SEAFLOOR SEDIMENTS AND SEDIMENTARY PROCESSES ON THE OUTER CONTINENTAL SHELF, CONTINENTAL SLOPE AND BASIN FLOOR

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SUMMARY

This report describes the surficial sediments in SEA4 and the sedimentary processes that are active in the area at the present day. The report is based on sidescan sonar images, multibeam bathymetry, sub-bottom profiles, seabed photographs and sediment samples. The Holocence and late glacial events and processes that contributed to the present day seafloor morphology and sediment distribution are reviewed, as is the present day occeanographic regime.

The major conclusions are that:

(1) The present day sedimentary environment of SEA4, seaward of the continental shelf edge at about 200 m water depth, is dominated by low sediment input and deposition rates, and by reworking of surficial sediments by bottom currents.

(2) The large scale seabed morphology was shaped mainly during the last glacial, when high sediment input resulted in glacigenic debris fan formation.

(3) Seabed sediments show a general decrease in grain size with increasing water depth, from mixed gravel and sand on the upper slope to mud in the deeper Norwegian basin below about 1500 m. However, this simple pattern is modified by the pattern of bottom currents. In general, stronger currents (correlating with coarser sediment) occur at greater depths in the relative narrow southern Faroe Shetland Channel and Faroe Bank Channel than in the more open basin further north.

(4) Sediment bedforms show that bottom currents are particularly active at water depths <500 m, under the NE directed slope current, where peak current velocities >0.75 m s^{-1} can be expected. In this area, mobile sand bedforms move over a predominantly gravel substrate. Gravel at the seabed and areas of seabed scour in the sill area between the Faroe Shetland and Faroe Bank Channels indicates local bottom currents > 1.0 m s^{-1}

(5) On the lower slope and over parts of the basin floor in the southern Faroe Shetland Channel and Faroe Bank Channel, sand and muddy sand deposits, often with a pattern of ripples on the sediment surface, suggest peak currents in the order of 0.3-0.4 m s^{-1}.

(6) No large-scale patches of deep water corals have been found in SEA4.

(7) A field of mud diapirs occurs in the southern Norwegian Basin. No evidence for fluid escape (or possible associated biological communities) have been found to date. However, there remains a possibility that localised areas of fluid escape may be active in the mud diapir province.

1. INTRODUCTION

1.1. Regional setting

The area covered by this report is centred on the eastern slope of the Faroe Shetland Channel but extends north into the southern Norwegian Basin and southwest into the Faroe Bank Channel (Fig. 1). The present-day seafloor morphology of the area is largely the product of late Pleistocene sedimentation, when ice-related processes transported large amounts of sediment to the continental shelf edge, from where it was distributed down slope by gravity –driven processes, such as debris flow (Stoker et al., 1991; Stoker, 1995). Present day surficial sediment distributions and processes reflect interaction between the relict Pleistocene seafloor and Holocene sediment redistribution, the latter mainly driven by bottom currents (Belderson et al., 1973; Kenyon, 1986; Stoker et al., 1998). Little new sediment has reached the continental shelf edge during the Holocene.

1.2. Morphology and oceanography

The Faroe Shetland and Faroe Bank Channels together form a narrow deep water trough separating the Faroe Islands platform from the west Shetland shelf to the east and the Wyville Thomson Ridge and several isolated banks to the south (Fig. 1). At it's narrowest point, near 60° 30'N, the deep water trough is about 90 km wide and 1000 m deep. North of 62° 45'N, the Faroe Shetland Channel broadens into the southern Norwegian Sea Basin, reaching a water depth of about 2400 m at the northern limit of the SEA4 area. The Faroe Bank Channel continues as a narrow trough for about 250 km to the southwest and west of the SEA4 area, finally connecting with the deep Atlantic basin. Regional slope gradients on the margins of the Faroe-Shetland and Faroe Bank Channels are generally low, typically in the range 0.5-1.5°. Steeper slopes occur locally on the eastern margin of the Faroe Shetland Channel near 61° 45' N (3-4°), on the northeastern flank of the Faroe platform near 62° 30' (7°) and on the northern flank of the Wyville Thomson Ridge (8°).

In general terms, the present day oceanographic regime in the SEA4 area consists of an upper layer of warm North Atlantic Water moving towards the northeast, overlying a lower layer of cold Norwegian Sea bottom water moving southwestward (Fig. 2) (Dooley and Meincke, 1981; Hansen, 1985; Saunders, 1990; Turrell, 1997; Turrell et al., 1999; Hansen, 2000). In detail five separate water masses can be recognised within the channel on the basis of their salinity and temperature characteristics (Turrell et al., 1999). Two distinct, warm, surface water masses are seen. Close to the west Shetland shelf edge, in a feature often referred to as the Slope Current, North Atlantic Water (NAW) flows northward from the Rockall Trough (Turrell et al., 1999). Modified North Atlantic Water (MNAW) flows clockwise around the Faroe Islands before turning northward in the Faroe-Shetland Channel to flow parallel to but offshore from the NAW (Hansen, 1985; Saunders, 1990). Typically the surface waters occupy the upper 200-400m of the water column, being thickest under the core of the NAW close to the west Shetland shelf edge. Below the surface layers, Arctic Intermediate Water (AIW) flows anticlockwise along the southern edge of the Norwegian Sea Basin and around the Faroe-Shetland Channel, typically between 400 and 600 m water depth (Blindheim, 1990). Below the AIW, two cold (typically ≤ 0° C) water masses, Norwegian Sea Arctic Intermediate Water (NSAIW) and Faroe-Shetland Channel Bottom Water (FSCBW), flow towards the south (Turrell et al., 1999). This cold water flow escapes southward into the Atlantic by way of the Faroe Bank Channel (Saunders, 1990; Hansen, 2000).

