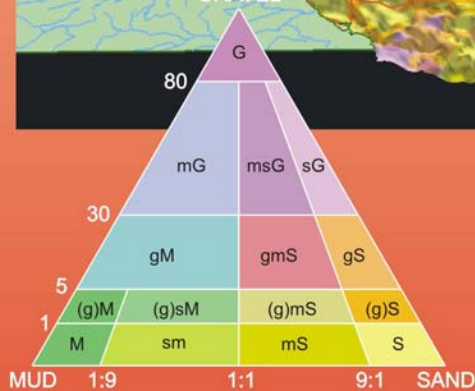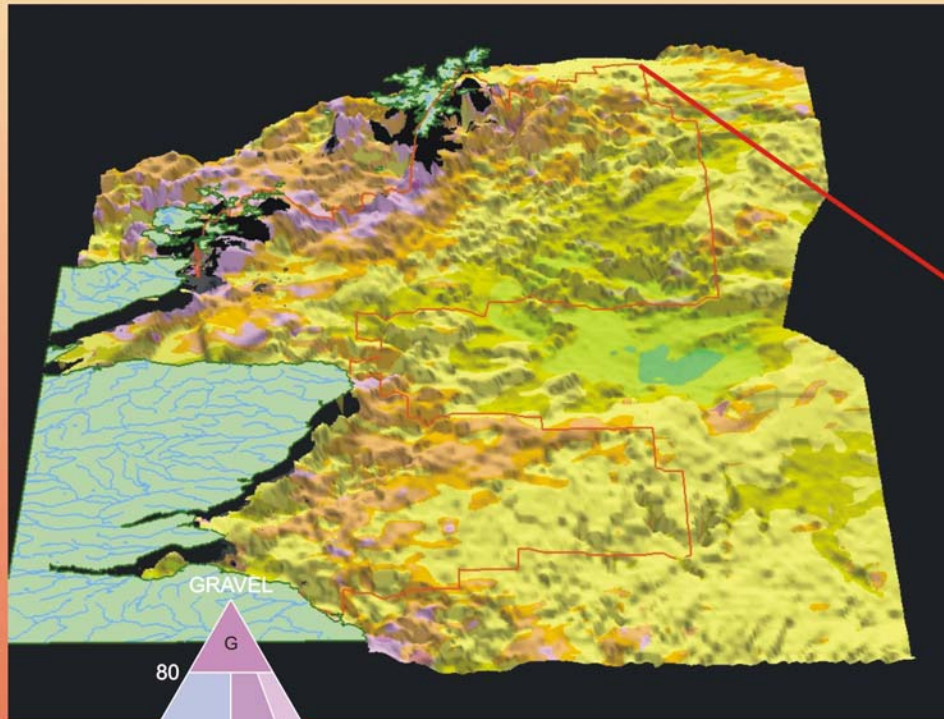# DTI Strategic Environmental Assessment area 5 (SEA5)

Geotek contract number: SEA5–Geology–BGS

Continental Shelf and Margins Programme

Commissioned Report:CR/04/064N (SEA5) Seabed and superficial geology and processes

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British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

BRITISH GEOLOGICAL SURVEY

DTI Strategic Environmental Assessment Area 5 (SEA5):

SEABED AND SUPERFICIAL GEOLOGY AND PROCESSES

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Front cover

Seabed sediments
In DTI SEA5 area of study

Geotek Contract reference: DTI-SEA5 Subcontract

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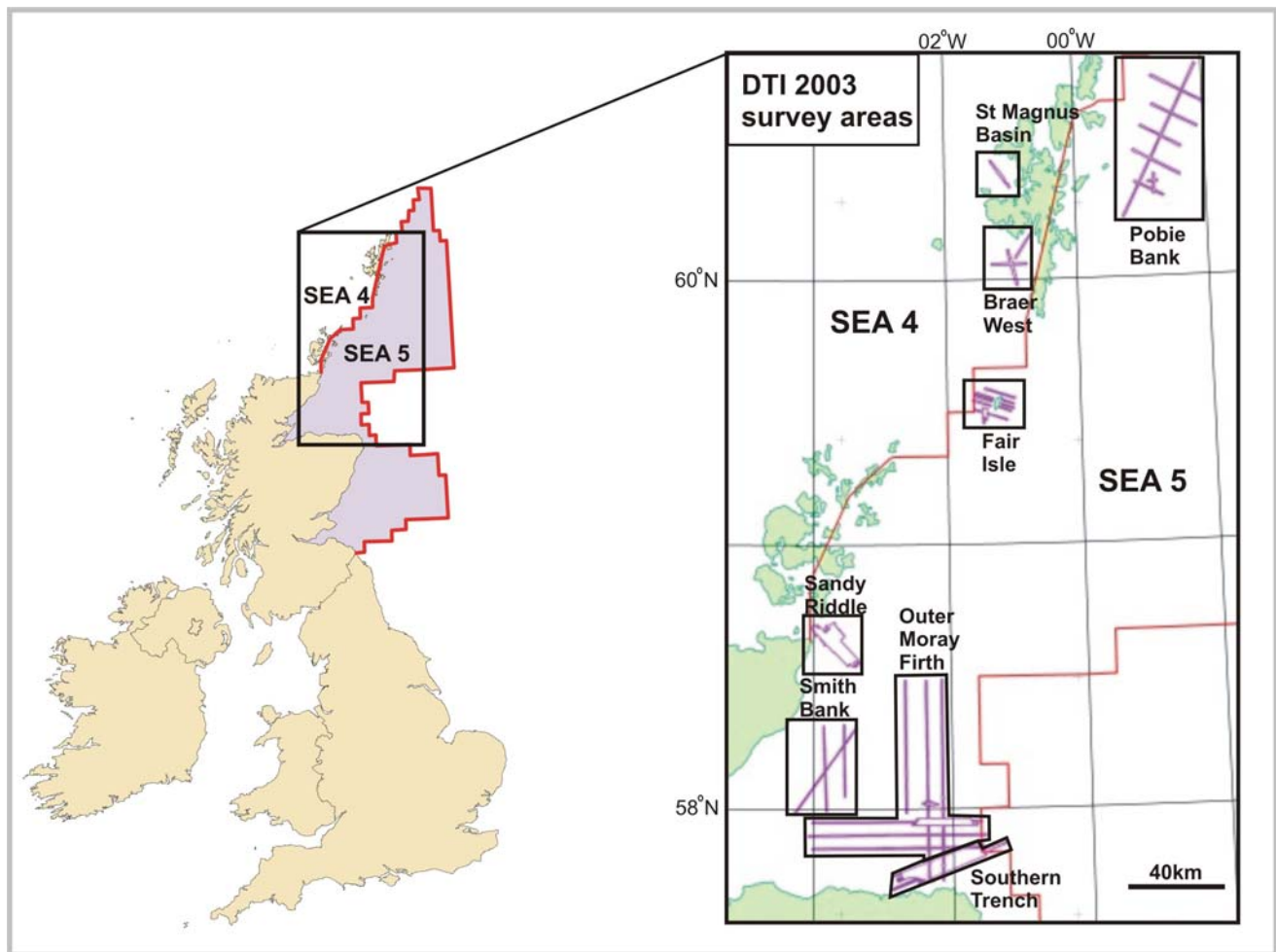**Explanation of frontispiece**

The image is composed of a colour-coded map of seabed-sediment classes draped on a shaded terrain image of seabed topography. These composite datasets illustrate that there is some correlation between the seabed topography and the seabed-sediment size classes on the open continental shelf. See Appendix 3 for an explanation of the derivation of seabed-sediment size classes.

Foreword

This report is the product of a desk study by the British Geological Survey (BGS) in response to a contract from Geotek Ltd to report on the seabed and superficial geology and geological processes in the Department of Trade and Industry (DTI) Strategic Environment Assessment area 5 (SEA5).

The programme of DTI Strategic Environmental Assessment is aimed at assessing the possible impacts of offshore developments prior to new licensing rounds. In the summer of 2003 the DTI carried out new surveys in order to collect environmental information in 6 project areas in SEA5 and 2 project areas in SEA4. The review areas for this report, including the new DTI 2003 surveys, are illustrated below. The data from the DTI 2003 survey included multi-beam bathymetry, sidescan sonar, seismic-reflection profiles, sea-floor photographs and samples. The principal aim of this work has been to produce a summary technical report on the seabed and superficial sediments based on an integration of the 2003 survey results with the pre-existing geological reports, maps and other publications in the scientific press.

Locations and geographical settings of the review areas.

Acknowledgements

Summary

This report reviews published and newly-acquired seabed geological data in an area of 78,000 square kilometres extending from the coast to more than 200 m water depth to the east of the British Isles. While it can be argued that the modern environment is a product of past environmental conditions, the basis for the review is also that our understanding of the modern environment can be significantly improved if new techniques, data and ideas are applied to a revision of the existing research knowledge. The purpose of the review is to place the characteristics of the seabed features that were surveyed by the DTI in 2003, and the processes forming them, into an improved understanding of their historical, local and regional context. In this way a strong element of the review is to include the results from exploration and discovery. The intention of the report is to provide a technical basis for the DTI Strategic Environmental Assessment prior to a new round of licensing and consents for oil and gas. Results from this report are also relevant to scenarios for development of potential offshore renewable energy sites in less than 40-50m water depth.

- The Beatrice Field is the only commercial reservoir in the study area. It is currently producing oil from Jurassic sandstone reservoirs (more than 140 million years old).
- Approximately 5% (4,100 square kilometres) of the study area includes seabed that is less than 40m deep.
- The coast and near-shore seabed of the North Sea and the Moray Firth have been partly shaped by deep geological structure and are also now rising or subsiding according to location and in response to both deep geological processes and climate-related sea-level change. In the future, the most significant net effects of these changes on the seabed area and the seabed properties are likely to be observed in the estuaries.
- Although the crust is now measurably moving, the region is assessed as being essentially low-risk with regard to earthquake activity with the potential for significant adverse impacts on future seabed developments.
- The recorded effects of tsunamis originating from a large-scale submarine landslide on the continental slope of Norway are summarised. One view is that similar events are unlikely in the short term because of the historical precedent that the last recorded events were approximately 8,200 years ago. There are, however, insufficient data to quantify the long-term risks posed by tsunamis to the coastal and nearshore environments.
- Modern shoreline variability on exposed coasts is related to the resistance of the coastal bedrock to erosion and in the estuaries to reworking of sediment input from rivers and from offshore.
- The new sedimentary input to the offshore area is small so that modern seabed sediment variability mainly reflects processes of seabed winnowing and sediment redistribution.
- Many large-scale features of the modern seabed topography and composition have been inherited from the effects of the regional terrestrial and tide-water ice sheets that covered most of the area during the last glaciation. The patterns of seabed variation associated with the marine reworking of former glacigenic features are imposed on the patterns of seabed topography and composition originating from marine reworking of underlying bedrock.
- Submarine biological shell-carbonate production mainly post-dates approximately 10,000 years ago and is continuing to the present day. It has played a significant part in influencing the patterns of modern seabed grain size and composition in the nearshore and bank environments. The variations of seabed composition due to the submarine accumulation and reworking of shell carbonates are superimposed on those originating from submarine reworking of underlying bedrock and the former glacigenic features.

- Interpretations of pre-existing regional data and the results from the detailed DTI 2003 surveys confirm that in the exposed continental-shelf environments, the peak near-bed tidal currents in combination with the effects of near-bed orbital currents originating from surface sea waves, both in stormy conditions, play a major part in the distribution patterns of seabed-sediment size classes, seabed sediment bedforms and the directions of net sediment transport. Thus modern processes involving the interaction between the seabed and the peak near-bed currents drive temporal adjustments to seabed composition and provide the latest and most dynamic contributions to seabed variability.

- A regional overview is that the variability of seabed-sediment texture and composition can be summarised in relation to four main types of seabed condition. These take into account the spatial and temporal variations of the seabed environments. More than one type of seabed condition usually relates to the observed seabed variability in an area. Type 1 describes a seabed condition where exposure to extreme near-bed currents results in bedrock crop at seabed or coarse unsorted seabed sediments with a lack of sediment fines, types 2 and 3 describe seabed conditions where there are local correlations of grain size with water depth and type 4 describes seabed conditions where interactions between the seabed configuration and directed near-bed currents have resulted in departures from type 1-3 conditions.

- Detailed surveys were made of the Sandy Riddle bank occurring to the east of the Pentland Skerries and banks to the east and west of Fair Isle. These banks are tied to sediments deposited in the lee of land and shallow-water obstructions during the exchange of water between the Atlantic margins to the west of the Orkney and Shetland archipelagos and the North Sea to the east. The banks are mainly composed of shell carbonate sand and shell gravel. These and other banks and shallow-water areas around the Orkney and Shetland archipelagos contain a significant part of the total shell carbonate in SEA5.

- Detailed surveys of Smith Bank and Pobie Bank indicate that they are stable and underpinned by bedrock.

- Detailed surveys of parts of the Southern Trench, a major enclosed basin with a seabed area of more than 550 square kilometres, indicate basin flanks with slopes of up to 50°. Some of the slope instability observed in the Southern Trench is related to bedrock failure.

- Well-sorted, fine-grained sand is being transported along the deep-water axes of the Southern Trench where the near-bed currents are accelerated due to lateral constrictions in trench-axis configuration.

- The axes of smaller enclosed basins situated to the north of the Southern Trench are sediment traps, either for muddy sediments deposited from suspension and bedload, or for sandy and gravelly bedload sediments that have spilled over into the basin axes from the surrounding shelf platforms.

- Results from legacy data and the new surveys indicate that local patterns of variation of grain size with water depth may be quantitatively described from seabed samples at a particular time of survey. As a result, some trends in grain size variation may be numerically predicted. Departures from the predicted local trends characterise some of the modern seabed sediment variability

- Preliminary results indicate that regional patterns of variation in the modal particle sizes within the sand-size class may be quantitatively described for sites where a good understanding of the seabed condition is constrained by knowledge of near-bed currents, interpretations of seabed topography, seabed backscatter, seabed photography and seabed sediment particle size analyses.

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1. Introduction

The project area extends from east of the coastlines of mainland Scotland, Orkney and Shetland Isles across the North Sea continental shelf (Figure 1).
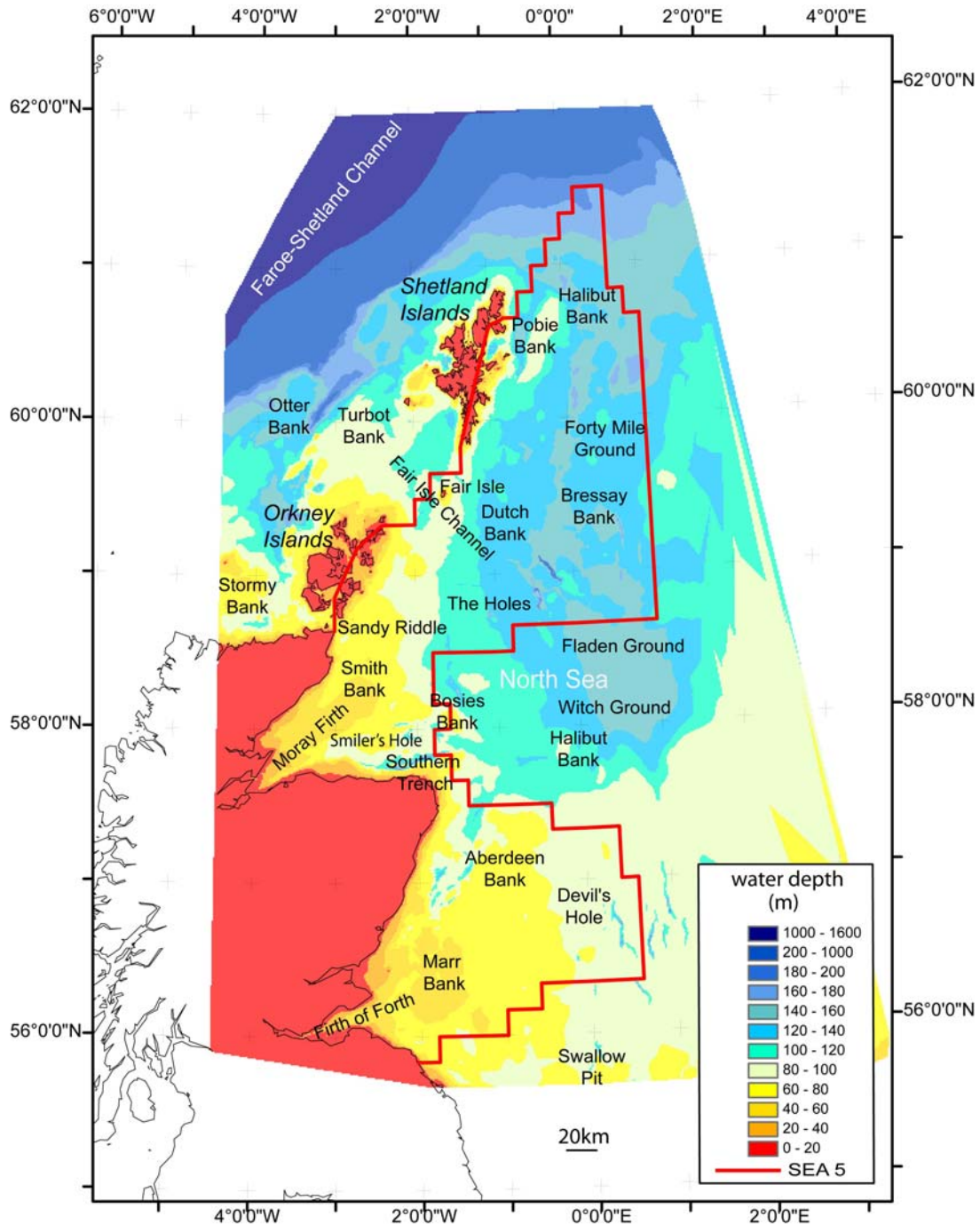
Figure 1. SEA5 location and bathymetric setting.

SEA5 has a seabed surface area of approximately 77,800 square kilometres. Most of the seabed is in less than 200m water, more than 50% is in water of 100m depth or less and approximately 5% of the area has 40m water depth or less (Table 1).

Water depth (m) less than --	20	40	60	80	100	120	140	160	180	200
area sq km	1,400	4,100	10,300	26,900	43,790	51,400	66,900	76,479	77,660	77,764
area %	1.79	5.27	13.23	34.57	56.28	66.06	85.99	98.30	99.82	99.95

Table 1. Quantification of seabed surface areas for selected SEA5 bathymetric intervals

The objective of this report is to consider the geological data that may contribute to the Strategic Environmental Assessment in area 5 (SEA5) The Department of Trade and Industry Offshore Environment and Decommissioning, Licensing and Consents Unit (hereafter DTI) is responsible to the UK government for administering legal environmental legislation applicable to the oil and gas industry offshore. One such piece of legislation is an EC Directive (2001/42/EEC). The Directive is generic and wide ranging 'on the assessment of the effects and certain plans and programs on the environment.' The activities regulated cover seismic surveys, drilling, seabed development operations and decommissioning of offshore development structures. The programme of DTI Strategic Environmental Assessment is aimed at assessing the possible impacts of offshore developments prior to new licensing rounds.

Features designated for scientific research include sandbanks, sand ridges and other sedimentary features that are either static or mobile. Some of the sandbanks occur in less than 20m water depth and form isolated features. Research on these sandbanks is included in the EU Directives because they fall within the definition of 'submerged sandbanks'. With their abundant sand eels, which find refuge in the sand, they are also sites of important food sources for sea mammals and sea birds, the last within the scope of interest covered by the Bird's Directive (79/409/EEC). Sandbanks and isolated basins on the open continental shelf are under consideration for preservation because they are 'with a small natural range by reason of their intrinsically restricted area'. Large spreads of seabed gravel with abundant attached and mobile biota, may technically fall within the definition of 'reefs' as specified in the Interpretation Manual of European Union Habitats (EUR 15/2). The gravel spreads also provide important seabed habitats, for example, as spawning areas for fish.

The content of the report accords with the tasks for the research, which were defined by the DTI as :

- A brief description with charts of the hydrocarbon geology
- Summarise from existing data and geological models the processes and features that have shaped the modern seabed
- Incorporate the new 2003 DTI offshore survey data into existing data
- Appraise the existing geological models and processes in the context of the new survey data
- Summarise the utility of existing seabed data in relation to incoming data and new techniques

In line with the scope of tasks, the method of approach in the first part of the main report has been to review our present knowledge of geological events and processes that have shaped the modern coastal and continental-shelf seabed topography and composition. The scale of this review ranges from global to local processes and mainly considers influences on the modern seabed configuration and

composition that have operated over the past 5 million years. This research task is an important component of strategic environmental research because much of the critical evidence for the magnitude of past and potential future environmental changes resides offshore. The second part of the report systematically reviews the results from the 2003 DTI detailed surveys in accord with the sites investigated. The new data acquired in the project area have been described and then interpreted in their historical and modern regional context. The new interpretations are then considered in the context of our previous understanding of the processes affecting the seabed. An evaluation of seabed processes is important to strategic environmental research because the modern processes impose independent variables on seabed properties at the shorter time scales.

Brief technical reviews in Appendix 1 summarise aspects of the potential for the adoption of commercial hydrocarbons 3D datasets for use in seabed topographic surveys, describe the applications of multi-beam and single-beam surveys for bathymetric mapping and summarise the characteristics of the existing regional seabed classification scheme based on grain sizes. An overall objective of the appraisals is to summarise some of the characteristics of the legacy and new datasets that have been combined for the strategic environmental assessment. The summaries and conclusions from the tasks completed for this part of the review are restricted to Appendix 1.

The DTI 2003 surveys included reconnaissance multi-beam and sidescan sonar surveys of the St Magnus Basin and Braer West areas occurring to the west of Shetland. These areas are adjacent to the 1993 M.V. Braer West oil spill and are in the SEA4 area. A brief review of the results and a comparison with the BGS model of seabed sediments is restricted to Appendix 2.

2.   Previous work

2.1   Regional structure and hydrocarbon geology

SEA5 is underlain by continental crust of the Eurasian tectonic plate. The geological structure of the bedrock that underlies the seabed is characterised by a complex pattern of down-faulted basins separated by platforms (relatively uplifted areas) (Figure 2).
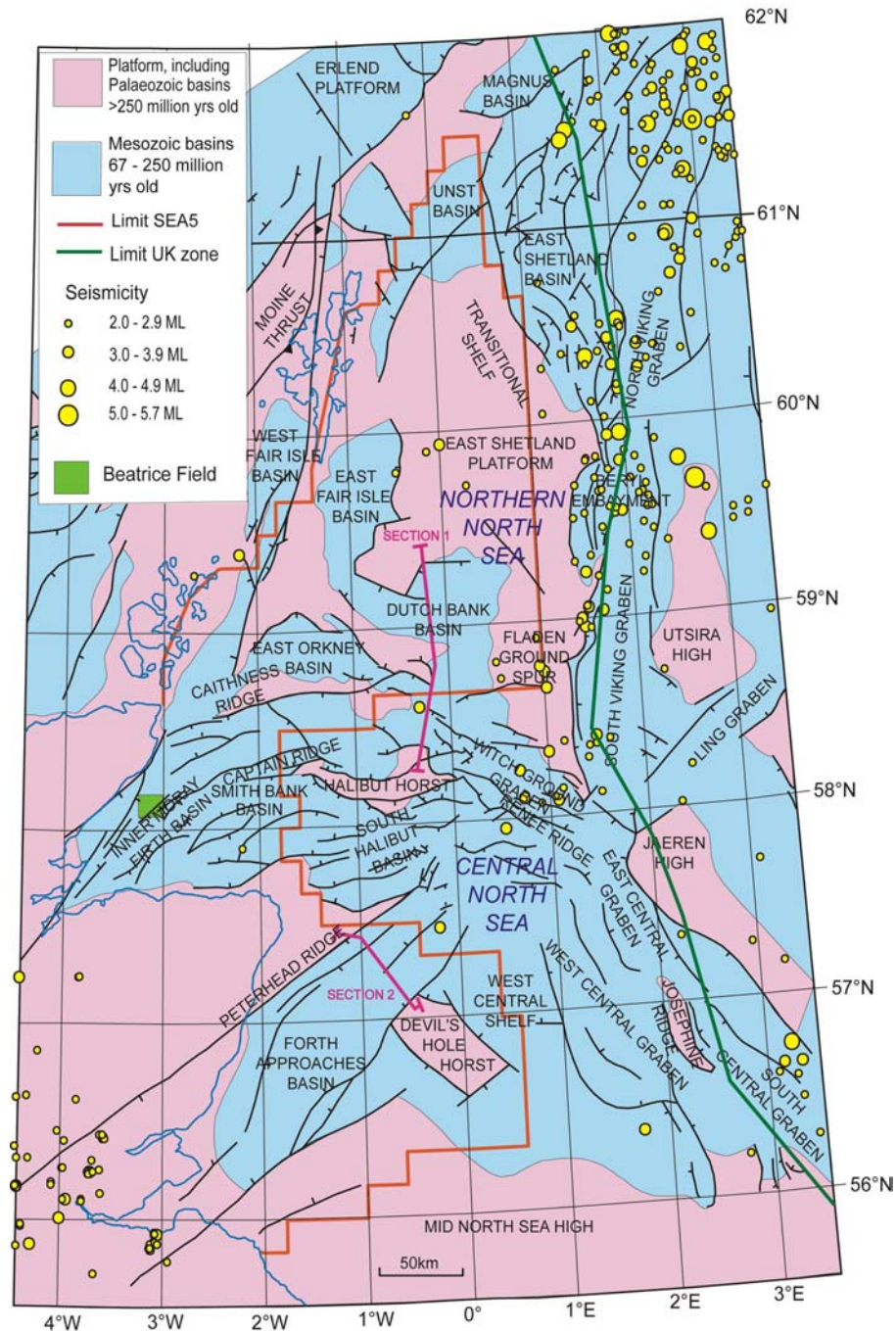
Figure 2. Structural geological framework and natural seismicity. The structural geological framework is adapted after Johnson and Leslie (2003).

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The area can be structurally divided into a northern sector including the East Shetland Platform and its marginal basins, a central sector over the Inner Moray Firth Basin and a southern sector containing the Forth Approaches Basin and basins on the west margin of the central North Sea (Figure 2). Mesozoic and Cenozoic (less than approximately 250 million years old) sediment cover is thin or absent in the northern sector except in the marginal basins which originated in Permo -Triassic times approximately 290-210 million years ago. Complex patterns of major late Jurassic (160-142 million years old) fault-controlled basins characterize the Inner Moray Firth Basin (Figures 2, 3a). Unlike the area to the east, which was characterized by subsidence, the Inner Moray Firth has been uplifted since the start of the Eocene approximately 55 million years ago (Argent et al, 2002). The southern sector includes the Forth Approaches Basin which was formed during the Carboniferous approximately 360-290 million years ago along SW-aligned structure (Figure 2). In this sector the younger sediments generally thicken towards the basins in the Central North Sea (Figures 2, 3b).
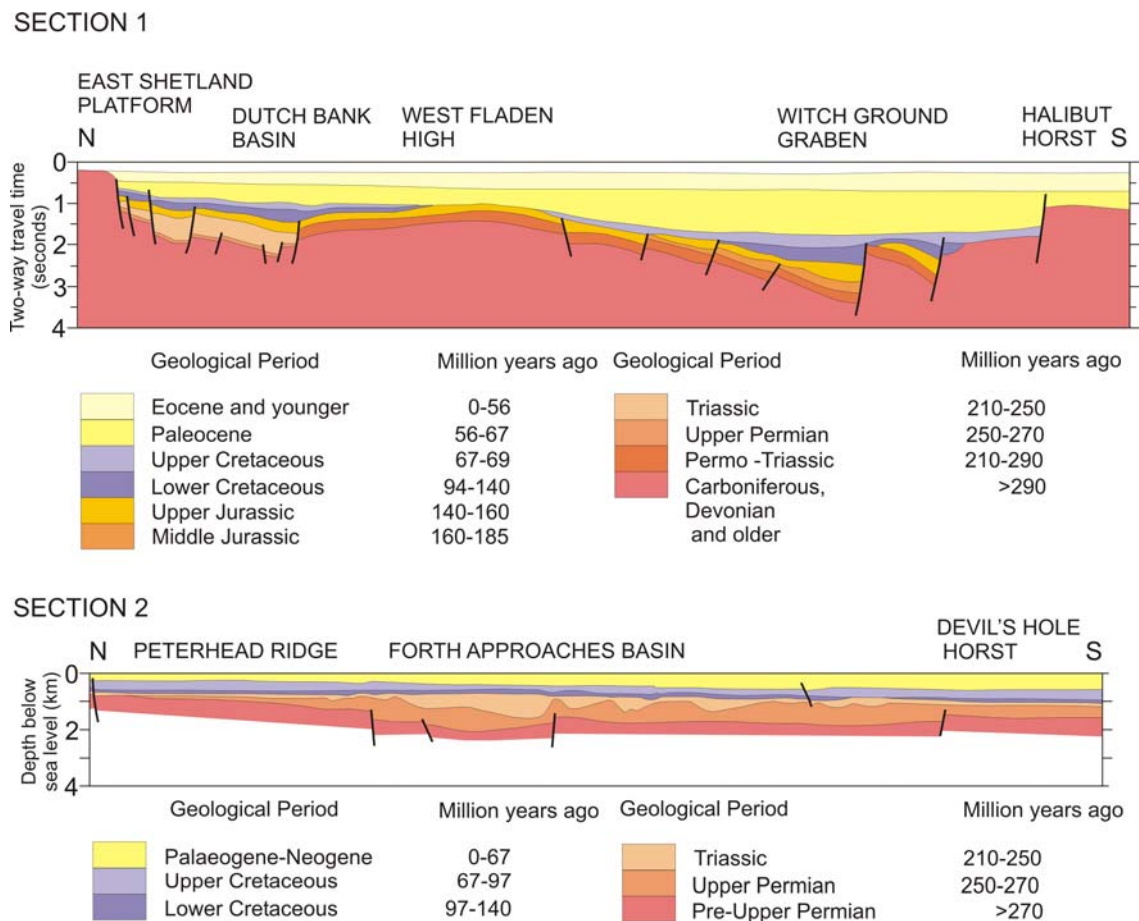
Figure 3. Generalised geological cross-sections (after Gatliff et al. 1994 and Johnson et al. 1993). For locations see Figure 1.

The uplifted platforms formed approximately 420 million years ago and underlie almost all of the modern coastline and nearshore areas (Figures 1, 2). The offshore basins are cut by basins formed during faulting, approximately 420 –142 million years ago and, to a lesser extent, at later times (Table 1).

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	Late Silurian (420 Ma)	Caledonian Orogeny.
PALAEOZOIC	Mid-late Devonian (388-362 Ma)	Extensional basins.
	Carboniferous (360-290Ma)	Strike-slip faulting forming Forth Approaches Basin
	Early Permian (290-256 Ma)	Extensional and subsiding basins.
MESOZOIC	Mid-Jurassic (180-160 Ma)	Uplift and erosion in the Central North Sea
	Late Jurassic (160-142 Ma)	Extensional Basins, major phase of basin formation.
CENOZOIC	Palaeogene – Neogene (65-0 Ma)	Overall subsidence central North Sea basins, periodic uplift basin margins and mainland, particularly in the Inner Moray Firth Basin.

Table 2. Summary of historical crustal movements shaping the North Sea and Moray Firth. Ma = million years ago

2.1.1. Commercial hydrocarbons extraction

The Kimmeridge Clay Formation (more than approximately 140 million years old) is the principal hydrocarbon source rock of the Central and Northern North Sea. The majority of oil and gas fields in the hydrocarbon provinces to the east of and adjacent to SEA5 were charged from this prolific source (Cornford 1998). Source rocks within the SEA5 area are believed to be rich in terrestrial plant matter that may be a shallow-water facies of the Kimmeridge Clay, not the deep-water marine clays that form the main source for hydrocarbons material further to the east. Alternative sources might include Devonian lacustrine mudstone, more than 360 million years old, and oil-prone, algal-rich mudstone and coal of the Jurassic Brora Coal Formation, more than 160 million years old (Cornford 1998 and references therein). The Beatrice Field in the Inner Moray Firth is the only reservoir in SEA5 which is currently producing oil (Figure 2). The reservoirs are uppermost Triassic to uppermost Jurassic marine sandstones, ranging in age from approximately 140 – 210 million years. The sandstones with porosities of 12 – 20%, contain 79% of the total reserves of oil and gas. The reserves are stacked in upward-coarsening sedimentary sequences. The main reservoir is a north-east-trending, tilted fault block that formed in the Upper Jurassic, between approximately 140-160 million years ago and is sealed by shaly mudstone (Thomson and Underhill 1993; Davies et al, 2001).

2.2 Earthquakes

Potential natural consequences of earthquakes include ground displacement tsunamis, pockmarks (excavated by fluid expulsion from the seabed) and submarine landslides. Although earthquakes are known to both precede and post-date subsurface fluid (gas and liquid) transfer, there is at present no identified connection between modern pockmark and earthquake activity in the North Sea. A large-scale submarine landslide 8,200 years ago in deep water off Norway generated a tsunami that reached the SEA5 area (section 2.8). However, in this instance, there is little possibility of relating the timing of the submarine landslide to historical earthquake activity.

Only nine earthquakes fall within the SEA5 polygon, which show a lower magnitude limit of 2.0 ML (Figure 2). The oldest event was in 1980, and the last in 2002, although the catalogue is complete up to early 2004. With so few events, any statistical analysis is subject to considerable uncertainty. The best fit to the Gutenberg-Richter equation that describes the relationship between earthquake frequency and magnitude is

$$\text{Log } N = 1.13 - 0.70 \ M$$

where N is the cumulative number of events per year above local magnitude M. From this equation, on average, an earthquake of magnitude 4 ML should occur once every 50 years, a magnitude 5 ML every 250 years, and 6 ML every 1,250 years. The reliability of these figures is poor. The potential importance of quantitative predictions such as these is that earthquakes of 4 ML or more are taken into account as part of the hazard assessment for development operations tied to seabed (Musson et al, 1997).

In conclusion, SEA5 shows very little modern earthquake activity and appears to be at low but not entirely negligible risk from future earthquake activity that could affect development operations.

