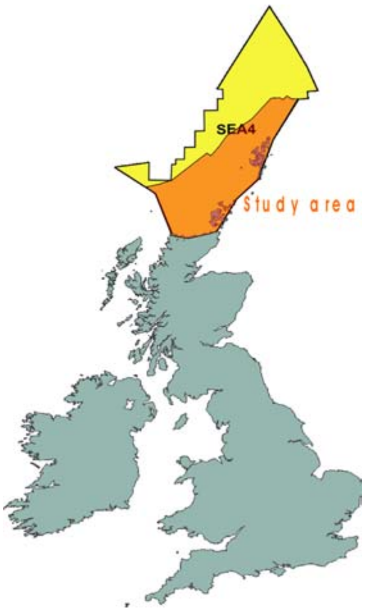
DTI Strategic Environmental Assessment Area 4 (SEA4): Continental shelf seabed geology and processes

Continental Shelf & Margins Programme

Commercial Report CR/03/081



BRITISH GEOLOGICAL SURVEY

COMMERCIAL REPORT CR/03/081

DTI Strategic Environmental Assessment Area 4 (SEA4): Continental shelf seabed geology and processes

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Bibliographical reference

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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 continental shelf seabed geology and processes. The study area is in the Department of Trade and Industry Strategic Environmental Assessment area 4 (SEA4).

This report has been produced separately from reports produced under the same contract for SEA 4:

1. BGS report CR/03/080 Subseabed geology
2. BGS report CR/03/082 Geological evolution Pilot Whale Diapirs and stability of the seabed habitat

The information presented for this report forms a small part of the seabed data available from the BGS series of 1:250,000 scale published maps and regional reports of solid geology, Quaternary geology and seabed sediments that cover SEA4 south of 62°N. The maps and reports are retrievable in hard copy through www.bgs.ac.uk. The maps were compiled from interpretations of regional single channel seismic reflection survey profiles and from seabed grab and core samples. Some of the published map information is available digitally.

The regional seismic reflection profiles used during compilation of the published maps were spaced some 10-15 km apart. The Quaternary and seabed sediment maps include supplementary information from interpretations of nearshore close-survey sidescan sonar and single-channel echo sounder data that has been released by the Hydrographic Office (HO) to the British Geological Survey (BGS) for publication at 1:250,000 scale. Other known systematic close surveys or swath regional surveys on the continental shelf include commercial site investigations for drilling rigs, development platforms, pipelines and cable routes. These data had been released for incorporation into the BGS maps up to the time of their publication completed in 1993. The post-1993 commercial sources of data have not been released and are not reviewed for this report.

The samples sites averaged less than 10km spacing but north of 61°N may be spaced up to approximately 15-20km apart. Most of the seabed samples were processed for particle size analyses, % carbonate in various size fractions and inorganic geochemistry. Many of the superficial and shallow cores were tested for geotechnical properties in addition to particle size analyses.

Acknowledgements

Funding for this project was managed by Geotek Ltd and funded by the Department of Trade and Industry.

Summary

This review presents a summary of the published data and their interpretations derived from the continental shelf seabed in the mature oil and gas areas of the West Shetland Shelf occurring to the north and west of the British Isles. The basis for this review is the premise that variations in the seabed geology will influence variations in the modern seabed habitat. The purpose is to review the seabed geomorphology, near-bottom currents, types of rock outcrop, variations in unconsolidated sediment texture, the variety and distributions of seabed bedforms and selected aspects of sediment inorganic geochemistry. It is intended that the review will provide a basis for a better understanding of conditions in the modern seabed environment and for possible future scenarios of strategic environmental interest.

The large-scale physiography of the inner-to-middle continental shelf has originated from varying degrees of rock and unconsolidated sediment resistance to the effects of erosion by ice-sheets during several glaciations since approximately 1.1Ma. Although ice-sheet erosion has also locally dissected the outer continental shelf, other variations in shelf physiography are identified with bedforms that were generated when sediments were deposited as the former ice sheets advanced and retreated across the continental shelf. There is little modern sediment input to the continental shelf. Thus the modern seabed environment now largely reflects the effects of reworking by near-bottom currents on the topography and the sediments that originated during the glaciations. The reworked sediments typically consist of large areas of relict seabed gravel on elevated topography, mobile sheet sand deposits on relatively flat seafloor and muddy sands and sandy muds in the sheltered coastal and nearshore areas and in basins on the open continental shelf. Rock crops at seabed and just below seabed in the areas of the inner and middle continental shelf that had previously undergone the strongest sub-ice erosion.

Tidal sand banks, tidal sand ridges and fields of migrating sandy bedforms typically form in water depths ranging from 20-100m or more and in the areas that are prone to the strongest wave and tide generated near-bottom currents. These bedforms and surrounding seabed areas locally consist of more than 60% shell fragments derived from the prolific post-glacial benthic biota in the nearshore environments.

Sedimentary sinks are typified by high metal values associated with fine-grained sediments and clay minerals, metal oxides and hydroxides and organic compounds. The anomalous values of zinc, for example, occur in sheltered basins adjacent to land but also in discrete areas on the outer continental shelf.

Contents

1 Geomorphology

This section describes large-scale geomorphological features associated with >20m interval height differences and with >5km plan scale in < 200m water depth (Figure 1) and then relates these features to the regional geology. The features described are associated with rock formations of >210 million years (>210Ma) age and unconsolidated Quaternary sediments of approximately <1.8Ma age (Figure 3 in Hitchen *et al*, 2003).

The continental shelf ranging over water depths of approximately 0-100m is characterised by a complex seabed topography. This has formed on rockhead cropping at or just below seabed and on thin undifferentiated Quaternary sediments (<5m thick) moulded on rockhead. The complex seabed topography is also identified with bedforms formed from thicker undifferentiated Quaternary deposits (Figures 1, 2).

The large areas of rockhead cropping at seabed and cropping less than approximately 5m under the seabed on the inner to middle shelf (Figure 2) have been strongly eroded during repeated glaciations. During the first major glaciation of the UK continental shelf an ice sheet may have extended from Norway to the West Shetland Shelf as long ago as 1.1 Ma (Holmes, 1997) and the last ice sheet possibly extended locally beyond the continental shelf to the upper slope (Holmes *et al.* 2003) since approximately 25Ka. Since the first glaciations the variations in rockhead elevation on the inner and middle continental shelf and on land have also originated from a combination of sea level and crustal movements (Hitchen *et al.* 2003). Thus the distribution patterns of submerged peat beds and the absence of raised beaches confirm the submergence of Orkney and Shetland since approximately 14Ka and into the present post-glacial era (Stoker et al, 1993).

