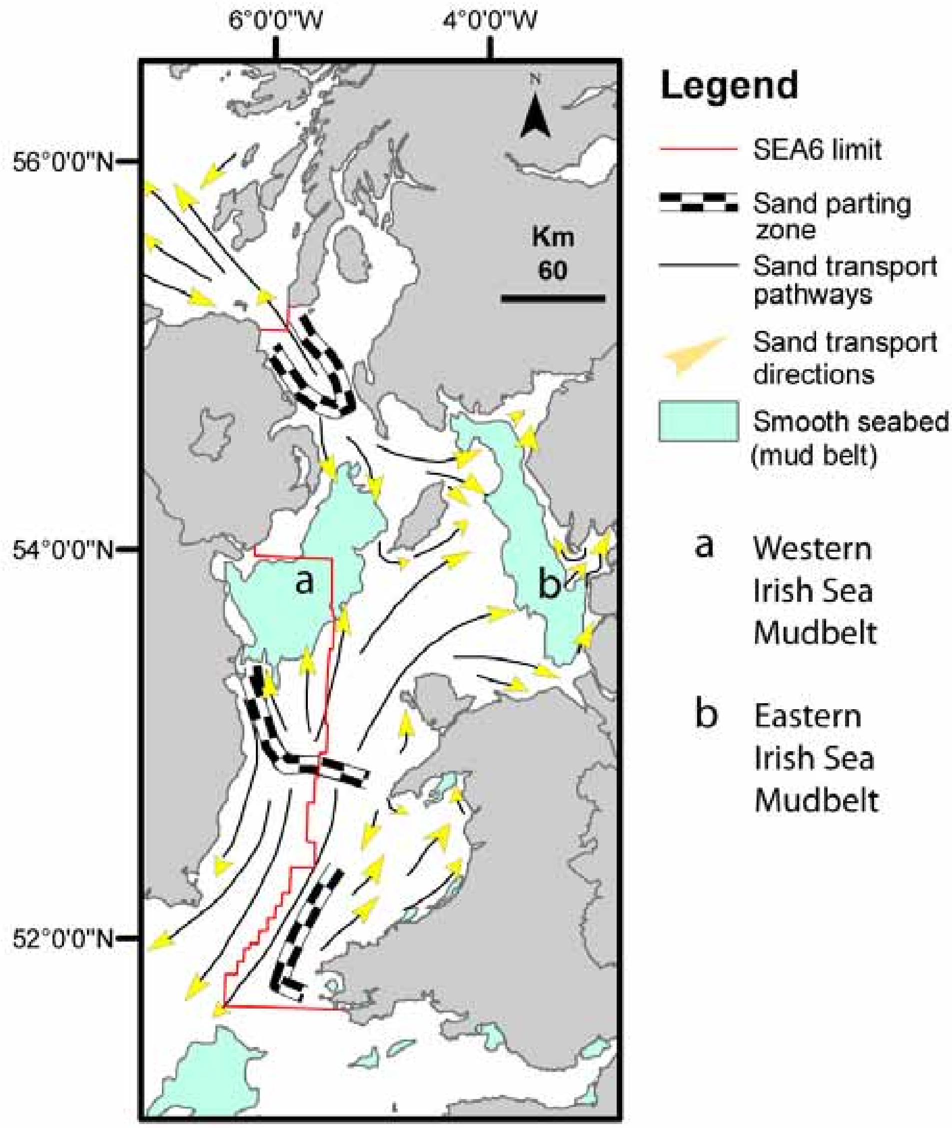


Figure 26 Net sand-transport pathways and directions.

Figure 26: Original concept adapted after (Stride, 1982), data modified after (Pantin, 1991; Jackson et al., 1995; Kenyon and Cooper, 2004) and modified by interpretations derived from the DTI 2004 SEA6 survey datasets. The location of the nearshore sand parting zone in the western Irish Sea has been modified on the basis of interpretations derived from the locations and geometries of banner banks charted on Admiralty Chart 1411.

A feature of Figure 26 is an indication that a pathway of sand exchange between the open shelf (more than approximately 30 km offshore) and the English coast appears to be situated to the south of the Eastern Irish Sea Mudbelt. The isolation and likely importance of the pathway may be taken into consideration for future development scenarios offshore from the North Wales coast.