2.3   Major processes influencing modern seabed configuration and composition

The influence of the large-scale geological structure on the seabed topography generally decreases with increasing distance offshore and with burial of deep geological structure by younger sediments (Figures 1, 2, 3). One reason for this is that since more than 25 million years ago to the present day, coastline shifts have responded to episodes of large-scale gradient changes as a result of changes of elevation of the earth's crust centred on broadly consistent regions of uplift and subsidence. Similar ('tectonic') episodes have been a characteristic of the North Atlantic, South Atlantic and Indian Ocean margins, in some cases possibly because of anomalous mantle conditions at depth (Lavier et al, 2001). The latest rapid and large-scale crustal movement appears to be related to plate tectonics or mantle conditions that affected Fennoscandia and the British Isles approximately 5 million years ago. It caused uplift of more than 500m followed by erosion and exposure of the SEA5 mainland and basin margin areas and was complemented by tilting and increased sedimentation in the basins further offshore (Japsen, 1997). Regional uplift of the British Isles and elsewhere also coincided with a change to a cooler climate (Table 3).

Large-scale crustal movements of the type summarised have been over-printed by global sea-level fluctuations. These were mostly driven by cyclical changes to polar ice volumes during glacial and interglacial periods and are commonly referred to as 'eustatic' sea-level changes. Post-dating approximately 760,000 years ago there was a shift to overall larger polar ice volumes (Funnel, 1995). During these times large-scale glaciations were nucleated, the glaciations were relatively stable, and the regional ice sheets extended to encompass large areas of the northern and middle British mainland and offshore areas. Sea level periodically fell to at least 100-140m below present level. This period included 7 major glacial cycles that were approximately 80,000 to 120,000 years long. These were followed by interglacial periods of approximately 10,000 to 15,000 or more years duration (Raymo, 1997). During and between the major glacial and interglacial periods there were other significant periodical climate and sea-level changes of 1,000 to 3,000, sometimes 5,000 years or more average periodicity (e.g. Clapperton, 1997). During these periods sea level fluctuated over a range of less than 10m to possibly 50m or more. Thus, from the geological perspective, there is nothing unusual in relatively rapid changes of sea level. What is significant is the risk posed by accelerations to changes (section 2.7) and whether the changes appear to be natural or not.

The inherited effects of tectonic and climate change over the glacial-interglacial and shorter climate cycles to the present day have meant that part of the diversity of the present seabed topography is a result of its shaping by global and regional processes over time periods in the order of 1,000 years or more. The shortest periodic inputs to seabed configuration and composition originate from seasonal and daily climate changes, gravity-driven tidal cycles, seabed failure and from foci for basin-wide fluid escape at seabed (Table 3).

PROCESSES/ FEATURES	GLOBAL	REGIONAL	LOCAL / MODERN
Vertical and horizontal earth movements (tectonics)	Earth's mantle and crustal stresses. Last major Atlantic margin uplift (500m or more), 5 million years ago. Uplift influences climate, ice sheet growth	Cyclical response to crustal loading and unloading driven by ice and rock thickness changes contributes to relative water depth changes. Time scale 5,000 year + periodicity	Continuing adjustments to historical ice and rock thickness and water depth changes. Crust movements average millimetres per year, earthquakes provide indirect evidence for instantaneous but unknown displacement.
Climate	Periodic changes of position of earth relative to sun influence global ice volumes and sea level changes. Climate belts shift and marine circulation patterns change. Periodicity: interglacials 10,000-15,000+ years, glacials 80,000-120,000+ years	Sea-level changes affect boundaries of former sub-ice and modern terrestrial, estuarine and submarine processes. Significant changes <1,000 years	Seasonal to daily calm/stormy wind and waves rework the continental shelf. Interglacial / modern biogenic inputs are important controls on variations of seabed chemical composition and grain size
Gravity	Position of earth relative to sun and moon and earth's rotation drives sea-level bulge and tides	Heights of tides and strengths of near-bed tidal currents shape coast, submarine seabed and seabed texture. Timing semi-diurnal, maximum (spring) and minimum (neap) tides, cyclicity 14.8 days	Near-bed currents mobilise seabed sediments, persistent tidal currents dominate on open continental shelves, wave-orbital currents intermittent Gravity-driven seabed failure on steep slopes. Basin-wide buoyancy-driven seepages (gas and liquid, sometimes associated with pockmarks).
Rock and unconsolidated sediment strengths		Resistance of pre-existing strata to processes influences seabed topography and texture	As regional

Table 3. Review of the major processes influencing modern coastal and seabed configuration and composition.

On the basis of this summary the processes can be usefully divided into those that are relatively slow and for most practical purposes essentially static, ranging to those that are dynamic and have an instantaneous effect on seabed properties.

2.4 Review of features and classes of published geological research on seabed and superficial features

A broad classification according to dynamic and static processes and the distinction between mid (open) continental shelf marine and coastal (ie. transitional marine to terrestrial) sedimentary environments have been adopted to compile a schematic illustration of the range of published research on seabed and superficial features in SEA5 (Figure 4).
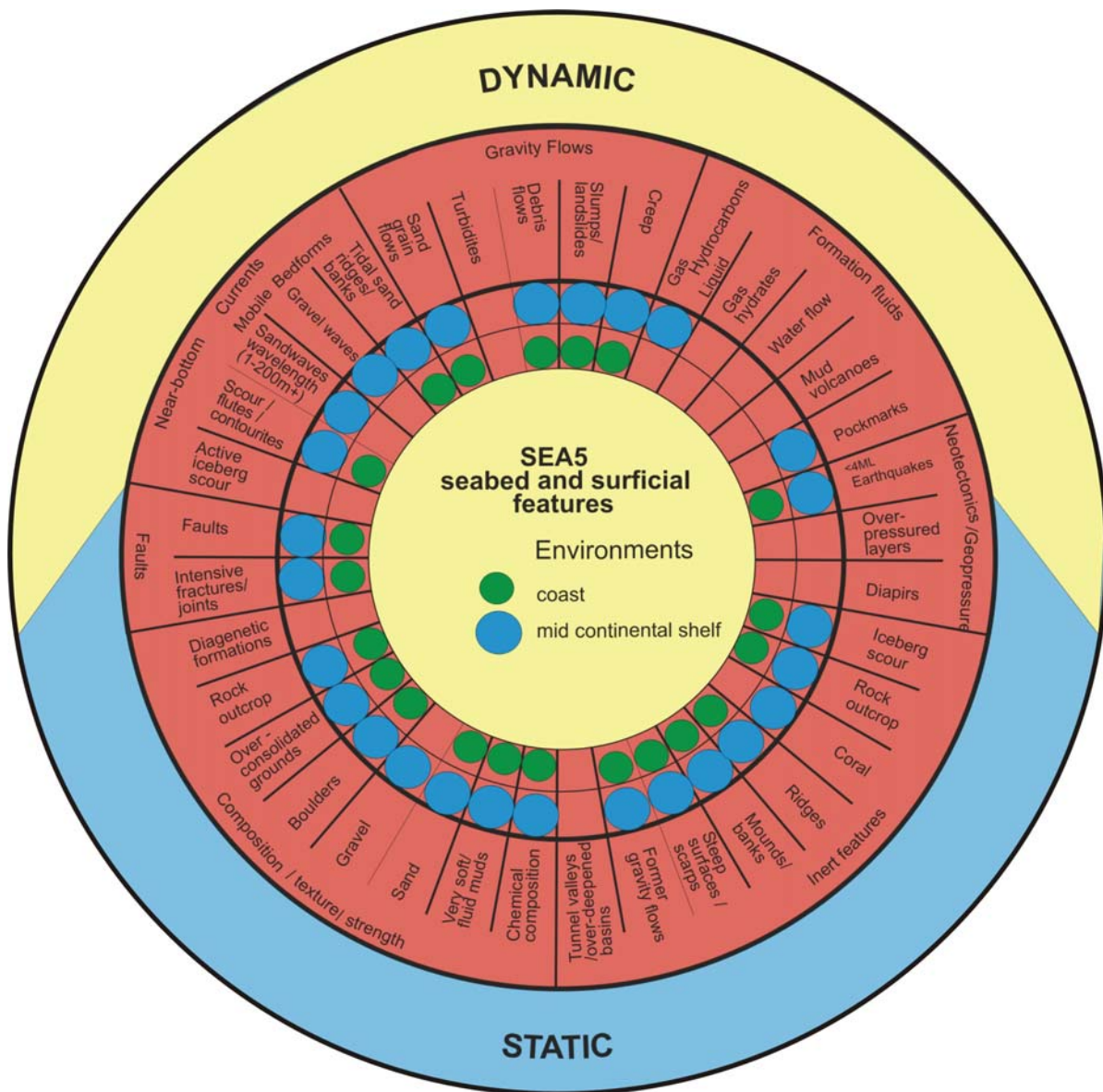
Figure 4. Summary review of populations and classes of published geological research on seabed and surficial features.

Figure 4 is intended to provide a prompt of the range of observed seabed and superficial sediment characteristics in SEA5 and has been compiled from peer-reviewed scientific papers and from the BGS Regional Reports and Maps and listed in the references at the end of this report.

2.5   Influence of geological processes active between approximately 22,000 –10,000 years ago on the modern environment

The modern sea floor/substrate provides evidence for former sea levels that were much lower than at present. The pattern of sea-level change during approximately 22,000-10,000 years ago began with low sea levels on the continental shelf, possibly as low as 140m below present. These low sea levels locally ranged to either side of the maximum limits of the last ice sheets extending into the North Sea. As the ice receded, the rising sea levels advanced landwards across the shelf even though land was undergoing uplift following ice removal (Smith, 1997).

The following account attempts to simplify the complex processes that have influenced the characteristics of the modern seabed since approximately 20,000 years ago.

2.5.1   Glacial palaeogeography: Former ice limits and shorelines

Theoretical studies have been undertaken to determine the patterns of ice-sheet cover and sea-level change affecting the North Sea since the last glacial maximum. Quantitative paleo-geographical models of former shorelines and ice limits have been produced by Lambeck (Lambeck, 1991a; Lambeck, 1991b; Lambeck, 1993; Lambeck, 1995), building on earlier modelling work by Peltier and Andrews (1976). These combine a model of crustal response to ice loading, with an ice model that describes the configuration of the last ice sheet across the British Isles since its maximum volume, which is assumed to be at around 22,000 years ago (Ballantyne et al. 1998). At this time, the model predicts that ice-margin positions were possibly well below present sea level. Presumed ice-margin deposits have been found at approximately 140m below present sea level on Viking Bank to the east of Shetland (Peacock, 1995) and at 60m to 100m below present sea level to the east of the Wee Bankie Moraine (Holmes, 1977) (Figure 5). For this report predictions of shoreline position since the last ice sheet have been obtained by modifying the Scottish ice model used in terms of evidence for ice limit, timing of the extent of the ice sheet, and ice thickness restricted to the period since approximately 18,500 years ago (Figure 5). The main variables taken into account in the models include the geophysical parameters of the Earth's mantle and crust, ice models for the last ice sheets, sea-level data points, and a high-resolution definition of coastal and submarine geometry.
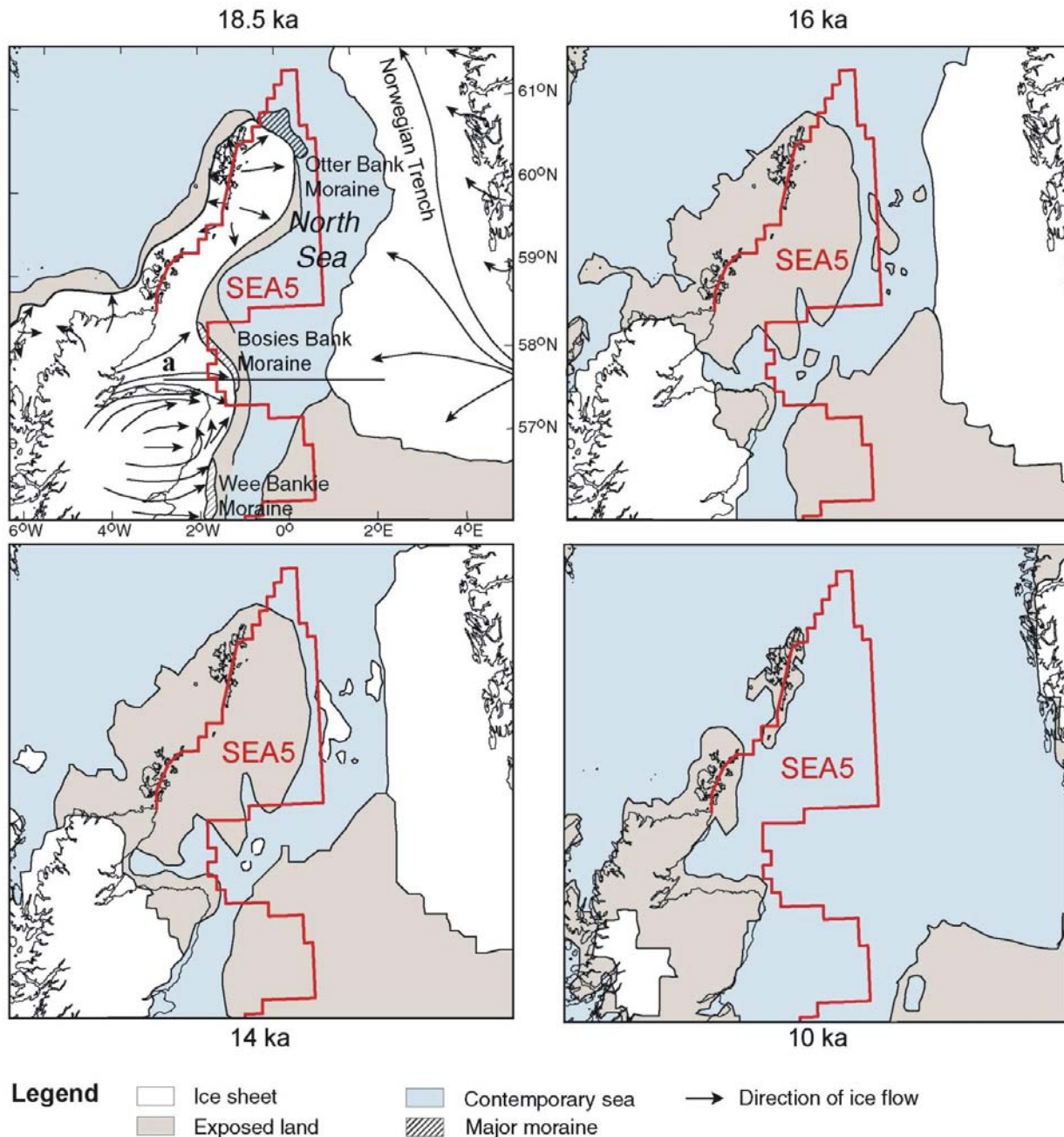
Figure 5. Evolution of shorelines and ice-sheet extents 18,500-10,000 years ago. Information modified after Lambeck (1995), Merritt et al (2003). ka= thousand years ago. Profile for 18.5 ka: see Figure 6. The moraines schematically shown for 18.5ka are only a subset of all those occurring in the region (Figure 7). The maps illustrated cover the same area.

The shifting boundaries between former glacier ice and former sea level generated a complexity of glacigenic processes and environmental settings that are not seen today (Figure 6). Their importance is that a significant part of the modern seabed topography is inherited from the bedforms originating when the ice sheets from former regional glaciations extended over the continental shelf.
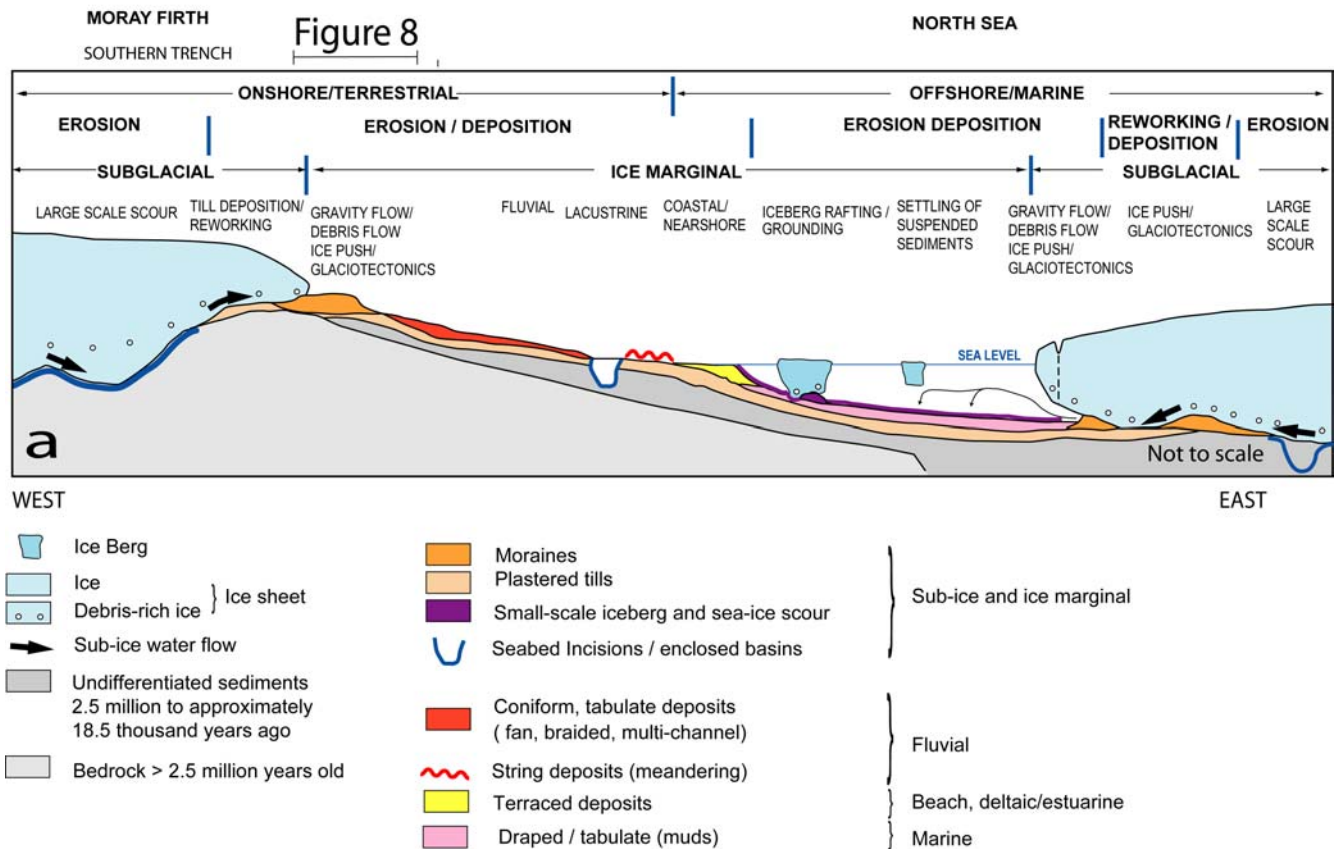
Figure 6. Schematic reconstruction of ice-marginal environments and processes approximately 18,500 years ago. Location of profile a. shown on Figure 5. An example of the effects on the modern seabed topography of a subset of the ice-marginal terrestrial environments is illustrated in Figure 8.

As the ice subsequently retreated the coastline advanced towards the mainland over former sub-glacial, peri-glacial and terrestrial features that were reworked under marine conditions.

Between 18,000 and 14,000 years ago, the North Sea shoreline remained almost stationary, as crustal rebound underpinning seabed uplift kept pace with sea-level rise from melting of the ice sheet. The major firths remained open to the sea, with water depths seaward of the Moray Firth and Forth of Firth estimated at around 30m at the ice margin (Lambeck, 1995). The movement of the shoreline in eastern Scotland between 16,000 and 14,000 years ago occurred at about the same rate as the retreat of the ice front. By 14,000 years ago the Firths of Forth and Tay are shown to be almost ice free, with raised shorelines along these and the Moray Firth coastline possible after this time (Figure 5). By approximately 10,000 years ago, the rate of near shore sediment uplift adjacent to the Scottish mainland is predicted to have exceeded the rate of sea level rise.

2.5.2   Sub-glacial and pro-glacial processes

Although Lambeck's model of crustal reponse and ice-land-sea interaction has been criticised (eg Ballantyne et al, 1998) it provides a first basis for understanding the evolution and variety of environments following the last glacial maximum.

Glacigenic features that are characterised by their large size, distinctive seabed topography and by resistance to modern erosion include the former terrestrial and submarine moraines and the enclosed basins formed at former lowland or tidewater ice-sheet margins. They are important because although they are widely distributed they may also form isolated features that fall within the meaning of the EU Directives (Figure 7).
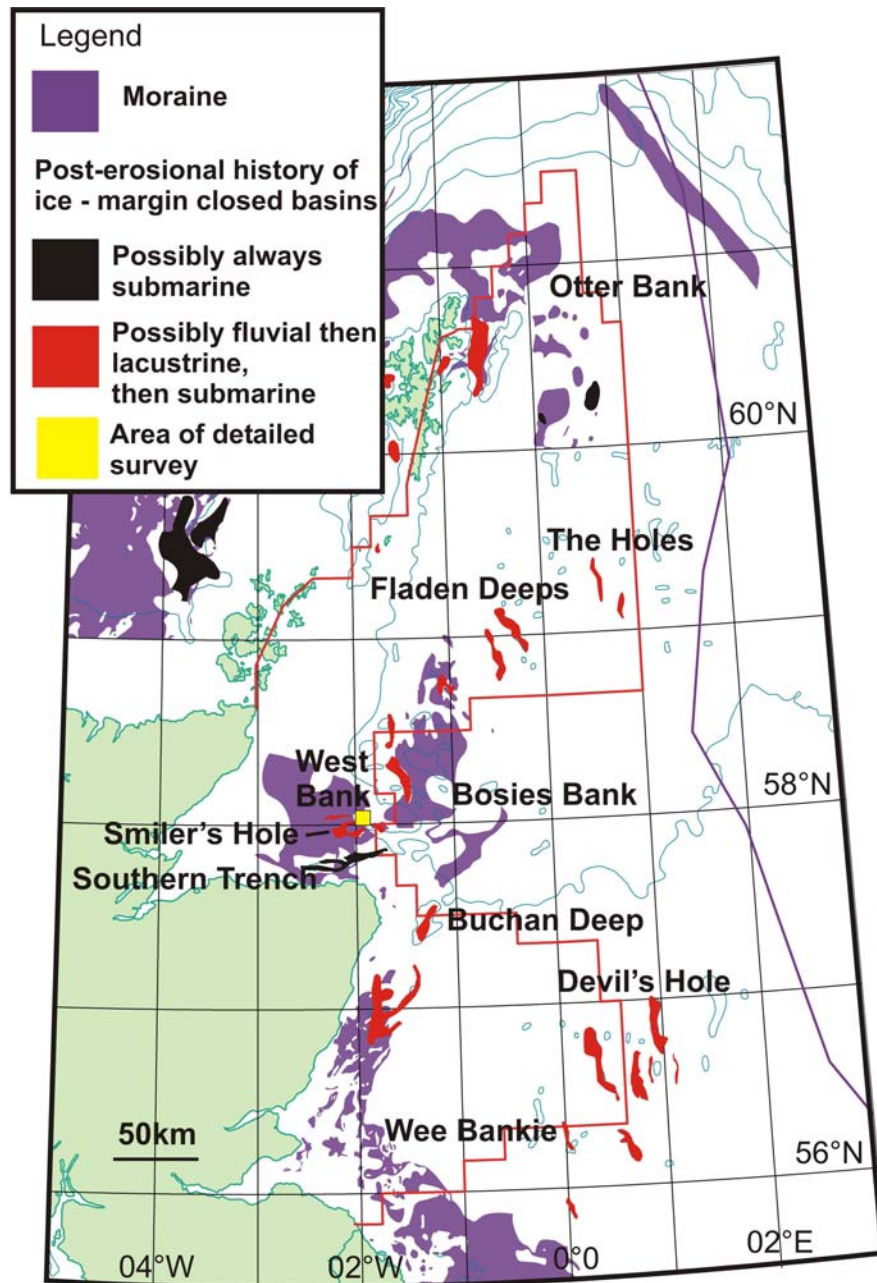
Figure 7. Distribution of former ice-marginal features preserved on the modern seabed: moraines and closed basins. Moraines reconstructed on the basis of BGS regional mapping after Holmes et al (1993). See Figure 6 for an interpretation of the conditions under which the moraines and closed basins are thought to have formed. The location of Figure 8 is indicated by the yellow rectangle.

The moraines commonly form seabed banks, they are immobile and often consist of an over-consolidated (hard) sediment substrate if exposed at seabed. They are also frequently the source of the large-scale gravel spreads now cropping at seabed (section 2.9).

Enclosed basins originated by erosion into the continental shelf seabed. They have greater than 100m incised depths (all are partly filled), 2km or more width and they may be up to 50km or more in length (Wingfield, 1990). Their importance is that they form isolated environments and, in areas of modern low near-bed currents, they are sediment sinks for fine-grained sediments that have settled out of suspension. In areas of strong near-bed currents they are sinks for bedload sediments that have spilled over the basin edges from the surrounding continental shelf. When the positions of the enclosed basins have been compiled with those of the moraines, they have been used as a basis for an interpretation of the regional extents of the former terrestrial and submarine ice sheet margins (eg. Ehlers and Wingfield, 1991). The local complexity of some of these margins can also be mapped from interpretations of detailed modern seabed topography (Figure 8).
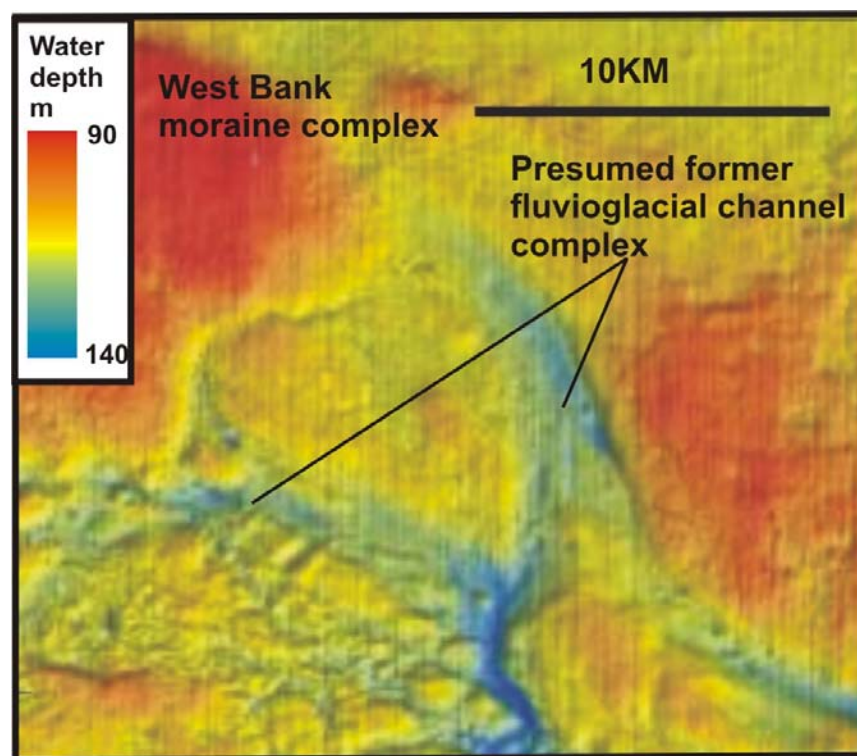
Figure 8. West Bank: Interpretations of possible former terrestrial moraine and fluvioglacial channel complex. Image generated from seabed picks of multichannel data from 3D commercial surveys. See Figures 7, 8 for location. The topographic boundary separating the West Bank moraine complex from the former fluvioglacial channel complex possibly marks the site of a former terrestrial ice margin.

One prediction from the Lambeck model is that large areas of the modern seabed in SEA5 were sub-aerially exposed in arctic conditions as late as approximately 16,000-14,000 years ago. This agrees with a maximum age of 14,100 years for the onset of glaciomarine sedimentation on former land in SEA5 in the central North Sea and evidence that polar water and sea ice were in the central North Sea until at least 13,200 to 13,100 years ago (Peacock and Harkness, 1990). The importance of this prediction is that during this period the sub-aerially exposed areas may have desiccated. A desiccation

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process has the potential to generate hardgrounds, the modern submarine extents of which are predictable (Figure 5). Another important prediction is that many of the modern seabed spreads of coarse seabed sediments consisting of pebbles, cobbles and boulders are former beach deposits.

2.6 Post-glacial and Holocene paleogeography and predicted modern coastal and nearshore mean sea-level movements

This period principally covers the times between de-glaciation and the run up to the modern interglacial environment. The present-day is within an interglacial period and is included within the Holocene that started around 10,000 years ago. Studies of historical and modern coastal and nearshore mean sea level and crustal movements are important because they can be applied to understanding and quantifying the likely future evolution of the coastal and nearshore areas in SEA5.

Between 10,000 to approximately 6,000 years ago there was a fall in relative sea level, mainly reflecting rebound of the deglaciated land mass. Haggart (1989) has calculated rates of relative sea-level fall during this period of 3 mm per year for the western Forth valley, and 6.9 mm per year for the western Moray Firth. This period was followed by a major rise in sea level, sometimes termed the 'Main Postglacial Transgression', which is associated with the formation of the 'Main Postglacial Shoreline', the highest level reached by the sea during the last 6,000 years. The Main Postglacial Shoreline has been studied in detail in many localities in eastern Scotland, where it forms one of the best-developed former shorelines (section 2.7, Figure 11c). It forms a major component of the variety of coastal scenery around Scotland and is important because reworking of the former beach deposits may locally have been the only main source of sediment input to the offshore.

The large body of sea-level data that have been collected and used to identify former shorelines can be used to determine patterns of Holocene uplift (10, 000 years ago to present day) thought mainly to be caused by the unloading of ice, rock and soil from the mainland of Scotland during the preceding glaciation (a process sometimes referred to as 'glacio-isostatic' uplift). The historical data can be illustrated by the construction of 'isobase' maps where the contours follow areas of equal net uplift relative to modern sealevel of a former shoreline of the same age. The most widely reported isobase map for Scotland is that for the Main Postglacial Shoreline (Sissons, 1983; Cullingford *et al.*, 1991; Firth *et al.*, 1993). The distribution of the Main Postglacial Shoreline has been used to produce a map, which broadly links locations where the evidence for a former shoreline has been observed at similar heights. The importance of the map is that it can be used to model patterns of historical regional uplift for offshore and onshore Scotland (Figure 9) and then used to compare against quantitative estimates for the rates of modern net uplift arising from the interaction between modern sea level rise and crustal movement (Figure 10). The combination of historical and modern information can then be used to predict the sensitive coastal areas that at most risk from modern sea-level changes.
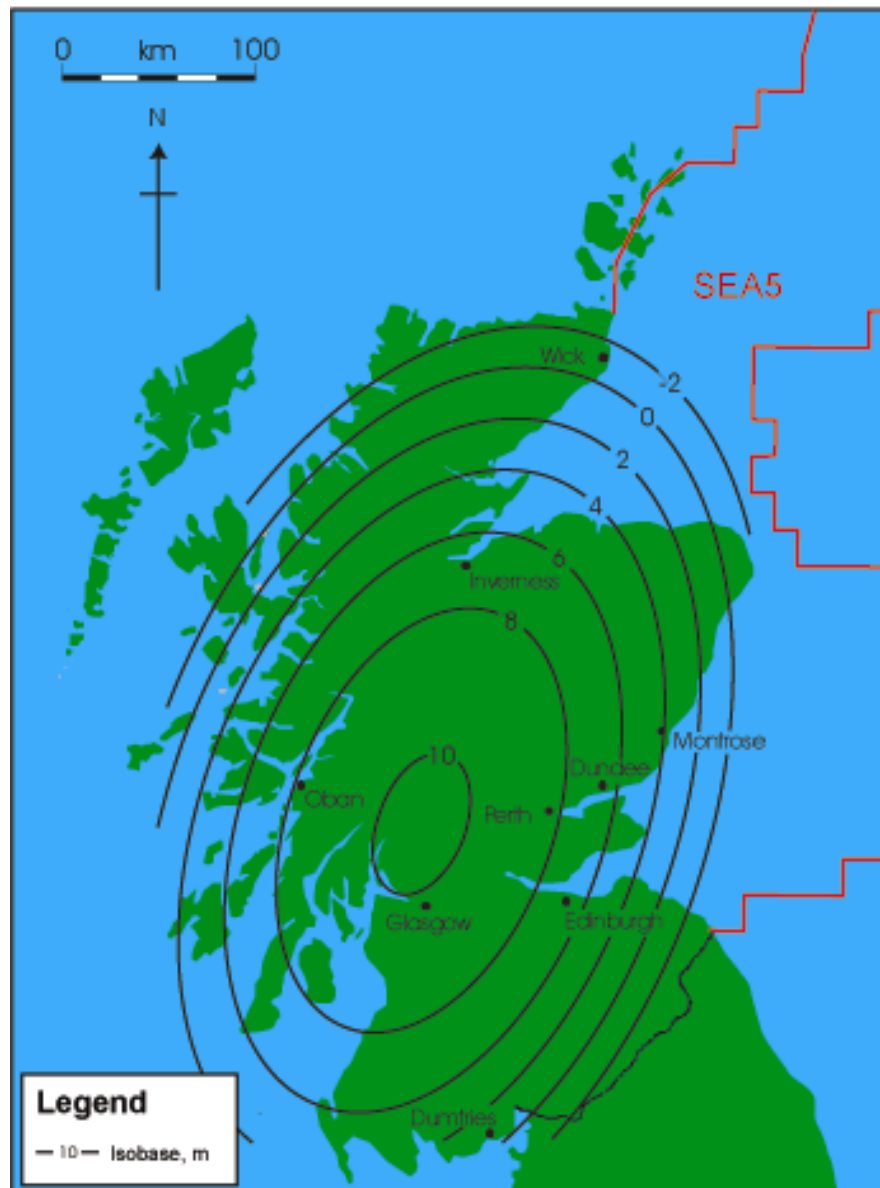
Figure 9. Isobase map of the Main Postglacial Shoreline.