The 80m isobath more or less defines the shoreward limits of thick unsorted overconsolidated (firm to hard, usually >40KPa shear strength) muddy and gravelly unsorted sediments. Sediments with these characteristics are commonly referred to as diamictons. They are mapped over most of the outer continental shelf and extend oceanwards to the 200m isobath (Figures 1, 2) and beyond that to the slope. Some of the diamictons originated in sub-ice or ice-proximal environments and were deposited as moraines as the ice retreated (Stoker and Holmes, 1991; Figures 2, 6). Significantly, the distribution patterns of the rock and diamicton correlate with areas of hard substrates at or just below seabed and are commonly associated with positive seabed topography.

The shelf break is defined by the locus of maximum gradient change between the continental shelf and continental slope. It is sharply defined south of approximately 61.25°N and more or less coincides with the 200m isobath where it is underpinned by the diamictons (Figures 1, 2). The well-defined shelf break marks a sharp boundary between the directions and maximum speeds of the near-bottom currents over outer continental shelf and upper slope (Figure 3). In contrast the shelfbreak is very poorly defined north of approximately 61.25°N so that it exhibits a ramp-like structural style in water depths ranging from approximately 140-200m+ (Figure 1). This gradual transition between the continental shelf and slope is not underpinned by diamicton but by formations of over consolidated mud (Figures 1, 2).

Deposits of normally consolidated muds (very soft to soft, usually <40kPa shear strength) were deposited in basins formed on the top surfaces of uneven diamicton and rockhead topography and probably originated as post-glacial marine sediments (Holmes *et al,* 1993). These muds underpin a relative flat seabed over large areas and are important because they extend under a wide range of gravely and sandy classes of relatively thin seabed and superficial sediments (Figures 1, 2, 4)

The area of shoaling seabed on the inner and middle shelf is broached by the NW extension of the Fair Isle Shetland Channel and also by the trace of a relatively deep-water shelf re-entrant that intrudes SW through the Foula Bight into the inner shelf. The re-entrant joins two glacially overdeepened enclosed basins that are more than 200m deep on the outer and middle shelves (Figure 1). It is uncertain if the re-entrant marks a site of erosion under the passage of a former fast-flowing ice stream originating from mainland Scotland or if it marks the limit of a former ice sheet that was pinned to align with the Orkney and Shetland Islands.

2 Near-bottom currents

The compositions and distribution patterns of the seabed sediments are influenced by the abundances of sediment sources and tidal, sea-wave, wind and ocean currents. There is also good correlation in the relatively shallow waters of the UK continental shelf between the orientation and distribution of the different types of mobile seabed sedimentary bedforms and the directions and strengths of surface currents (Kenyon and Stride, 1970). The ocean currents flow as dominant currents towards the NE and are parallel to the trends of the bathymetric contours on the outer continental shelf and upper slope (Figure 3). In SEA4 the surface and near bottom currents are strongest on the inner shelf with speed in excess of 1m/s in the shallow waters around Orkney and Shetland (Figure 3) and the net directions of sediment transport are largely determined by tidal currents that are related to the strengths and durations of the peak, ebb and flood streams (Johnson et al, 1982). When generated from wind-waves the estimated maximum orbital near-bottom currents may have more than 10 fold higher speeds than the measured tidal currents (Figure 3). These orbital currents are therefore important energy sources for mobilising and maintaining the suspension of sediment grains entrained in the tidal streams. Strong winds may also generate storm-surge currents that propagate mass movements of sediment when in conjunction with tidal currents (Pantin, 1991). There are strong opposing tidal currents of almost equal strength in the Fair Isle Channel between Orkney and Shetland so that the non-tidal current flowing towards the North Sea determines the overall direction of sediment transport (Johnson et al, 1982).

3 Seabed geological formations

Seabed geological formations can be broadly divided into areas of consolidated rock outcrop and areas with unconsolidated seabed sediments of <10Ka (Holocene) to modern provenance.

3.1 ROCK OUTCROP

The submarine rock outcrops on the continental shelf seabed principally consist of sedimentary rocks of more than 210Ma age and crystalline metamorporhic rock of more than 545Ma age (Hitchen *et al.* 2003). The sedimentary rock outcrops are mostly well-cemented, strong (broken only by heavy hammer blows) Devonian (360-410Ma age) formations. Outcrops of extremely strong (sound rings, sparks may fly with hammer blows) crystalline metamorphic rock occur adjacent to the SW perimeter of the SEA4 area but also map to the coast and nearshore areas around the Shetland Islands (Figure 4). The well-cemented sedimentary rocks and the crystalline rocks typically underpin an extremely rugged seabed micro-topography. These rock formations have strongly resisted repeated sub-ice erosion during the glaciations (Section 1). They are now mostly swept clean of mobile sediments by very strong near-bottom currents and typically feature fields of cobbles (6.4-25.6cm diameter) and boulders (>25.6cm diameter).

3.2 GRAVEL

Gravel ranges in size from granules (>2mm), pebbles (>4mm), cobbles (>64mm) to boulders (>256mm). The Shipek sampler sample used for the BGS sample surveys did not sample boulders and would rarely sample cobbles. The data presented in Figure 4 thus mostly refers to the extent of gravel fields identified from samples of seabed with grain sizes <64mm.

The seabed sediment grain size data for gravel (and all other sediments) are presented for this report with reference to weight % grain size classes regardless of mineral composition, provenance or, in the case of small carbonate biota, what proportion was acquired alive or dead (Figure 4). The non-carbonate component of the gravel includes rocks of sedimentary, metamorphic and igneous origin that vary in abundance and composition with proximity to source, the pathways of re-distribution by historical ice- and fluvial-transport processes and the vigour and direction of reworking by submarine processes. In many locations, but particularly on topographic highs at all scales, lithic and carbonate gravel fields form lag deposits that are exposed at seabed or are occasionally covered by thin mobile seabed sediments. Thus, for example, large fields of seabed gravel occur on large features such as the Otter, Papa, Stormy and Solan Banks situated to the north and west of Orkney (Figures 1, 4). In contrast, narrow ridges of gravel concentrates, the distributions of which may only be accurately resolved by regional sidescan survey calibrated by photography and sampling, occur on the berms formed by the seabed ploughing processes associated with ice-berg scour (see 4.1.2 below).