In summary, northward flow dominates in the upper 600 m of the water column over the west Shetland shelf edge, with southward flow at greater depths. However, the boundaries between the various water masses are complex and can be variable on timescales ranging from decades to hours (Turrell, 1997; Turrell et al., 1999; Bett, pers comm, 1998). For example, in two sections in the Faroe-Shetland Channel, measured only 4 days and 100 km apart, warm surface waters were recorded at maximum depths of 300 and 600 m (Turrell, 1997). Currents in the upper water mass are typically 0.3 - 0.6 m s^{-1} towards the northeast, and in the lower water mass 0.1 - 0.2 m s^{-1} towards the southwest (Saunders, 1990). Information on peak current velocities is limited, but suggests that they can significantly exceed the typical velocities given above. Measured near-bottom current velocities indicate peak currents over 0.75 m s^{-1} towards the northeast on the upper continental slope west of Shetland and over 0.6 m s^{-1} towards the southwest in the deeper basin (Graham, 1990a; Graham, 1990b; Strachan and Stevenson, 1990). Sediment bedforms observed on the upper slope, such as small barchan-type sand waves, longitudinal sand patches and comet marks (Werner et al., 1980), confirm currents in the range 0.4 - > 0.75 m s^{-1} (Kenyon, 1986). Excursions from the 'typical' current regime could be driven by a variety of phenomena, including tides, storms, benthic storms, internal waves, and eddies and meanders within the current system.

1.3. Survey areas and techniques

Survey data used in this report includes sidescan sonar images, multibeam bathymetry, sub-bottom profiles, seabed photographs and sediment samples. This data was collected during a number of surveys funded by the Atlantic Frontier Environmental Network (AFEN) in 1996 and 1998 and by the DTI in 1999, 2000 and 2002.

Sidescan sonar data was collected using two systems, the 30 kHz TOBI system in water depths greater than 200 m and a 100 kHz ORE or Widescan system at depths shallower than 200 m. The TOBI instrument package included 30 kHz sidescan sonar, 7.5 kHz profiler, three axis fluxgate magnetometer, CTD and an ultra-short baseline navigation transponder beacon. The TOBI sidescan sonar images a 6 km swath with a nominal resolution of 5-10 m and can be used in water depths from 200 to 6000 m (Murton et al., 1992). In the Faroe Shetland and Faroe Bank Channels in water depths between 200 and 1500 m, where the seafloor is relatively heterogeneous, 30 kHz sidescan sonar was the primary tool used for seafloor sediment facies mapping (Fig. 1). A reconnaissance survey of selected areas along the continental shelf edge was carried out using 100 kHz sidescan sonar, imaging a swath width of 750 m along each survey line with a resolution in the order of 1-2 m.

Sub-bottom profiles were collected using the 7.5 kHz profiler mounted on TOBI and a 3.5 kHz surface towed profiler. In general, the deep-towed 7.5 kHz system provided excellent high-resolution topographic profiles along the TOBI tracks, but gave little sub-bottom penetration except in the finest grained sediments of the deep basin. Greater sub-bottom penetration was achieved using the 3.5 kHz profiler, although this system also failed to penetrate the thin veneer of coarse Holocene sediments which covers much of the upper slope.

Seabed photography was carried out using the SOC WASP system, an off bottom towed camera operated at an altitude of approximately 5 m and taking overhead views of 15 - 20 m^2.

Three different sampling devices were used to cope with the wide range of surface sediment types, ranging from coarse gravel to mud, found in the SEA4 area. Note that for the purposes of this report, gravel is used as a general term for all grains >2 mm diameter. In fine grained sediments, a hydraulically damped multiple corer with up to twelve 10 cm internal diameter core tubes was used to obtain high quality cores up to 30 cm in length. In coarser sediments, particularly where significant quantities of gravel were present, this was replaced with a USNEL-type box corer capable of collecting a square section sample of 0.25 m^2 and up to 50 cm in length. In very coarse sandy gravels, where other sampling devices failed, a Day grab was used as a last resort. In practice, sediment distributions dictated that the multiple corer was used mainly below 600 m water depth, the box corer between 600 m and the shelf edge, and the grab on the shelf and along the shelf edge.