Models of present-day crustal movements for the British Isles are based on sea-level data and tide-gauge records and can illustrate the rates of modern net land vertical movements allowing for post-glacial uplift and eustatic sea-level rise. A recent revision (Shennan and Horton, 2002) of earlier work on Late Holocene land and sea-level changes (Shennan, 1989), gives maximum relative land uplift for central and eastern Scotland of around 1.6 mm per year, falling to less than 0.5 mm per year in the north and south (Figure 10).
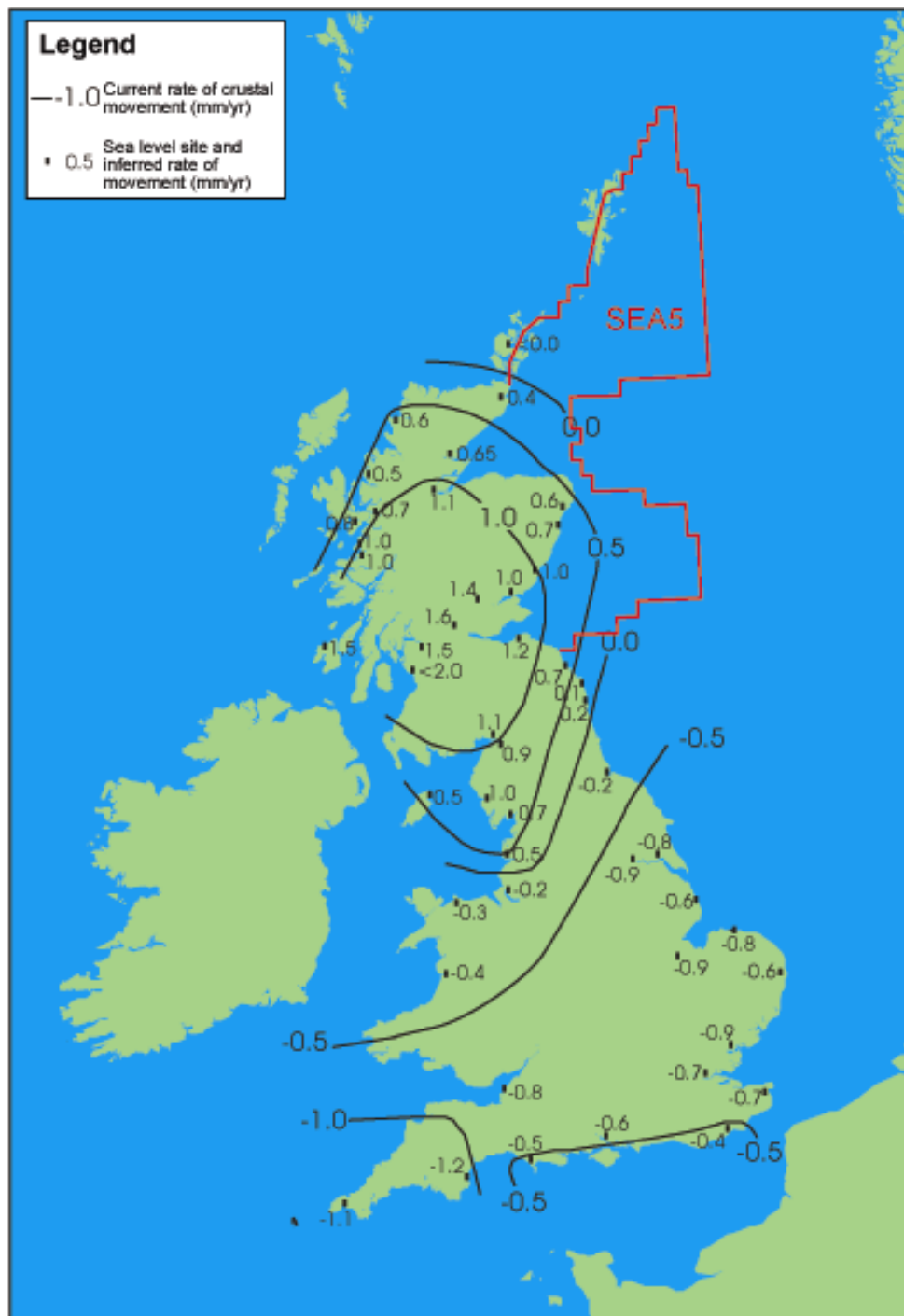
Figure 10. Modern rates of net land vertical movement.

Global mean sea-level rise during recent historical times, the past 100 years, is estimated at between 0.3 and 3.0 mm per year, with most estimates in the range 1-2 mm per year (Gornitz, 1995). Results from recent Intergovernmental Panel on Climate Change models, indicate that Scotland could be subject to a net rise (accounting for changes in land level) of between 0 cm and 69 cm over the next 80 years (Price and McKenna, 2003). A more conservative estimate, based on UK Climate Impacts Programme models, suggests a rise of between 15 cm and 28 cm over the same time period (Price and McKenna, 2003), amounting to a rise of between 1.9 and 3.5 mm per year. This predicted reversal in

sea-level tendency could have a significant effect on the character of the Scottish coastline (section 2.7).

2.7   Modern coast variability

The modern Scottish coastal scenery reflects the interaction between land uplift, sea-level change, resistance of coastline rocks and unconsolidated sediments to erosion and the sediment supply to the coast since the end of the last glaciation (Smith, 1997). The east coast of mainland Scotland displays a regular open character, with substantial unconsolidated former glacial deposits that have been reworked into coastal landforms during the last 10,000 years. Given that relative sea-level changes are regional, the distribution of unconsolidated glacial deposits, along with the underlying solid-rock geology, largely determines the variability of the local present-day coastal landscape. The present-day distribution of landforms along the east coast of mainland Scotland is illustrated schematically (Figure 11).
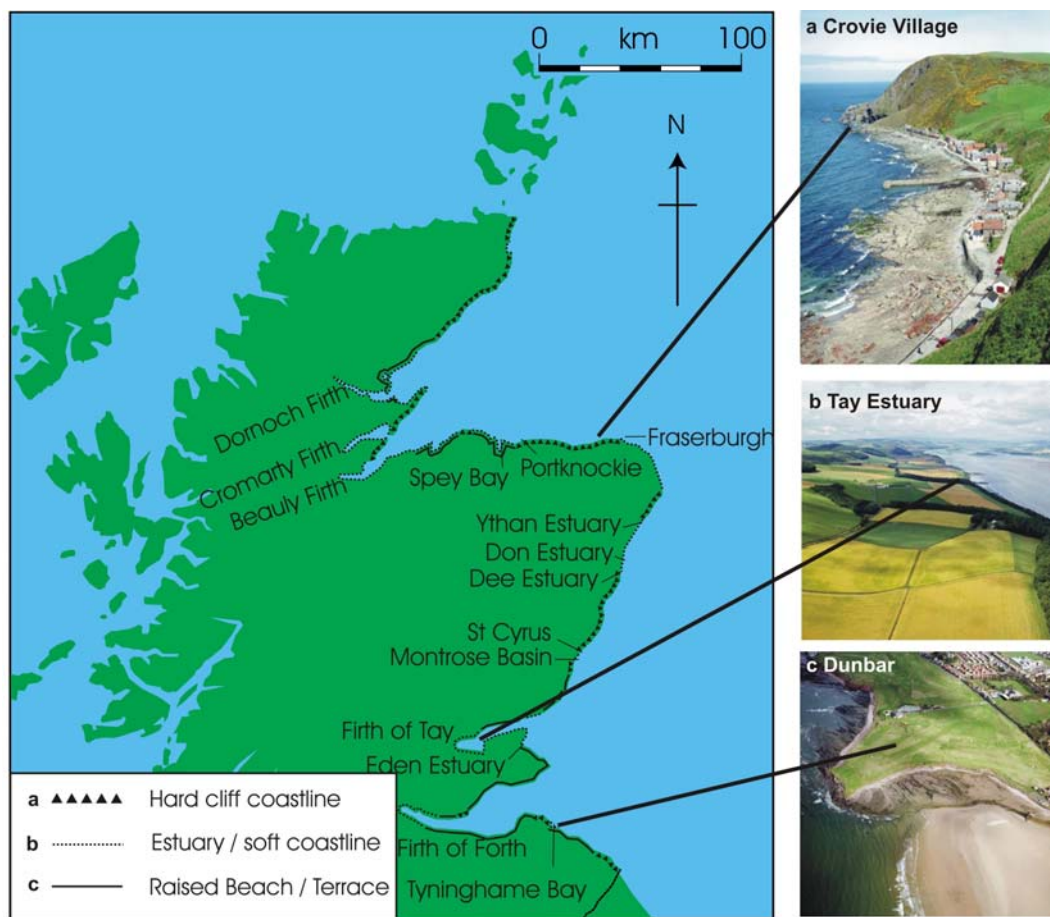
Figure 11. Schematic classification and examples of coastal landforms
a. hard cliff coastline **b**. estuary/soft coastline **c**. raised beach/terrace

A predicted reversal in sea-level tendency from relative sea-level fall to relative sea-level rise is likely to affect open coast depositional landforms (Pethick, 1999). The combination of a lack of available sediment, and a rise in sea level will mean many of the landforms that are regarded as essential components of the modern Scottish east coast system may be lost in the future (Hansom, 1999).

Whereas rates of erosion of the hard rock, cliffed coastlines are relatively small, depletion of fronting dunes and gravel beaches could affect the erosion rates of the softer rock cliffs over the medium term, as, for example, along the sandstone cliffs of Fife (Pethick, 1999). It is suggested that the effects will be even more profound within the firths, where landward migration of the estuarine morphology is likely to occur, causing loss of outer estuary habitat and increased risk to outer estuary lowland areas from flooding and erosion. Erosion in the outer estuaries, together with the landward migration of estuary-mouth sands, is predicted to lead to an increase in wave energy at the shore, which could pose potentially serious coastal management implications within the Dornoch, Ythan, Don and Dee estuaries as well as in the larger systems of the Forth and Tay (Pethick, 1999).

2.8   Recorded tsunami events

Tsunamis are long-wavelength ocean waves generated primarily by submarine landslides, volcanic collapse or earthquakes. When the tsunamis slow down in shallower waters, for example on the continental shelf, they transform into waves tens to hundreds of metres high that have the potential power for catastrophic coastal and inshore marine inundation. Tsunamis are sometimes erroneously referred to as tidal waves. Although they are sometimes considered as events that only affect the Pacific Ocean, they do occur elsewhere and have been known to affect the seabed and coast of SEA5. The most extensive is the tsunami triggered by the Holocene Storegga Slide offshore mid-Norway about 7,250 ^{14}C yrs BP (radiocarbon years before present), equivalent to approximately 8,200 calendar years before present. Although this tsunami originated from outside SEA5, a brief consideration of tsunamis is important because the source of the latest event was such a short distance away. Should an identical event happen, less than 1 hour warning could be given from the time it occurred until the resulting tsunami and before it entered SEA5. The study of historical tsunami events and the observed impacts therefore leads to scenario planning.

The Storegga Slide was first studied in detail in the 1980's (Bugge, 1983). Three massive submarine landslide events displacing a total of 5,500 km³ were interpreted to have taken place on the mid-Norwegian continental slope in glacial to post-glacial times (Jansen et al, 1987). One of these events was subsequently linked to an anomalous sediment deposit found on the eastern coast of Scotland and interpreted as a tsunami deposit (Dawson et al, 1988, Long et al 1989). Detailed studies of the Norwegian coastline have since identified similar and more extensive tsunami deposits dated to 7,500 ^{14}C yrs BP (Svendsen and Mangerud, 1990, Bondevik et al 1997a, b). Similar sites have also been located in the Faroes (Grauert et al., 2001) and Iceland (Hansom and Briggs, 1991) and further sites recognised along the northern and eastern coasts of the UK (Smith et al, in press). The impact of the Storegga Slide events on Scotland was a tsunami that struck the north and eastern coasts extending as far south as Lindisfarne in northern England (Horton et al, 1999, Smith et al, in press) (Figure 12).

 Figure 12. Sites of tsunami deposits attributed to the Storegga Slides approximately 8,200 year sago (red dots)

Depending on the local coastal topography the waves would locally have extended several hundred metres inland of the former shoreline. On the basis of the tsunami deposits there was a minimum run up height of 1-2m in open areas and much greater in enclosed bays or lochs (Long et al, 1989) (Figure 13).
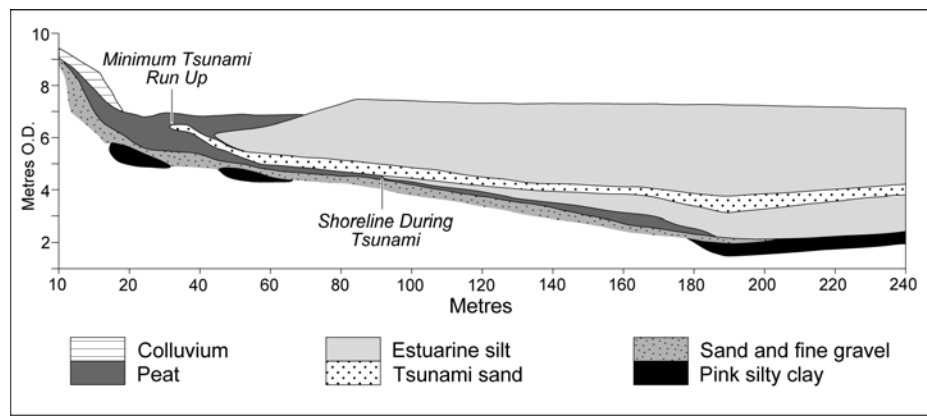
Figure 13. Profile illustrating geological setting and processes of deposition of tsunami deposits within SEA5 coastal sediments.

Maximum run-up values are found at the heads of narrow inlets with the highest values in the north. Sullom Voe is a large north facing inlet with run-up values > 20m (Bondevik et al , 2003c). These figures are based on sediments that were preserved, so they represent minimum run-up values (Figure 14).

Figure 14. Marine sand layer deposited from the tsunami affecting Sullom Voe, Shetland. The sand layer is the thin yellowish brown layer approximately 6cm thick which is sandwiched between black peat. The modern coastline is seen in the background.

The presumption is that the human impact was small due to the low population levels approximately 8,200 years ago during the Mesolithic. However the deposit has been found at sites of human habitation and the prediction is that if it occurred today the consequences would be catastrophic. The geological model for the Storegga Slide area indicates that major submarine landslides are a regular component of the glacial / interglacial cycle (e.g. Berg et al in press). For a major submarine landslide to occur again in the Storrega Slide area it is thought that another glaciation is required to rebuild the sedimentary pile that failed 8,200 years ago in the current interglacial period. Submarine landslides have occurred on many other parts of the continental margin adjacent to SEA5 (Long and Holmes, 2001) and there is an unknown risk as to when or where others may occur in the future. For example, there are many areas where submarine slides have occurred prior to the last glaciation but where there

are no historical records of a post-glacial submarine landslide. There are insufficient data on the ages and settings of the large-scale submarine landslides on the continental slopes adjacent to SEA5 to quantify the risk of future tsunami events.

2.9   Seabed sediments

Seabed sediments vary from mainly gravel spreads in the exposed nearshore and relatively shallow-water areas to predominantly sandy and muddy sediments on the open continental shelf further offshore. Sheltered bays and estuaries (firths) contain large areas of muddy sediments in locations sheltered from tidal and wave currents and sand sheets. They also contain sandbanks in exposed nearshore and tidally-constricted locations that are characterised by relatively high rates of sediment supply or sediment re-circulation (Figures 15, 18).
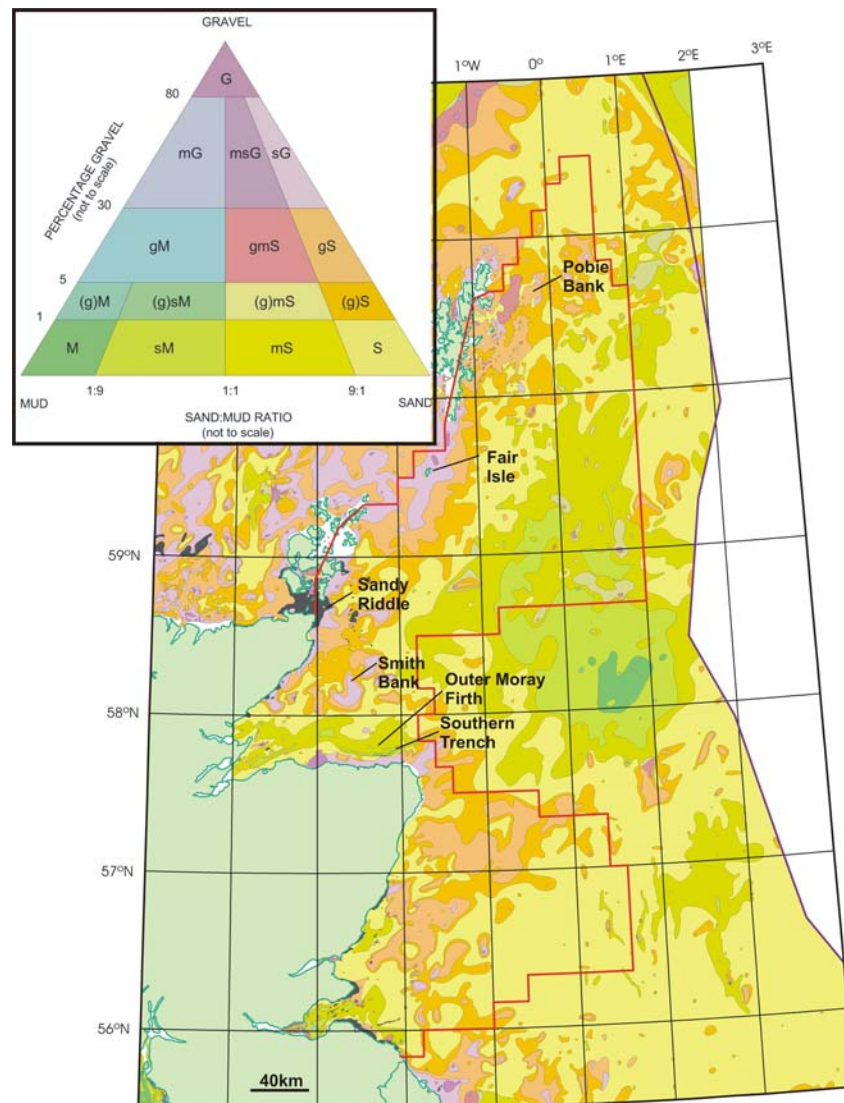
Figure 15. Distribution of seabed sediment size classes. Definitions of the particle size ranges of gravel, sand, silt and clay are shown in Appendix 3. Mud is a mixture of silt and clay. Locations of the main DTI 2003 detailed surveys are indicated schematically.

2.10   Seabed carbonates

A lack of major river sediment input to the northern SEA5 and the resistance of most of the shorelines to erosion, has resulted in only minor amounts of clastic sediment (rock and soils) input from the coastal areas to offshore over the last 10,000 years. The post-glacial sea-level rise was associated with the opening of gateways for movement of NE Atlantic water into the North Sea around the coastal boundaries across the Orkney and Shetland Islands (Figure 5). Strong tidal and non-tidal currents, the lack of clastic input and the variety of seabed substrates subsequently provided favourable environments for the proliferation of calcareous seabed biota, the remains of which have profoundly affected the composition of modern seabed sediments. The shallow nearshore and coastal areas are now major high-latitude centres of modern shallow-water carbonate accumulation (Farrow et al, 1984). As a result, the proportions of calcium carbonate in the seabed sediments are highest around the inner shelf and nearshore environments of the Orkney and Shetland Islands and the adjacent NE Scottish mainland. The mid-continental shelf banks are also major sources of modern biogenic carbonate to seabed sediments. In places the biogenic carbonate content of the sand fraction in seabed sediments may comprise up to 100% (Figure 16).
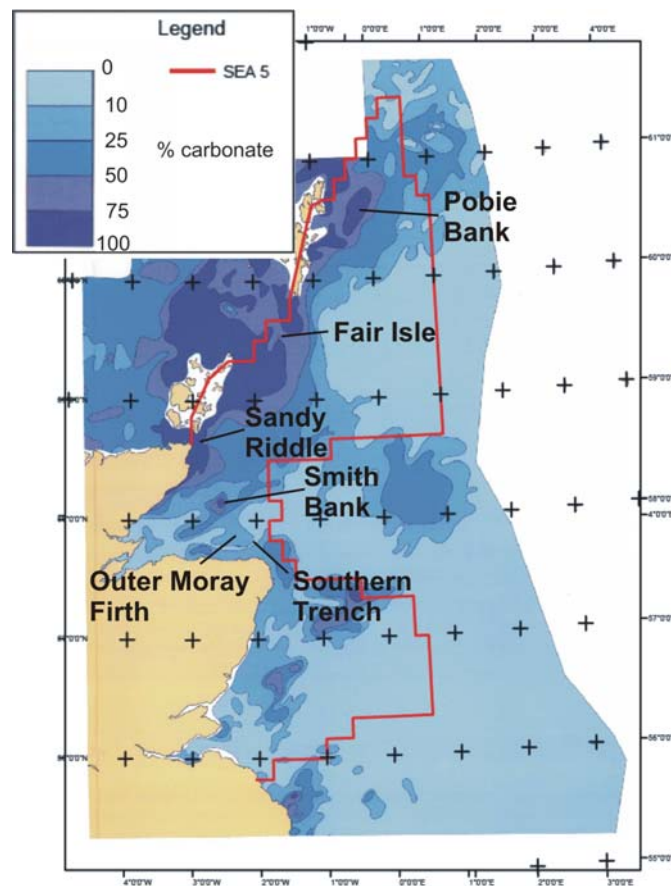
Figure 16. Concentrations of biogenic carbonate in the sand fraction of seabed sediments.
Locations of the main DTI 2003 detailed surveys are schematically indicated.

Concentrations of more than 50% carbonate in the sand fraction of seabed sediments are also found on some of the banks, for example, Smith Bank, Aberdeen Bank and Marr Bank (Figures 1, 16).

2.11   Seabed sediments and near-bed currents

The near-bed currents that interact with the seabed are mainly driven by the interaction between wind and tide. Of these, the effects of tides are the most predictable (Figure 17).
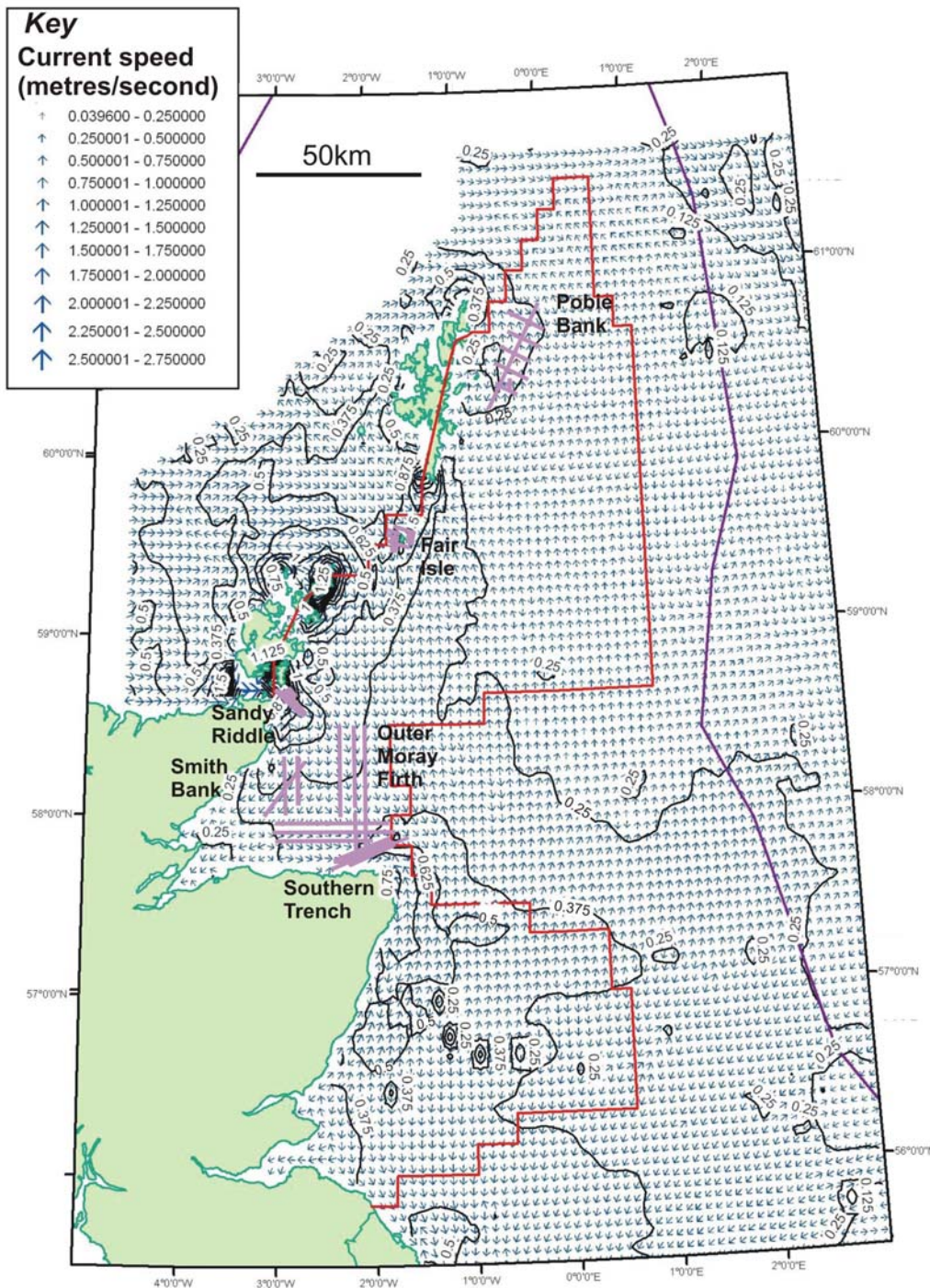
Figure 17. Mean peak spring-tide near-bed current speeds and directions. The data has been generated using the POLCOMS model described by Holt and James (2001) for stormy (October) conditions. Locations of the main DTI 2003 surveys are outlined schematically in purple.

Wind-driven North Atlantic Surface Water currents flow persistently to the north and interact with the seabed on the continental slope and shelf west of mainland Scotland, Orkney and Shetland. These ocean currents are diverted into SEA5 by east-directed flow through the gaps separating the Orkney and Shetland archipelagos and the Scottish mainland. The result is that the strongest tidal currents in these areas usually flow more strongly towards the east, for example through the Fair Isle Channel, thus directing bedload sediment transport also to the east and south (Figure 18). Departures from the rates of inflow of the ocean currents and the symmetry of tidal ebb and flood currents also occur with bias introduced by surge- and wave-induced currents.

If a pressure gradient from an external storm surge moves from the NE Atlantic margins into SEA5 it moves in easterly and southern directions across the gaps between the Shetland and Orkney archipelagos and the Scottish mainland. It generates south- and east- directed currents that prevail in the Moray Firth and the North Sea (Flather, 1987). Internal storm surges are generated in response to strong winds and may occur as separate or composite events to the external storm surges. The impacts of the extreme storm surges on the seabed are periodic and severe but even the less extreme surges may contribute to the variability of mean peak spring-tide near-bed current speeds and directions in stormy conditions (Figure 17).

The speeds and directions of the near-bed currents are also influenced by the interactions of tidal currents and currents generated from swell- and wind-driven currents with the seabed topography. Waves generate wave-orbital currents that interact with the seabed. These currents are non-directional but in stormy conditions they are commonly an order of magnitude higher than the directional peak tidal currents. They interact with seabed to water depths equivalent to approximately 50% of their wavelength (Pantin, 1991). Swell and wind waves are generated from wind. Wind waves typically have wavelengths up to approximately 130m (OTO 2001). Although the wavelengths of the swell waves overlap with those of the wind waves, the swell waves have potentially much longer wavelengths, especially in relatively deep water. For example, storm swell waves with more than 300m wavelengths frequently impinge on the outer continental shelf. The effects of waves are very important because the orbital currents from waves can stir up the seabed sediments in a range of relatively deep water where tidal currents otherwise could not do so. The grains are suspended by the orbital currents and are then moved on by tidal and other directed near-bed currents so that both the orbital currents and tidal currents, whether reinforced by storm surges or not, contribute to the overall process of seabed winnowing.

The wind factors influencing the wave climate are wind speed, wind duration and the length of fetch (the distance the wind is blowing over the sea). These wind factors may be more or less dependent on season and location. For example, severe winter storms frequently track from west to east across the northern areas of SEA5 but the longest fetch (uninterrupted by land or shallow water) occurs when the wind and wave direction is from the north and east. Wave directions associated with the peak wave heights (and wavelengths) originate from the north in the central and northern North Sea and the peak wave heights are higher in the northern North Sea (OTO 2001). One possible regional effect is that the seabed in the northern North Sea with mean peak spring tide near bed speeds of less than 0.25m/sec is characterized by sand, but the seabed in equivalent water depths, shelf setting and mean peak spring-tide near-bed currents in the central North Sea is characterized by muddy sand and sandy mud (Figures 1, 15, 17). The wave directions are also important on a sub-regional scale. For example, wave energy may be dissipated by the interactions of wave-orbital currents with the seabed across a bank. In this case the flanks facing the oncoming waves are exposed to the stronger wave-orbital currents.

The effects of orbital and directed currents direct stress onto the seabed so that the grains remain or move on in response to the stress. Although an overall regional trend of decreasing grain size with increasing water depth may be correlated more or less with decreasing seabed stress, consistent departures from the trend indicate that the variability of seabed sediment grain sizes is not satisfactorily described by local variations in water-depth-related trend (Owens, 1981). Four main types of seabed condition can be reported in relation to the regional trends and the departures from the regional trends. They are described below and they have been adapted from the descriptions of seabed sediments by Owens (1981), Andrews et al (1990) and Gatliff et al (1994). The boundaries of the types overlap and will vary at a location with time. They are not meant for use in a quantitative manner, rather as an informal method of describing the seabed response to different seabed processes.

Type 1 is observed where biogenic and clastic very coarse-grained sands and gravels are exposed to extremely high hydraulic activity originating from the combination of near-bed surge, tidal and wave-oscillatory currents in storm conditions. These sediments may appear to be unsorted because the constituent grains are mainly above the threshold size and density for movement even in severe storm conditions. In this environment the seabed texture and composition may more or less reflect proportions of boulders dislodged from jointed bedrock, former beach deposits, former glacigenic deposits, deposits from former severe storms and coarse-grained sediments derived from rock fragments and from fragmented biological carbonate material. There is a negligible silt fraction.

Type 2 is a deeper-water zone of transition between extreme exposure (Type 1) and deposition (Type 3). Sediment transfer may be indicated by a substrate of seabed sands, sandy gravels and gravelly sands that show the effects of winnowing in terms of overall decreases of grain size in the sand fraction with increasing water depth. The gravels may be lithic (stony) and/or biological carbonate. The proportions of mud are less than approximately 2%. In areas where patches of mobilised sediments have been deposited over the gravel-prone sediments, the mobilised sediments show little variation with water depth over a small depth range and have sediment compositions that reflect temporal variation and weaker hydraulic activity.

Type 3 occurs in the deepest waters and is characterised by very fine-grained sand and mud deposition, a very small or absent proportion of gravel and decreases of grain size with increasing water depth and with further decreases of hydraulic activity. The coarsest grain sizes are commonly biogenic carbonates so that the contribution from these may not reflect near-bed hydraulic conditions but may place the total sediment into the slightly gravelly class of sediments.

Type 4 encompasses departures from the regional variations summarised for conditions 1-3. They are characterised by variations of sediment composition across areas of equivalent water depth. The variations reflect asymmetry in exposure to the prevailing surge, near-bed tidal currents and/or to wave-orbital currents that have been forced by changes to the seabed configuration. They may also reflect the impact of gravity-driven seabed failure on the steep slopes found in the enclosed basins.

> Type 4.1. Asymmetry observed with position across features on the open continental shelf associated with their configuration relative to dominant storm surge, tidal or wave directions
> Type 4.2. Variations observed in enclosed basins where sands are observed in the constricted parts and muds in the open parts.
> Type 4.3. Variations observed as a result of gravity-driven seabed failure and down-slope sediment transfer on slopes with high gradients

The types of seabed condition summarised above are generalised.

Where the sediment supply is abundant and the near-bed currents are much higher than the threshold required for bedload transport, the seabed is shaped into mobile sediment waves. These vary in size, orientation and mobility with time and in relation to the directions and speeds of the near-bed currents. The composition and topography of the seabed then depends on the strength of currents and the size, shape and density of the underlying seabed-sediment grains where these grain properties vary with mineral composition. Although the sediment waves may be mainly mud, sand or gravel, those in SEA5 are mainly sand (Figure 18).

Together with wave-orbital currents, tidal currents have the most persistent influence on SEA5 seabed composition. They are characteristically accelerated by the restrictions caused by changes to seabed configuration and by decreasing water depth. Tidal currents are thus generally strongest around the coastal headlands on open coasts, between islands and in the shallow waters (Figures 1, 17). Sheltered bays, the 'lee' sides of islands or banks and the configurations of enclosed basins to prevailing currents conditions provide the potential for seabed conditions (type 4) where there are departures from correlations between water depth and near-bed current speed.

In agreement with the preceding summary, there is only some spatial correlationbetween the sediment-size classes and water depth (Frontispiece). The contour of 0.25 metres per second of mean peak near-bed spring tide current speeds in stormy conditions is almost completely contained within the boundaries of gravelly sediment but cross bathymetric contours (Figures 1,15, 17). These observations demonstrate some of the potential for the better correlation of seabed composition with directed near-bed currents rather than with water depth.

It is noteworthy that the map data compiled for the BGS maps were obtained from sediments that were sampled in calm-weather (summer) conditions. The distribution patterns of sediment classes shown on the BGS maps probably therefore reflect some variability that has been driven by the seabed adjustments to storm, including storm surge, conditions. Variations in the distribution patterns of seabed sediment can therefore be broadly summarised in terms of the effects of the interactions with time between seabed topography, tides and weather and the composition of the sediments underlying the seabed sediments.