The areas of seabed rock and gravel provide a very favourable environment for a diverse and prolific calcareous biota. These make a significant contribution to proportion of calcium carbonate in the seabed sediments around the inner shelf and nearshore environments of the Orkney and Shetland Islands (Figure 5). These environments are major high-latitude centres of modern carbonate production (Farrow et al, 1984). Death assemblages of gravel-size biota consist mainly of bivalve and echinoid fragments, serpulid tubes, barnacle plates and bryozoans, the proportions and ages of which vary with location. For example at locations near Shetland barnacles and attached serpulids may dominate, at locations west of Orkney bivalves predominate but the radiocarbon dating indicates that the times of carbonate shell input between taxa and for individual taxa have varied during the Holocene (Wilson, 1979). Fragments of the cold-water coral *Lophelia pertusa,* which in size terms fall within the gravel class, were found on positions of elevated seabed on moraines and rockhead to the NW of Shetland (Figure 6).

3.3 SAND

Sand is mobilised by the near-bottom currents away from the topographic highs to re-position itself on surrounding low-lying seabed. The style and scale of sand deposits captured by this process vary from large tabular sand fields on the outer and middle shelf (Figure 4), sand bedforms with positive topography at various scales (see below), to sand infilling the hollows formed in iceberg ploughmarks on the outer shelf.

3.4 MUD

Accumulations of seabed muddy sediments are rare on the SEA4 continental shelf. The exceptions are accumulations of muddy sediments in sheltered sea lochs and, in mid-shelf enclosed basin sites with shoulder to axis differences of seabed elevation of more than approximately 40m (Figures 1, 4). These sites of muddy seabed sediments may overlie thicker accumulations of Holocene (<10Ka age) and Pleistocene (>10Ka age) muddy sediments without visible discontinuity. At some sites thick sequences of sub-seabed mud occur under seabed and superficial sands and gravelly sands (Section 1).

4 Seabed bedforms and sediment transport

4.1 IMMOBILE BEDFORMS

4.1.1 Moraines

The connections between moraines, diamictons and regional seabed topography are summarised in section 1 above.

The importance to the modern intra-shelf habitat of the moraines and associated diamicton lies in their potential to form a hard (barrier) substrate at and just below seabed, as elevated seabed sites associated with the potential for local diversion of sediment transport directions, as sources of winnowed sediments and as a source and stable foundation for the relict gravel spreads at seabed.

Mobile sediments generally fine with distance from sources with a heterogeneous grain size distribution. Thus, the relict and mobile seabed sediments over much of the continental shelf will have components of the mineral, geochemical compositions and sediment textures that more or less reflect the processes of dispersion or concentration of the components derived from reworking of the underlying sediments. The importance of this process is that if the compositions of the diamictons reflect those of their origin then the signatures from that origin will be dispersed or concentrated in the seabed sediments. Conversely, should contamination affect the seabed, then comparisons of the normalised signatures from natural (background) with contaminated sites will identify the likely sources for the contaminants.

4.1.2 Iceberg ploughmarks

Iceberg ploughmarks originated when drifting grounded icebergs ploughed into the seabed. They occur most abundantly at seabed in >120m water depth although some are buried or have otherwise been obliterated by strong near-bottom currents following the late-glacial at approximately 14Ka. They typically form pseudo-random patterns of cross-cutting and discontinuous furrows and enclosed basins that are more than 2m deep and at least 10m wide across the axis of the propagation direction. The furrows are flanked on both sides by ridges. These typically consist of upturned overconsolidated gravelly sediment now crowned by gravel lag deposits. The furrows are partly filled with sediment, usually sand. Their importance is in their links with the variety of sink and source seabed substrates and with very varied near-bottom hydraulic micro-environments over a wide area of the outer continental shelf.

4.1.3 Rock

The distribution patterns of rock at seabed are summarized for the major part of the continental shelf in Sections 1 and 3.1.

The transition zones from the subaerial to submarine environments across the rocky shoreface around Shetland, Orkney and the Scottish mainland are important contributors to the environmental variability of the submarine habitat. The shoaling water to highest astronomical tide is associated with the extreme changes to the hydraulic, temperature, salinity, nutrient, pollution and light environments. Thus the shore interface provides a very large range of environmental settings, varying from modern erosion and sediment transport in the most exposed areas to the deposition of very fine sediments within the sheltered coastal backwaters. Unfortunately, because of these extremes, the neashore environment is most difficult to survey and data are not available for most of this important zone (Figure 2).

4.1.4 Pockmarks

Pockmarks commonly occur in fine-grained sediments and in the SEA4 area they occur in a deeper-water area of the mid-shelf (Figure 6). Pockmarks are closed seabed depressions that are typically 2-5m deep, 50-200m wide and are usually elongated in the direction of the predominating near-bottom currents. The largest pockmarks occur in the softer and finer grained muds. They formed following seabed excavation by processes involving fluid, gas or liquid, escape at seabed and are the presumed loci for spasmodic sediment suspension. The pockmarks that have been identified in SEA4 have not been studied in detail.

4.2 MOBILE BEDFORMS

4.2.1 Sand streaks, sand ribbons and sand patches

These bedforms are ubiquitous on the shelf and because their dimensions are continuous they do not fall into natural size classes. The definition of their names based on their geometries is then a matter of opinion. The smaller-scale sand streaks and sand ribbons are usually thought of as centimetre-scale to metre-scale elongated features and occur where the mobile sediment supply is relatively limited or where the near-bottom currents are very strong. Sand patches are commonly described as more equant and also as cm-scale to metre-scale features but have also been described as relatively large-scale features with km-scale dimensions. They occur where sediment transfer to seabed is relatively more abundant and stable.