4 Strategic overview

HYDROCARBONS PROSPECTIVITY

The hydrocarbons-prospective sedimentary basins are characterised by source rocks, an abundance of structured regional petroleum reservoir and seal rocks and by suitable timing of geothermal events for generation and transfer of petroleum products from the source rocks to the reservoir rocks. The area is at a mature exploration stage and current gas and oil producing fields are set within the areas of known source rocks (Figures 3, 4). The focus of the strategic overview for this section of the report is based on a presumption that the undiscovered and undeveloped reserves of oil and gas probably lie in areas with source rock and in or immediately adjacent to currently licensed acreage.

The licensed acreage around the Dragon Discovery is set in an environment of seabed scour and sediment bypass (Figures 3,7,19). New developments are unlikely to have a significant long-term impact on the composition of the coarse-grained predominantly sandy and gravelly seabed sediments in this area. Seabed exposure to stress derived from very strong tidal currents indicate that there is a risk of foundation undermining by seabed scour in this area (Figures 3, 8, 10).

The licensed acreage of the eastern Irish Sea gas and oil fields spans from east to west across a wide range of seabed sediment types over a horizontal distance of less than 50km (Figures 3, 7). An decreasing mean seabed stress from west to east is expressed by transitions from seabed scour and gravelly sediments in the west to fields of mobile sandwaves and then to a relatively featureless seabed over the Eastern Irish Sea Mudbelt (Figures 3, 8, 19).

Regional syntheses show that there is a low sand bank, within a zone of regional sand convergence, that extends for at least 40km to the east from the northern coast of the Isle of Man (Figures 7, 23). This bank is one of several banks where sand-size particles swept from the northern part of the eastern Irish Sea would be expected to temporarily reside, and is where monitoring of some of the possible effects of new developments may be appropriate. The bank is set in the wider regional context of net sand transport that is directed to the east towards the Eastern Irish Sea Mudbelt (Figure 26).

In the areas of mobile sand, there are potential geohazards to seabed foundations associated with sandwave movement and with the variety of sediment types underlying the fields of sand ribbons, sandwaves, sand patches and sand ripples (Figures 19, 21). The interpretation of data from the DTI 2004 shipwreck surveys have shown that there is a geohazard to seabed developments arising from the potential for foundation undermining by seabed scour across the range of high to low seabed stress sedimentary environments in the eastern Irish Sea (Figure 17).

If sediments are discharged to seabed or reworked from seabed as a result of new developments in the Eastern Irish Sea Mudbelt, protection measures may be appropriate to prevent long-term adverse alteration of the natural environment. For example, part of the pollution potential from artificially discharged sediments is that sand-size and coarser sediment particles will accumulate. The DTI 2004 shipwreck surveys have shown that if fine-grained sediment particles (silt and clay) are discharged from upstanding developments surrounded by seabed scour, the pollution potential is for discharged fine-grained sediment particles to be distributed to the wider seabed (Figure 17, shipwrecks 1 and 3).

SEDIMENTARY PROCESSES

The following strategic overview is for the whole of the study area.

Open shelf seabed sedimentary processes are driven by seabed stress originating from interaction of the seabed with strong currents generated by tidal streams and waves. The scale of the variability in seabed stress varies from regional (between mainlands, varying shelter around headlands) to macroscopic (around boulders and pebbles). Thus, during the fair to moderate weather conditions characteristic of the late spring, summer and early autumn seasons, the seabed sediment types on the open continental shelf are dominated by the effects of the stress imposed on the seabed by the strengths and flow directions of the peak tidal currents. These, in turn, are influenced on the regional scale by the coastal configurations. In areas where the seabed stress from waves is dominant, seabed stress from waves is dependent on wave power that varies with weather, wave fetch, seabed slope, wave direction and water depth.

There are knowledge gaps on possible regional changes to seabed properties when the seabed is stressed by extreme weather events that generate storm surge and storm waves. These knowledge gaps are thought to present a potential risk to the safety and cost of future seabed development scenarios.

Exposed bedrock and diamicton are scoured mostly clean of sand-size and finer unconsolidated sediments in areas with the strongest mean peak tidal currents, but boulders, cobbles and pebbles may also be observed as relict sediments in these most highly stressed seabed environments. Environments of least seabed stress are characterised by fine-grained muddy sediments. An overall sense of regional seabed sediment transfer is from and across areas of high seabed stress to areas of lower seabed stress. .

Mobile sandwaves are characteristic of areas where bedload sediments are transported from areas of high stress to areas of lower seabed stress. A re-interpretation of the connections between quantified seabed stress patterns, bedform geometries and seabed sedimentary processes has led to modification of a pre-existing regional model of sand transport pathways and directions (Figure 26). This is is a synthesis that provides a summary of the natural seabed function for more than 80% of the total area of the open continental shelf of SEA6.