2.12   Bedload transport (bedforms)

Bedload transport by the mobile seabed bedforms provides one component of the total sediment flux, the other being suspended load. This section is primarily concerned with bedload transport associated with the mobile seabed bedforms, generally referred to as sediment waves, or as sand or gravel waves if their grain size compositions are known (Figure 18). Their mobility is a major cause of seabed variability with time.
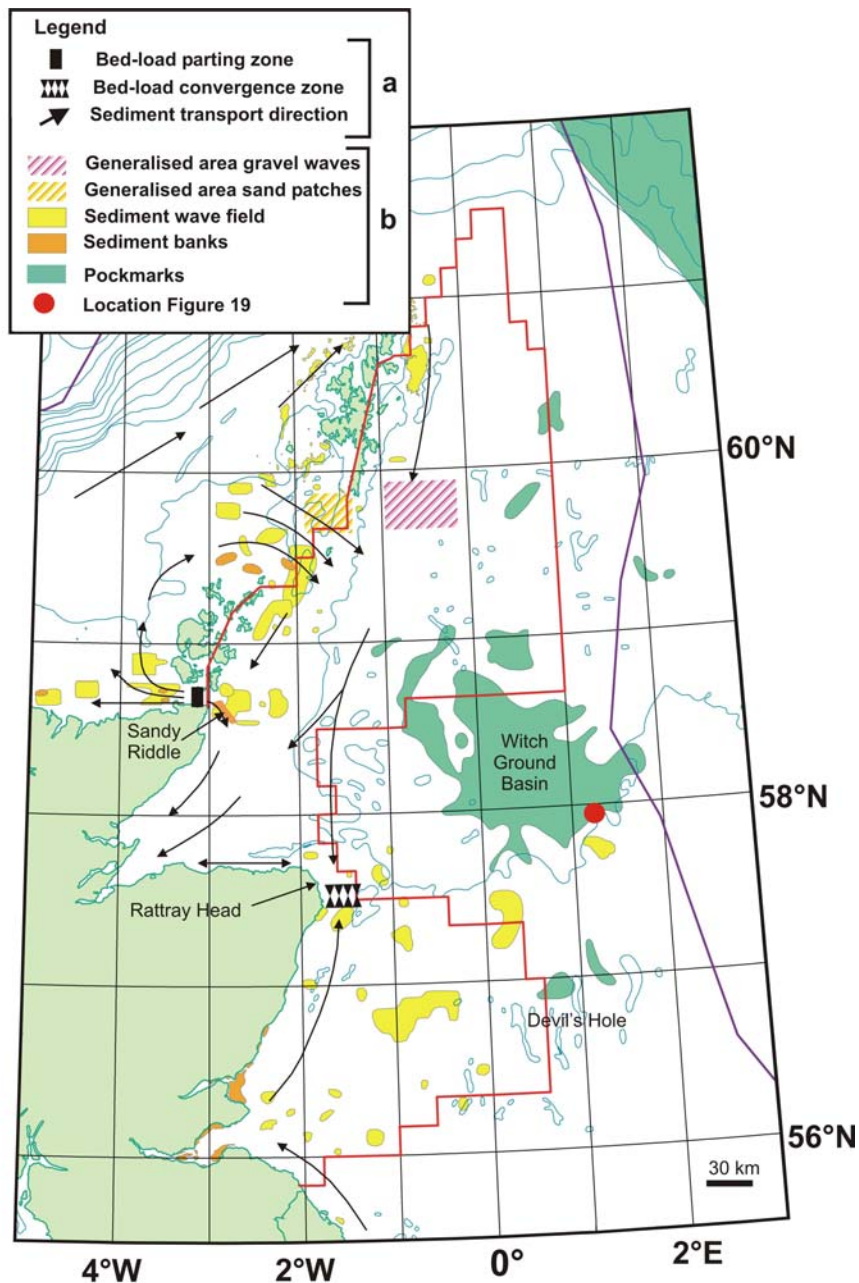
Figure 18. Distribution of mobile sediment bedforms and pockmarks. Mobile sediment bedforms derived from the BGS regional database. Net sediment transport paths adapted after Johnson et al (1982). Pockmark distributions after Fyfe et al (2003).

Other ridge- and bank-like features may have comparable dimensions to the larger sediment waves and may also be covered with sand and gravel, but because they have a core of glacigenic sediments or bedrock, they are not mobile bedforms and they are not classed as sediment waves.

The mobile sandy and gravelly bedforms can be monitored by seismic-reflection surveys (for example, sidescan sonar, multi-beam bathymetry) to yield regional information on the directions of net sediment transport directions. For example, where mid-water currents exceed 1 metre per second (m/s) sand ribbons with long axes parallel to current direction are formed. If these are formed behind seabed obstacles to linear near-bed current flow they may form 'comet marks', the tail of which points in the direction of sediment transport. In weaker current velocities sand waves with long axes that are transverse to current direction are formed (Belderson et al. 1971). In this situation the face with the steeper slope points in the direction of bedload transport at the time of survey. The near-bed mean peak spring current contour for 0.25m/s speed encompasses the distribution of sediment waves that are larger than ripples (Figures 17, 18). Sediment banks and fields of sediment waves in gravelly sediments are mainly restricted to the nearshore in a zone extending offshore from the NE tip of mainland Scotland and joining the Orkney and Shetland Isles. This includes areas where carbonate concentrations in seabed sands are more than 50% and where near-bed mean peak spring currents are more than 0.375m/s (Figures 16, 17, 18).

Ripples are defined for this report (after Ashley, 1990) as bedforms with wavelengths (distance between the sediment wave crests) of less than 60cm. If near-bed current speeds are relatively weak, for example, in water depths between approximately 60-100m, during calm conditions, the seabed is characterised by extensive sand sheets that have been corrugated into sand ripples as the main type of sediment wave (Gatliff et al., 1994; Johnson et al., 1993). Very small to very large sediment waves have wavelengths varying from 60cm to more than 100m and characteristically occur in areas of overall stronger near-bed currents. Banks also occur as isolated features, they may have charted names, and are observed together with the smaller sediment waves in the mid-shelf to near-shore areas. Their long axes may be unbroken for more than 10km.

Because of their small volumes, the smallest sediment waves respond the most rapidly to the near-bed currents and their facing directions may also indicate different directions of net sediment transport compared to larger sediment waves in the same field. The largest banks are thus the most stable of the mobile sediment waves in an area. If their interaction with near-bed currents has been reduced by the long history of rising sea level, they are essentially inactive or 'moribund'. In contrast, the bulk volumes and positions of the so-called 'banner banks' are associated with very strong prevailing currents. In this case their bulk is inherently stable because they are tied to sediment deposition on the sheltered sides of headlands, islands or submerged shoals (skerries).

From the viewpoint of seabed-surface area, frequency of occurrence and mobility, a review of information from the BGS regional surveys has identified that the sediment-wave fields have significantly more impact on the variability of seabed sediments in SEA5 compared to the sediment banks: 18 sediment banks have a total area of approximately 370 square kilometres and 40 sediment wave fields with mobile sediment waves have a total area of approximately 2,820 square kilometres (Figure 18).

Longitudinal sand patches aligned with the dominant near-bed currents have been identified throughout most of the report area (Andrews et al., 1990; Johnson et al., 1993; Gatliff et al., 1994). Longitudinal sand patches occur to the east and northeast of Shetland where the main sediment transport path is towards the south and southeast (Johnson et al., 1993). They also occur to the southeast of Shetland

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and are orientated northeast. These sand patches seem to have originated during storms because the dominant near-bed current velocities in calm weather are weak, averaging 0.2 m/s (British Geological Survey, 1998). Linear sand patches in the Inner Moray Firth are aligned parallel to the Buchan coast indicating both east and west sediment transport directions (Andrews et al., 1990). Longitudinal and transverse sand patches are the dominant bedform in the centre of the Outer Moray Firth (Reid and McManus, 1997). The distribution patterns of sand ribbons and sand patches are not presented in the figures for this report because they have not been systematically mapped by the BGS.

Sandbanks in the Tay and Forth Estuaries represent shallow, coastal accumulations of sand that may also be described as inter-channel sand ridges or sand spits. The crests of these features may occur in less than 20m water depth and many are exposed at low tide (Graham et al, 2001) where they may be important hauling-out areas for seals.

Proudman Oceanographic Laboratory supplied the near-bed current datasets from July 2001 (calm conditions) and October 2001 (stormy conditions). The data has been processed using the POLCOMS model described by Holt and James (2001) and presented in this report for stormy conditions (Figure 17). The fair weather July 2001 mean peak spring- tide near-bed current speeds and directions (not shown) do not closely follow the sediment transport compiled from bedform-facing directions to the north of Rattray Head. Inconsistencies between the net sediment transport direction and the near-bed current direction in calm conditions also occur in the Moray Firth, West Shetland Shelf and around Shetland. The model of October 2001 mean peak spring tide near-bed current speeds and directions for stormy conditions more closely follow the net sediment transport directions (Figures 17, 18). The observations indicate that tidal currents modified by stormy conditions and storm surge are the major influence on the net movement of seabed sediments.

2.13   Pockmarks

Pockmarks are shallow seabed hollows originating from the release of shallow gas or fluids at the sediment/water interface. They may therefore be regarded as originating from buoyancy- or gravity-driven seabed failure (Table 3).

Pockmarks occur in densities of up to 20 per square kilometres and are up to 200m in diameter and range from approximately 2-10m in depth within the Witch Ground Basin, (Gatliff et al., 1994). The expulsion of gas or fluids disturbs cohesive fine-grained sediment, lifting it into suspension. The sediment is consequently transported in suspension and as bedload by bottom currents before being re-deposited elsewhere (King and MacLean, 1970). These processes excavate and shape the pockmarks so that in very soft cohesive sediments they are commonly ovoid in plan with the long axis parallel to the direction of the dominant near-bed currents (Figure 19). Pockmarks are mostly restricted to seabed composed of a range of sediments from muddy sand to mud, the largest pockmarks most often occurring in the finest-grained sediments. This is because gas-bubble or fluid escape also occurs in coarse-grained sediments but in these situations the fluids escape more freely and the sediment grains are heavier so the fluid expulsion does not excavate the seabed (Gatliff et al., 1994; Johnson et al., 1993). The main areas of pockmarks occur outside SEA5 in the Witch Ground Basin (Figure 18) and in the Norwegian Channel. For the reasons explained above, the pockmarks are excluded from the areas dominated by sands and gravels typifying most of SEA5 (Figures 15, 18).
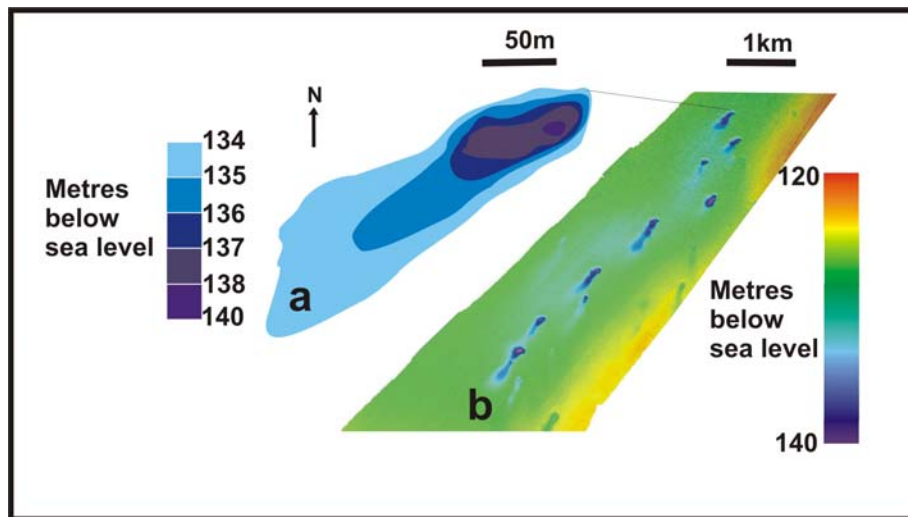
Figure 19. Extract image of seabed pockmarks. The area of survey is in SEA2 (see Figure 18) but the image is illustrative of the geometry of some types of pockmarks extending into SEA5. **a.** is a plan enlargement of the pockmark shown connected to the northern-most pockmark in b. **b.** is a perspective view of an example of a linear field of large pockmarks. The axis of each pockmark is aligned sub-parallel to near-bed currents.

Research in the northern North Sea indicates that once a migration pathway for the escaping gas/fluid has been established, the pockmark can remain active for several years. For example, a pockmark, with active methane seeps has been identified in UK block 15/25 (outside SEA5). It has a depth of 18.5m below the surrounding seabed and is colonised by chemo-synthetic species and carbonate-cemented sediments, the growth of which has been sustained by the escaping methane. The importance of pockmarks from the conservation viewpoint is that some of the carbonates formed from leaking fluids may form 'reefs' and they also have a small natural range (Dando et al., 1991). Active pockmarks have not been reported from SEA5.

3.   Results from DTI 2003 surveys

The review incorporates the detailed DTI 2003 geophysical-survey data into the existing regional data held by the BGS. The methods of approach and types of data generated from the commercial 3D surveys, regional, BGS surveys and the detailed surveys are very different. These differences are briefly reviewed in Appendix 1in terms of comparisons of DTI 2003 multi-beam data with examples of commercial 3D-seismic data and with BGS regional single-beam data. A summary of the methods of construction of the BGS model of seabed sediments is also given in Appendix 1.

The DTI 2003 surveys included the acquisition of reconnaissance multi-beam and sidescan sonar data from SEA4. The areas of survey were St. Magnus Bay, west of Sullom Voe, and 'The Deeps' west of Mainland Shetland in the area affected by oil spillage following the grounding of *M.V. Braer West* in 1993. These areas are outside SEA5 and the results from the new surveys are briefly reviewed in Appendix 2.

The seabed sediments acquired by the DTI in 2003 were sieved to remove gravel so that the particle size analyses were reported for grains with less than 2mm diameter (Black, 2004). Summaries of particle-size scales and classes, particle-size analysis procedures and the sediment-classification scheme adopted by the BGS for its regional mapping are given in Appendix 3.

Sidescan sonar records of seabed backscatter were collected during the DTI 2003 surveys over Pobie Bank, Fair Isle, Smith Bank and the Outer Moray Firth. The returns of very high to high seabed backscatter are recorded as structured patterns of dark grey in areas where bedrock, over-consolidated muds and pebble and cobble gravels are exposed at seabed and as patterns of lighter grey or white where well-sorted granular gravels, sand and muds return moderate to very low seabed backscatter. Only selected examples of seabed backscatter have been presented in the figures for the following review. Instead, summaries of seabed variability have been compiled from interpretations of the seabed backscatter observed on the sidescan-sonar records (Table 4). These interpretations have been calibrated with reference to the DTI 2003 particle-size analyses of seabed samples and from observations taken from seabed photographs. The summary data show that although the crest of Pobie Bank and surrounding flanks are set in the deepest waters, the returns of seabed backscatter indicate that the seabed has the highest proportion of exposed hardgrounds or relatively coarse -grained sediments. Also, the crest of Sandy Riddle is set in the shallowest waters, yet it has the lowest proportion of high to moderate backscatter. These are examples of how the intensity of seabed backscatter derived from the sidescan sonar surveys may be used to identify departures from a regional trend of an overall decrease in grain size with water depth. The regional trends and local departures from the trends are further examined in the following sections.

	Sidescan sonar backscatter very high to high: bedrock, over-consolidated sediment and sandy gravel	Sidescan sonar backscatter high to moderate: gravelly sand	Sidescan sonar backscatter low to very low: well- sorted granular gravel,sand and mud	Area of DTI 2003 sidescan sonar survey (sq. km)	Shallowest water of survey (m)
Pobie Bank	29.14%	43.26%	0.00%	71	57
Fair Isle	24.03%	70.23%	5.74%	32	20
Smith Bank	17.16%	36.49%	46.35%	30	35
Sandy Riddle	2.00%	0.00%	98.00%	34	16
Outer Moray Firth	14.48%	16.00%	74.80%	176	40

Table 4. Distribution patterns of seabed backscatter derived from DTI 2003 sidescan-sonar surveys related to sediment-size classes, water depth and location. The locations of the sidescan-sonar surveys are shown schematically in Figure17. The Southern Trench was not surveyed with sidescan sonar.

3.1   Pobie Bank

Pobie Bank is elongated in a northeast to southwest trend which is parallel to underlying structure in the bedrock geology (Figure 20).
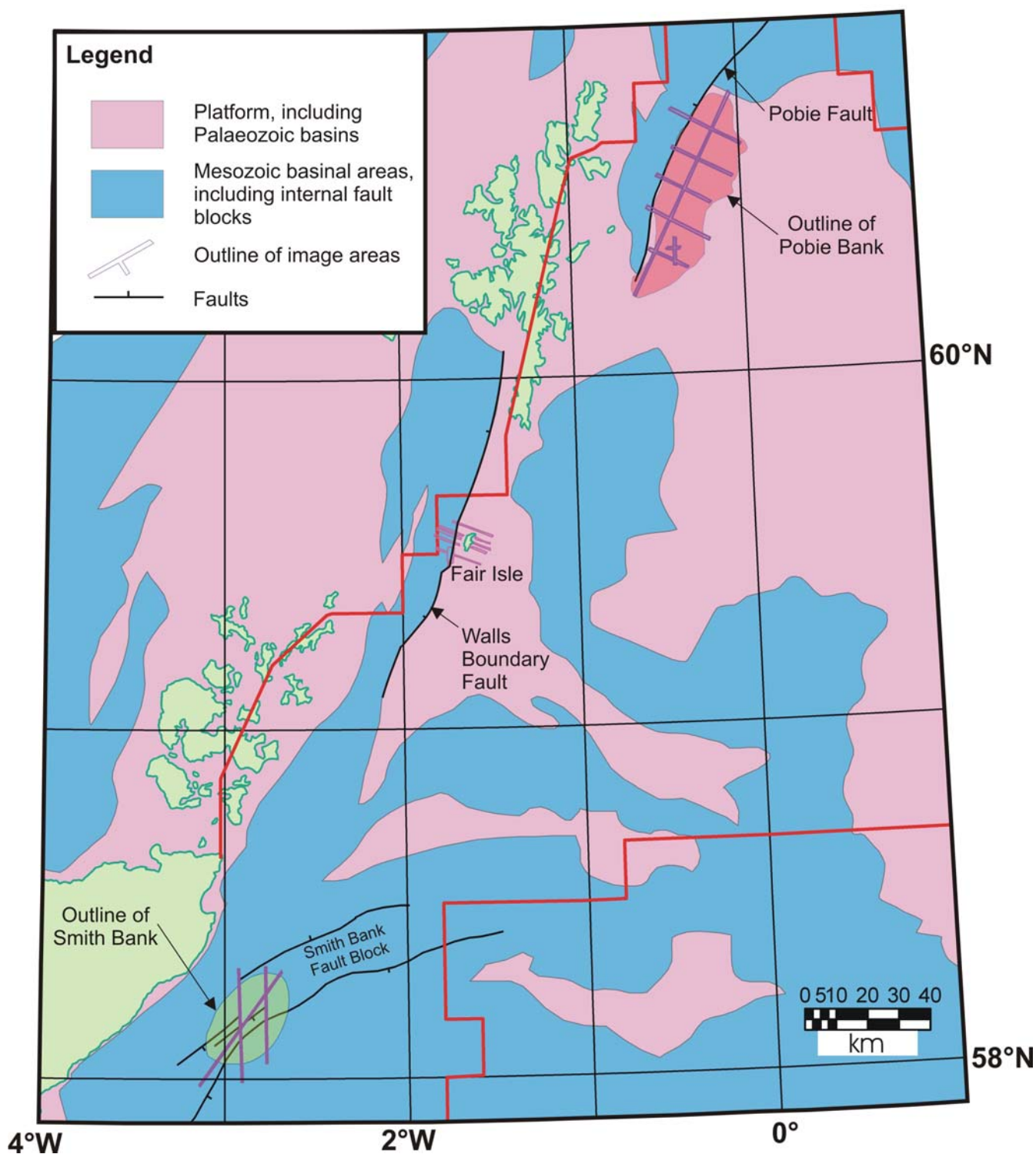
Figure 20. Pobie Bank, Fair Isle and Smith Bank: locations of surveys and underlying bedrock structural setting.

Pobie Bank rises from approximately 110m below sea level (deeper on the northwestern margin) to less than 80m water depth along the crest. Samples were taken in the water depth range from 86-131m (Figure 21).
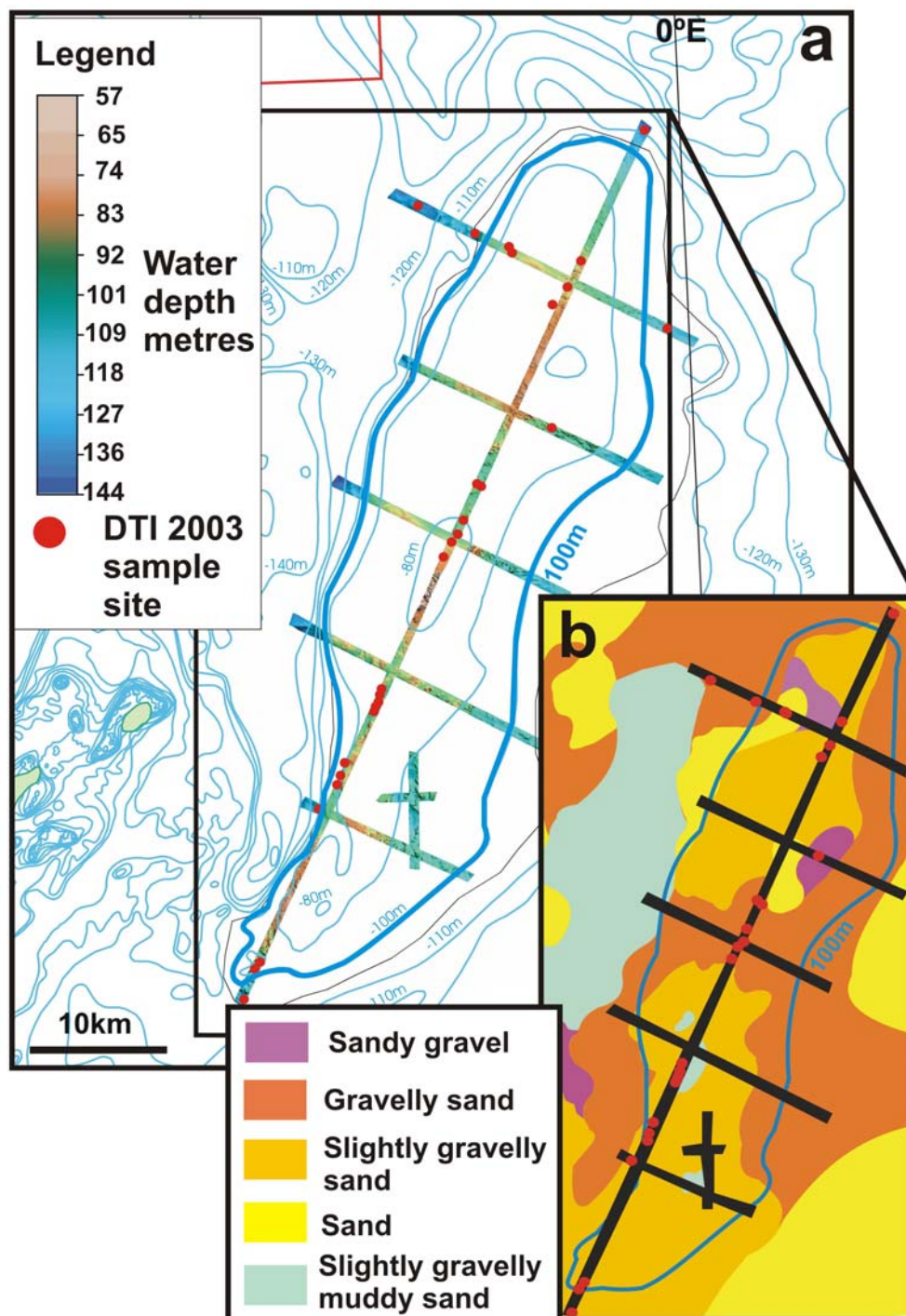
Figure 21. Pobie Bank: swath bathymetry colour-shaded image and seabed-sediments
a. swath bathymetry colour shaded image and sample locations **b.** BGS model of seabed sediment classes. For key to classification system see Appendix 3.

The bank is approximately 70km long (from northeast to southwest, 025° / 205°) and up to 20km wide. It has a seabed-surface area shallower than 90m water depth of approximately 600 square kilometres.

The western margin of Pobie Bank follows the line of the Pobie Fault (Figure 20). This fault brings a platform area in the east consisting of very hard sedimentary and metamorphic rocks under Pobie Bank into lateral contact with a basin containing softer sedimentary rocks to the west. Unconsolidated sediment cover is thin or absent over Pobie Bank, the bulk of which is bedrock. These data indicate that bulk volume of Pobie Bank is tied to the underlying bedrock geology and that the bank is stable.

The swath images show a bank crest with elevated features interpreted as bedrock outcrops (Figure 21a). The bedrock commonly shows a northwest–southeast trend, although whether this is related to bedding, jointing or erosion, is uncertain.

Pobie Bank is located in an area where mean peak spring-tide near-bed currents range from approximately 0.25-0.375 m/s. A low of less than 0.25m/s is modelled for the south and west bank margins (Figure 17). Seabed sediments over Pobie Bank comprise sand and gravelly sand with patches of sandy gravel located on the northern and eastern margins of the bank and slightly gravelly muddy sand on the southern and western margins and southern bank crest (Figure 21b). Overall, the patterns of distribution of the seabed sediment classes indicate type 4.1 (section 2.11) seabed conditions with the asymmetry of the sediment classes across the bank indicating the impact of winnowing by higher energy near-bed currents on the north and east flanks. These patterns are consistent with the predictions for the mean peak spring-tide near-bed currents in stormy conditions and peak near-bed orbital currents having the greatest impact on the northern flanks of Pobie Bank in stormy conditions (section 2.11). The bank is enriched in sand-size biogenic carbonate relative to the surrounding seabed (Figure 16). The composition of the DTI 2003 sediments taken from Pobie Bank are typified by sands ranging to sandy gravels, as indicated by the textural classification diagram (Figure 22).
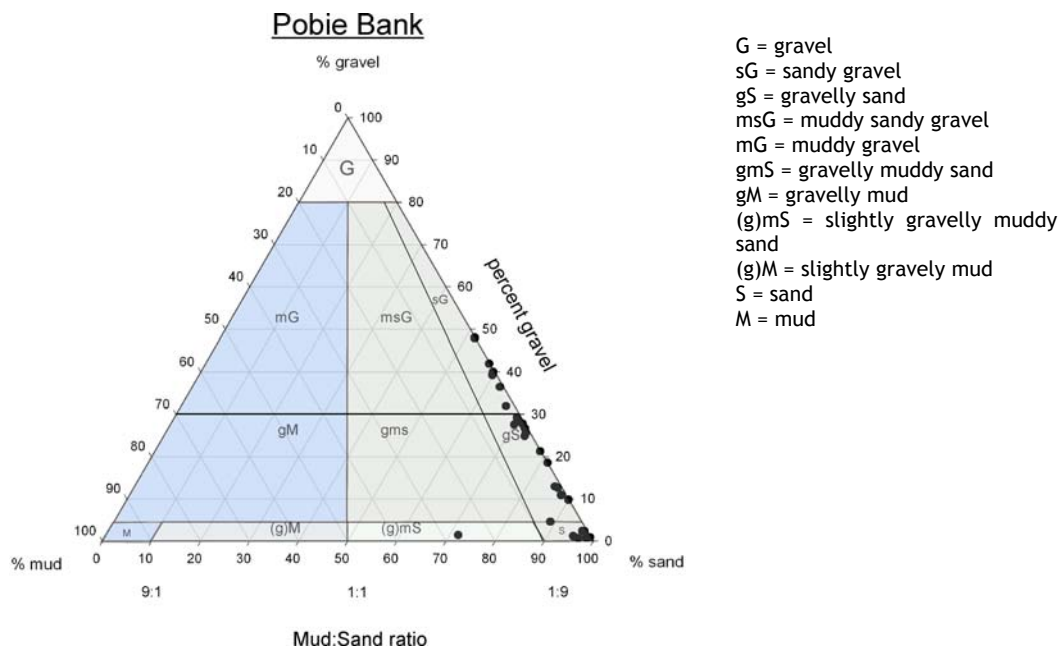
Figure 22. Pobie Bank: seabed-sediment textural classification.

The modal grain size for samples varies between 227-1202 microns (1 millimetre = 1000 microns) in the fine to very coarse-grained sand range. There are two main modes present in the sediments from Pobie Bank. Samples 1, 5, 8, 12, 14,18, 27, 29, 30 and 33 show a dominant 100-500 micron (fine to medium-grained sand), some of which also display a coarse gravelly tail. The mode observed in the remainder of the samples is very coarse-grained sand to gravel (>500 microns) (Figure 23). All the sediments are almost devoid of fine-grained silts and clays (<100 microns).
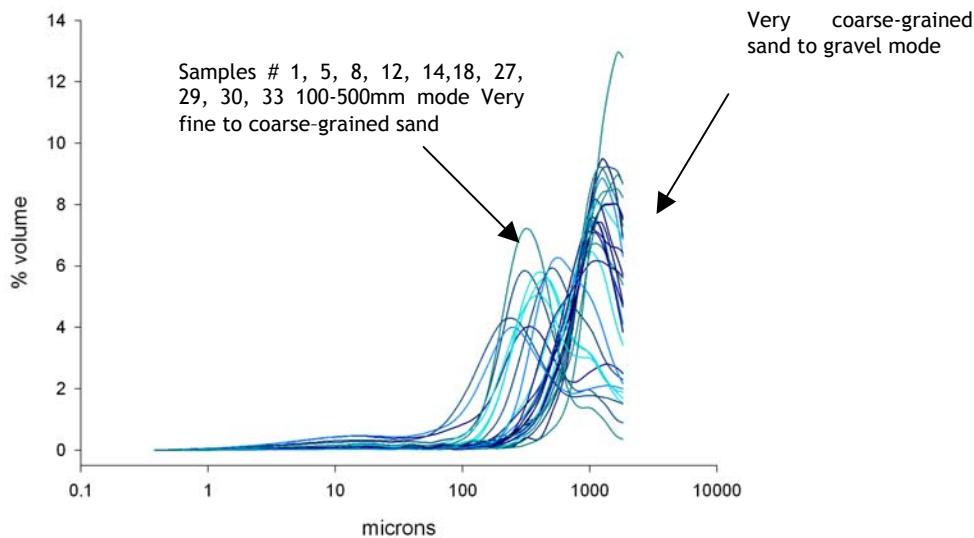
Figure 23. Pobie Bank: particle size analysis curves

The particle-size data show that from approximately 100 to 140m water depth there is an overall coarsening of modal grain size ranging from fine-to medium-grained sand with decreasing water depth. Shallower than approximately 100m there is an abrupt shift to a cluster of coarse to very coarse-grained sands that show no overall trends with water depth. These observations, the asymmetry of distribution of the sediment size classes, the apparent anomalous areas of hard seabed and coarse sediment compared to its regional setting (Table 4) and the almost complete removal of fine-grained (muddy) sediments suggest that the top sediments in water depths less than approximately 100m had been stirred up by long-period storm waves and probably by storm surge. It is suggested that these directed extreme conditions on the seabed (types 1 and 4.1) at some time prior to the time of survey. It is thought that sediments in more than100m water depth were below extreme wave base and a seabed in type 2 conditions (section 2.11). One importance of the observed variations is that they may be used to predict the likely water depths of severe natural seabed erosion.

3.2   Smith Bank

Smith Bank lies in the northwest area of the Moray Firth, approximately 25km southeast of the Caithness coast. The bank is approximately 35km long from southwest to northeast and 20km wide (Figure 2). It rises from a base level of between 50 and 60m below sea level to less than 35m. The northwest flank is slightly steeper but its seabed slope does not exceed 0.5°. Estimates from the BGS regional data indicate that the seabed area of the bank in less than 50m depth of water is approximately 40 square kilometres.
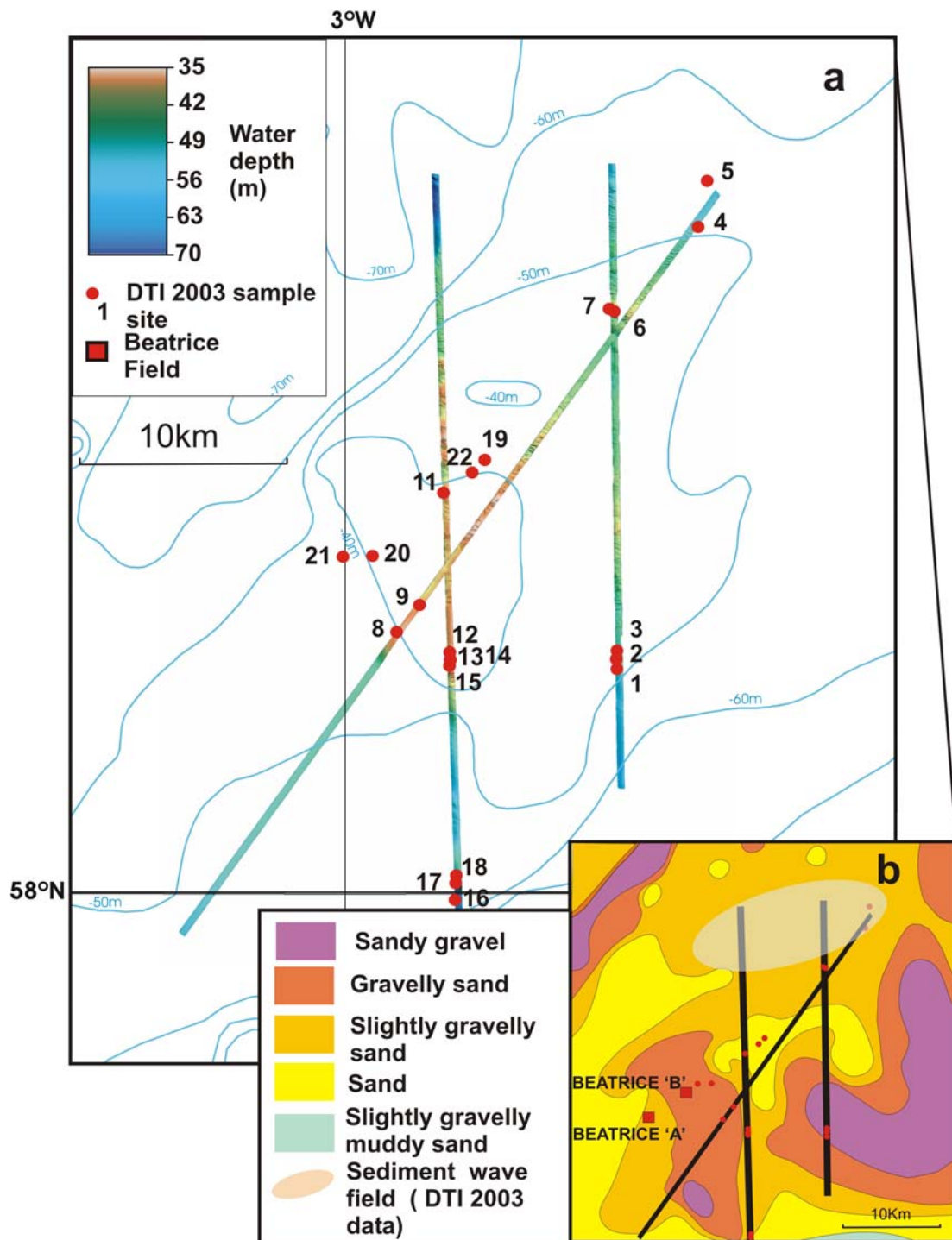
Figure 24. Smith Bank: swath bathymetry colour-shaded image and sample sites. a. swath bathymetry colour shaded image and sample locations **b.** BGS model of seabed sediment classes. For key to classification system see Appendix 3. The area of the sediment wave field is shown schematically and has been derived from interpretations of the DTI 2003 swath bathymetry and sidescan sonar data.