4.2.2 Tidal sand banks and sand ridges, transverse sand bedforms

The sizes of the submarine flow-transverse bedforms cluster into two main populations. Globally these are separated by few bedforms between approximately 0.5 to 1.0m wavelength and in nature there is no bedform wavelength discontinuity between ‘megaripples’ and ‘sandwaves’ in the 1-1000m+ wavelength class. For this report the identity of the term ‘ripples’ with bedforms less than approximately 0.6m wavelength is adopted and potential for size ambiguity associated with the use of terms ‘megaripples’ and ‘sandwaves’ is avoided. Instead the division of the larger transverse bedforms into classes with wavelengths (L) of small 0.6-5m, medium 5-10m, large 10-100m and very large >100m is adopted (Figure 6, inset modified after Ashley, 1990).

Fields of mobile flow-transverse small to very large sand bedforms are distributed in the inner shelf areas around Shetland subject to 1.0- 2.0 m/s maximum spring-tide current speeds (Figure 3, Figure 6). The steep side of these bedforms face in the directions of net sediment transport (Figure 6).

Fields of tidal sand ridges and sand banks around Orkney map to maximum spring-tide current speeds of >2m/s (Figure 3, Figure 6). These bedforms are orientated sub-parallel to the coast and the axis of at least one tidal sand ridge appears to have shifted with time (Farrow et al, 1984).

4.3 SEDIMENTARY SINKS

Particles are deposited within sedimentary sinks where the conditions are favourable, such as in areas of relatively weak currents over topographic depressions of the seafloor. The sizes of these ‘topographic depressions’ may vary from sub-millimetre to several kilometres. For example, muddy (silt and clay) fine sediments (<63 microns) may be trapped in the pore spaces between seabed sand (>63 microns) and gravel (> 2 millimetres) even on the open continental shelf, or they may be trapped in relatively deep-water in basins on the continental shelf (Figures 1, 4). The sediment grain size is therefore important to understanding how sediments are transported and deposited in the marine environment and as to how a sediment sink may be defined.

An alternative way of characterizing the sedimentary sinks is to look at the geochemistry of the seabed sediments, particularly the concentrations of the transition metals. The technique of element-ratio normalization has been used to identify anomalous concentrations relative to background and so identify areas where pollutants may have accumulated on the UK continental shelf (Stevenson, 2001). Fine grained seawater-suspended particulates <60-70 microns diameter are the most important medium for transporting metals (Eisma, 1981, Eisma and Irion, 1988). Clay minerals, the oxides and hydroxides of iron and manganese are the most important sources of metal in the fine-grained particulates. Where the supply of oxides and hydroxides of iron and manganese are low, organic material from biota or pollutants become more important as potential sources of metal. The main sources of these particulates are rivers, coastal erosion and seafloor erosion. When they settle out they contribute to metal values in the seabed sediments. Thus the positions of the highest values of zinc in total sediment, for example, should broadly correlate with the topographic lows and with proximity to land. The zinc distribution patterns appear to confirm that the mid-shelf basins are the sinks for zinc, as are the nearshore areas around Shetland (Figures 1, 2, 7). Relatively pure sands may contain fine particulates that become trapped in sand grains (Kersten et al, 1988) so that normalization of zinc concentrations with lithium (tightly bonded to clay minerals) largely removes the identity of the high zinc concentrations in the basins and nearshore Shetland with anomalous zinc values (Figure 4 in Stephenson, 2001).

High concentrations of zinc depart from the models summarized above at locations sited west of Shetland and adjacent to the 200m isobath (Figure 7) and also the Clair Field. Normalization does not remove the zinc anomaly (Figure 4, in Stevenson, 2001). The first well on the Clair Field was drilled in 1972 and the samples taken for the BGS geochemical surveys were acquired in the period from 1977-1980. Although the zinc anomaly may have possibly originated from early development operations, further work is required to fully investigate possible natural sources for the zinc and to see if the zinc anomaly exists today.

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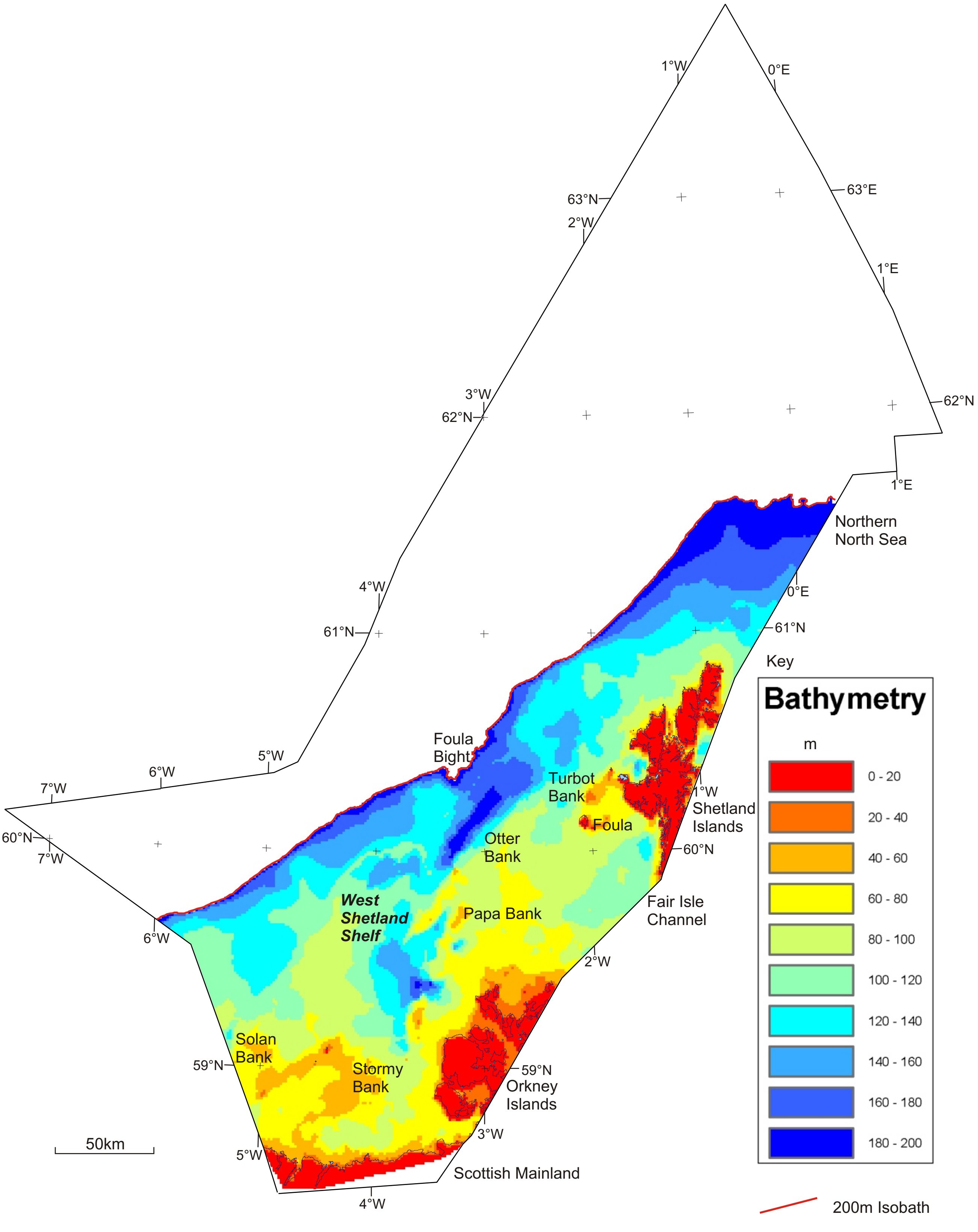