Investigations of shipwrecks less than 100m in length indicate that the amount of seabed disturbance is several-fold larger than the profiles of seabed obstacles presented to near-bed current flow. The observations reveal scales of seabed scour asymmetry that are consistent with model predictions of mean peak tidal current speeds and the prediction of sand transport directions based on regional interpretations of the geometries of natural bedforms. Wreck studies could therefore be used to calibrate quantitative modelling on the likely long term impacts of future seabed development scenarios.

The observations summarised above indicate that if large-scale disruptions to the natural seabed habitat are to be avoided, the development scenarios should be assessed to avoid situations that could have a significant impact on the regional distribution patterns of seabed stress and related seabed sediment types. For example, a gateway for sand exchange between the open shelf and the eastern Irish Sea coast off England appears to be defined by a zone situated between the North Wales and the southern limit of the Eastern Irish Sea Mudbelt (Figure 26). Until a fuller understanding of the sand exchange across this zone is obtained, developments that could impede the natural sand exchange through the zone should be avoided. However, based on the current analysis of hydrocarbons prospectivity, hydrocarbons developments on a large scale in this area are unlikely in the near future.

The regional data indicate that an increase of sea surface biological productivity in the western Irish Sea overlies an increase in the percentage of biogenic carbonate in the sand fraction in muddy seabed sediments and pockmark fields in the Western Irish Sea Mudbelt (Figure 12). There are knowledge gaps in the amount of influence that active pockmarks, sea surface productivity and carbonate grain transfer have had on regional variability in the seabed carbonate composition of sands in the mudbelts.

Previous sections of this report have described features that are worthy of particular attention because of their unusual nature, isolation and effects on seabed physiography and composition and contribution to seabed habitat diversity. Active pockmarks, bioherms, banks in less than 20m water depth and some shipwrecks are already regulated by conservation measures. The following geological features are also worthy of consideration for preservation because they are irreplaceable:

Static bedforms — sarns, pingos, upstanding rock outcrops in mud belts

Mobile bedforms — banner banks and the isolated low banks associated with them in less than 20m water depth, estuary banks and spits

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6 Glossary of terms

Astronomical tide	The tide levels and character thatwould result from the gravitational effects of the Earth, Sun and Moon without any atmospheric influences
Bathymetry	Water depth
Bed	The bottom of any body of water, e.g. seabed
Bedforms	Features on the seabed (eg sandwaves, ripples) resulting from the movement of sediment over it, from seabed erosion, from deposition of stable sediment
Bedload	Sediment particles that travel near or on the bed
Bed-shear stress	The way in which waves and currents transfer energy to the seabed
Bioclastic (sediments)	Sediments derived by processes of derivation from biota
Biogenic	Having a biological origin. The biogenic component of seabed sediments in SEA6 commonly consists of shell fragments that have originated from bivalves
Boulder	Rock that is greater than 256 mm in diameter, larger than a cobble. The Wentworth grain-size scale includes boulders and cobbles within the gravel grain size class (Figure 27)
Clastic (sediments)	Sediments mainly composed of non-biogenic sediments that have been produced by the processes of weathering and erosion of rocks
Clay	A fine-grained sediment with a typical grain size of less than 0.004 mm (Figure 27). Clay possesses electromagnetic properties which bind the grains together to give bulk strength or cohesion
Coast	A strip of land of indefinite length and width that extends from the seashore inland to the first major change in terrain features
Coastline	The line that forms the boundary between the coast and the shore
Cobble	Rounded rocks, ranging in diameter from ~64–256 mm (Figure 27)

Cohesive	Said of soil that has relatively high shear strength when air-dried or drained following compression, and has cohesion even when wet, e.g. mud.
Cohesive sediment	Sediment containing a significant proportion of clays, the electromagnetic properties of which cause the particles to bind together, e.g. muds, muddy diamictons.
Comet marks	Seabed features that form in the lee of structures such as wrecks or all classes of gravel. May result from sediment scour or accumulation
Continental shelf	That part of the continental margin that is between the shoreline and the continental slope (or, when there is not a noticeable break with the continental slope, a depth of 200 m). Around the UK it is characterised by its very gentle regional slope of 0.1° or less
Contour line	A line connecting on the land or under the sea with points of equal elevation. See also isobath
Crest	Highest point on a bedform
Crust	The outmost layer or shell of the Earth, defined according to various criteria, including seismic velocity, density and composition.
Current	Flow of water generated by a variety of forcing mechanisms (e.g. waves, tides, winds, storm surges etc)
Datum	Any position or element in relation to which others are determined
Deep water	Water too deep for waves to be affected by the seabed ?(typically taken as half the wavelength)?
Depth	Vertical distance from still water level or other specified datum, commonly the lowest astronomical tide, to the seabed
Diamicton	A general term for an unsorted sediment consisting of gravel, sand and mud. The use of the term diamicton avoids giving an unsorted sediment a name that is based on its origin. Diamictons can originate from sub-glacial, periglacial, subaerial and submarine