The position, elevation and orientation of the bank are associated with the underlying Smith Bank Fault block (Figure 20) and the distribution patterns of moraines underlying the seabed sediments do not appear to be related to the overall elevation of Smith Bank (Figures 7, 24). The bulk of the bank volume is therefore thought to be composed of bedrock and the bank is stable. The 'top' of Smith Bank shows structures that do not appear to be from sediment waves, but might relate to structures in bedrock (Figure 24a).

In the area of the Smith Bank mean peak spring-hide near-bed current speeds decrease from 0.375-0.50 m/s to <0.25m/s to from northeast to southwest (Figure 17). Maximum orbital current velocities derived from the effects of storm waves are between 2.0 and 3.0m/s (Pantin 1991). Seabed sediments on the Smith Bank show an asymmetry with the coarsest sediments (sandy gravels) distributed on the north and east flanks (Figure 24b). The swath image of the bank shows some evidence of sand patches and sheets with low sediment waves. At the time of survey, the fields of low sediment waves were restricted to the north flanks of the bank (Figure 24a, b). The sediment waves have crests of approximately 1.5-0.5m height and wavelengths of approximately 50m. They are in approximately 45 to 60m water depth migrating to the south and west in a direction that is consistent with the direction of flow of mean peak spring-tide near-bed spring currents in that area (Figure 17). A field of sediment waves was not observed on the south ('lee') flank in equivalent water depths. The patterns of near-bed tidal currents and seabed sediment classes are consistent with an association of Smith Bank with type 4.1 seabed conditions (section 2.11).

BGS core sampling (unpublished) indicates that seabed and superficial sediments on the bank crest are characterised by a sheet of sand and gravelly sand that is more than 2m thick. The relatively high concentrations of biogenic carbonate in the sands distributed across the bank indicate that biological input has influenced the seabed composition (Figures 1, 16).

The DTI 2003 sediments recovered from Smith Bank have a modal peak for the particle-size analysis curves of 433microns, indicating medium to coarse-grained sand on the sand patches with the level of sorting indicated by the curve shape that is generally high (Figure 25).
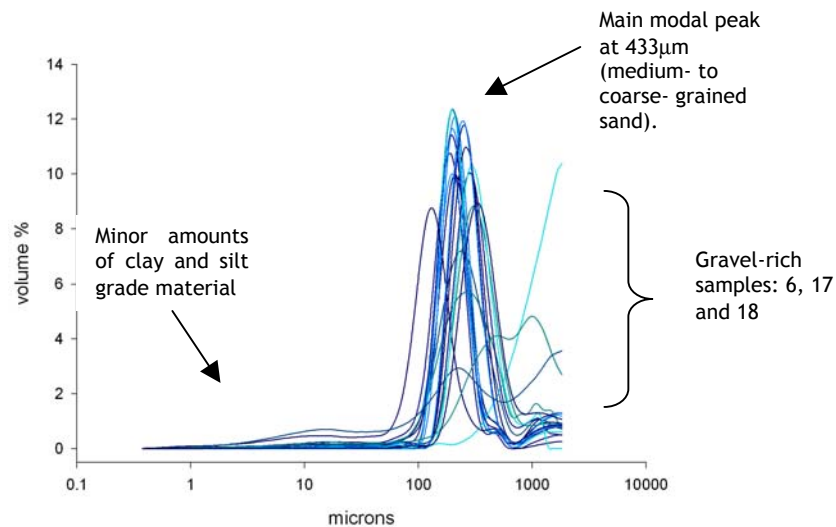
Figure 25. Smith Bank: particle-size analysis curves.

The cluster of the modal peaks (Figure 25) and scatter plots of modal grain sizes against water depth indicate that there is no overall systematic variation of grain size with sample position on the bank over a depth range of 39 to 56m. The particle-size distributions derived from the analytical curves are essentially mono-modal, although these sediments are also characterised by small quantities of fine-grained sediments consisting of clay-and silt-grade material. The fine-grained sediments could interpreted as being due to fluctuations in current velocity at this site. Only three samples fall into the sandy gravel category defined in the textural-classification diagram (Figure 26).
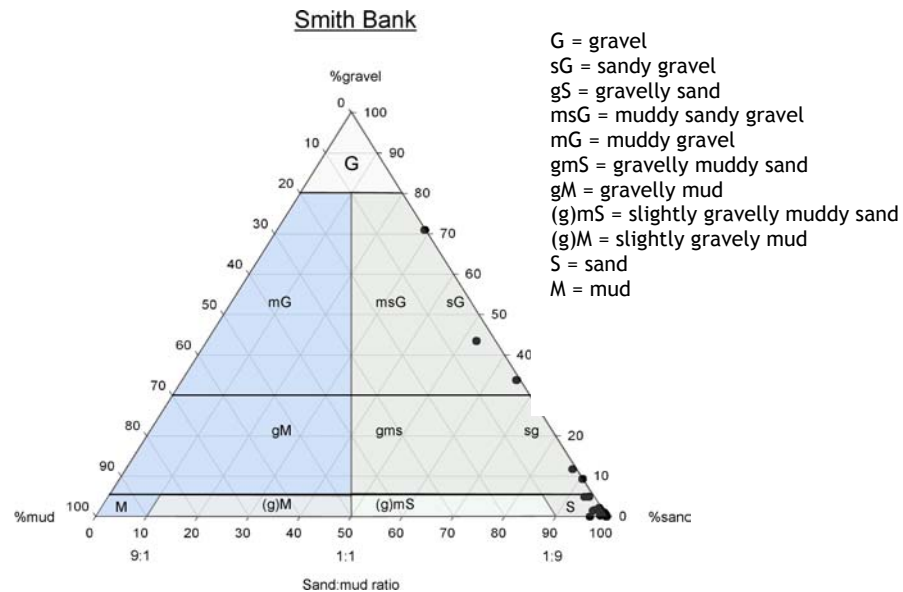
Figure 26. Smith Bank: seabed-sediment textural classification

It is thought that the gravel-rich sediments, imaged as patches of relatively high backscatter from the sidescan-sonar data obtained from the DTI2003 surveys and from Southampton Oceanography Centre surveys (not illustrated), extend beneath the sand. Sidescan-sonar and swath-backscatter data show that sand patches on the bank have sharp boundaries and tend to be elongated. These patches are aligned in several directions. They have a predominance of NNW-SSE trends but can have any direction in relation to the dominant current direction. Their formation is characteristic of areas where the directional currents (tidal and surge induced) are too weak on their own to move bedload, except on rare occasions. The modelled extreme, depth averaged, surge currents over 50 years are about 0.60-0.80m/s (Flather 1987). Overall, the sand patches require that they are formed and mobilised when the currents induced by long-period storm waves enhance the directional currents. The process by which the patches maintain a fairly constant 2m height and thickness, together with steep sides, is not fully understood. One possibility is that storm-wave currents sweep sand from the gravel areas into the patches and that 2m is the typical maximum height to which the storm waves can carry the sand into suspension (Belderson et al. 1982). The sand patches, their geometry and an overall lack of fine-grained sediment is consistent with the sand patches having been surveyed in type 2 conditions following stormy periods. The distribution patterns of gravel are thought to be relict from types 1 and 4.1 seabed conditions (section 2.11).

3.3   Fair Isle

Fair Isle is an island lying between the Orkney and Shetland archipelagos in the SEA5 area (Figure 27).
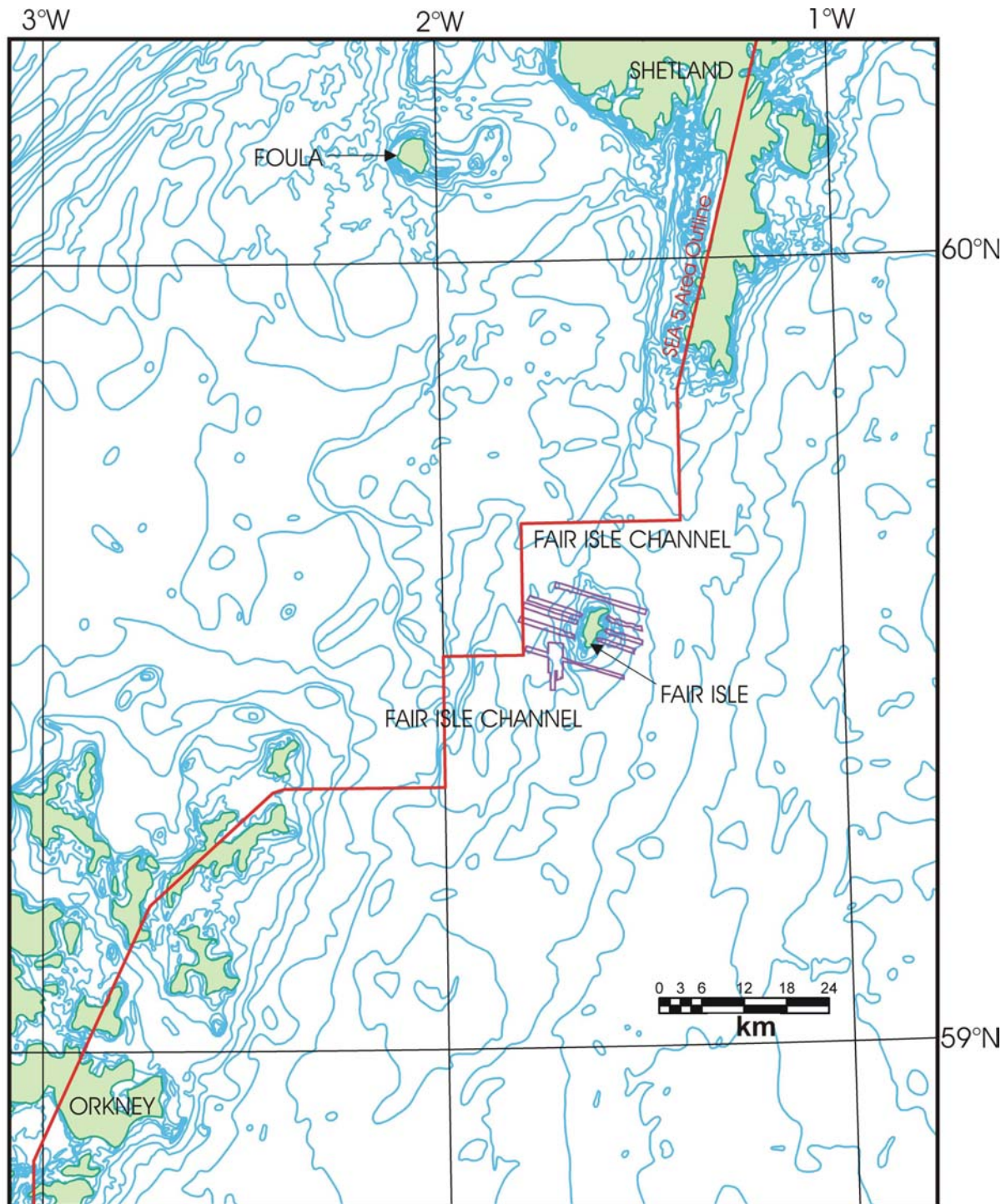
Figure 27 Fair Isle: regional physiographical setting and location of 2003 DTI SEA survey (outlined in purple)

The Fair Isle Channel in which Fair Isle sits is one of the major gateways for North Atlantic Surface Water flowing eastwards into the North Sea. Mean peak spring-hide near-bed peak current speeds are predicted to exceed 0.5m/s when flowing to the northwest around Fair Isle in calm weather. They are forced to the southeast in stormy weather (Figure 17).

Structurally, Fair Isle and the surrounding seabed is similar to Pobie Bank to the north, with an emergent crest related to uplift of a faulted block (Figure 20). Ridges imaged from the DTI 2003 survey show a northeast to southwest orientation, which is related to crop of the bedrock at seabed. The seabed surrounding the island deepens away from the shore to a depth of approximately 100m below sea level in the study area in an overall concentric pattern that is disrupted by a low bank to the west of Fair Isle and a larger-relief and larger-area bank to the east. A 190m deep closed basin, the Fair Isle Deep, is deeply incised into the seabed to the southwest of the island (Figure 28).
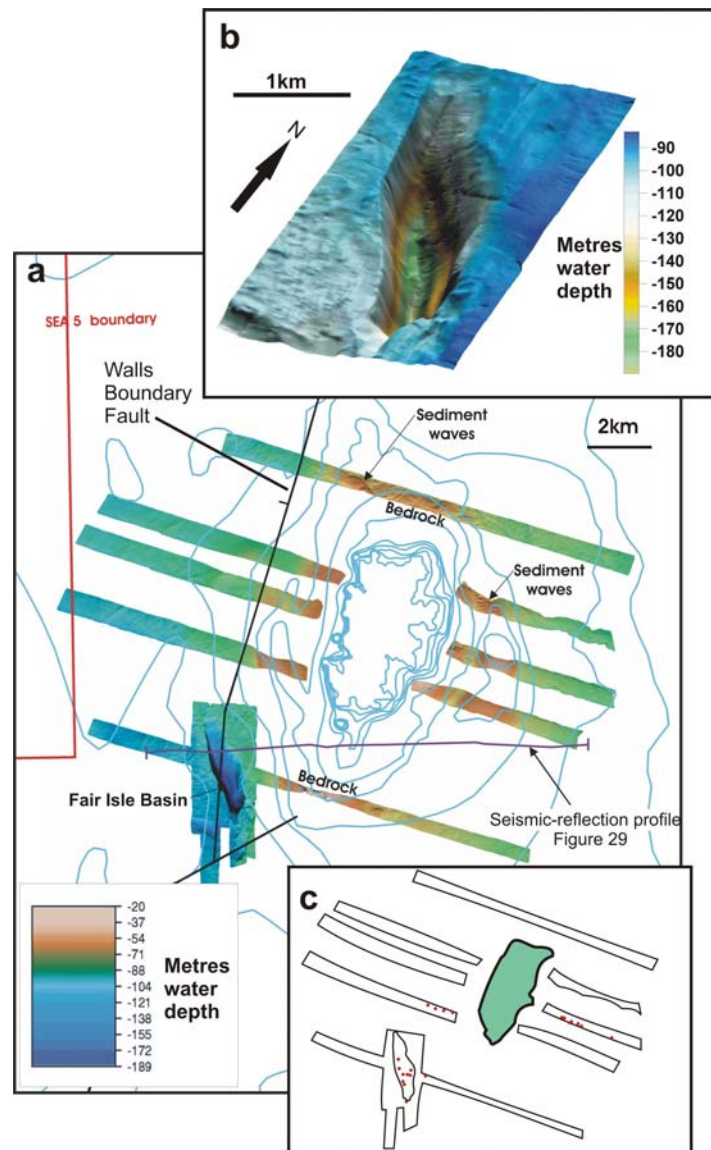
Figure 28. Fair Isle: regional physiographical setting and sample sites. a. Swath bathymetry and interpreted seabed solid geology **b.** Perspective elevated terrain model of the enclosed Fair Isle Basin **c.** Sample locations

The Fair Isle Deep is approximately 3 km long and 900 m wide and is sited over the location of the Walls Boundary Fault (Figure 20). It has a seabed surface area of 2.4 square kilometres. A slope model derived from the multi-beam data (not illustrated) demonstrates that the west flank has seabed slope of up to 50° and on the east flank there is an average slope of approximately 25°. From the basin shoulder, at approximately 90 m water depth, to its deepest axis the seabed drops by approximately 95 m (Figures 2 and 3). This feature probably originated at the margin of a former ice sheet (Figure 7).

A shallow seismic-reflection profile across the basin confirms that it has been deeply eroded into bedrock (Figure 29). The east flank and the basin axis appear to be covered by sediments that are partly infilling the basin but it is likely that the west flank has been kept largely free of sediment deposition because of down-slope sediment movement on its exceptionally steep slope. The west flank consists of jointed bedrock on which are perched isolated patches of sand and gravel and attached biota (Figure 29a).
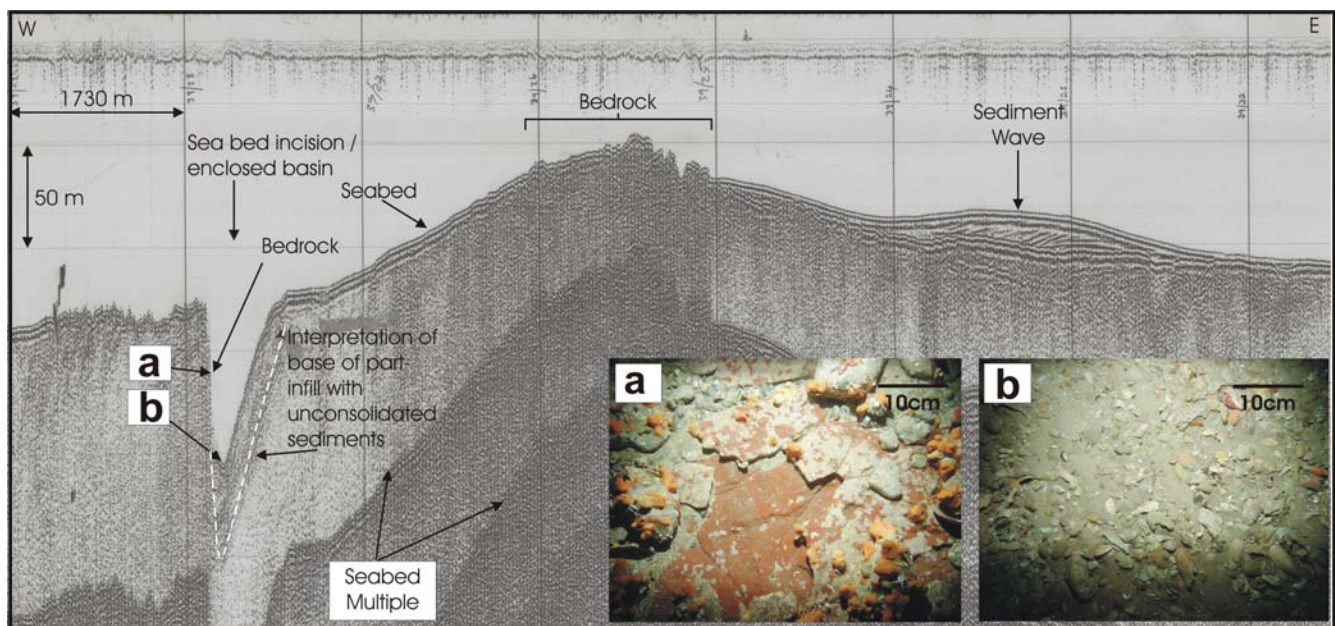
Figure 29   Fair Isle: seismic-reflection profile illustrating the seabed and sub-seabed geological setting of the enclosed basin. The inserts **a** and **b** are seabed photographs that were taken at the locations indicated on the seismic-reflection profile **a.** bedrock exposed on seabed with approximately 50° slope **b.** very poorly sorted sandy gravel deposited within the basin axis (see also Figure 33). The gravel fraction mainly consists of shell fragments.

To the south and east of Fair Isle a large-scale sediment wave has internal structure that appears to show that it has prograded towards shallower water (Figure 29). It is disconnected from the shallower bedrock and the bathymetry demonstrates that the profile is a section of a large bank situated to the east of Fair Isle. A smaller bank or ridge also occurs to the west of Fair Isle and the sample sites straddle both banks at approximately equivalent ranges of water depth (Figure 28). Sediment waves are migrating from the northern margin of Fair Isle onto the bank. A synthesis of all the data (Figures 28, 29) indicates that the eastern bank is probably tied to the north and south headlands of Fair Isle so that it appears to have some of the attributes of a 'banner bank' (Dyer and Huntley, 1999). In this case it is thought possible that the prograding strata observed on the profile data (Figure 29) were formed in a

gyre shed in the 'lee' of Fair Isle during times of very strong east-flowing currents, the asymmetry between the east and west flanks indicating a prevailing east-directed flow.

BGS seabed-sediment maps show a cover of sandy gravel becoming gravelly sand between 7 and 15 km from the Fair Isle coast. Biogenic carbonate in the sand fraction of seabed sediments exceeds 50% over most of the study area (Figure 16). The BGS regional data indicate that the DTI 2003 samples were taken in a relatively high-energy gravelly and sandy seabed environment (Figure 15) and this is confirmed in the DTI 2003 samples by the very low mud content of the sediments (Figure 30).
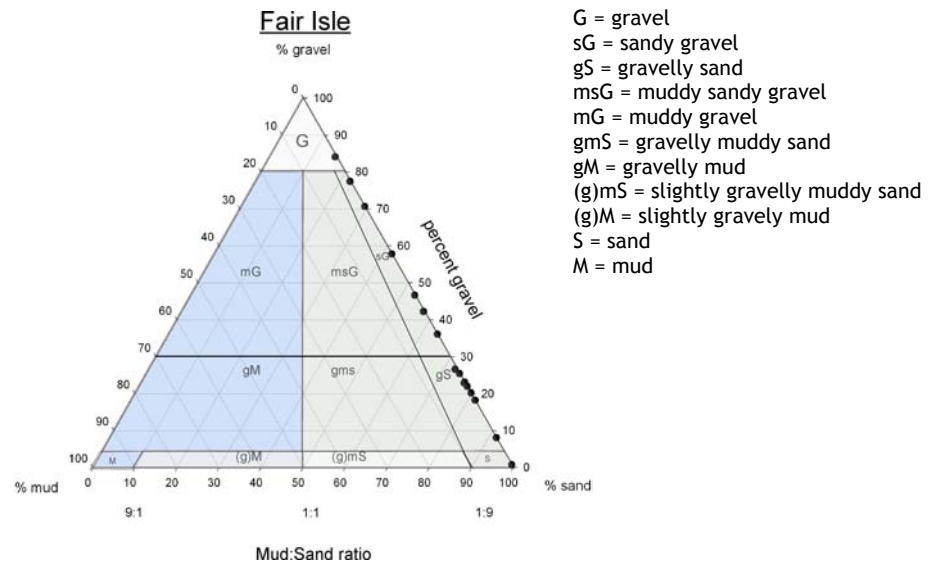
Figure 30.   Fair Isle: seabed sediment textural classification

The particle-size distribution curves for the gravel-free components of sediments taken from the Fair Isle region can be broadly divided into 3 groups, the first two overlapping to some extent and occurring on the open shelf around the Fair Isle.

The first group displays a well-sorted mono-modal peak within the 500-1000 microns size range (coarse-to very coarse-grained sand) from samples taken to the east of Fair Isle (Figure 31).
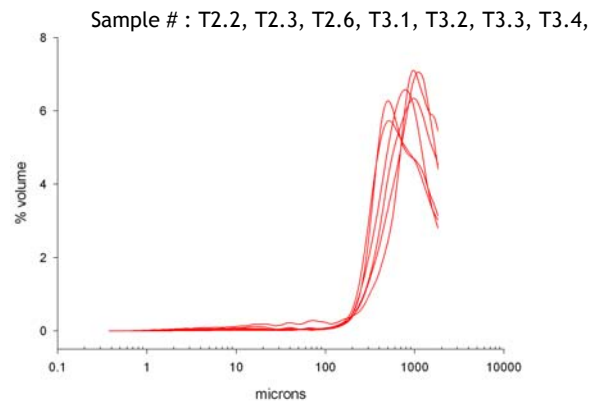
Figure 31. Fair Isle: particle-size analysis curves: category 1, dominantly unimodal, well sorted, east of Fair Isle.

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The second mode is defined by polymodal curves in the very coarse-grained sand-size range but which show a more persistent gravel grain-size tail. These samples occur to the west of Fair Isle (Figure 32).
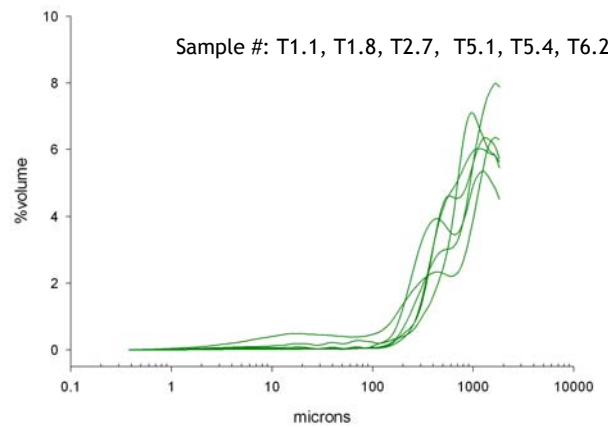
Figure 32.   Fair Isle: particle-size analysis curves: category 2, polymodal poorly sorted, west of Fair Isle.

The asymmetry of the grain-size distributions across the banks is interpreted to suggest that there is exposure of the seabed to stronger wave and tidal currents on the west side of Fair Isle. The distribution patterns of seabed sediments around Fair Isle are therefore showing the effects of type 4 .1 conditions.

The third group of curves shows very poorly sorted coarse and very coarse-grained sediments with a polymodal distribution. These sample sites are located within the enclosed basin. The steepness of the flanks and the very poor sorting suggests that several categories of sediments have been mixed into the samples by a process of gravity-driven grain flow. The seabed photographs show that there is a very high proportion of gravel-size shell in these sediments (Figure 29c). In this case the suggestion is that the enclosed basin is a sink for rock-clastic and bioclastic sediments that have spilled over into the basin from the open shelf. The lack of significant proportions of fine grained (<100micron) sediments in the samples indicate that, although it is enclosed, the basin remains exposed to tidal currents that have prevented the deposition of fine-grained sediments from suspension (Figure 33).
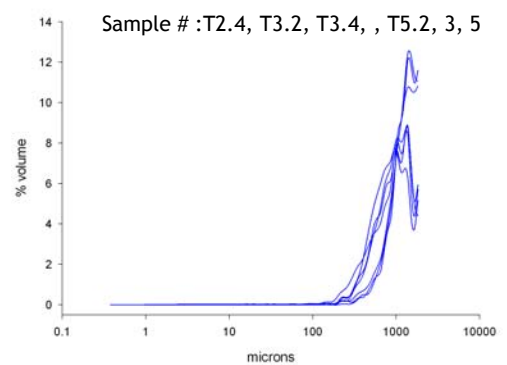
Figure 33. Fair Isle: particle-size analysis curves-category 3, polymodal, very poorly sorted, Fair Isle Basin axis.

The findings from the flanks around Fair Isle are important because they lead to a prediction that the headlands and the islands and skerries that are exposed to strong tides will be coupled to stable banks formed from sediments that have accumulated in the shelter of the headlands, islands and skerries. The data also demonstrate the asymmetry of the sediment particle distributions in exposed and relatively sheltered environments across similar ranges of water depth (section 2.11, type 4.1). The findings demonstrate that enclosed basins set in strong currents are sinks for coarse-grained sediments and that in areas with steep slopes and seabed-sediment failure there is no relationship between water depth and grain size in type 4.3 seabed conditions (section 2.11).

3.4   Sandy Riddle

Sandy Riddle is a carbonate sandy gravel bank that rises from more than 80m water depth to less than 20m water depth. It has an estimated total surface area of 34 square kilometres. It lies adjacent to the eastern Pentland Firth and to the south and east of the Orkney Islands archipelago (Figure 34).
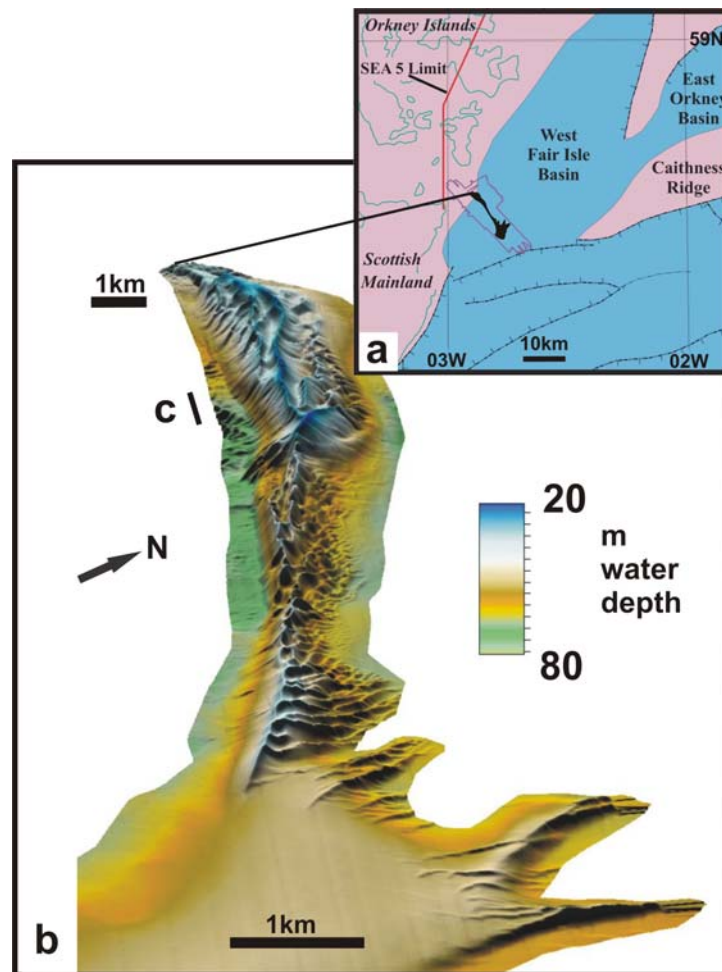
Figure 34.   Sandy Riddle a. regional geological setting b. seabed perspective terrain model c. location of extract of seabed slopes (Figure 35). The different sizes of the scale bars are a measure of the perspective used to illustrate the variation of seabed topography along the bank axis.

Sandy Riddle is set at the east end of the Pentland Firth in one the major northern gateways of influx of NE Atlantic waters into the North Sea. The region is characterised by high current speeds generated

from tidal streams that are constricted between the headlands of the Scottish mainland and the Orkney archipelago (Figure 34 a). The bank provides an extreme example of type 4.1 conditions.

East-flowing surface tidal streams of 5.3 m/s are recorded to the west of the Pentland Skerries, at which time a strong tidal eddy extended some 3.2 km to the southeast. Weaker and less prevalent west-flowing surface tidal streams generate a smaller eddy to the NE of the Pentland Skerries (Admiralty Chart 2162). Near-bed spring-tide currents are more than 2.75 m/s near the head of Sandy Riddle and decrease rapidly to around 0.875 m/s further to the southeast (Figure 17). During storm surges there are easterly directed currents (Flather, 1987) that, when added to peak tidal currents, will be the times of most bedload transport. Wave-induced currents, which are non-directional, will be added to the directional currents, and will be especially significant during storms affecting shallower water. The top of the Sandy Riddle will thus be one of the most active places for bedload transport in this region. For example, the banks near Sandy Riddle here are claimed to be higher in summer, when there are fewer storms, than in winter (Farrow et al, 1984).

Because it is tied in position both to the rocky cluster of islets forming the Pentland Skerries and the tides, the Sandy Riddle is a 'banner bank' (in the sense of Cornish, 1914) of type 3A of Dyer and Huntley (1999). The location of the heads of banner banks are attributed to tidal eddies to either side of headlands. They have been modelled by Pingree (1978), and by Signell and Harris (2000); Bastos et al (2002); Duffy et al (2004). The gyre of sand circulation, as deduced from sand-wave asymmetry, is in the same sense as for eddies, i.e. away from the headland in the outer area of sea and then back towards the headland in the shelter of the headland. The eddy hypothesis requires that there is a gap between the headland and the bank. The sand does not simply circulate within the strongest eddy. Instead, the line of bedload convergence located at or near the crest of the banner banks can extend well beyond the area of the shoal-water eddies occurring at the head of the bank (e.g. Bastos et al 2002, 2003).

Seabed slope breaks between 2° and 3° and higher angle slopes more or less sharply define the bank margins. The geometries of the slope breaks formed on either side of the ridges on the bank can be interpreted to infer net sediment transport directions on the bank (Figures 35, 36). At this location on Sandy Riddle the ridges are the crests of very large sandy gravel waves.
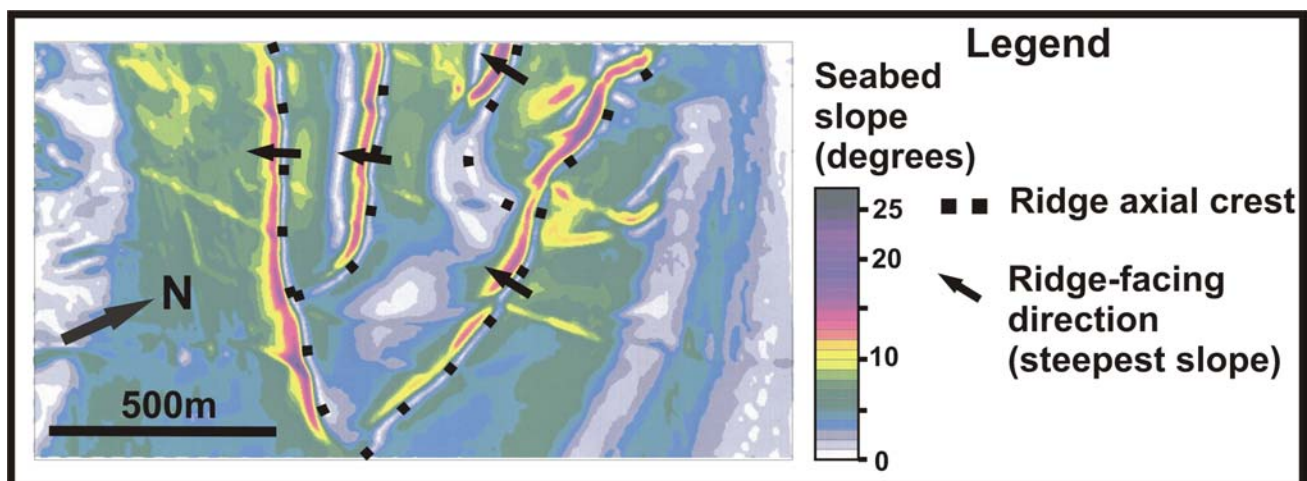
Figure 35. Sandy Riddle: interpretation net sediment transport directions based on an extract of seabed slopes. In this case the overall sense bedload movement is from the east margin of the bank and converging towards the stream of the strongest near-bed currents directed to the south and east.