Figure 1 Bathymetry

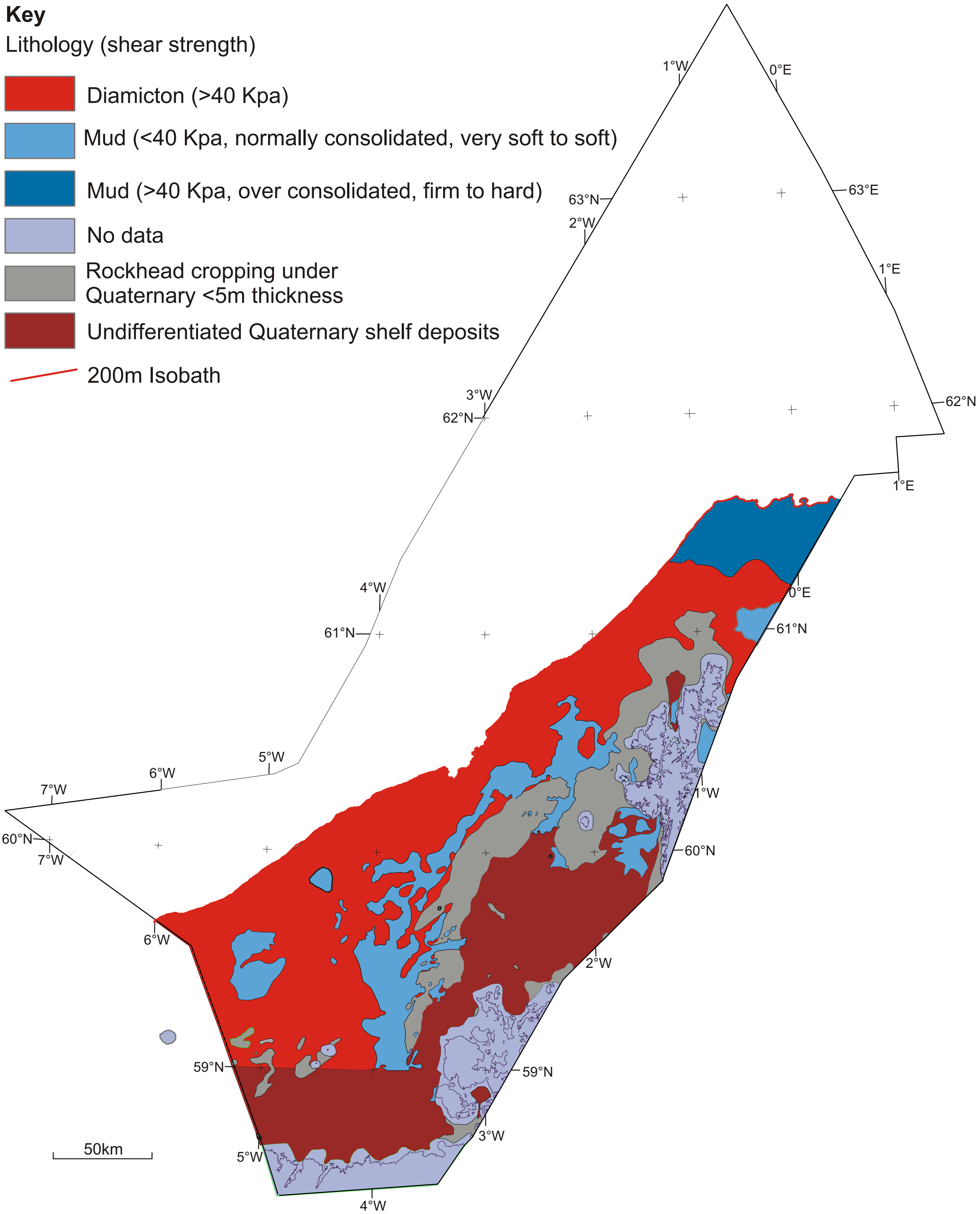

Figure 2 Subseabed Quaternary and older formations
Modified after Holmes *et al.* 1993.