processes. Diamictons exposed at seabed in SEA6 commonly have cohesive strength due to a high content of clay grains in the mud fraction. Very high shear strengths (hard to brittle) in diamictons exposed at seabed may have originated because of compression under the ice sheet, if it dried out during periods of low sealevel or if it underwent chemical changes after deposition. The term 'till' may be restricted to diamictons that have been deposited by glacial processes under ice. The origin and designation of a till may be pieced together after an understanding has been obtained of its depositional setting, sediment composition, sedimentary structures, sediment textures and likely age.

Direction of current	Direction toward which current is flowing
Direction of waves	Direction from which waves are coming
Direction of wind	Direction from which wind is blowing
Diurnal	Having a period of a tidal day 24.84 hours
Dyke	In SEA6 these are intrusions of igneous rock into other bedrock formations. Typically, they are buried at least 5metres below the seabed sediments and are near-vertical sheets of basalt varying from a few metres to more than 10m thickness
Ebb tide	Period of time during which the tidal level is falling
Erosion	Wearing away of the land or seabed by natural forces (wind, waves, currents, chemical weathering)
Eustatic	Pertaining to worldwide changes of sea level that affect all the oceans. Eustatic changes may have various causes, but the changes dominant in the last few million years were caused by additions of water to, or removal of water from, the continental icecaps
Extreme	The value expected to be exceeded in a given (long) period of time
Facies	The sum of features such as sedimentary rock type, mineral content, sedimentary structures, bedding characteristics, fossil content etc, which characterise sediment as having been deposited in a given environment
Fetch	Distance over which the wind acts to produce waves
Flood tide	The period of time when tide levels are rising

Fluvial	Of or pertaining to a river or rivers
Flux	Rate of mass transfer measured as rate at which the volume or the dry weight of sediment crosses a metre length per unit time. May be divided into components, e.g. sediment classes (sizes, types), drivers of velocity (tides, winds, waves, surges) and fluid setting (bedload or suspended load)
Geographical Information System	See GIS below
Geomorphology	The investigation of the history of geological changes through the interpretation of topographical forms
GIS	Geographical Information System—a system of spatially referencing information, including computer programs that acquire, store, manipulate, analyse and display spatial data
Glacigenic	Originating from a glacier or an ice sheet
Gravel	Loose, usually rounded fragments larger than sand but smaller than cobbles. Material larger than 2 mm (Wentworth scale used in sedimentology) or 5 mm (used in dredging industry). This report uses the Wentworth scale (Figure 27). In isolation, the term is not indicative of mineral or organic composition. Thus around the UK the seabed gravel is commonly mainly rock, but in many areas of SEA6, the gravel fraction in the pebble to granule size range in the seabed sediments commonly consist of 20-100% biogenic carbonate.
Highest astronomical tide (HAT)	The highest tide level that can be expected to occur under average meteorological conditions and under any combination of astronomical conditions. HAT is not an extreme level as certain meteorological conditions can cause a higher level (see storm surge)
High water	Maximum level reached by the rising tide

Holocene	A time period which started around 10 000 years ago and extends to the present day. In the temperate latitudes of the northern hemisphere its start is identified on the basis of the latest ongoing interglacial climate period
Hydraulic	Pertaining to a fluid in motion, or to movement or action caused by water
Hydrodynamic	The aspect of hydromechanics that deals with forces that produce motion
Inshore	Areas where waves are transformed by interactions with the seabed
Intercalated	Said of layered material that exists or is introduced between layers of a different character; or relatively thin strata of one kind of material that alternate with thicker strata of some other kind, such as beds of former seabed sand that may be intercalated in surficial sediments in a bodies of gravel or mud
Isobath	Lines connecting points of equal water depth. Seabed contours
Littoral	Pertaining to the benthic submarine environment or depth zone between high water and low water, also pertaining to the biota of that environment
Longshore	Parallel and close to the shoreline
Longshore current	A current located in the surface zone, moving generally parallel to the shoreline that is generated by waves breaking at an angle with the shoreline
Longshore drift	The movement of sediment driven approximately parallel to the shoreline by waves breaking at an angle with the shoreline
Low tide	See low water
Low water	The minimum height reached by a falling tide
Lowest astronomical tide (LAT)	The lowest tide level that can be expected to occur under average meteorological conditions and under any combination of astronomical conditions. LAT is not an extreme level as certain meteorological conditions can cause a lower level (see storm surge). Admiralty Charts and the SEA6 STI 2004 survey bathymetric data have been reduced to the LAT datum.