Seabed on the Sandy Riddle mainly consists of very coarse- to coarse-grained shelly sand and gravel. The gravels are 100% carbonate and made up of broken and whole shell fragments. Carbonate in the sand on Sandy Riddle varies between 23-29%, averaging at around 15% (Black, 2004). The carbonate fraction is rich in barnacles and bryozoans. Fragments of these decrease in size and increase in abundance towards the southeast along the Sandy Riddle as a result of their being prone to fragmentation and current transport. Conversely, serpulid worm fragments decrease towards the southeast (Allen, 1983).

The Sandy Riddle and adjacent seabed can be broadly subdivided into three sectors on the basis of the seabed geometry. The northern sector 1 is some 3 km south-east of the Pentland Skerries and extends southeast for 6 km (Figure 36).
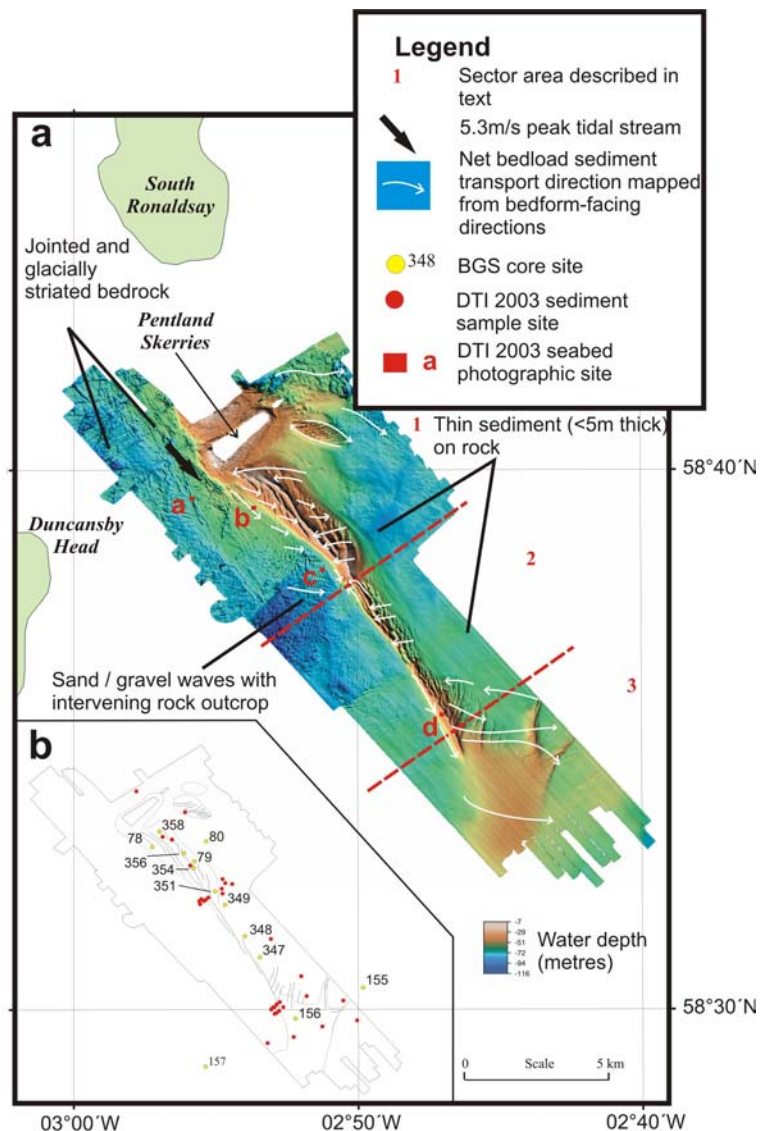
Figure 36. Sandy Riddle: net sediment transport. a. sector areas and summary interpretation **b.** seabed sample and core sites

In the north and west parts of sector 1 adjacent to the Sandy Riddle the areas with the strongest near-bed currents are swept clean of sediments to expose fault- and joint-related lineations in bedrock and also gulleys in the bedrock (Figure 37a).
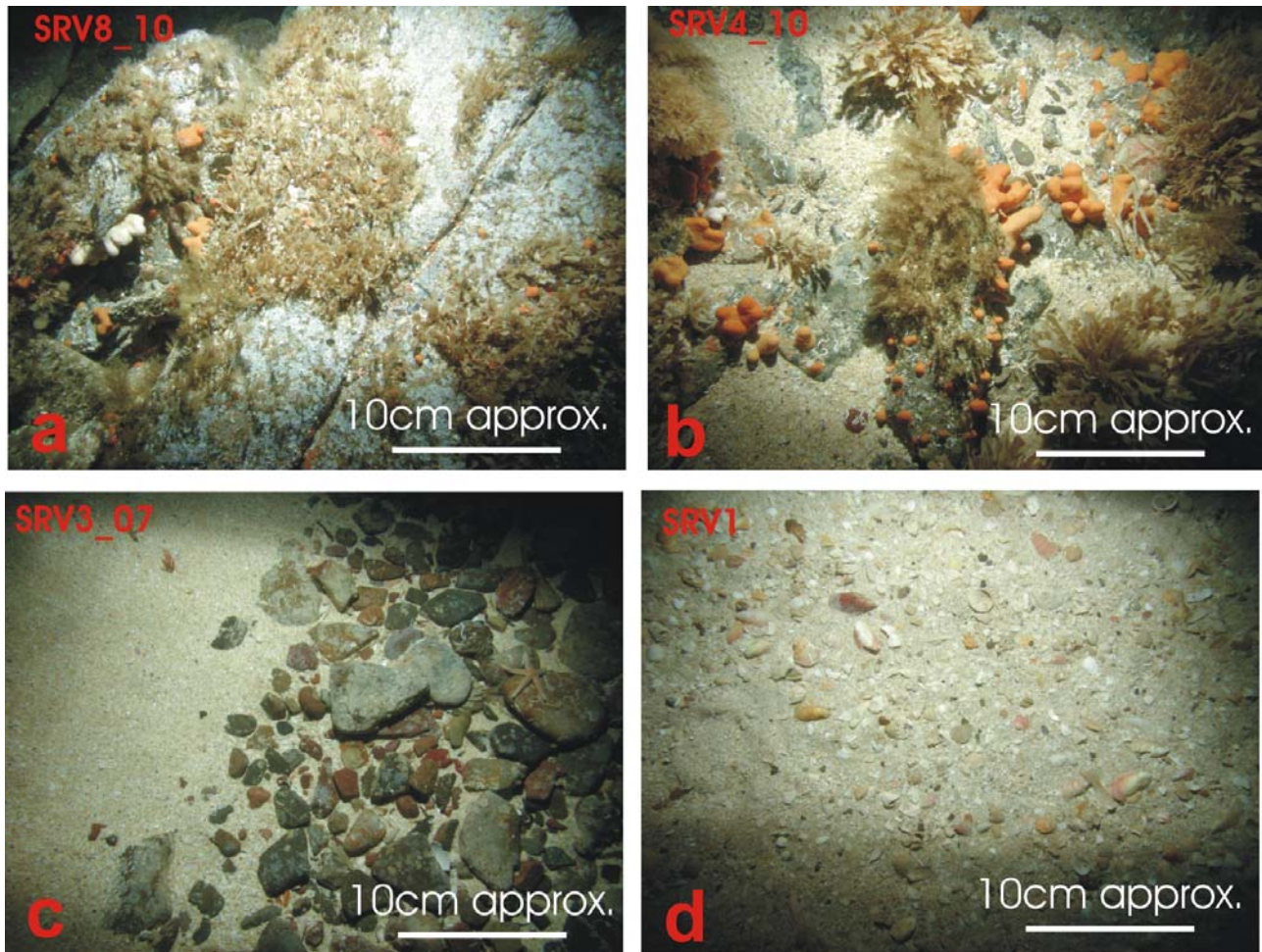
Figure 37. Sandy Riddle and adjacent areas: seabed photographs of the effects of near-bed currents a. exposed bedrock **b.** boulders and cobbles with sand **c.** sediment-wave migration **d**. shelly gravelly sand. See Figure 36 for locations

The largest of the gulleys cut across bedrock boundaries and probably originated from former glacial scour (Figures 34, 36). Areas with strong currents and with cobbles and boulders are also largely swept clean of sandy sediments except in the spaces between the rocks. The sandy sediment is thin and presumed to be in transit. In this sediment-starved environment the surfaces of the pebbles and cobbles are characterised by abundant attached biota (Figure 37b). In areas of weaker currents the seabed is characterised by cobbles and pebbles but also by mobile bedforms with coarse-grained sands. The mobile sands are thick enough to migrate as sediment waves over the seabed and periodically bury the underlying pavement of cobbles and pebbles. This process appears to prevent the establishment of abundant permanently attached biota on the pebbles and cobbles (Figure 37c). Sand and gravel carbonates accumulate in areas of weak currents or convergent currents, thus forming the Sandy Riddle (Figure 37d).

The east margin of the Pentland Skerries has also shed a banner bank into sector 1. This is much smaller than the main body of Sandy Riddle and the bedform-facing directions indicate that it also accumulated in an eddy (Figure 36a).

Six shallow BGS samples (78, 79, 351, 354, 365 and 358) were recovered from sector 1 prior to 1987 (Figure 36). These comprise gravelly sand or sandy gravel with between 5 and 80% shell gravel with most samples more than 50% shelly gravel. The Munsell Colour is 5Y 8/3 (pale yellow) and the sediment contains fragments of echinoids, molluscs, sponges and foraminifera. There was no overall trend of grain size with position across the bank.

In the 'central' sector 2, the ridge complex at the centre of Sandy Riddle is smaller and approximately 1km in width. The feature comprises one or two ridges with axes in northwest orientation, with smaller subsidiary ridges to the northeast (Figure 3). In this setting it is presumed that the migration of the main bank of the Sandy Riddle to the west is prevented by sediment removal by the tidal stream flowing to the southeast. Three BGS samples (347, 348 and 349) were taken from sector 2 and show coarse-grained gravelly sand overlain by a thin (5mm) veneer of muddy sand. The gravelly sand comprises 100% shell material and is distinguishable from the sector 1 samples by a finer grain size. There were no trends of mean grain size of sand with position from west to east across the bank.

At its southeast end the main ridge is 20m in height and diminishes in height into a trapezoidal sand sheet (sector 3). The sand sheet appears to thin gradually to the west and south and more abruptly to the east, these geometries indicating an overall east-directed bedload transport. The location of the sand sheet appears to originate from the decrease in near-bed current speed and accords with its expected place along the velocity gradient.

The DTI 2003 samples are almost completely free of mud and are consistent with those from the BGS indicating that sector 1 consists of overall coarser-grained sediments compared to parts of sectors 2 and 3 (Figure 38).
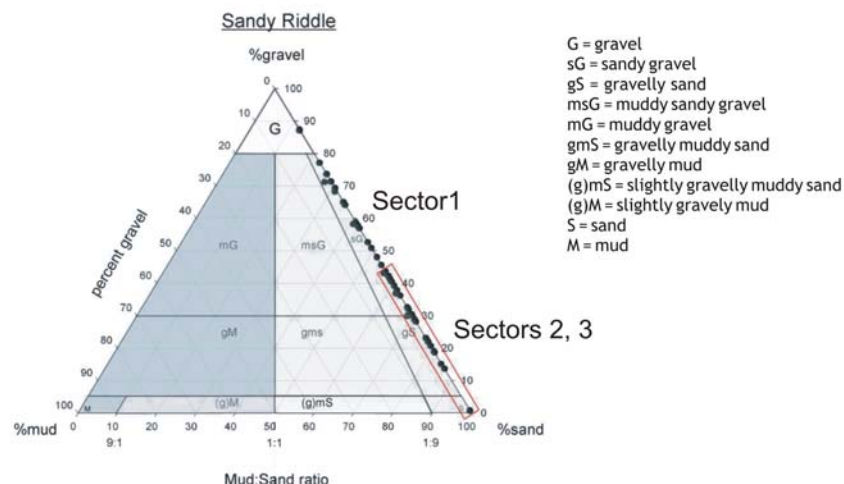
Figure 38. Sandy Riddle: seabed sediment textural characterisation related to sector. Sector 1. northern Sandy Riddle, sectors 2, 3 southern Sandy Riddle. For sector locations see Figure 36.

There is also an overall subtle higher seabed backscatter in the low to very low range returned from the northern end of sector 1 of the main bank (Figure 39). It is likely that both trends are related to an overall decrease in the size of skeletal carbonate to the south (see above). The mean grain size of the sand fraction in the gravel-free fraction of the seabed sediments did not vary systematically with position from east to west across the bank. Grain diameter values within the gravel-free fraction fall between the 1000-1250 microns range and are within the very coarse-grained sand range.
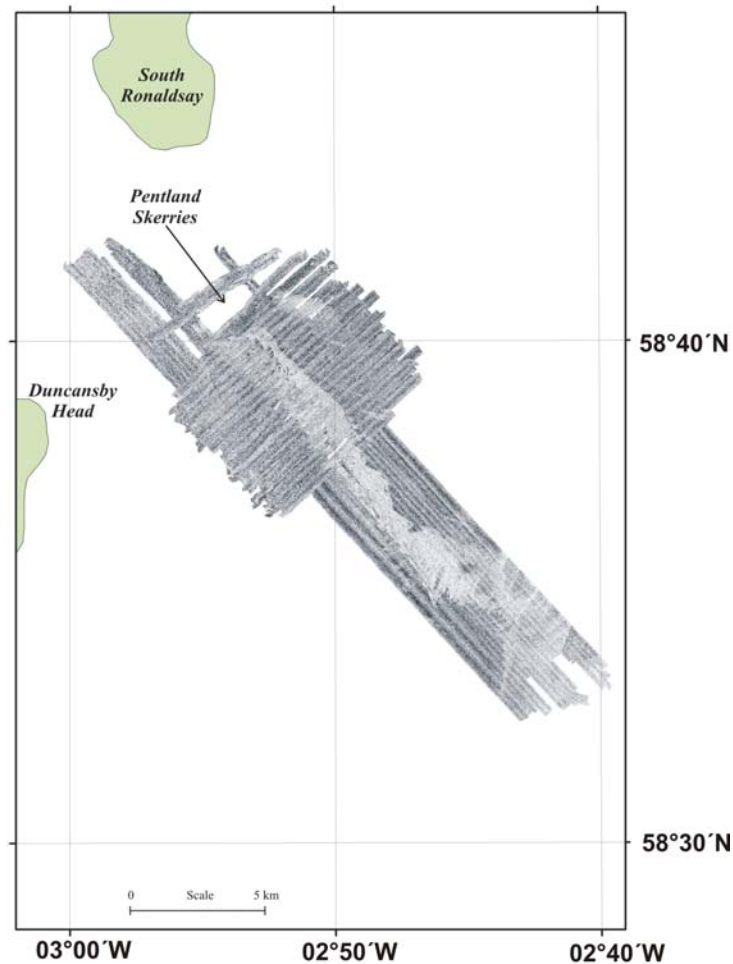
Figure 39. Sandy Riddle: sidescan sonar image of seabed backscatter. Areas of relatively high backscatter, indicated by the darkest shades, are related to the distribution patterns of coarser-grained sediments and/or bedrock at seabed.

The interpretations from seabed-sediment analyses and bedform-facing directions are consistent with the head of the Sandy Riddle originating by the deposition of shell carbonate in a cell of a anti-clockwise gyre occurring to the west and south of the Pentland Skerries. These interpretations show the importance of sediment re-circulation to maintaining the configuration of the bank. The bank to the south and east of the Pentland Skerries is maintained by clockwise sediment circulation, also in an area of sediment convergence. The implications are that other bi-polar carbonate banks will be generated by eddies shed from headlands if the headlands are open at both ends and transverse to the strongest near-bed currents.

3.5   Outer Moray Firth

3.6   Southern Trench

The Southern Trench is enclosed seabed basin at least 250m deep, which lies in the southeastern part of the Outer Moray Firth, 10km north of the Fraserburgh – Banff coastline (Figure 40). Part of the Southern Trench lies directly over the location of the Banff Fault (Andrews et al. 1990). The fault separates >250Ma and older (Palaeozoic) rocks on a platform to the south from the 250-67Ma old (Mesozoic) sedimentary basin of the Moray Firth.
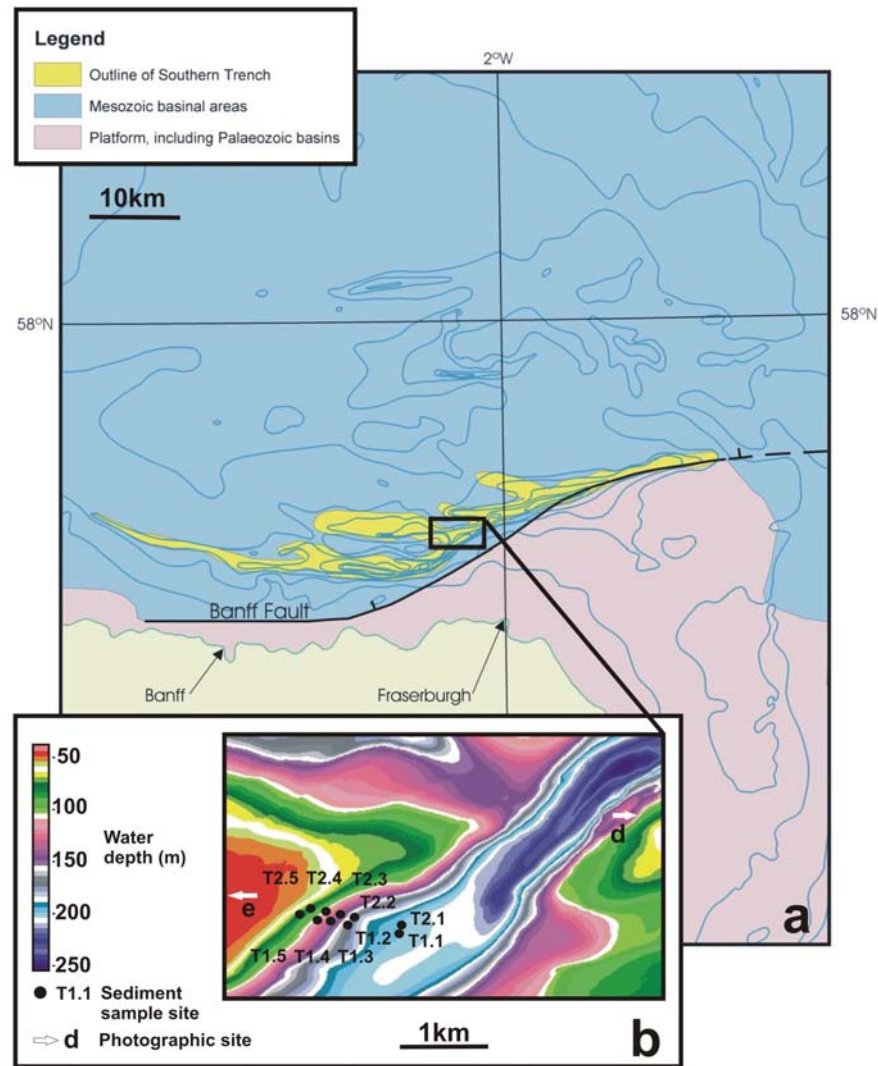
Figure 40. Southern trench: regional geological setting a. regional geological setting **b.** example of variation of seabed bathymetry, contour intervals derived from DTI 2003 multi-beam surveys. Locations of selected seabed-sediment sample and photographic sites are shown, the data from which are incorporated into Figures 41, 43, 44.

At more than 120km in length and with a total seabed area below 100m water depth of 550 square kilometres, the trench is the longest of a series of closed basins in the Moray Firth. The detailed seabed topography clearly shows that the main trench and its sub-trenches were formed from at least two erosion events in different directions (Figure 41 a, b). These events may have been driven by different

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processes of fluvial and/or ice-marginal erosion, for example, by movement of a fast stream of glacier ice, sub-ice water or possibly from the catastrophic release of meltwater, termed jokulhaup (Wingfield, 1990) (Figures 7, 8). Ice streams during the last glaciation are interpreted to have been from west to east, approximately parallel to the Buchan coast, but they are also curved towards the southeast (Merritt et al, 2003). It is thought that such ice movements, partly influenced by the bedrock geology, dominated the shaping of the trenches and sub-trenches.
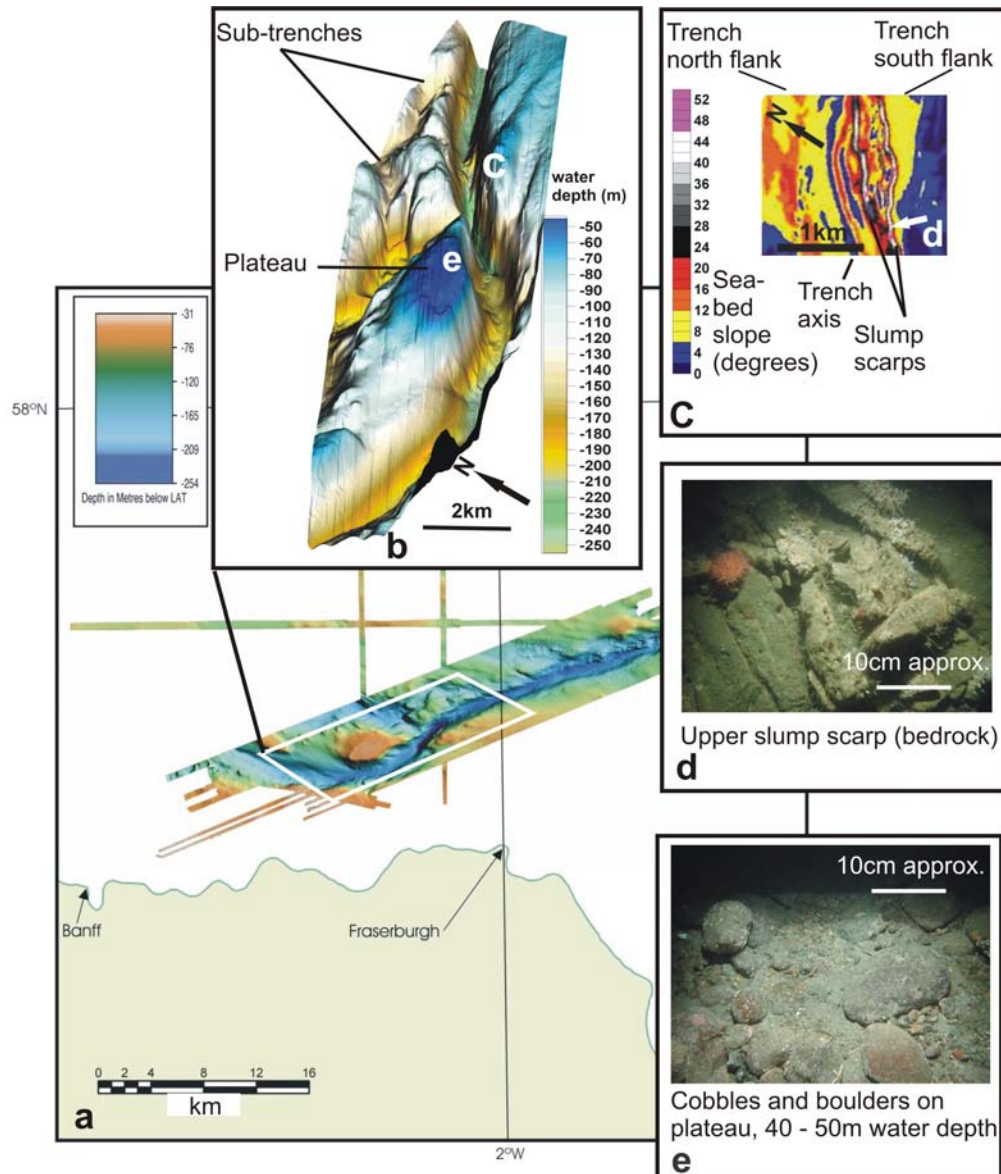
Figure 41. Southern Trench: physiography a. colour-shaded topography, DTI survey 2003 **b.** extract of seabed-terrain model **c.** example of seabed-slope changes associated with submarine slumps, southern flank **d**. bedrock at the presumed slip surface of the uppermost slump scarp **e.** seabed armour of pebbles, cobbles and boulders, extract from extensive photographic survey of the plateau. For more detail on bathymetric setting of **d** and **e** see Figure 40.

Seabed slopes vary from horizontal on the trench axis to more than 50° on the flanks with 'average' gradients commonly in the range of 6° to 22°. Arcuate scarps on the south wall have slopes of 50° or

more in an area of seabed slumping (Figure 41c). The upper scarp faces north and marks the uppermost edge of a former sediment and rock slump. The lower scarp faces south (up-slope) and is on the top of the trailing edge of the slumped sediment. The slump scarp faces are more than 1km long, the slump excavation zone has an estimated area of approximately 0.3 square kilometres and the estimated vertical drop between the top of the slump scarp and the top of the trailing edge of the slumped sediment is approximately 35m. Parts of the upper scarp consist of a planar and loosely-jointed bedrock that may have been the slip surface for the slump failure (Figure 41d). Previous sediment failures of unconsolidated sediments on the north wall at the east end of the trench are interpreted to be a result of peri-glacial activity since approximately 18,000 years ago (Long and Stoker, 1986). This was thought to be linked to differences in former insolation when parts of the south-facing flanks could have been warmed, leading to unfreezing and slope instability. However, an interpretation of the data from the slump discovered during the DTI 2003 surveys indicates that failure in bedrock lithology has also played some important part in trench instability. The slump is very small and slumps of this type are not thought to pose a significant risk of a tsunami wave in the Moray Firth.

The trench is set in an area where peak near bed peak spring tidal currents increase from <0.375m/s to >0.625m/s and are directed from west to east (Figure 17).

Sediments in the Southern Trench area are characterised by low carbonate contents (Figure 16). Overall, the sediments sampled within this area could be considered to be well-to moderately sorted fine-grained sands characterised by a dominant peak in the particle-size analysis curves at around 170 microns (fine-grained sand) (Figure 42).
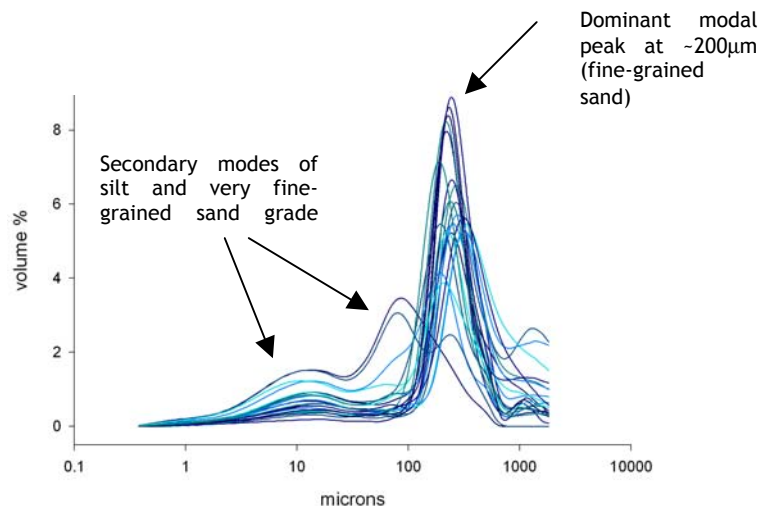
Figure 42. Southern Trench: grouped particle-size analysis curves

The polymodal grain-size distributions indicate that either the current velocity is not stable or that sediment mineral composition or biological activity may be contributing to the variation.

When polymodal and mono-modal distributions are put in their regional context a clear relationship between sample position and curve attributes is observed. Samples located within the trench axis (T1.1, T2.1, T3.7 and T3.9), show very well-sorted sands, with minor amounts of silt and fine-grained sand. Samples in distal areas from the axis of the trench display a stronger polymodal distribution pattern with two, possibly three, distinct modes (Figure 43).
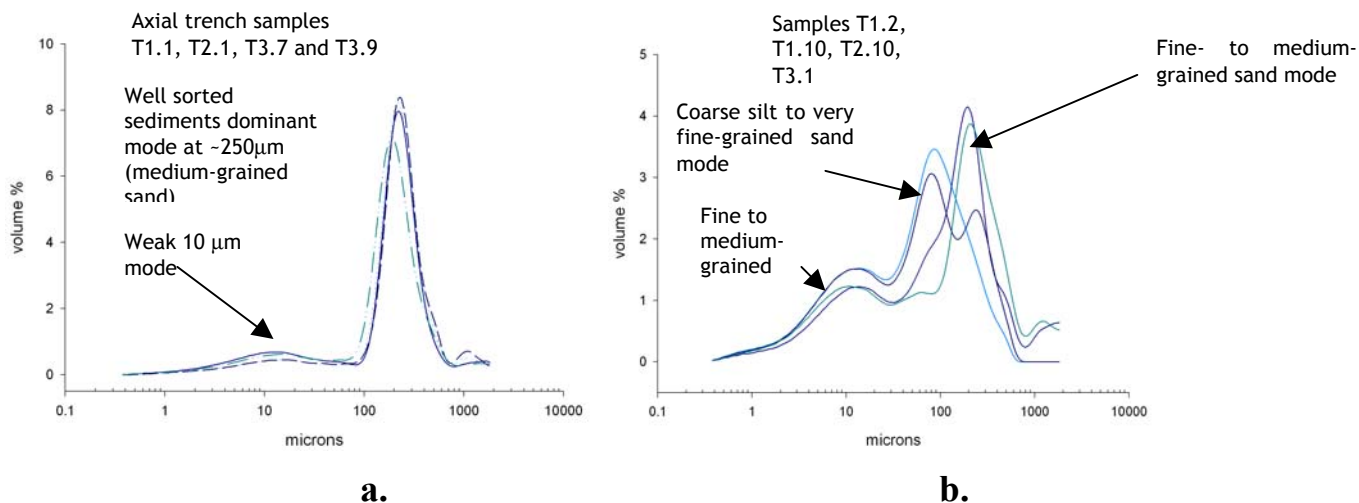
Figure 43. Southern Trench: particle-size analyses curves axial and flank samples. a. axial samples b. flank samples.

These observations are interpreted to suggest that at the time and place of survey the deeper-water trench axes were swept by faster currents and that the sinks for the finest-grained sediments were on the trench flanks, not the axes. A clarification of the depth of the boundary separating the areas of relatively high and low seabed stress at the times of survey can be obtained by comparing water depth with modal or mean grain sizes. A scatter plot of mean grain size against water depth indicates that the near-bed currents associated with the well-sorted sands locally occur below approximately 190m water depth (Figure 44).
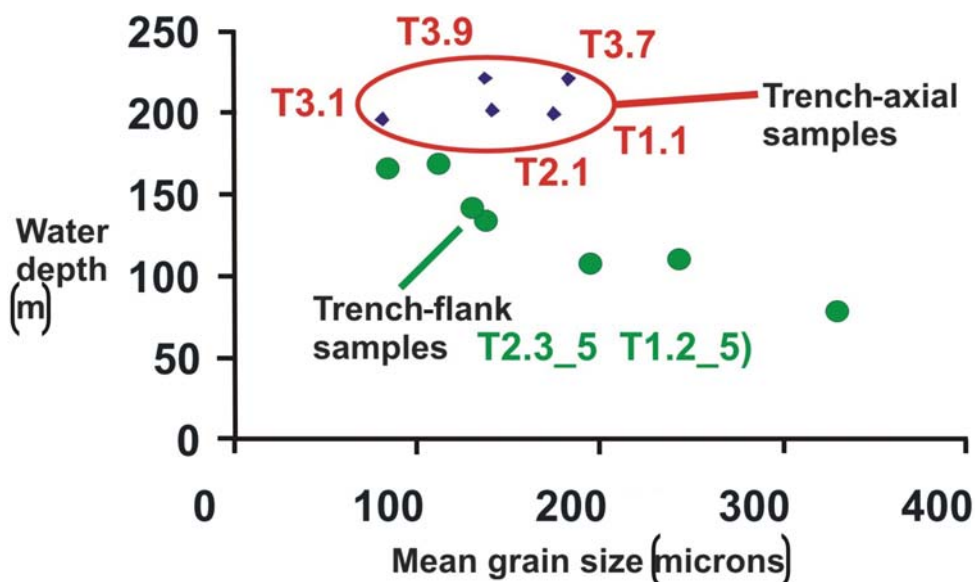
Figure 44. Southern Trench: variation of mean grain size with water depth

Notably, sample 3.1 appears to be consistent with the mean grain size trends observed on the flanks. This sample has been taken at a location where the trench axis with seafloor slopes less than 2° is broader (approximately 500m wide) compared to the axis of the trench associated with the very well-sorted seabed sands (less than 100m wide). It is therefore thought that the well-sorted axis sands are possibly unique to the most constricted deeper-water areas of the trench in type 4.2 conditions (section 2.11). The trench-flank samples show properties typical of a type 3 seabed condition (section 2.11). A significant feature of this type of seabed variation is also that it can be numerically modelled.

The DTI 2003 surveys did not sample the isolated plateau occurring to the north of the Southern Trench, the top of which ranges from approximately 50-40m water depth. Mean peak spring-tide near-bed current speeds range between approximately 0.25-0.374 m and are relatively low for the inner shelf in that region (Figure 17). The plateau top was examined by seabed photography in traverses extending north and east. An extract from the photographs show that parts of the seabed are characterised by well-rounded pebbles, cobbles and boulders forming a seabed 'armour'. There are relatively small areas of coarse-grained sand (Figure 41e). These observations are contrary to the blanket of muddy seabed sands mapped on the top of the plateau by the BGS (Figure 15). The seabed observed on the photographs is thought to reflect a mixed origin from former beach processes, isolation from bedload transport from the adjacent regions and exposure to extreme storm waves in type 1 seabed conditions (section 2.11) prior to the time when the photograph was taken.

Reconnaissance surveys, Outer Moray Firth

The smaller reconnaissance surveys undertaken by the DTI in 2003 had the objective of looking at the variability of seabed in areas of the Outer Moray Firth occurring outside of the detailed surveys of the Southern Trench and Smith Bank (Figure 45 a). The area is typified by very variable seabed topography and by relatively low mean spring-tide near-bed current speeds ranging from approximately 0.25-0.375 m/s (Figures 17, 45a). This part of the report summarises the results from each of those surveys. Some of the features and areas surveyed have not been previously named. The names assigned to these surveys therefore accord with the alphanumeric system adopted during the DTI 2003 surveys.