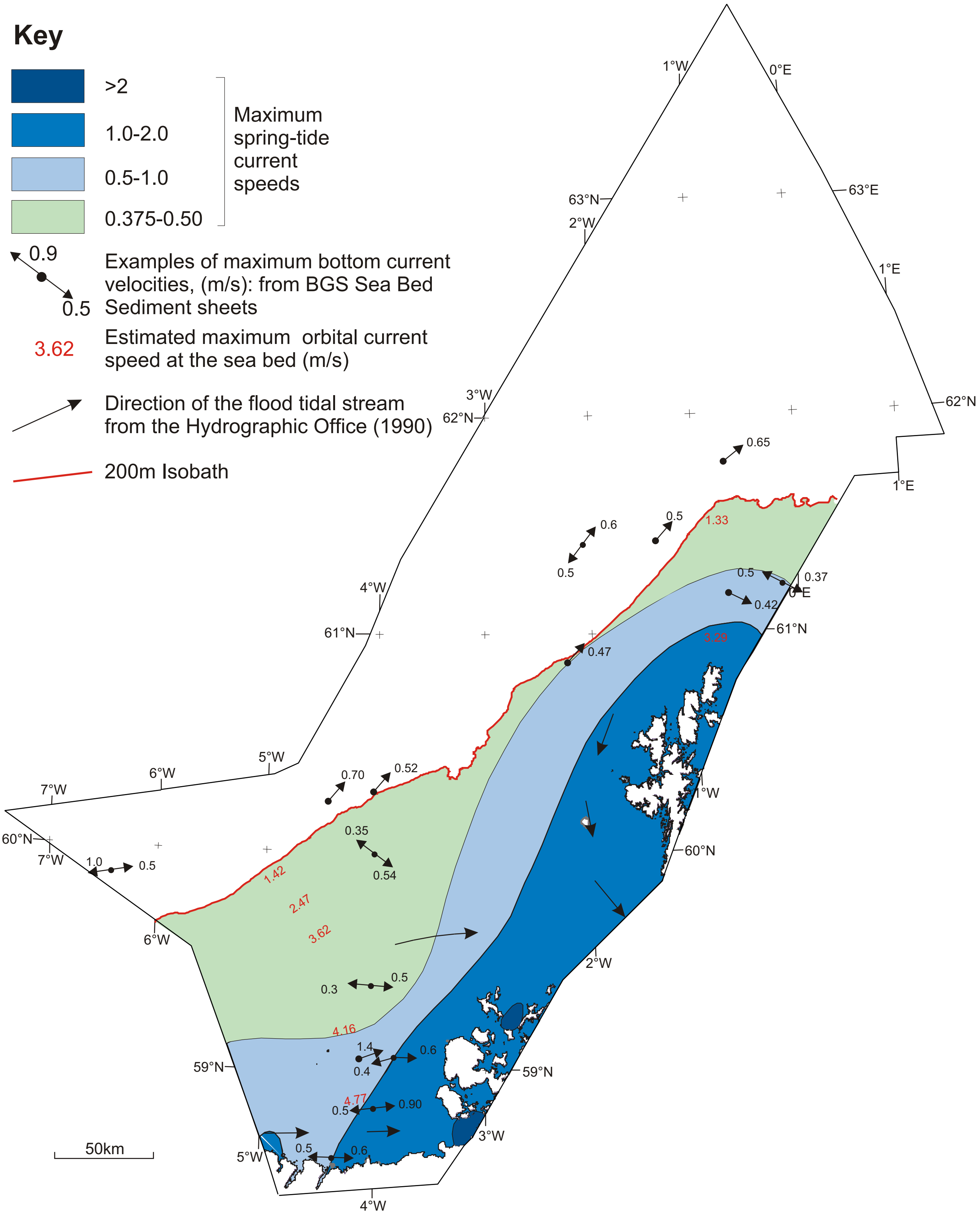

Figure 3. Near-bottom currents
Modified after Pantin (1991), Stoker *et al.* (1993)

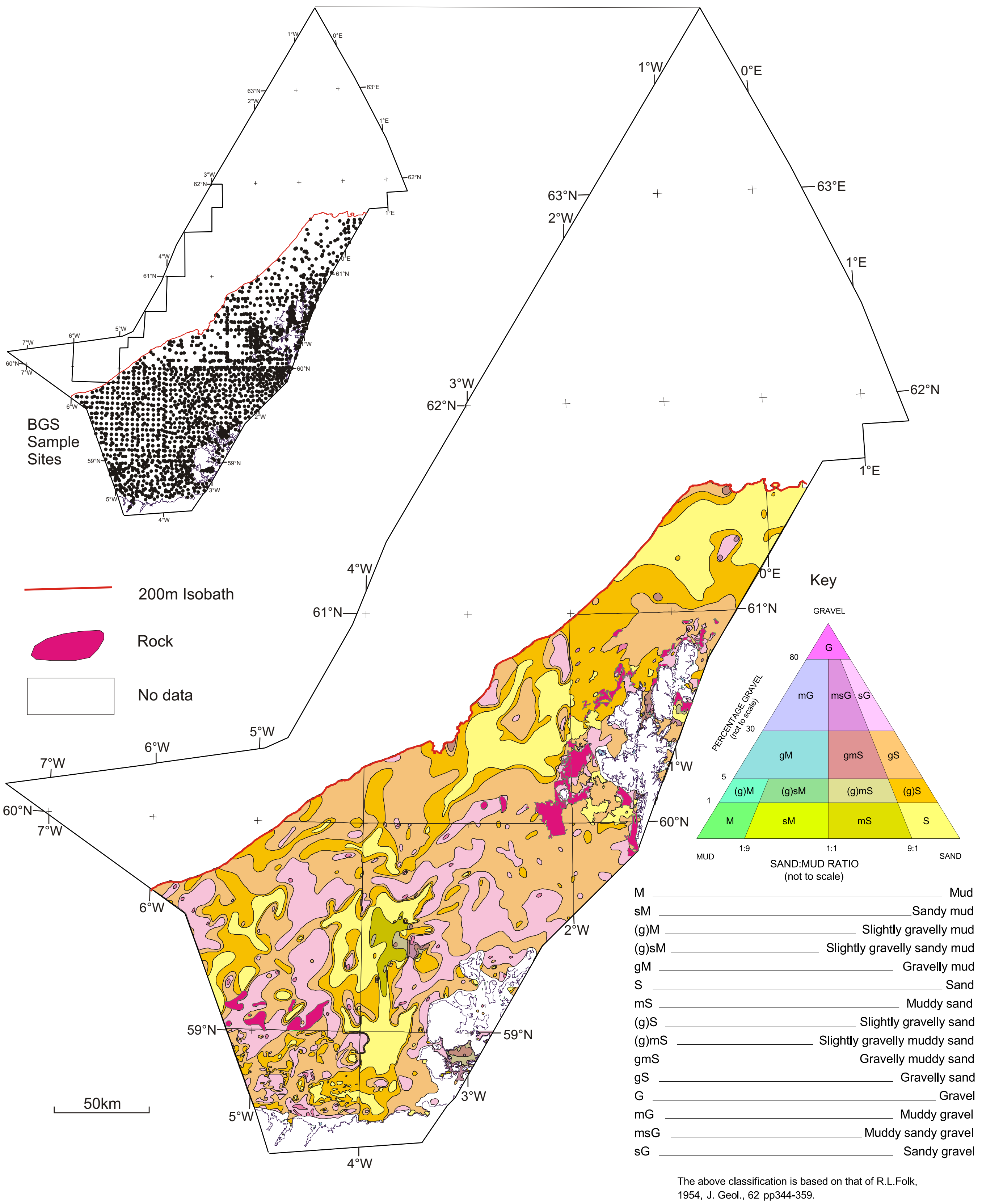

Figure 4 Seabed sediments
Modified after Pantin(1991)