2. SURFICIAL SEDIMENTS AND SEAFLOOR CHARACTER

2.1. Outer continental shelf

The continental shelf break lies at around 200 m water depth. Only a small area of continental shelf (<200 m water depth), was mapped in reconnaissance mode only (Fig.1). Sediment type is typified by variability on a scale of metres to hundreds of metres. At a regional scale, three main seafloor facies can be recognised:

(a) Gravel overlain by mobile sand bedforms
(b) Iceberg ploughmarks
(c) Sand sheets

2.1.1. Gravel overlain by mobile sand bedforms

West of Shetland, large areas of the continental shelf south of 60° 10' N and between 60° 36' to 60° 58' N are characterised by longitudinal sand patches overlying a gravel substrate (Figs. 3, 4a). Individual sand patches are usually strongly elongate, typically a few tens to two hundred metres wide by hundreds of metres to several km long. The predominant trend of the elongate patches is NE to ENE. On the basis of sidescan sonar data, sand cover varies from <5% to >95%, but is typically in the 10-60% range. Samples from this area are mainly sand or gravelly sand. However, a very large proportion of the sampling attempts in this area failed, almost certainly because the grab sampler used was unable to close in the gravel substrate; it can therefore be assumed that gravel is under represented in the sampling results. Bedform orientations are consistent with published information on sediment transport directions in the west of Shetland area, indicating predominant transport towards the northeast and east-northeast (Stride, 1982; Kenyon, 1986). This sediment type is characteristic of water depths less than about 150 m (range 90-150 m), except for an area near the shelf edge between 59° 50' and 60° 15' N, where its distribution extends down slope to about 200 m water depth.

2.1.2. Iceberg ploughmarks on the continental shelf

Areas characterised by iceberg ploughmarks (see Section 2.2.1) are marked by irregular gravel ridges slightly raised above a generally sandy seabed (Fig. 3b). The ridges are randomly oriented and may show cross-cutting relationships. Individual ploughmarks often consist of paired ridges, separated by a shallow depression, typically 100-500 m in width. The ridges are the remnants of debris pushed aside by icebergs (Belderson et al., 1973), the central depression marks the central trough of each ploughmark, usually largely filled with younger sandy sediments. Relict iceberg ploughmarks characterise the continental shelf between 60° 15' and 60° 36' N immediately west of the Shetland Islands (Fig. 4).

2.1.3. Sand sheets

Two areas of smooth seafloor showing low backscatter on sidescan sonar images are interpreted as sand sheets burying older seafloor topography. Boundaries with adjacent facies are transitional. This sand sheet has been mapped in two small areas on the shelf, one centred on 60° 25' N and 02° 45' W, the other on 61° 25' N, 00° 55' W (Fig. 4).

2.2. Upper continental slope

2.2.1. Iceberg ploughmarks

Iceberg ploughmarks, which typically consist of a pair of raised ridges separated by a central depression, result from the grounding of floating icebergs and the ‘ploughing’ of a furrow into the seabed by the keel of the iceberg (Fig. 5). Ploughmarks are the dominant morphological feature of the continental slope west and north of Shetland from 200-450 m water depth

(Masson, 2001), as they are at many high latitude sites worldwide, (e.g. Belderson and Wilson, 1973; Belderson et al., 1973; King, 1976; Pudsey et al., 1997; Bass and Woodworth -Lynas, 1988; Todd et al., 1988). Only a few ploughmarks are seen below 450 m water depth, with the deepest extending to about 500 m. Sidescan sonar images of iceberg ploughmarks show intricate linear to irregular patterns of high and low backscatter (Fig. 5a). Within these patterns, individual features appear as paired, parallel, high-backscatter lineations separated by a low-backscatter central stripe. In some cases individual ploughmarks can be traced laterally for 10 km or more, although in many areas confusion between cross-cutting features makes lateral tracing of individual features impossible. Instead, an intricate mosaic pattern is seen (Fig. 5a). The upper limit of the ploughmark zone originally extended onto the outer continental shelf, but many of these shallow water ploughmarks have been partly erased or buried by post-glacial sediment redistribution (Fig. 4; see Section 2.1.2). Towards the deeper limit of the zone, ploughmarks become fewer in number, but larger and more continuous.

Typical ploughmarks are several tens to a few hundred metres in width. The paired high-backscatter lineations of individual ploughmarks correspond to ridges of material pushed aside by the iceberg, while the central stripe corresponds to the central gouged groove (Belderson et al., 1973). Seabed photographs show a coarse gravel substrate in the ridge areas (= high-backscatter) and relatively less coarse grained material in the central grooves (= low backscatter) (Fig. 6a, b). Sediment sampling in the ploughmark area confirms the general coarse-grained character of the seafloor sediments, which are mainly sands and gravels, with a high degree of local variability (Fig. 7). As with the continental shelf sediments, seabed photography suggests that gravel is probably under-represented in the sample data because of the difficulty in sampling coarse sediment. The topography of the plough-marked seabed is highly variable, with ploughmark depths typically up to about 5 m (rarely 10 m). In many cases, however, ploughmark topography is subdued or even absent, indicating erosion of the upstanding ridges by bottom currents and/or filling of the central groove by late- or post-glacial sediments (Fig. 5b).