3.7   Smiler's Hole

Smiler's Hole is an enclosed basin that was formed at the margin of a former ice sheet (Figure 7). Only the southern part of the Smiler's Hole was surveyed in detail in 2003, this part of the basin forming approximately 50% of the total area of the basin complex. The surveyed basin is arcuate with the convex side facing north. It is more than 175m deep and 25km long in the area of survey (Figure 45).
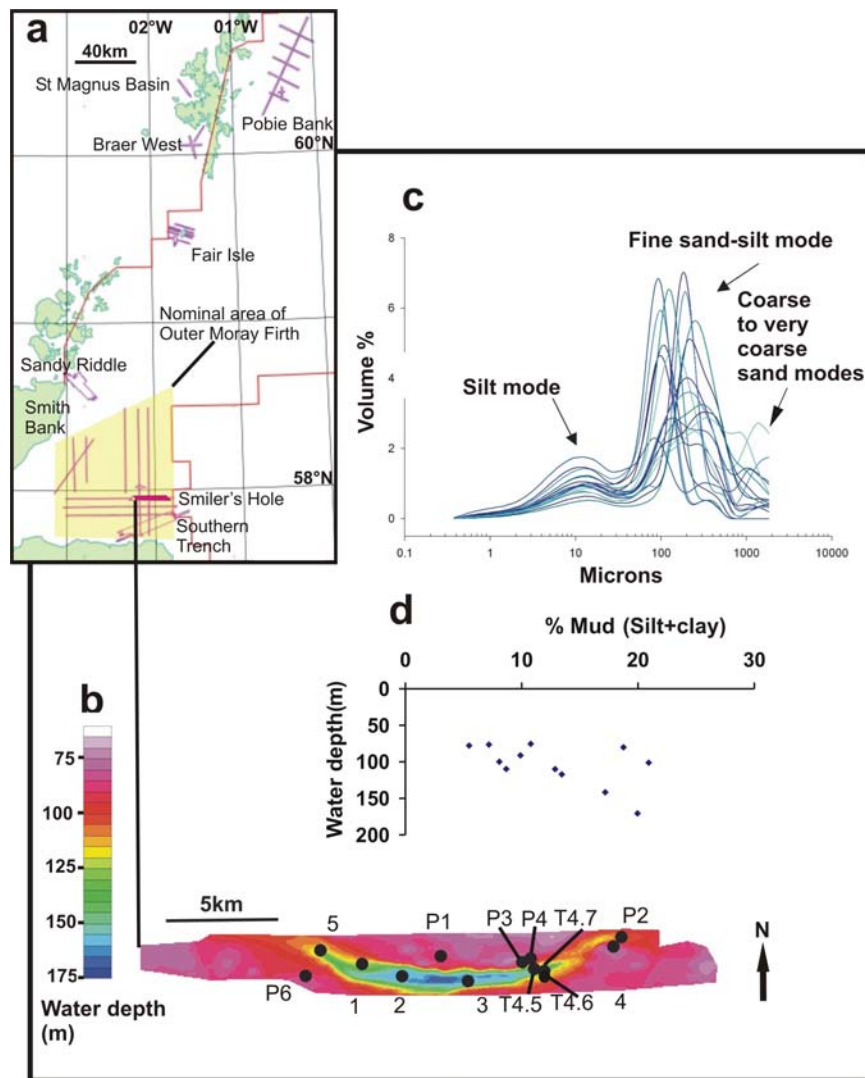
Figure 45. Smiler's Hole: regional setting and summary particle-size analyses
a. location **b.** contoured bathymetry extracted from swath surveys **c.** particle-size analyses summarised from samples **d.** water depth plotted against percentage volume of mud in the size fraction of sediments less than 2mm diameter.

Smiler's Hole is sited in a region of relatively weak near-bed peak mean spring currents (less than 0.375m/s, Figure 17). The sediment samples taken from the Smiler's Hole are characterised by polymodal grain-size distributions with at least three dominant size intervals in the fraction of sediments less that 2mm diameter (Figure 2c). The samples are classed as muddy sands. The largest fraction, less than 2mm diameter, has a modal particle-size distribution at around 100microns (very fine sand). Gravelly sediments are restricted to sites P1 and P6, which are in shallow water on the basin shoulders with P6 having more than 18% shell carbonate (Black, 2004). The polymodal distribution patterns are consistent with an environment that allows both sedimentation of the finest-grained muds and a process sediment of re-suspension under conditions of stronger near-bed currents. Under these conditions it is presumed that the sediments are sorted into fine- and very fine-grained sands, but they retain the underlying mud component. The overall trend of increasing mud with water depth on the basin flanks is consistent with the Smiler's Hole being a sink for fine-grained sediments (Figure 45d).

Unlike the Southern Trench, the confined axes of the Smiler's Hole are also sinks for fine-grained sediments. There is therefore an overall seabed setting of type 3 conditions in the Smiler's Hole.

3.8   Outer Moray Firth Area 1

Part of the survey is over a small enclosed basin occurring to the north of Smiler's Hole. The intention of the survey was to map topography and then sample seabed over water depths ranging from 65 to 85m outside the enclosed basin. The survey is set in bank topography associated with the crop of moraine at seabed and the basin is part of an assemblage of deeps identified with the locations of former ice margins (Figure 7). At this site, gravelly and coarse-grained sandy seabed sediments occur over the morainal banks in less than 65m water depth. Fine-grained seabed sands have been deposited within the enclosed basin in water depths of more than approximately 110m (Figure 46 b,c,d).
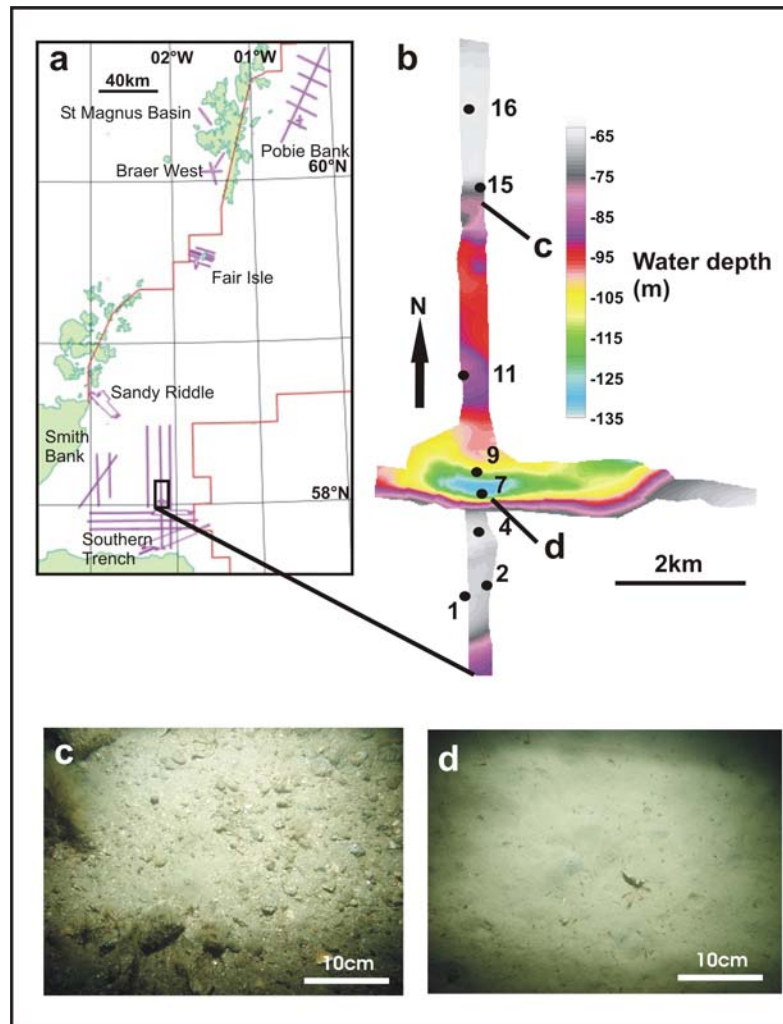
Figure 46. Outer Moray Firth, Area 1: physical and sample sites **a.** location **b.** contoured bathymetry compiled from swath surveys **c**. seabed photograph taken on moraine flanks: analysis of a sample taken in this area yielded 52% gravel, 46% coarse-grained sand and 2% mud **d**. seabed photograph taken from enclosed basin: analyses of a sample taken in this area yielded 0% gravel, 89% very fine-grained sand and 10% mud.

Coarse-grained sands are distributed within the range of 65 to 85m water depth outside the enclosed basin (Figure 47). Outside of the basin the coarse-grained sands do not show a consistent trend of modal grain sizes with a range of 66-69m water depth, or any systematic changes of percentage sand; the range of water depth is too small to suggest an environmental meaning for these observations.
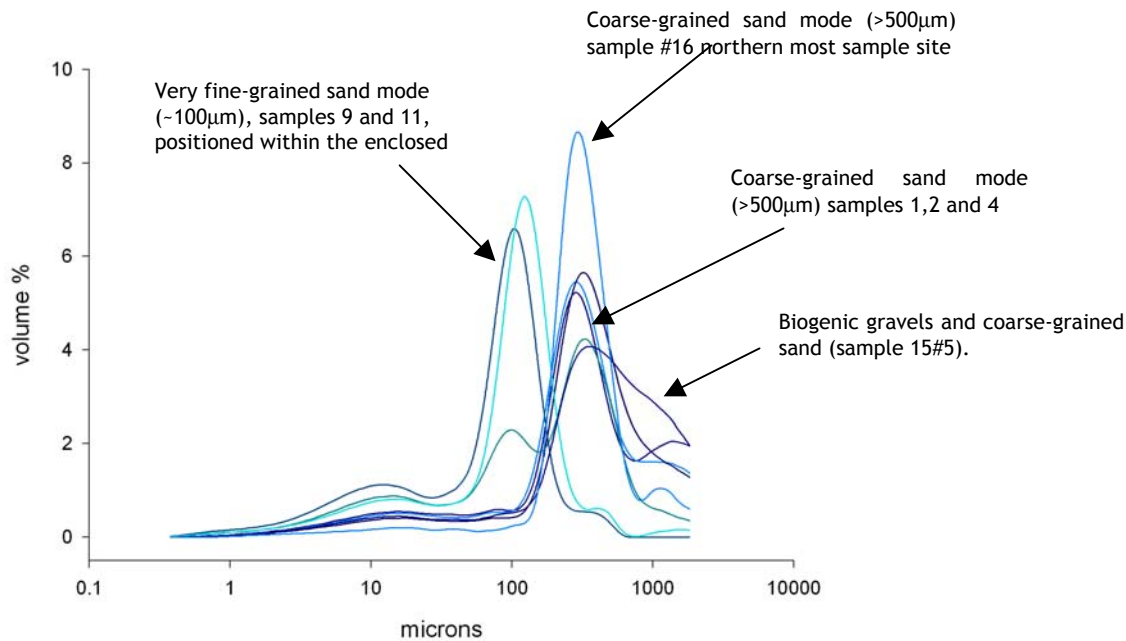
Figure 47. Outer Moray Firth Area 1: particle-size analysis curves and variation with sample water depth and position.

The observations from within the enclosed basin confirm a bi-modal distribution curve that is a characteristic of muddy sands deposited in enclosed basins in type 3 conditions.

3.9 Outer Moray Firth Area 2

This area was sampled over a water depth range of approximately 50 to 70m in order to compare the variations of the images of backscatter derived from sidescan sonar surveys with the particle-size analyses of sediments. The results show that a distinct boundary is observed on the sidescan sonar records at the junction between predominantly sandy and gravelly sediments. This boundary is also characterised by a distinct break in the gradient of the seabed slope (Figure 48). The data are insufficient to test for a fit to a seabed condition summarised in section 2.11.
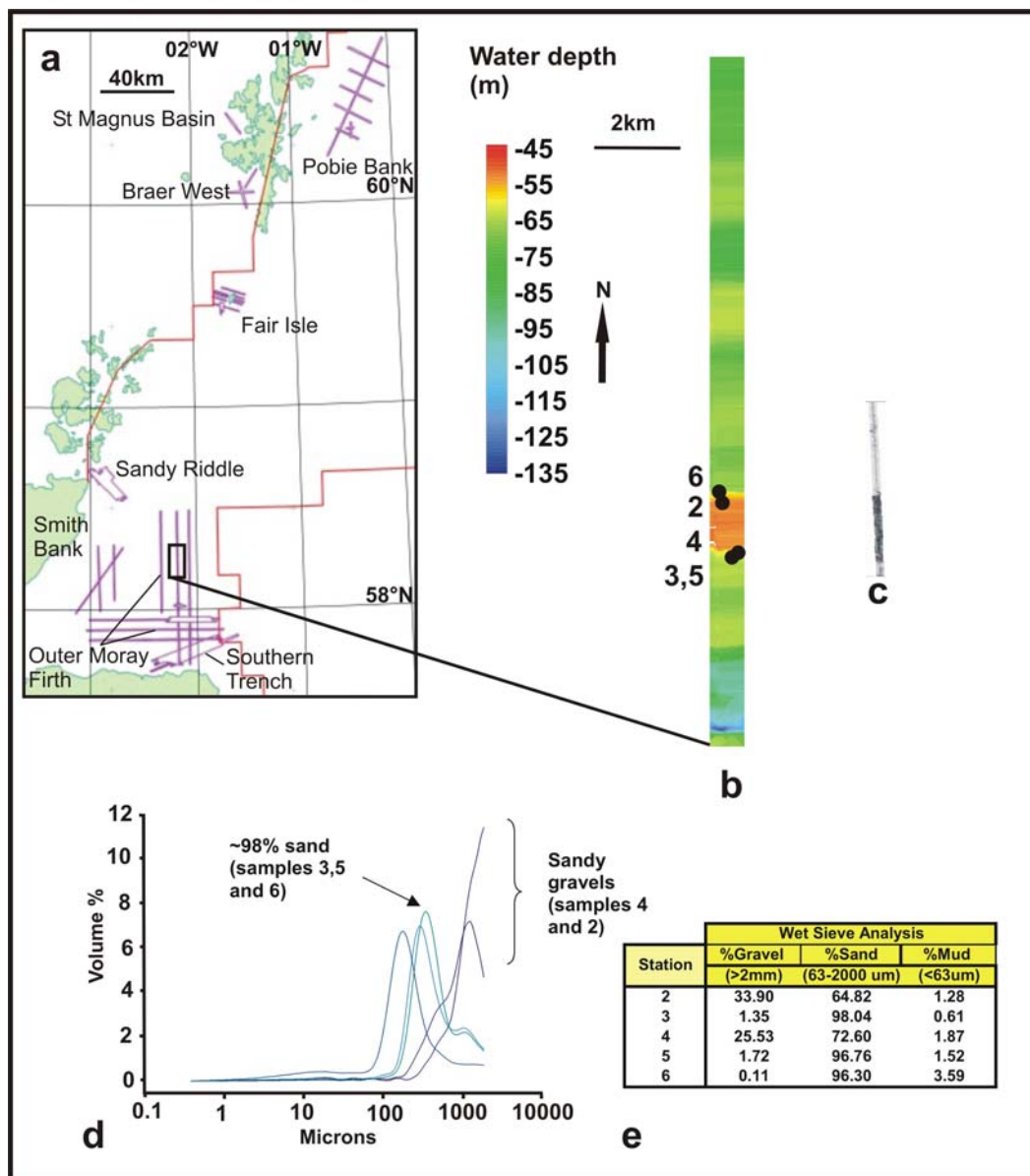
Figure 48. Outer Moray Firth Area 2: comparison of sidescan-sonar and swath-bathymetry records with sediment particle size analyses. a. location of survey **b**. contoured bathymetry extracted from swath survey **c.** sidescan-sonar record central to image in b: increasing sidescan-sonar backscatter is recorded with proportionally darker tones and is related to the coarser-grained sediments **d**. particle size analyses from less than 2mm diameter sediment fraction **e**. particle-size analyses of total sediment.

3.10 Outer Moray Firth Area 3

This area was sampled over a water-depth range of approximately 60 to 80m. Compared to Outer Moray Firth Area 2 (above) samples have been taken over seabed with gentler rolling topography with the seabed returning more subtle changes of backscatter intensity (Figure 49 a, b, c, d).

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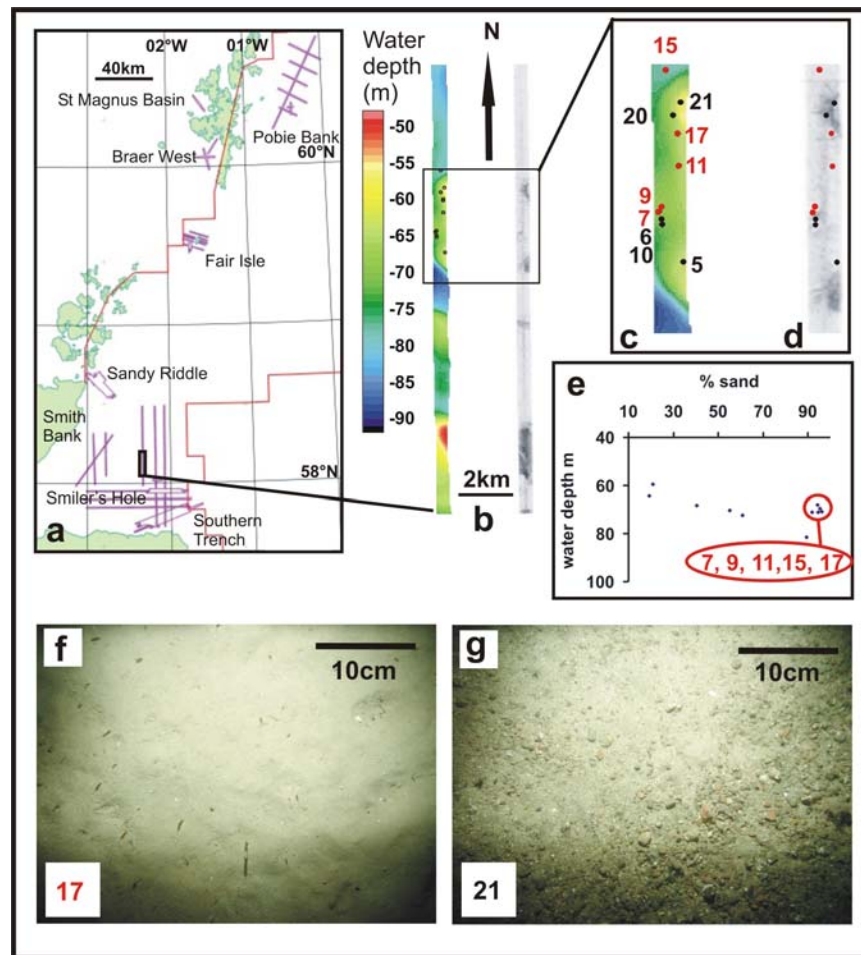
Figure 49. Outer Moray Firth Area 3: comparison of sidescan-sonar and swath-bathymetry records with sediment particle-size analyses. a. location of survey **b.** overview of contoured bathymetry (left) and sidescan sonar (right) **c**. extract of swath bathymetry with sample-station numbers and **d**. sidescan-sonar records of area in c **e**. scatter plot of variation of % sand content in total sediment with depth **f.** seabed photograph at sample position 17: well-sorted, fine-grained sand with ripples **g.** seabed photograph at sample position 21: sandy gravel.

The results show that approximately 50% of the study area is characterised by diffuse patches of low to high sonar backscatter. The areas returning the highest backscatter are gravelly sands and sandy gravels with a range of 4-75% of lithic gravel in the total sample (samples 5, 6, 10, 20, 21). These samples show a uniform increase of the percentage of sand with water depth indicating that sand has been winnowed from the shallower parts of the bank. This trend is broken in the mid-range of water depths by a cluster of sites on sand patches with sand ripples (Figure 49 f, g). These sediments are well-sorted fine- to coarse-grained sands with less than 2% gravel and show anomalously high percentages of sand compared to the depth-related trend for the gravelly sediments (Figure 49e). The sands are also finer-grained than those associated with the gravels (Figure 50).
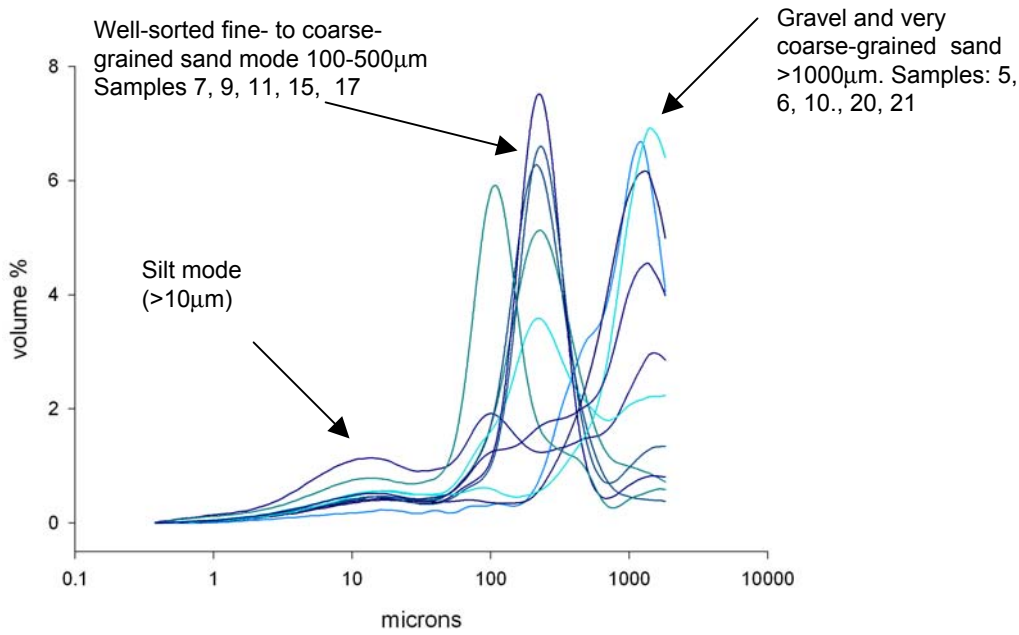
Figure 50. Outer Moray Firth Area 3: particle-size analysis curves

The observations are important because they demonstrate that significant changes of seabed texture can be quantified across the boundaries of the mobile bedforms. Variability in the composition of the seabed seems to be encapsulated in terms of a low- to medium-energy deposit (well-sorted sands) overlying a relatively high-energy deposit (gravelly sands). Unlike the samples from Smith Bank, there is a significant volume of silt indicated by the height of silt mode, so that it is thought that the sand patches were not formed in storm conditions. In this case it is suggested that the sand patches were formed as an adjustment to relatively weak near-bed currents that are a characteristic of the area in calm weather (Figure 17). It is thought that the gravelly sediments are relict and that they formed prior to deposition of the sand patches. The sidescan sonar images indicate that the gravelly sediments are more or less centred on the topographic highs indicating that there appears to be no north-or south-directed stress across the banks. On the basis of all the evidence, the area of seabed survey appears to be set in type 2 conditions.

3.11 Outer Moray Firth Area B

This area was investigated with a single swath of multi-beam survey and then sampled along the multi-beam survey in a 30km length transect extending to the west of the Southern Trench (Figure 51a). One objective of the survey was to look at an area of possible pockmarks (Figure 51a, area 1, Figure 51b). These have not been previously reported for this area (Figure 18). The second objective was to quantify the variation of gravel-free modal grain sizes over a regional transect approximately 30km long in a range of approximately 50 to 100m water depth (Figure 51a, surveys 1 and 2).
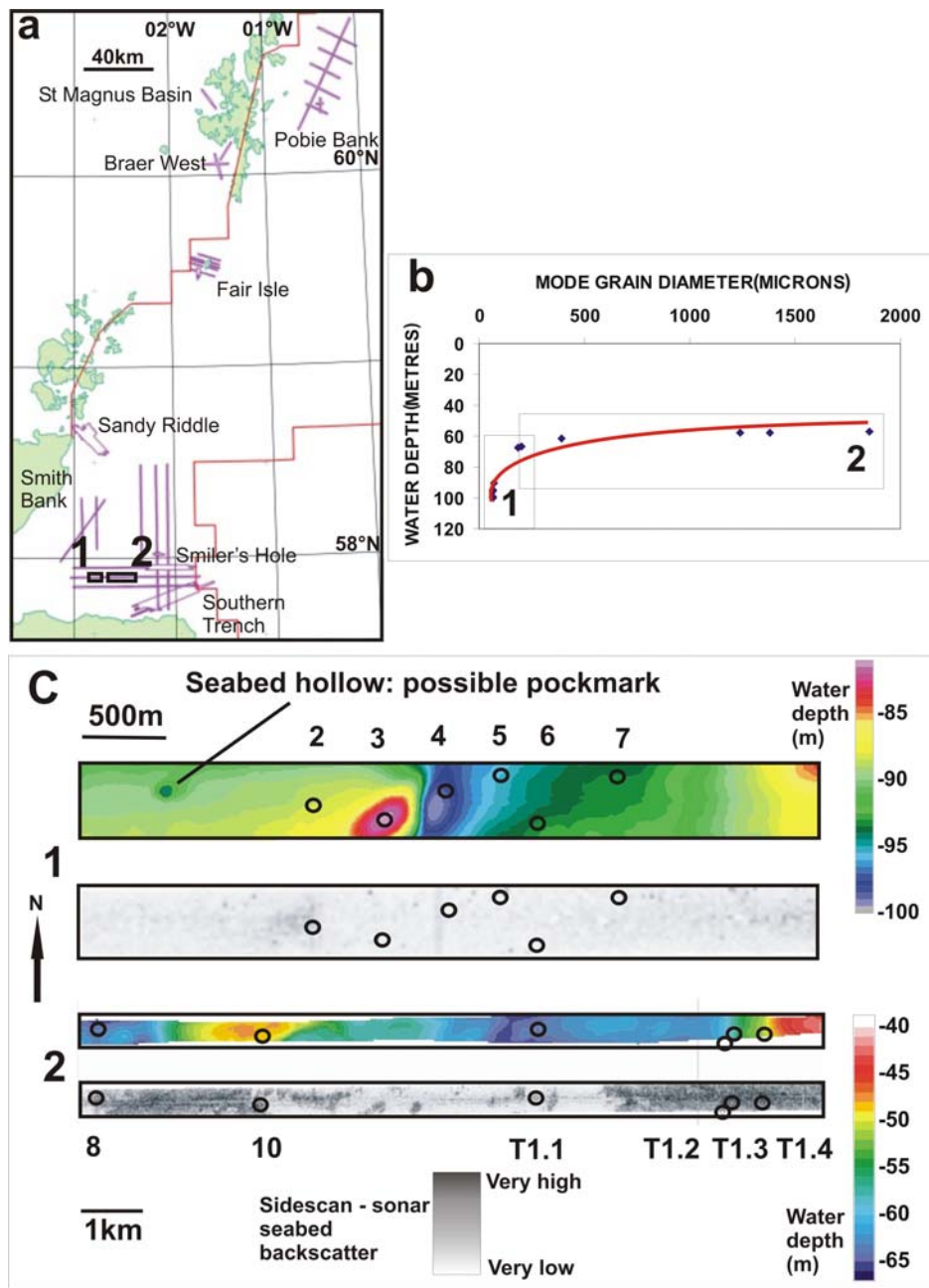
Figure 51. Outer Moray Firth Area B: locations and settings of swath-bathymetry survey and sediment sample sites. a. locations of surveys 1 and 2 **b.** extracts of swath bathymetry and sample locations, survey 1 **c.** synopsis of regional variation of mean grain diameter with water depth, surveys 1 & 2. Note the different scales for the image extracted for surveys 1 & 2.

An enclosed basin situated to the east of a possible pockmark has more than 1500m width. Although its length has not been quantified, it is at least 500m. The feature is approximately 10m deep from the shoulder at its east margin to the basin axis (Figure 51b). A seabed ridge occurs to the west of the enclosed basin. Samples from the enclosed basin consist of muddy sands with mean grain diameters ranging over approximately 66-72 microns (very fine-grained sands). The basin dimensions, the mean grain size of the seabed and its regional topographical setting indicate that it is more likely to be a small glacigenic enclosed basin than an exceptionally large pockmark. However, the sediments within the

enclosed basin appear to have higher carbonate and organic carbon than samples taken adjacent to the deep-water basin margins (Black, 2004). The characteristics of this feature require further investigation before the basin can be classed as a pockmark or not.

Sample survey areas 1 and 2 are adjacent to each other in an area joined by east-trending sidescan sonar and multi-beam surveys (Figure 51). The area is not characterised by large sediment waves (Figure 18) so that local variations in seabed topography are thought to originate from the underpinning bedrock structure and possibly from former moraines (Figure 7).   Except for site 10, which was marginally to the east of a bank crest, the 12 samples were on the west flanks of ridges and banks or on a bank crest. The distribution patterns of higher seabed sidescan backscatter indicate that more gravelly sediments occur on the west flanks than on the east flanks (Figure 51c). The sample transects are in a region where east-flowing near-bed peak mean tidal currents prevail in calm and stormy conditions (Figures 17, 51). The asymmetric patterns of seabed backscatter are thus thought to have originated because west flanks have been more strongly winnowed.

The sediments in survey area 1 show a correlation of deeper water with fining of very fine-grained sand over a 20m interval in the range of approximately 80-100m water depth in type 3 conditions. Sediments from survey 2 also show a correlation of deeper water with fining sediments in the fine- to coarse-grained sand classes in a range of 57- 67m water depth (Figure 51 c), probably in type 2 conditions. A detailed interpretation of extracts from the multi-beam data and from the sidescan-sonar records indicate that the samples were not taken from isolated sand patches or fields of sediment waves resting on gravel. A best-fit curve for both areas summarises the variation of the modes of the particle-size distributions in the gravel-free component of seabed sediments as:

$$Y = -12.54 \, Ln \, (X) + 144.8, \, R^2 = 0.84$$

where Y is water depth and X is the dominant mode of the particle-size distribution (Figure 51b). The regression coefficient (R^2) for the equation is a measure of the fit of the data to the equations, where 1 is a perfect fit and 0 indicates that there is no fit.

The equation appears to describe a regional trend of overall fining in the gravel-free fraction of seabed sediments with increasing water depth on the west flanks of the banks. On the basis of the open setting of the regional survey it is possible that the high regression coefficient may be tied to the imposition of a relatively uniform regional stress gradient imposed on the seabed along the line of section. Although these findings are in the context of a well-understood sample setting on the exposed flanks, the statistical basis for the equations is poor. Furthermore, there are no data for an analysis of seabed-sediment grain-size variations on each bank, or for comparison of the west flanks with the more sheltered east flanks. Further sampling in carefully controlled settings needs to be done to research the possibility of numerically modelling the spatial variability of seabed-sediment composition with position across the non-mobile banks.

3.12 Conclusions

1. Variations in seabed topography and composition are influenced by the structure and composition of underlying bedrock, the configurations and composition of features originating at former terrestrial and submarine ice-sheet margins, carbonate biological sedimentary input and by the interactions of all these with the near-bed currents.

2. Sea passages between the Scottish mainland and the Orkney and Shetland isles are major gateways for water input from the NE Atlantic continental shelf margins into SEA5. These gateways are characterised by very strong tidal and non-tidal near-bed currents and by potentially favourable conditions for a wider distribution of banner banks than previously supposed.

3. The low rates of sediment input to the region from the land relative to high rates of bioclastic input reworked from the seabed and deposited from suspension have resulted in large areas of the seabed around the Shetland and Orkney archipelagos being characterised by sand-wave fields, banks and intervening seabed deposits of almost pure bioclastic carbonates.

4. From interpretations of the attributes of seabed sediments from the tops of the banks in the range of 100m to 80m or less on Pobie Bank and 56-39m on Smith Bank it is concluded that the seabed had been stirred up during stormy conditions prior to the time of survey. Other site-specific surveys confirm the importance of storm conditions and post-storm readjustments as an influence on the regional and local variability of seabed composition.

5. The Sandy Riddle is a large banner bank, the complexity of which had not been previously appreciated. The bulk volume of the bank is stable due to being tied to very strong tidal streams flowing southeast around the west headland of the Pentland Skerries. The bedform-facing directions indicate that bank stability is partly tied to the recirculation of almost pure shelly carbonate gravel and well-sorted very coarse-grained sand.

6. A smaller bank with a mirror image of sediment recirculation was discovered to the east of the Pentland Skerries. A bank surveyed in 2003, which appears to be tied to the east side of Fair Isle, may also be a banner bank.

7. Parts of the enclosed deep of the Southern Trench and all of the Fair Isle Deep were surveyed in detail in 2003. These were originally formed at the margins of former ice sheets. They have very steep flanks, both locally more than 50° and both contain evidence that gravity-driven down-slope failure has locally affected modern seabed variability in the trenches. The conclusion from the Southern Trench is that bedrock failure along jointing has probably played a significant part in determining basin-flank instability.

8. The axes of both the Southern Trench and the Fair Isle Basin are associated with silt-free sediments. The conclusion from the DTI 2003 survey is that the well-sorted sands in the Southern Trench are possibly only distributed in areas where tidal flow has accelerated through constricted trench passages below approximately 190m water depth. The conclusion for the Fair Isle Basin is that its axis and flanks are not protected from the near-bed strong tidal currents that prevail in the surrounding shallower waters. Other enclosed basins that are protected from prevailing currents on the open continental shelf are more or less permanent sinks for fine-grained sediments.

9. Preliminary results from the new surveys indicate that variations showing an overall relationship of decreasing modal particle size with increasing water depth may be quantitatively described for seabed conditions that are below extremely energetic near-bed currents and for the flanks of banks facing the prevailing near-bed currents.

10. Significant departures from the regional relationship between decreasing particle size with increasing water depth are consistently observed where there is asymmetry in the exposure to prevailing near-bed currents with position across the banks. This variation is registered across and within the sediment size classes. It has been broadly identified both as a result of the DTI 2003 surveys and the preceding BGS regional surveys. Its lack of characterisation is a gap in our knowledge in terms of understanding processes and being able to monitor possible significant seabed environmental changes.

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Appendix 1. Technical basis: improving the understanding and utility of existing and new data

1. Comparison of seabed topography derived from multi-beam and 3D-seismic data

A Simrad EM1000 Multi-beam echosounder,1000Hz frequency with Fugro Starfix MN8 DGPS was used for primary navigation throughout the DTI 2003 surveys. Differential corrections from the AOR (E) satellite were received through the JRC 45 MK 1 Inmarsat 'M' dome, and converted by a Frequency Translator Unit (FTU). Raw GPS data are received by a dedicated antenna. GPS and differential data are then decoded by the Fugro Starfix VBS MK II unit and interfaced to the MRDGPS software, version 2.05.03.