Mean sea level	The average level of the sea over a period of approximately 12 months, taking account of all tidal effects but excluding surge events
Megaripples	Outdated term for bedforms of wavelength approximately 0.6 to 10 m, sometimes more and height approximately 0.1 to 5 m. The term 'megaripple' was used for a wide variety of transverse bedforms which which were generally smaller than large sandwaves (10-100m wavelength) but larger than ripples (<0.6m wavelength). The definitions used in this report for the wavelengths of transverse bedforms is summarised in Figure 29a..
Metadata	Text that describes the key points relating to a particular dataset, paper or report
Mineral	A naturally occurring inorganic crystalline solid that has a definite chemical composition and possesses characteristic physical properties.
Morphology	(a) The shape of the Earth's surface geomorphology (b) The external structure, form and arrangement of rocks in relation to the development of landforms
Mud	An unconsolidated sediment consisting of clay and/or silt, together with material of other dimensions (such as sand), mixed with water without connotation as to composition
Neap tide	A tide that occurs every 14.8 days at or near the time of half moon and which displays the least positive and negative deviation from mean sea level
Nearshore	The zone which extends from the zone where waves break on the shore (sometimes referred to as the swash zone) to the position marking the start of the offshore zone (approximately 15-20 m water depth around the UK continental shelf))
Numerical modelling	Refers to the analysis of l processes using computational models
Offshore	The zone beyond the nearshore zone where wave induced sediment motion effectively ceases and where the influence of the seabed on wave action has usually become small in comparison with the

	effects of tide
Onshore	A direction landward from the sea
Outwash	Detritus, sometimes stratified, that has been removed or “washed out” from a glacier by meltwater streams and deposited in front or beyond the end moraine or the margin of an active glacier or ice sheet. The coarser material (chiefly sand and gravel) is rapidly deposited nearer the ice front and large quantities of mud may be rapidly deposited further away from the ice front
Overburden	The upper part of a sedimentary deposit, compressing and consolidating the material below
Particle size	In dealing with sediments and sedimentary rocks, it is necessary that precise dimensions should be applied to such terms as clay, sand etc. Numerous scales have been developed and the Wentworth scale is widely accepted as an international standard (Figure 27)
Permanent current	A current that runs continuously and is independent of the tides or other forcing mechanisms. Permanent currents include large scale ocean circulatory flows and the freshwater discharge from rivers
Quaternary	The youngest geological period from approximately 2.6 million years ago to include the present time
Residual water level	The components of water level not attributable to astronomical effects
Ripple	Sediment bedform produced by when fluid movement shapes unconsolidated sediments. Oscillatory currents produce symmetric ripples whereas a well defined current direction produces asymmetric ripples. The crest line of a ripple may be straight or sinuous. The characteristic features of these bedforms depend upon current velocity, particle size and the persistence of current direction. Ripples usually have low amplitudes (~ <0.06 to 0.1m)
Rocks	An aggregate of one or more minerals that falls into one of three categories: igneous rock that is formed from molten material; sedimentary rock that results from the consolidation of loose sediment; and metamorphic rock that has formed from pre-existing