Analysis of the ploughmarks suggests that it is possible to sub-divide them into four morphological types, reflecting variations in the processes of their formation and/or later modification by post-glacial sedimentary processes (Masson, 2001).

(a) Randomly oriented cross-cutting ploughmarks, tending to become sub-parallel to the contours in deeper water (Fig. 5a). This is the commonest ploughmark type, covering more than 75% of the plough-marked area. These 'typical' ploughmarks are interpreted as having been cut by floating icebergs.

(b) Ploughmarks partly to largely buried or erased by later sediment deposition. This ploughmark type is similar in pattern to (a), but with subdued backscatter contrast and relief. It occurs in discrete patches, mainly between 300 and 450 m water depth (Fig. 4). Boundaries between areas of ploughmarks of type (a) and (b) are usually gradational. Although it might be suspected that this ploughmark type would correlate with areas of enhanced post-glacial sedimentation or relatively finer-grained sediments which could be more susceptible to reworking by post-glacial bottom currents, there is no evidence for this in the mapped sediment distribution (Fig. 7).

(c) Lineated, parallel ploughmarks. These occur as groups of extremely straight, parallel lineaments up to 10 km in length, oriented north-northeast to northeast. They are restricted to areas shallower than about 350 m. These groups of ploughmarks closely resemble iceberg flutes, observed on the continental shelf in both the Arctic and Antarctic and believed to have been formed beneath moving icesheets (Pudsey et al., 1997; Shipp and Anderson, 1997; Solheim and Elverhoi, 1997). They are interpreted as due to scour beneath a floating or grounded icesheet moving towards the northeast.

(d) Circular to elongate cross-slope depressions, restricted to narrow contour parallel bands. These are best developed in the southern part of the study area between 60° 08' and 60° 13' N, but extend in a narrow band both to the north and south (Fig. 4). Depressions are typically between 500 and 1500 m across and up to 25 m deep. The depressions are characterised by partial infill of relatively fine-grained material. They are interpreted as scour holes formed at (or beneath?) the margin of an icesheet which extended to the shelf edge. This is compatible with the known extent of late Pleistocene icesheets in the area (Stoker and Holmes, 1991; Stoker, 1997b).

2.2.2. Wyville-Thomson Ridge

An intense pattern of cross-cutting iceberg ploughmarks, similar to those seen on the eastern slope of the Faroe-Shetland Channel, covers the crest and upper slopes of the Wyville Thomson Ridge (Fig. 4). Photographs and samples show that the ploughmark area corresponds to an area of coarse gravel seafloor. On the southern flank of the ridge, the downslope boundary of the ploughmark zone is clearly defined at a water depth of 500-550 m. However, this boundary is more difficult to define on the northern flank of the ridge, where sonar images show features similar to iceberg ploughmarks extending to water depths >700 m (and possibly to 1000 m). Profiles show a rough seafloor which extends down slope to water depths >700 m; below this it gradually becomes smoother. The origin of the rough relief which extends below 500 m water depth on the northern flank of the Wyville-Thomson Ridge is unclear, although it seems probable that it corresponds to an area of iceberg ploughmarks. Why ploughmarks should extend below 500 m in this area and not elsewhere on the West Shetland slope is not clear. However, it can be noted that ploughmarks have been recorded to 700 m on the southern flank of the Iceland-Faroe Ridge immediately to the west of the Faroe Bank Channel and to depths of between 700 and 850 m in other parts of the North Atlantic and Arctic (Werner, 1990; Vogt et al, 1994).

2.3. Lower continental slope

The lower continental slope is defined to extend from 450 to approximately 1000 m water depth. Sidescan sonar images from this area show a gradual down slope change from moderate/relatively high backscatter at around 500 m water depth, to low/moderate backscatter at 1000 m (Fig. 4). Seabed photography and sampling show that the down slope changes in backscatter correlate with a change from a mixed gravel/sand seafloor in the shallower part of the area to muddy sand in the deeper part. The gravel/sand sediments, called "gravel lag contourites" by Stoker et al (1998) result from the reworking and winnowing of Pleistocene glacial sediments by strong Holocene bottom currents. Locally, areas of very low backscatter occur near the base of the continental slope. These correspond to patches of well-sorted sand or silty sand deposited by bottom currents (see Section 3.2.3). Sampling shows that the surficial sediment layer, corresponding to post-glacial sedimentation, is typically between 5 and 15 cm thick, and that it overlies a predominantly muddy sequence of late glacial age (Stoker et al., 1991; Graham et al., 1996).

Superimposed on the area of high backscatter are a variety of subtle features interpreted as bedforms, both erosional and depositional (Fig. 4). In the southern part of the study area, south of 61°N, slope parallel erosional features, mainly furrows, predominate and large-scale depositional bedforms are absent. North of 61°N, depositional sedimentary features, such as mud waves, sand waves and sand sheets are seen, although erosional furrows also occur (see Sections 3.2.1 – 3.2.4) .