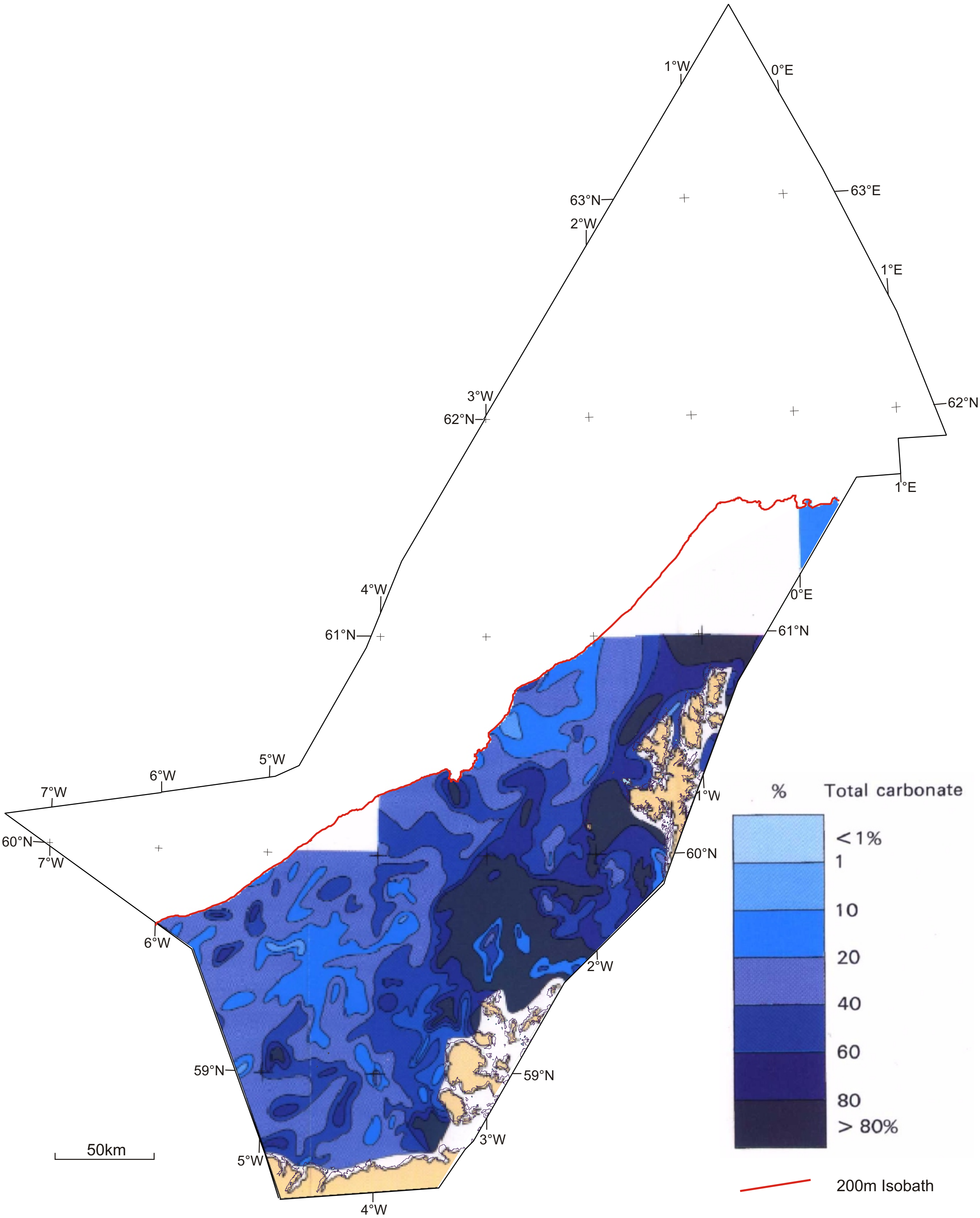

Figure 5 Percentage carbonate in total seabed sediments
Modified after Pantin (1991)