	rock as a result of heat or pressure or both heat and pressure
Sand	Sediment particles, with a diameter of between 0.062 mm and 2 mm (Wentworth scale), or less than 5mm (dredging industry). Sand is generally classified as fine-, medium- or coarse-grained (Figure 27). The term is not indicative of particle composition. Thus around the UK the seabed sand is commonly mainly of quartz, but the weight percentages of other minerals and carbonate biogenic grains in the sand fraction of seabed sediments varies considerably in SEA6 (Figure 12)
Sandwave	Term used for a bedform, usually asymmetric, with height of up to approximately1/3 water depth and wavelength greater than ripples (approximately 0.06 to 0.1 m). Asymmetric sandwaves may be used to give an indication of the predominant direction of sediment transport (Figure 29a).
Sediment	Particulate matter derived from rock, minerals or biogenic matter
Sediment flux	The flow of sediment in suspension and as bedload across the seabed
Sediment sink	A point or area at which sediment is lost for a significant time from a coastal cell or transport pathway, such as an estuary, deep channel in the seabed, areas of open shelf with very little seabed stress, or in banks formed in areas of sediment convergence.
Sediment source	A point or area from which sediment arises such as an eroding cliff, seabed itself, or river mouth
Sediment transport	The movement of a mass of sedimentary material by the forces of currents and waves. The sediment in motion can comprise fine-grained material (silt and mud), sand and gravel. **Potential** sediment transport is the full amount of sediment that could be expected to move under a given combination of waves and currents, i.e. not supply limited
Sediment-transport pathway	The routes along which net sediment movements occur
Semidiurnal	Having a period of approximately one half of a tidal day (12.4 hours). The predominating type of tide throughout the world is semidiurnal with two high waters and two low waters each day
Significant wave height	The average height of the highest one-third of the waves for a given period of time

Silt	Sediment particles with a grain size between 0.004 mm and 0.062 mm, i.e. coarser than clay but finer than sand (Figure 27)
Sink	A depositional area (estuarine, coastal or offshore) into which sediment moves and finally settles out (see sediment sink)
Slack water	The state of the tidal current when its velocity is virtually zero, particularly when the reversing current changes direction
Sorting	Process of selection and separation of sediment grains according to their grain size, grain shape and specific gravity
Source	An erosional area (cliffs, interidal or subtidal) from which sediment is released for sediment transport
Spring tide	A tide that occurs every 14.8 days at or near the time of the full or new moon and which displays the greatest positive and negative deviation from mean sea level
Stillwater level	The surface of the water if all wave and wind action were to cease
Storm surge	A positive or negative storm surge occurs respectively with a rise or fall of water against the shore, positive sometimes produced by strong winds blowing onshore, negative surge sometimes produced by strong winds blowing offshore. These may interact with or be independent of regional atmospheric pressure gradients that also force the sea level to change and generate storm surge. Storm surges may originate internally or externally to an affected area. Storm surges may cause sea level to rise above highest astronomical tide or below lowest astronomical tide and the currents produced by storm surge can predominate over the speeds and directions of the tidal streams and local wind-driven currents
Substrates	The substance, or base or the medium, in which an organism lives and grows, or the surface to which a fixed organism is attached, e.g. soil, rocks. This is usually at seabed but can be below seabed
Surf zone	The nearshore zone along which waves become breakers as they approach the shore
Surge	Changes in water level as a result of meteorological forcing (wind, high or low barametric pressure) causing a difference between the recorded water level and that predicted by harmonic analysis. The surge may be positive or negative (see also storm surge)

Suspended load	The sediment particles that are light enough in weight to remain lifted indefinitely above the bottom by turbulent flows
Terrestrial	Occurring on the land or continent in a non-marine environment
Tidal current	The alternating horizontal movement of water associated with the rise and fall of the tide
Tide	The periodic rise and fall of the water that results from the gravitational attraction of the moon and sun acting upon the rotating Earth
Till	Dominantly unsorted and unstratified sediment, generally unconsolidated, deposited directly by and underneath a glacier without subsequent reworking by meltwater, and consisting of a heterogeneous mixture of clay, silt, sand and gravel ranging widely in size and shape. The term is used for a diamicton where it is thought that the sub-glacial origin of the diamicton has been firmly established.
Topography	The form of the features of the actual surface of the Earth in a particular region considered collectively
Trough	A long and broad submarine depression with gently sloping sides, or trough of a wave or sedimentary feature
Unconformity	A break or gap in the geological record where a rock or unconsolidated unit is overlain by another that is not next in the stratigraphical succession
Unconsolidated	Sediment grains packed in a loose arrangement
Water level	The elevation of a particular point of a body of water above a specific point or surface, averaged over a given period of time
Wave direction	The direction from which the waves are propagating
Wave height	The vertical distance between the crest and the trough
Wavelength	The horizontal distance between consecutive wave crests
Wave period	The time it takes for two successive crests (or troughs) to pass a given point
Wind current	A current created by the action of the wind on the water surface

Appendix 1 Sediment analyses and seabed-sediment classification

Sediment analyses have been derived from samples taken from seabed to approximately 10cm below seabed. After laboratory quantitative analysis of dried sediments, the BGS classifies seabed-sediment textures to accord with modified Folk (1954) classes, which are based on weight percentages sediment grains over a range of Wentworth size classes (Figure 27). The values of weight % carbonate in the total sediment and in the sediment size classes are also routinely determined. These values can be interpreted as a measure of the inputs to the sediment from biological sources of calcium carbonate.