2.4. Basin floor

‘Basin floor’ is used to describe areas of very low slope gradient and essentially includes all areas deeper than 1000 m water depth within SEA4. Three distinct provinces, the Faroe Bank Channel, Faroe Shetland Channel and Norwegian Basin are distinguished. The boundary between the latter two areas is taken at approximately 62° 40’N.

2.4.1. Faroe Bank Channel

At a regional scale, strong contrasts in sediment type characterise the floor of the Faroe Bank Channel. Much of the channel floor west of 5° 40’ W is covered by a veneer of sand or muddy sand, deposited by bottom currents during the Holocene (Fig. 8). However, much coarser sediments occur along the northern edge of the basin floor and grainsize generally increases towards and onto the lower slope of the Faroe platform. This gravel area is cut by a spectacular pattern of sub-parallel furrows which occur between 750 and 1200 m water depth (Fig. 8; see Section 3.1.1). Profiles show that most of the basin is underlain by parallel-bedded sediments, often shaped into sediment drifts, although glacigenic debris flows occur in the subsurface in the east (Figs. 4, 9a,b).

Large parts of the Faroe Bank Channel floor shows evidence for seafloor erosion (furrows and scours; Fig. 8) and sediment transport/deposition under the influence of bottom currents (sediment drifts and contourite sheets, Fig. 9a). Many of the bedforms observed on sidescan images, profiles and seabed photographs appear to be active at the present day and are thus representative of the active bottom current regime. The key bedforms, which occur at a variety of scales, are discussed in Section 3.8.

2.4.2. Faroe Shetland Channel

The floor of the Faroe-Shetland Channel is characterised by relatively featureless even moderate/low backscatter on TOBI images (Masson, 2001). 3.5 kHz profiles show several tens of metres penetration into acoustically layered sediments, suggesting a mainly fine grained glaciomarine sequence (Fig. 9c). Sediment sampling recovered mainly mud and muddy sand with some gravel, with a general decrease in grain-size towards the northwest (Fig. 7). Note that the boundary between muddy sand and mud at the seafloor gradually moves deeper in the basin as it become narrower towards the south, reflecting the increasing importance of bottom currents as the Faroe Shetland Channel becomes more constricted towards the south (Fig. 10). Seafloor photographs show a surprising amount of gravel at the seabed, suggesting low Holocene sedimentation rates. The sampling programme confirms this, showing post-glacial sediment thicknesses varying between 1-5 cm (Graham et al., 1996).

2.4.3. Norwegian Basin (North Sea Fan)

A surface veneer of mud covers the floor of the Norwegian Basin below 1000 m water depth (Figs 7, 10). Glacigenic debris flow sediments of the North Sea Fan, imaged on sub-bottom profiles as thick sequences of acoustically transparent material, underlie much of the area (Fig. 4; Section 3.4.2). Down slope lineations on the surface of the fan, seen in sidescan sonar data, probably mark edge of individual debris flows. Mud diapirs, marked by areas of rough, elevated, topography rising 100 m or more above the level of the local ‘background’ seafloor, occur in a limited area between 62° 30’ and 63°N and 1° and 2°W (see Section 3.5).

A NW-trending scarp, up to 100 m high, crosses the northern part of the study area between 63° 10’ and 63° 40’N, marking the sidewall of a large submarine slide, the Tampen Slide (Section 3.4.4; Evans et al. 1996) (Fig. 4). A number of relatively small channels and gullies extend upslope away from the Tampen Slide sidewall (Fig. 4; Section 3.3). These are a few tens of metres deep at most, and tend to die out upslope. They seem to post date the last episode of North Sea fan debris flows and are unlikely to be active today.

3. SEDIMENTARY FEATURES AND PROCESSES

3.1. Erosion by bottom currents

3.1.1. Furrows

Furrows, best seen on sidescan sonar data, occur as groups of distinct straight to slightly sinuous sub-parallel lineaments, with individual lineaments up to a few tens of metres wide and up to several tens of km long (Figs. 8a, 11a). They have a consistent along slope trend, except in the Faroe Bank Channel where can be clearly oblique to the contours (Masson et al , in prep). No examples of bifurcating lineations are seen. Furrows are common on the West Shetland continental slope between 500 and 1200 m water depth (Masson, 2001), in a small area on the NE Faroe Platform at about 1000 m water depth, and on the lower slope of the SE Faroe Platform between 800 and 1200 m water depth (Fig. 4). Furrows occur on the continental slope mainly in areas of gravel and sand covered seafloor. Some correlate with subtle depressions a few metres deep, although many are below the resolution of the profiling systems used in this study. Some furrows in the Faroe Bank Channel occur in the ‘moat’ which separates sediment drifts from the adjacent continental slope (Fig. 8), or in association with large-scale scours (see Section 3.1.2). Such moats and scours are likely to correlate with localised peaks in bottom current strength. On the West Shetland slope between 61° and 62° 30’N, furrows occur within broad depressions up to 10 m deep between wave-like bedforms (probably elongate sediment drifts) which are sub-parallel to the regional slope. Individual furrows and the associated bedforms can be traced along slope for several tens of km (Fig. 4).