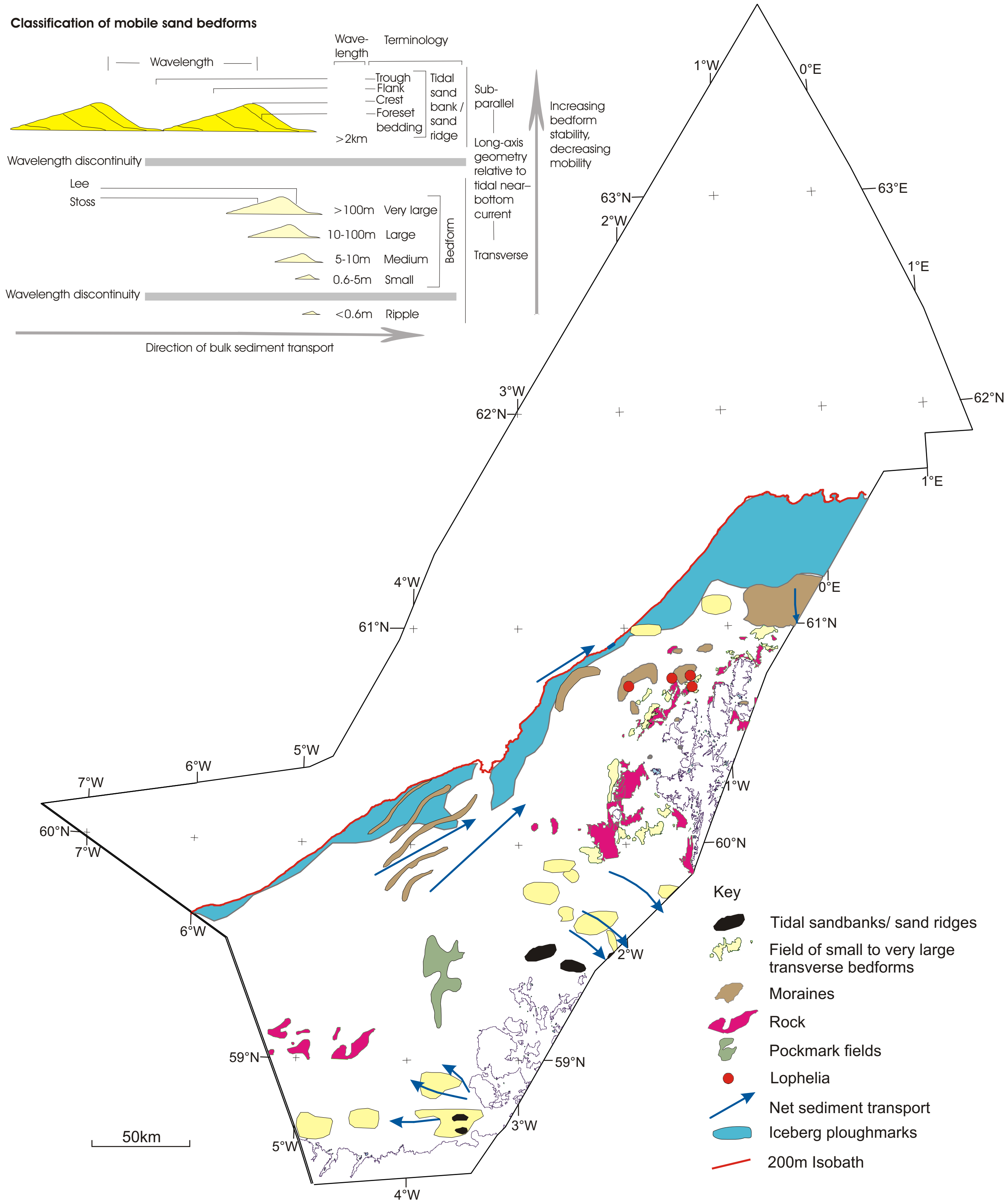

Figure 6 Seabed bedforms and net sand transport directions
Data modified from the BGS dataset

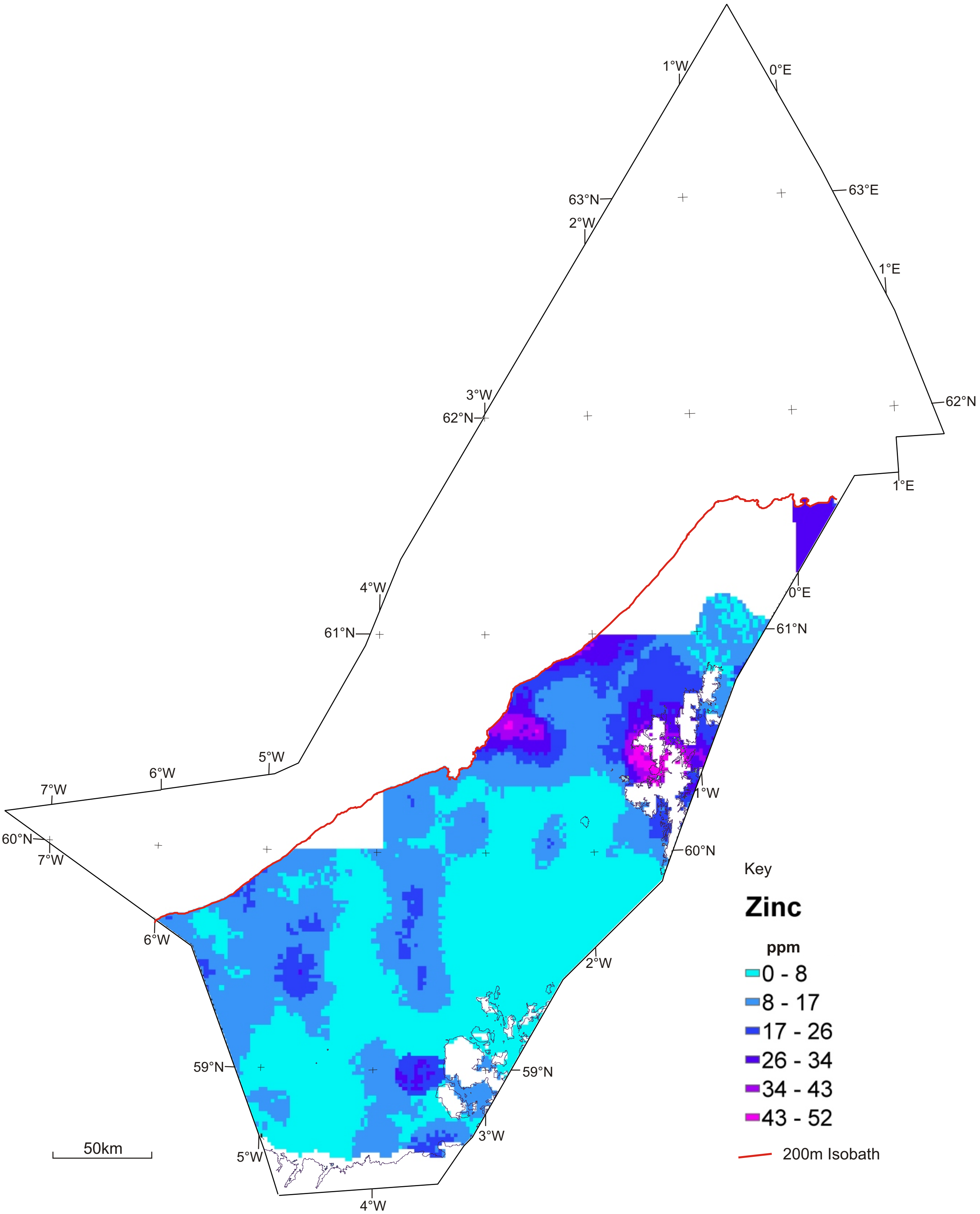

Figure 7 Concentration of zinc in total seabed sediments
Data modified from the BGS dataset