1 Grain-size scale

GRAIN-SIZE SCALE FOR SEDIMENTS				
Millimetres	Microns	Phi (Φ)	Wentworth Size Class	
			Boulder	GRAVEL
256		-8		
			Cobble	
64		-6		
			Pebble	
4.0		-2		
			Granule	
2.0		-1		
			Very Coarse	SAND
1.0		0		
			Coarse	
0.5	500	1		
			Medium	
0.25	250	2		
			Fine	
0.125	125	3		
			Very Fine	
0.063	63	4		
			Coarse Silt	MUD
	32	5		
			Fine-med Silt	
	4	8		
			Clay	

Figure 27 Wentworth grain-size scale used in sediment-size classifications for sediments.

2 Outline procedures for particle-size analysis

For the BGS regional surveys, the proportions of mud, sand and gravel were quantified by wet sieving using a 63micron sieve to determine mud (a mixture of silt and clay) and with a 2mm sieve to determine gravel (in the granular gravel to pebble and larger size classes). The results were presented as percentage dry weight with many samples further quantified at ½ phi intervals.

3 Seabed-sediment classification

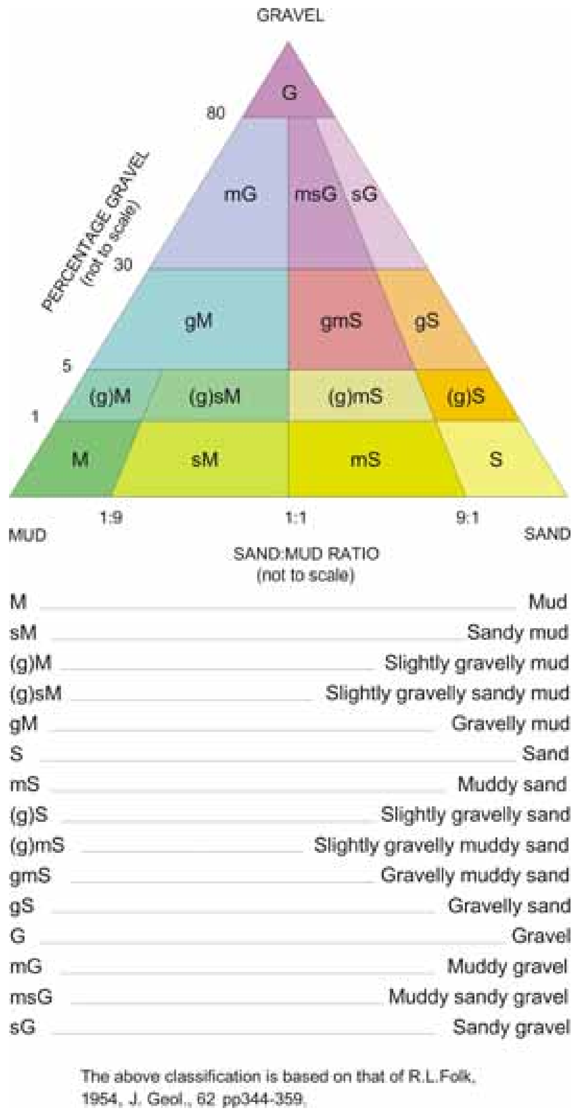

Figure 28 Seabed-sediment classification scheme.