10m xyz grid of bathymetry was created from the multi-beam data where the quoted horizontal positioning accuracy is in the region of 1.5 to 2m.. It is quoted that the vertical resolution of the EM1000's soundings can typically be in the order of 0.3% of water depth or 15cm (whichever is greater). Data were referenced to lowest astronomical tide.

The shaded-relief image shown in Figure 1 was generated by ER Mapper software using the standard shaded-relief algorithm with illumination from the north to permit direct comparison with the 3D dataset covering part of the same area.
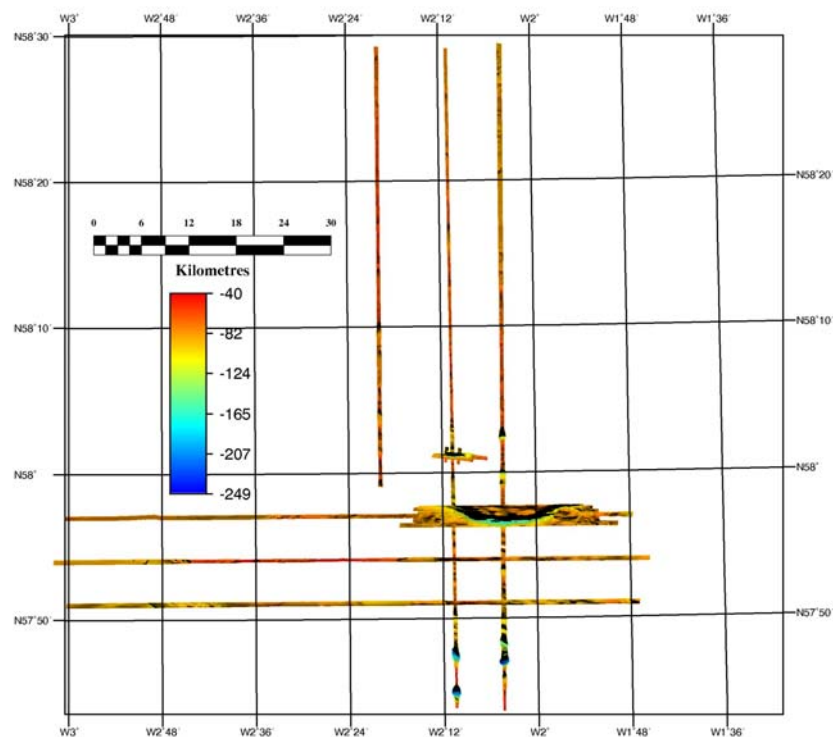
Figure 1. Shaded-relief image of multi-beam bathymetry in the Moray Firth.

The original and primary purpose of the seabed pick from the 3D commercial dataset was to help identify the live traces within the data volume. To this end only a limited number of seed points were used and the tracking parameters were relaxed sufficiently to enable the propagation of the horizon throughout the volume. This has given rise to a very noisy horizon, which is observed in both the shaded-relief image and on the comparative profile.

A survey footprint is a data artefact that is defined as systematic noise that correlates with the primary acquisition direction. They are seen as pronounced linear corrugations in the surface. Two sets of footprint are observed in the seabed image from the 3D dataset indicating that the data volume has been generated by merging at least two separate surveys. The primary footprint direction is north-south for most of the data. On the eastern part of the image a local footprint with a northwest-southeast orientation is observed.

Event skipping on the 3D dataset is where the auto-tracker has jumped from the seabed event to a deeper horizon that may be locally stronger. This is caused in part by relaxation of the tracking parameters to propagate as widely as possible throughout the volume. In Figure 2, event skipping is observed in the northern half of the image.

The low frequency content of the 3D commercial seismic data gives rise to a low vertical resolution, approximately 20m. The seabed image can be thought of as representing a composite response of the first 20m or so of the seabed and near seabed sediments, depending on which wavelet gave the most consistently pickable horizon. The composite response only partly accounts for the consistent deeper seabed pick obtained from the 3D commercial survey compared to the multi-beam survey.

The trace-to-trace separation of the 3D seismic grid is 25m. As the data volume has been migrated this represents the practical limit of horizontal resolution for the 3D data.

A shaded-relief image of the 3D dataset was generated using ERMapper software (Figure 2). A standard shaded-relief algorithm was used with illumination from the north to minimise the impact of survey footprint. To improve the visual quality of the image the original imported horizon was interpolated using Fast Fourier Transform (FFT) interpolation to fill in minor data gaps.

The datasets from the DTI 2003 surveys and the 3D commercial surveys overlap only along one thin zone of data. Figure 2 shows the location of a north-south profile taken along the overlap zone. Figure 3 shows a scatter plot and comparative profiles that compare the multi-beam bathymetry with the 3D pick depth, this last converted from two-way-time to water depth assuming a 1500m/s interval water velocity.
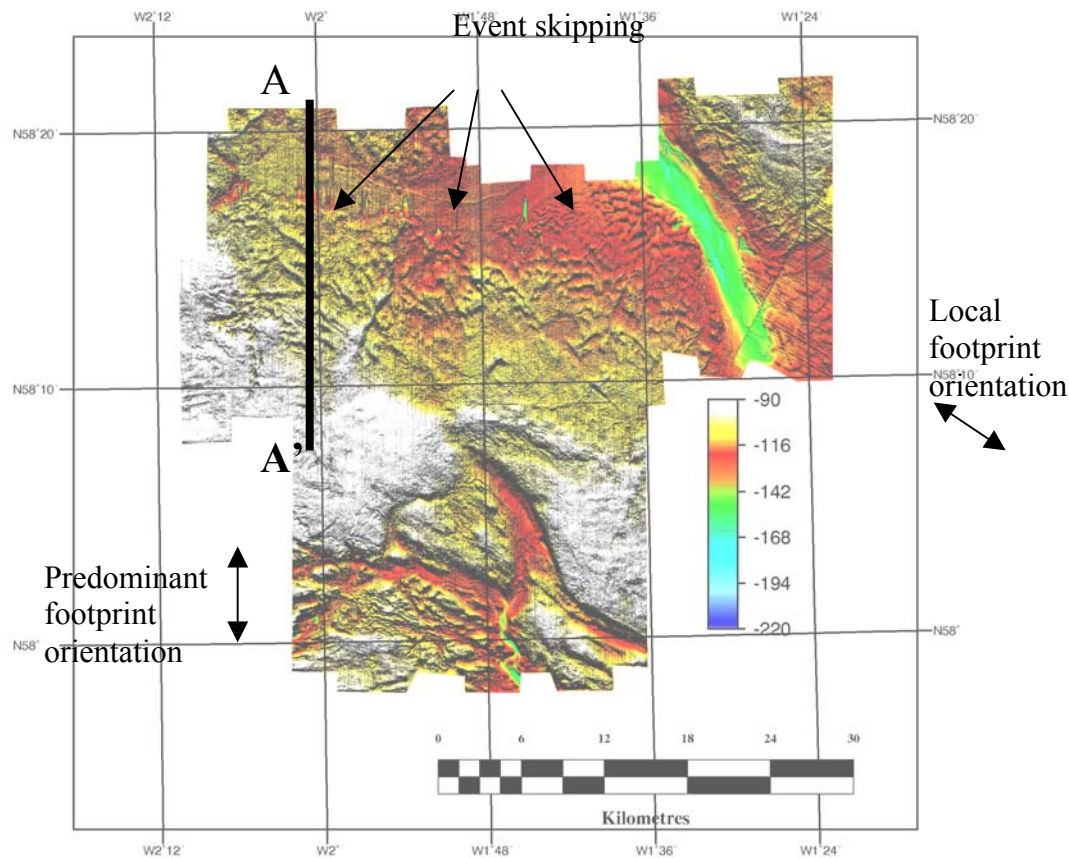
Figure 2. Shaded-relief image of depth-converted 3D seabed pick horizon in the Moray Firth. Assumed interval velocity of sound in water is 1500m/s. Illumination from the north to reduce visual impact of footprint artefacts. Profile AA' is the location of Figure 3.

The overall regression statistic is high, as is reflected in the profile view where the two bathymetric datasets mirror one another closely. Although the 3D-seismic data may not be used as a proxy for accurate measurements of water depth, the significance of the comparison between the datasets is that the seabed image provides an excellent basis for precisely mapping relative changes of seabed topography. Some of the discrepancies between the datasets are discussed below.

(A)

(B)
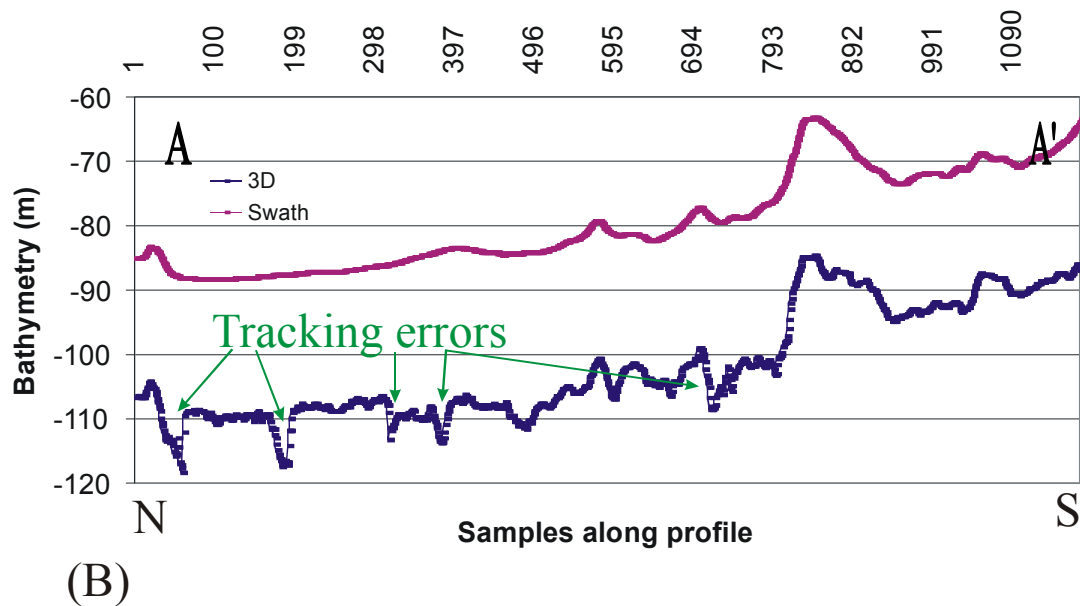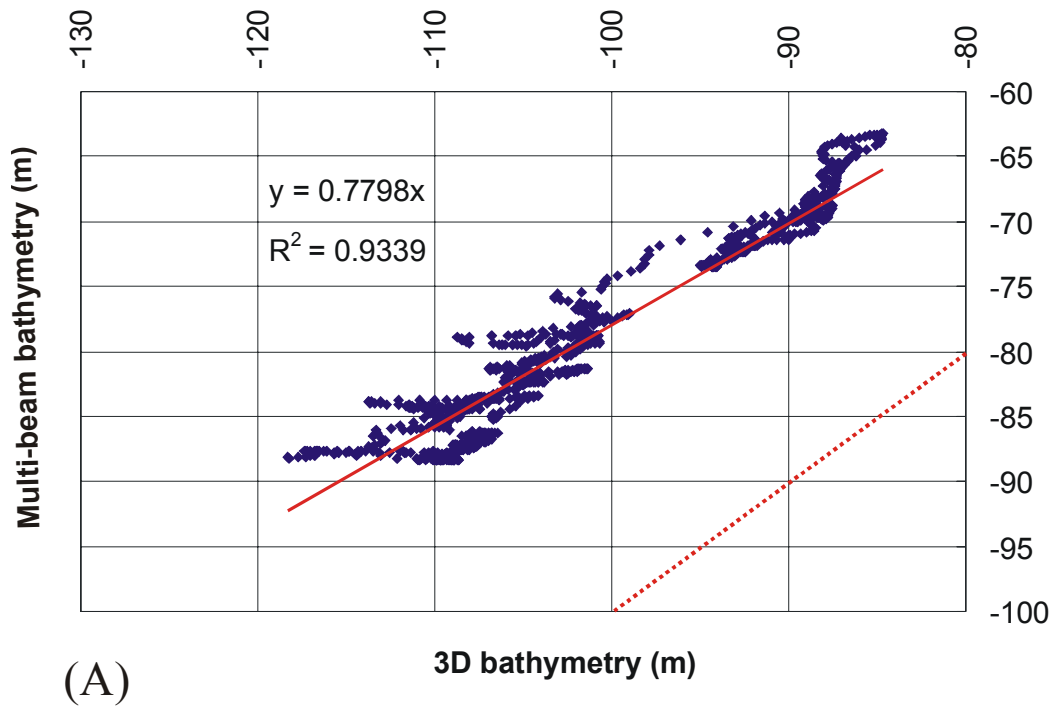
Figure 3. Comparison of swath (multi-beam) bathymetry and 3D seabed pick horizon. Depth converted for the 3D data using 1500m/s for the speed of sound in water. Location shown in Figure 2. (A) scatter plot of the two bathymetry values. Solid red line is least squares fit, dashed red line is the one-to-one line. (B) north-south profile plot. Note the noise observed in the 3D, especially the tracking error spikes. Note also that the 3D estimate of bathymetry shown in the uncorrected blue plot is consistently deeper than the swath by approximately 20m.

There is a static shift between the two depth curves of approximately 20m. The low frequency content and minimum phase characteristics of commercial deep seismic often results in deeper water-depth estimates. It is also common for seismic surveys to have additional static errors due to minor processing imprecision and interval velocity errors. For example, the correlation gradient is less than unity, suggesting that the use of a water velocity of 1500m/s may be too high in this area.

It is clear that the 3D seismic is noisier than the swath in this instance. As has been alluded to above, the horizon generated from the seismic volume was originally intended to help identify live traces rather than to accurately image the seabed reflection. This is particularly evident in the large number of tracking errors observed on the profile view and the scatter plot.

It has been commonly observed that in deep water (>300m) the seabed event on commercial 3D seismic is as good as, if not better than swath bathymetry. However, in shallower water, the reverse is true due to refraction and supercritical energies contaminating the seabed return on 3D surveys. Water depth, seabed conditions (velocity) and the minimum shot to receiver offset distance become critical factors in determining the quality of the seabed event on any particular survey. In general, surveys designed to optimally image shallow targets (1-2 km deep) will give good seabed returns whereas those designed to image deep targets (3-6 km deep) will give poor or highly contaminated seabed returns. In either case, we can expect higher noise levels on 3D-survey picks than from swath bathymetry. Furthermore, the noise will increase with decreasing water depths. The shallow-seabed imaging problem has been discussed in greater technical detail in Bulat (2004).

REFERENCE

Bulat, J. 2004. Imaging the seabed in shallow water areas (<300m) using 3D surveys. *British Geological Survey Internal Report*, IR/03/168.

2. Comparison of seabed topography derived from multi-beam and BGS regional single-beam data

The digital model of regional geomorphology (Figure 1) has been extracted from DigBath250 which is a digital contoured bathymetry of UK and adjacent European waters (www.bgs.ac.uk/products/DigBath250). The digital bathymetric contours have been copied from a series of published BGS 1:250,000 seabed sediment maps. The SEA5 area includes seabed mapped in part by seventeen BGS 1:250,000 map sheets published, with one exception, between 1984 and 1990.

The bulk of the data used to produce these map sheets were collected during offshore surveys conducted by BGS between 1969 and 1985 with the majority run in the1970's. Therefore much of the data is over 25 years old. The surveys took place before the advent of powerful personal computers and software, the inception of global positioning systems and the development of digital survey technology, such as multi-beam swath-bathymetry survey, which has revolutionised the volume, quality and resolution of geophysical and bathymetric data gathered during offshore surveys.

The bathymetric data collected by BGS were produced by a single-beam echo sounder which measured the water depth beneath a survey ship as it sailed along a survey line and displayed a profile of the seabed as a continuous line on a paper echo-sounder record. For an interpretation, depth values were generally plotted at 1:100,000 scale for contouring by hand prior to final compilation at 1:250,000 scale. Along the survey line bathymetric point data could be plotted at distances of 150m or less. However the value of this relatively high sample rate is compromised by a number of factors:

1. Navigation systems used during this period could only produce positional accuracies measured to tens or hundreds of metres.
2. Although echo sounders could measure water depth beneath survey ships to accuracies of 0.1m none of the bathymetric data collected by BGS has been corrected for tidal variation. Within the SEA5 area the mean spring tidal range off the Scottish mainland is generally 3m to >4m and declines eastward to about 1.5m. Where survey lines have crossed, variations in depth values of up to ±5 m have been noted. This is primarily due to the lack of tidal correction.
3. The BGS survey lines have been run on a grid system and although some lines are as close as 1km the majority are around 10km apart, with some as wide as 22km. This effectively means the across-line resolution varies from 1000m to 22,000m.

The pattern of BGS geophysical surveys within the SEA 5 area is a rectangular grid of north–south and east-west trending lines over most of the seabed with a change to north-east – south-west and north-west–south–east design out from the Moray Firth.

Although the regular grid pattern produces a systematic coverage its spacing can only pick up large-scale regional features and even then can only give a general impression of their morphology. Examples of this are the north-south trending deeps at the eastern margin of the SEA5 area (Figure 4).

Smaller scale features such as the pockmarks that occur frequently on the seabed 150km east of the Orkneys cannot be resolved by this grid pattern. Pockmarks are ovoid depressions, which can reach depths of 10m but are commonly 2–3m deep and 50 to 200m in diameter. A cross profile of a pockmark could be picked up by a single BGS line but its extent could not be mapped.

Although the bathymetry displayed in DigBath250 is based on relatively old data it is satisfactory as a regional scale dataset. It displays all the primary morphological features based on a regular grid of bathymetric soundings and has value and utility for regional planning and assessment.

The geophysical survey conducted for the SEA5 programme in 2003 investigated 13 discrete areas and there was no intention to cover the whole seabed with a systematic grid like the BGS surveys. Bathymetric data was acquired during the survey with a modern multi-beam system (Appendix 1 part 1). This measures water depth across a wide area of the seabed beneath a survey ship, unlike single beam echo sounder which creates only a thin line of data. The vertical accuracy of the multi-beam data is of the order of 0.3% of water depth or 15cm. In 100m of water this would be 30cm. Positioning and navigation was provided by a Differential Global Positioning System (DGPS) with horizontal accuracy quoted as in the region of 1.5 to 2m. Modern survey and navigation technology has certainly improved the resolution and accuracy of survey data compared to DigBath 250 (Figure 4). However, the value of the modern data is currently limited to relatively small discrete areas. This limitation now represents a significant data gap for strategic thinking and resource evaluation purposes.
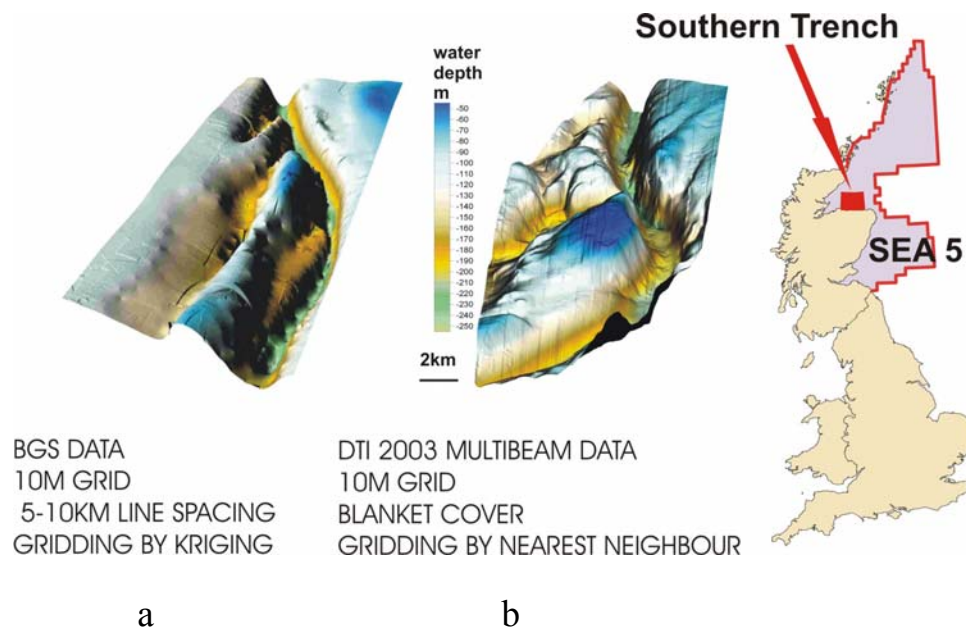
Figure 4. Comparison of submarine topography derived from single-beam and swath (multi-beam) databases. a. extract from BGS single-beam regional seabed survey **b**. extract from DTI 2003 multi-beam seabed survey. The digital-terrain models are presented at the same horizontal and vertical scales and the perspective view looks towards the east.

3.   BGS model of seabed sediments

The digital model of regional seabed sediments (Figure 15) has been taken from DigSBS250, which is an attributed digital seabed sediment map of UK and adjacent Irish waters. Exactly like the DigBath250 digital bathymetry described in A1.2 the DigSBS250 data have been copied from the series of BGS 1:250,000 seabed sediment maps published, with one exception, between 1984 and 1990.

The sediments are classified by grain size according to the relative proportions of gravel, sand and mud based on a modified version of the Folk gravel/sand/mud triangle (Folk, 1954) and on the Wentworth Grain Size Classification scheme.

The bulk of the data used to produce these seabed-sediment map sheets were collected during offshore sampling surveys conducted by BGS between 1969 and 1985 with the majority run in the1970's. These were generally undertaken after the geophysical surveys that collected the bathymetric data used in DigBath250. The sampling and coring programme was designed to help in the interpretation of the geophysical data collected by BGS therefore the seabed samples and cores are generally positioned on geophysical lines. The spacing of samples is similar to the geophysical-line spacing varying from 1km to 15km but average around 8-10km depending on area.

The standard Shipek grab used by BGS for sampling the seabed collects the top 10 to 20cm of sediment and may disturb the sample on impact with the seabed. It also has a relatively small footprint of 200mm x 200mm. A coarse gravelly seabed with cobbles and boulders may not be properly sampled because some gravels may be too big for the jaws of the grab. A similar constraint applies to the use of core samples because a BGS corer generally has an internal core diameter of 85mm, any sediment larger than this would not be sampled.

The caveats described for the DigBath250 data with regard to the accuracy of position fixing for BGS geophysical lines also hold true for the seabed sediment sample locations. The sediment boundaries on the maps are generalisations and at a regional scale. However, the major sedimentary environments are adequately resolved for regional planning and assessment. The dataset indicates that in a number of areas a strong relationship exists between the morphology of the seabed and the nature of the seabed sediments. (Frontispiece).

Appendix 2 SEA4 DTI 2003 St Magnus Bay and Braer West Surveys

SEA4 DTI 2003 St Magnus Bay and Braer West Surveys

Reconnaissance sidescan sonar and multi-beam swath-bathymetry surveys were completed by the DTI in 2003 in areas to the southwest of Shetland. The surveys are in the region affected by an oil spill originating when the oil tanker *M.V. Braer* ran aground in January 1993. Oil first spread shoreward adjacent to the grounding site at the south tip of the Mainland Shetland peninsula. The oil spill then migrated northwards in a direction coincident with the boundary separating SEA4 and SEA5 and then westwards (Figure 1).
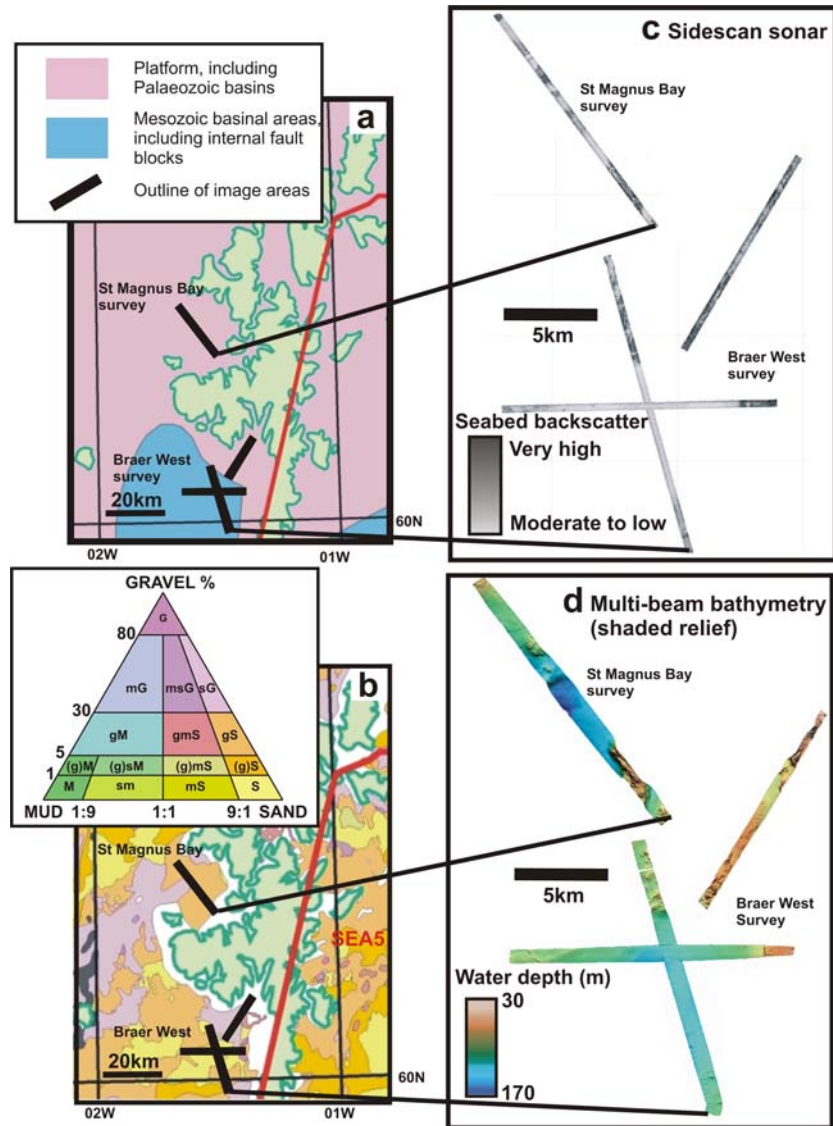
Figure 1. West of Shetland: St Magnus Basin and Braer West surveys. a. summary of bedrock geology **b**. summary seabed sediments **c**. sidescan-sonar images of seabed backscatter **d**. swath multi-beam bathymetric-survey images of seabed shaded relief. Surveys **c** and **d** are centred over the same lines of survey.

The purpose of the DTI 2003 surveys was to verify the seabed geological setting of the spillage region by running selected surveys over areas with known variable seabed. These areas had been previously regionally mapped by the BGS using data that had been acquired more than 24 years ago. The DTI 2003 surveys did not acquire data from seabed photography or from seabed-sediment sampling.

St Magnus Bay

The survey is situated over a former glacially over-deepened basin that has approximately 170m water depth (Figure 7). The basin has been eroded into an uplifted platform that includes Palaeozoic bedrock more than 290 million years old (Figure 52 a). Seabed sediments are mainly gravelly sands with 40-100% shell carbonate in the total sediment (British Geological Survey, 1998). Net seabed sediment transport is driven by tidal currents and is towards the north across the western approaches to the St Magnus Bay and is anti-clockwise in the nearshore areas within the bay.

The patterns of very high sidescan-sonar backscatter coincide with the multi-beam images of structured seabed, (Figure 52 c,d). These observations indicate that bedrock probably crops at seabed, the strongest evidence for which is seen at the southeast margin of the survey. This pattern of bedrock crop at seabed had not been previously resolved on the BGS regional seabed-sediment map because it occurs in a 'white' zone where there was no data (Figure 52b).

Braer West

The Braer West surveys were completed over a former glaciated enclosed basin up to approximately 120m deep. The basin is sited across a boundary separating uplifted platform from a Mesozoic basin (Figure 52 a).

Seabed sediments consist of sands, gravelly sands and sandy gravels with 40-100% shell carbonate in the total sediment. The highest carbonate percentages occur in the sandy gravels (British Geological Survey, 1998). The seabed with sandy gravels is also characterised by patches of bedrock crop at seabed or just below seabed (British Geological Survey, 1998). The bedrock crop is associated with elevated seabed topography, patches of strongly structured seabed and seabed returns of the highest sidescan-sonar backscatter (Figure 52c, d). Zones of seabed with moderate sidescan-sonar backscatter coincide with areas of gravelly sand. Seabed returning the lowest backscatter occurs in the areas mapped as sands (Figure 52 b, c).

Net sediment transport is driven by tidal currents and is towards the northwest on the outer approaches to the survey area. It is anti-clockwise around the coastal margins of the bay. Sediment waves of height 4-6m have been observed in the northern part of the bay (British Geological Survey, 1998) but were not observed in the data acquired during the DTI 2003 surveys.

The results for this area are significant because comparison of the BGS sediment-distribution map with the DTI 2003 sidescan-sonar surveys indicate that the boundaries of the major sediment classes appear to have been more or less stable over the last 24 years or more.

BRITISH GEOLOGICAL SURVEY. 1998. Shetland 1:250,000 Map (Edinburgh, Scotland: British Geological Survey) Sea-Bed Sediments

Appendix 3   Sediment analyses and seabed-sediment classification

1. Grain-size scale used for sediments

GRAIN SIZE SCALE FOR SEDIMENTS

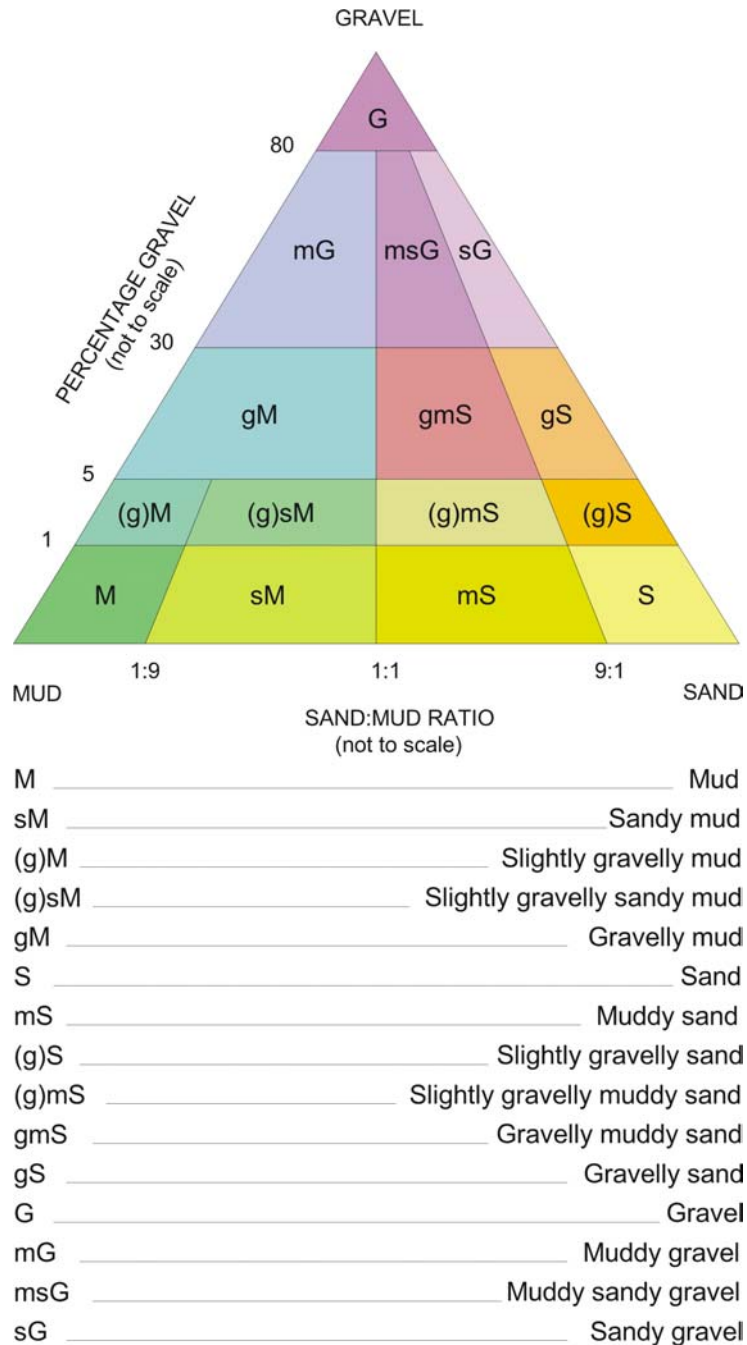| Millimetres	Microns	Phi (φ)	Wentworth Size Class	
			Boulder	
— 256 —		-8	Cobble	
— 64 —		-6		GRAVEL
— 4.0 —		-2	Pebble	
— 2.0 —		-1	Granule	
— 1.0 —		0	Very Coarse	
— 0.5 —	500	1	Coarse	
— 0.25 —	250	2	Medium	SAND
— 0.125 —	125	3	Fine	
— 0.063 —	63	4	Very Fine	
	32	5	Coarse Silt	
	4	8	Fine-med Silt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

Figure 1. Grain-size scale for sediments.

2. Outline procedures for particle-size analysis

Particle-size analyses were undertaken using a Coulter LS230 Laser diffraction instrument (Black, 2004). The size range capability is 0.4microns (clay) to 2000microns (very coarse-grained sand) where 1000 microns = 1 millimetre. The size classes within the gravel fraction (>2000microns) are therefore not quantified by the laser diffraction method and were not presented in this report. The results for the non-gravel fraction of the sediments are presented as volume percentages. There is no accurate method of transforming these into weight percentages.

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.

3. Seabed-sediment classification

M _____ Mud
sM _____ Sandy mud
(g)M _____ Slightly gravelly mud
(g)sM _____ Slightly gravelly sandy mud
gM _____ Gravelly mud
S _____ Sand
mS _____ Muddy sand
(g)S _____ Slightly gravelly sand
(g)mS _____ Slightly gravelly muddy sand
gmS _____ Gravelly muddy sand
gS _____ Gravelly sand
G _____ Gravel
mG _____ Muddy gravel
msG _____ Muddy sandy gravel
sG _____ Sandy gravel

The above classification is based on that of R.L.Folk,
1954, J. Geol., 62 pp344-359.

Figure 2. Seabed-sediment classification scheme.