In addition to furrows, broader along slope-oriented depressions, with the appearance of shallow (< 10 m deep) channels are seen on the West Shetland slope between 400 and 500 m water depth (Fig. 11b; Masson, 2001). They are up to 800 m wide and 20 km long. On sidescan images, they are seen as subtle low-backscatter bands, suggesting a sedimentological contrast with the surrounding areas. They are believed to be related to along slope sediment transport by bottom currents.

Erosional furrows similar to those in the SEA4 area are common on tidally-swept gravel seafloor on the continental shelf (Stride, 1982, Belderson et al, 1988). This interpretation is supported by the composition of the seafloor in the furrowed area, where photographs show a predominantly gravel/sand substrate (Fig. 4). On the continental shelf, furrows in a gravel seafloor occur in areas of strong (0.7-1.5 m s^{-1}) unidirectional currents, (Table 1).

3.1.2. Large-scale scours and erosional scarps

Two elongate depressions, interpreted as areas of large-scale scour, occur in the eastern Faroe Bank Channel, immediately to the southwest of the sill at 60° 25'N, 5° W, (Fig. 4). Each is up to 50 m deep, 5 - 10 km across and 10 - 20 km long, with a steep scarp on the upcurrent (northeast) side (Fig. 12; Masson et al, in prep). On sidescan images, the floors of these depressions have a strong linear fabric, parallel to the trend of the elongate basin floor. The fabric comprises both furrows (Section 3.1.1) and broader elongate bands of varying backscatter, probably sand and gravel ribbons. A profile across the eastern scour suggests that it is partially filled by sediment drift material (Fig. 12).

The scours described above are part of a larger area of scouring, most of which lies immediately to the north in Faroese waters (Stoker et al, 2002). Some scours in this area are over 200 m deep and cut down into Eocene strata. Stoker et al (2002) interpret the scours as relict features because some are filled with Miocene and younger sediments. However, features such as furrows suggest activity at the present day.

To the west of the area of the scours, the southern flank of the Faroe Platform is marked by several south-facing scarps, some up to 75 m high (Fig. 4). These occur mainly between 1000 and 1200 m water depth, within an area characterised by gravel and rock outcrop at the seabed (Fig. 10). They are interpreted to be erosional in origin.

3.1.3. Comet marks

Areas of coarse sediment on the continental slope are characterised by bedforms at a variety of scales (Stoker et al, 1998; Masson, 2001). Large-scale bedforms include furrows (Section 3.1.1) and barchan dunes (Section 3.2.2). The most common small-scale bedforms are comet marks (Fig. 6d) formed by a combination of erosion around, and deposition in the lee of, obstacles in the bottom current flow (Werner, 1980). Comet marks are associated with the numerous large glacial dropstones seen on the seabed in SEA4. They indicate peak current velocity > 0.75 m s^{-1} (Kenyon, 1986; Masson et al, 2000).

3.2. Deposition by bottom currents

3.2.1. Mud and sand waves

On the West Shetland continental slope, mud waves occur between 61° 05' and 61° 20' N and in water depths of 500 to 650 m (Fig. 4; Masson, 2001). They are best seen on 3.5 kHz profiles (Fig. 13a). Penetration of 3.5 kHz energy to a depth of up to 25 m indicates a predominantly fine-grained sediment sequence, although sampling suggests the waves have a veneer of coarse sediment (Fig. 7). The mud waves have a wavelength of 2-3 km and an amplitude of 5-10 m. The internal structure of the waves clearly shows long term wave crest migration towards the southwest (Fig. 13a). However, the uppermost sediment layer (2-3 m maximum thickness) is thickest on the northeast face of individual waves, suggesting reversal of the migration direction during the most recent development of the waves.

Large-scale 'sand' waves occur between 61° 05' and 61° 40' N in about 600 to 750 m water depth on the West Shetland slope (Fig. 4; Masson, 2001). Wave crests are irregular and oriented E-W to ESE-WNW. Wavelength is 1 - 2 km and amplitude typically < 5 m. In contrast to the mud waves, little sub-bottom penetration of 3.5 kHz energy is apparent in the sand wave area and sub-bottom reflectors are absent or very weakly developed, suggesting a coarser grained, sand-rich sequence (Fig. 13b). Seabed samples from the sand wave area recovered mainly sands with small amounts of gravel and mud (Fig. 7).

3.2.2. Barchan dunes

Fields of barchan dunes were seen near 61° N, 02° 10' W on the West Shetland slope at about 350 m water depth and in the Faroe Bank Channel near 60° 15' N, 5° 45' W in about 1100 m water depth (Fig. 4; Masson, 2001; Masson et al, in prep). Individual dunes seen on sidescan images are 50 to 150 m in length (Fig. 14), although smaller dunes, individually below the resolution of the sidescan, were also seen on a photographic traverse adjacent to the main field in the Faroe Bank Channel (Fig. 6f; Wynn et al, 2002). Barchans on the West Shetland slope are concave towards the northeast, indicating transport in that direction; in the Faroe Bank Channel transport is towards the southwest.