Appendix 2 Sediment waves

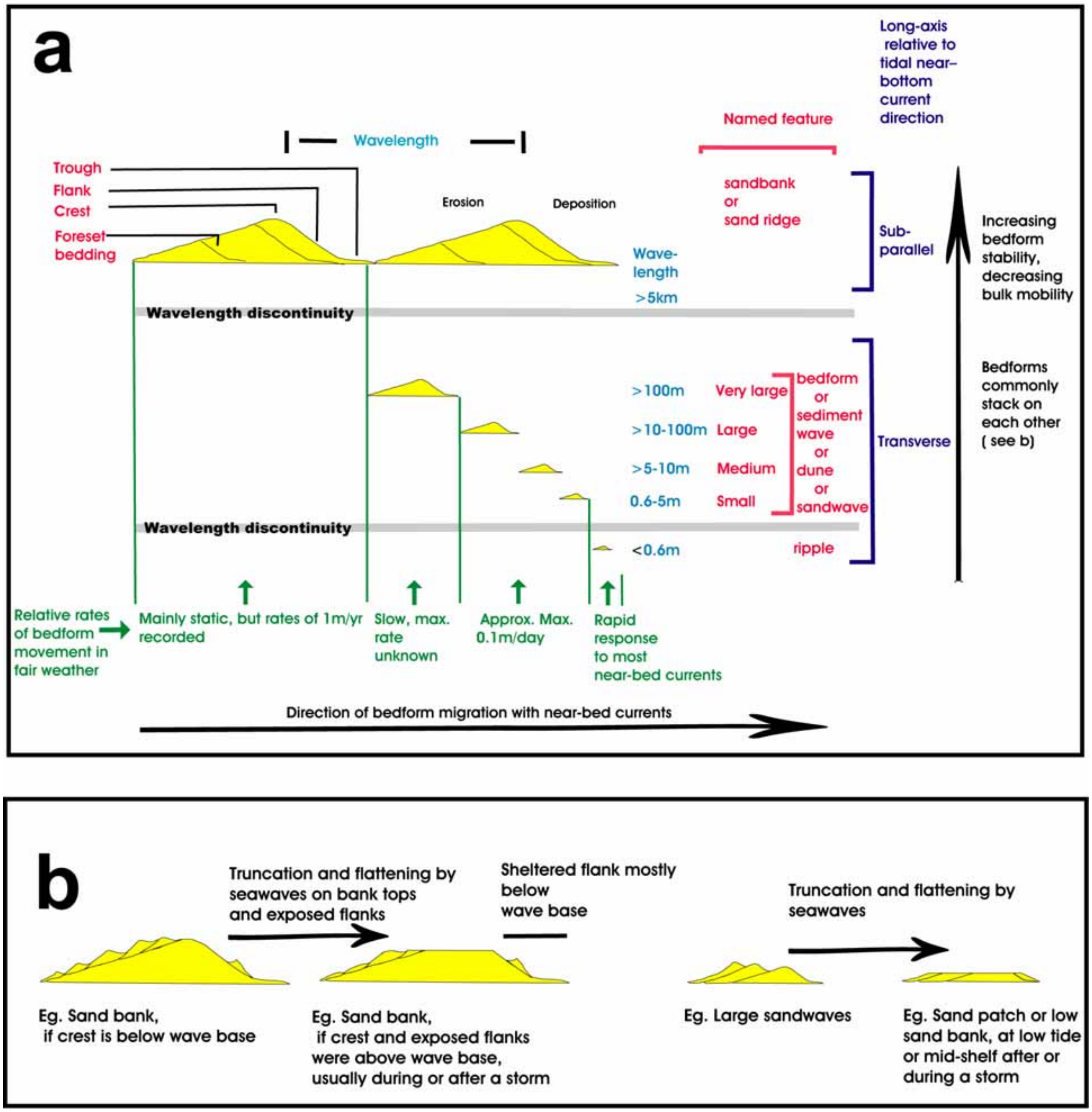

Figure 29 a. Generalised geometries and characteristics of sandwaves and tidal sandbanks related to tidal currents **b.** observed effects of wave-driven processes on tidal sandbanks and sandwaves

Transverse sediment sandwave size classes shown on Figure 29a are adapted after (Ashley, 1990).

Features of the open shelf sandwaves and sandbanks in SEA6 are:

- They mainly occur in areas of directed near-bed currents
- There is a natural continuity break between the size ranges of ripples and sandwaves at less than 0.6 m. wavelength, and a continuity break between sandwaves and sandbanks at less than 5km wavelength
- Although sandwaves with distinctly separate wavelength size ranges are often observed in one sandwave field, from the global perspective there is a continuum in the size ranges of sandwaves in the range of 0.6 m to more than 100 m.
- They open shelf sediment waves are most commonly composed of sand
- Mud sediment waves on the continental shelf usually have a smaller range of wavelengths, e.g. less than approximately 5metres in the Irish Sea
- Where they are asymmetric, the facing direction of steepest face is their direction of movement
- The smaller sediment waves move faster so that the sandbanks which are formed sub-parallel to prevailing near-bed currents and the largest transverse sediment waves, are the least mobile
- Migration of sandwaves over and through each other contribute to both the build up and dispersal of sand on sandwaves, sand patches and sandbanks