Barchan dunes have been observed widely on the continental shelf and upper slope off western Europe (Stride, 1982; Kenyon, 1986). They appear to be indicators of a limited sediment supply and peak currents in excess of 0.4 m s^{-1} (Table 1; Kenyon and Belderson, 1973; Kenyon, 1986).

3.2.3. Sandy and muddy sand contourites (see also Section 2.3)

A thin sheet of muddy sand or sand occurs at the seafloor along the lowermost continental slope in the Faroe Shetland Channel and in the deepest part of the Faroe Bank Channel (Fig. 10; Masson, 2001; Masson et al, in prep). These sediments are interpreted as contourites transported and deposited by bottom currents (Howe et al., 1994; Howe, 1996; Armishaw et al., 1998; Stoker et al., 1998; Masson et al., 2000; Masson, 2001). Photographs show widespread ripples on the seafloor (Fig. 6e, Masson, 2001), indicating peak current current speeds >0.25-0.3 m s^{-1} (Table 1; Southard and Boguchwal, 1990; Baas, 1999). The near complete absence of gravel at the seabed, in both cores and seabed photographs, is a unique feature of this seabed facies and indicates a Holocene age for its deposition (Fig. 6e). Profiles across the low backscatter zone show no differences relative to surrounding areas. This is compatible with evidence from sediment cores which indicate that the distinctive layer is a thin surface veneer, typically 5-15 cm in thickness (Graham et al., 1996) and below profiler resolution.

On the West Shetland slope, the upslope limit of the slope-parallel contourite band occurs at about 500 m water depth in the NE of SEA4, but deepens to about 1000 m in the SW (Fig. 10). This reflects increasing current speeds as the basin becomes narrower towards the SW. The down slope limit of the contourite band also deepens (from 1000 to about 1300 m) towards the SW, but in an irregular manner, probably influenced by the local slope topography. In the Faroe Bank Channel, contourite sediments are limited to the deepest part of the basin, below 1000 m water depth

On sidescan sonar images, area of unusually low backscatter are recognised within the contourite (Fig. 8). The low backscatter response tends to correlate with the cleanest well-sorted contourite sand and is only seen where the sand is more than about 10 cm thick (Masson, 2001; Masson et al, 2002). The boundaries of the low backscatter area with adjacent areas of relatively higher backscatter are generally gradational, and are interpreted to result from a gradual change in sediment facies. In the deepest part of the Faroe Bank Channel for example, samples and photography suggest gradual changes from sand (low backscatter) to more muddy sediments (low/moderate backscatter) or to muddy sand with variable amounts of gravel (higher backscatter).

3.2.4. Sediment drifts

A number of sediment drifts, recognised as mounded accumulations of sediment showing slightly asymmetric deposition across the drift crest are recognised on profile data from the Faroe Bank and Faroe-Shetland Channels (Fig. 4). In the Faroe Bank Channel, the largest drift can be traced for 20 km, parallel to the contours and separated from the northern slope of the Wyville-Thomson Ridge by a distinct moat (Fig. 9a; Masson et al, in prep). It has the typical form of an elongate drift, formed where a bottom current is constrained against a steep slope (Howe et al, 1994; Stoker et al, 1998; Masson et al, 2002). Smaller drift-like sediment bodies occur within two large scours in the Faroe-Shetland Channel (Fig. 12). These drifts are separated from the headwall scarps of the scours by moats and are interpreted as elongate drifts which parallel these scarps.

In the Faroe Shetland Channel, a series of along slope-oriented wave-like bedforms occur in 800 to 1350 m water depth between 61° 20' and 62° 40' N. These have a wavelength between 1 and 3 km and a height of up to 10 m (Fig. 13c). They are not directly visible on sidescan images, but the troughs between individual 'waves' are clearly marked by large-scale erosional furrows (Section 3.1.2) which define the bedform orientation as parallel to the bathymetric contours (Fig. 4). The close spatial association of the waves and furrows indicates suggests formation by bottom currents. Our preferred interpretation is that the wave field is a complex elongate drift. Similar, although generally somewhat larger features are seen in the northern Rockall Trough (Howe et al, 1994; Stoker et al, 1998; Masson et al, 2002).

3.3. Channels

Few channels are developed in the SEA4 area. The best defined group of channels occurs in a discrete area on the West Shetland slope between 60° 40' and 60° 55' N and 03° 30' to 04° W (Figs. 4, 15) (Kenyon, 1987; Masson, 2001). These channels are interpreted as feeders for a debris flow fan of glacial age (Section 3.4.2; Stoker et al., 1991). Channel widths vary from 50 to 250 m, and depths range from a few metres to over 40 m (Fig. 15). All channels are straight-sided and sub-parallel along most of their lengths; only one example of channels merging is seen. Most channels start abruptly at about 650 m water depth and end abruptly at 1000 m and are between 15 and 18 km long. The reasons why the channels start abruptly in mid-slope is not clear, although the faint traces of two channels extending further upslope suggests the possibility that some or all of the channels once had a greater extent. It is possible that the channels originally formed a complete connection between ice streams which reached the shelf edge in this area (Stoker and Holmes, 1991) and the debris fan on the slope, and that the upper parts of the channels have subsequently been infilled (Kenyon, 1987).

An additional area of largely infilled channels is seen near 60° 10' N and 04° 45' W, in about 500-550 m water depth (Fig. 4). These channels are seen as poorly defined low backscatter stripes which correspond to shallow (around 3 m) depressions.

A number of channels and gullies extend upslope away from the Tampen Slide sidewall on the North Sea fan in the northern part of SEA4 (Fig. 4; Section 2.4.3). These are a few tens of m deep at most, and die out upslope. They post date the last episode of North Sea fan debris flow emplacement, so have probably been active since 14,000 years. They appear to be inactive at the present day.

3.4. Landslides

3.4.1. AFEN slide

A single example of a surficial slope failure and resultant debris flow, the AFEN slide, was imaged in SEA4 (Masson, 2001). The well defined slope failure is centred on 61° 12' N, 2° 27' W, in water depths between 900 and 1100 m. It is about 11 km in length by between 2 and 4 km in width, broadening down slope and affecting an area of about 35 km^2 (Fig. 16). The landslide scar consists of a distinct headwall, below which an area of erosion, characterised by rough topography, extends some 4 km down slope. A profile taken across the mid part of this rough zone shows up to 15 m of erosion. The lower part of the debris flow consists of a depositional lobe with a relief of between 5 and 10 m . The age of the debris flow has not been determined precisely, although it clearly post-dates the deposition of the glacial muds which blanket the area. Cores taken within the slide scar contain an upper layer of sandy sediment up to 0.3 m in thickness of inferred Holocene age. Thus an early Holocene age can be inferred for the debris flow emplacement. This is supported by ^{14}C dating of foraminifera in the overlying sandy sediments (Holmes et al., 1999).

3.4.2. Glacigenic debris flows

Much of the West Shetland slope is underlain by thick sequences of glacigenic debris flows, with a number of discrete depocentres (Rona Apron [Stoker, 1995; Holmes et al, 2002]; Foula Apron [Stoker, 1995]; North Sea Fan [King et al, 1998; Nygaard et al, 2002]). Note that the terms 'apron', 'wedge' and 'fan' have been applied to these features by various authors in an interchangeable manner. High resolution (3.5 kHz) profiles show a transparent sub-bottom sequence, typical of debris flow deposits (Fig. 9b, d) Dowdeswell et al., 1997; Stoker et al., 1991; King et al, 1998; Nygaard et al, 2002), in sharp contrast to the stratified sequence seen in basin areas away from the debris fan area (Fig. 9c, d). Glacigenic debris fans are relict features associated with the last glacial period. They are not generally exposed at the seabed at the present day, although the overlying sediment may consist of as little as a few centimetres of coarse grained lag deposits in areas where strong bottom currents have restricted Holocene deposition. Glacigenic debris fans are the cause of the gently undulating seafloor topography seen on parts of the lower slope of the Faroe Shetland Channel (e.g. Fig. 9b; Holmes et al, 2002).

3.4.3. Landslides on the NE Faroe slope

Much of the small-scale seafloor topography of the part of the NE Faroe platform which falls into SEA4 is associated with relict landslide scars and buried landslide deposits. These landslides appear to be part of a much larger landslide complex which extends along much of the northern margin of the Faroe platform (van Weering et al, 1998). The age of the slope failure is not known but it is believed to be Late Pleistocene.

3.4.4. Tampen Slide

The sidewall of the Tampen Slide is marked by a NW-trending scarp, up to 100 m high, crossing the northern part of SEA4 between 63° 10' and 63° 40'N (Fig. 4). The slide scar is clearly partially infilled by glacigenic debris flows, indicating a relict, largely buried feature (see Section 2.4.3). Evans et al (1996) suggest that it may pre-date the mid-Pleistocene onset of outer shelf glaciation. Its headwall lies under Norwegian sector of North Sea fan.

3.5. Mud diapirs

Mud diapirs (or shale diapirs if the material is relatively consolidated) result from the upward migration of fluid/plastic mud or semi-consolidated sedimentary rock, often leading to extrusion at the seabed. Diapirs are often associated with fluid overpressure in the subsurface and may act as conduits for fluid escape. In SEA4, mud/shale diapirs are limited to an area between 62° 30' and 63°N and 1° and 2°W (Fig. 4). These diapirs are marked by areas of rough, elevated, topography, and high backscatter on sidescan sonar data. Individual diapirs reach 5 or 6 km across and 100 m or more above the level of the local 'background' seafloor (Figs. 9d, 17). The morphology of the diapirs changes from large coherent structures in the east to fragmented and possibly partially buried structures in the west, although some of the western diapirs may be diapir complexes rather than single structures. An area of high EM120 backscatter occurs in association with the topographically defined diapirs (Fig. 4). This may be related to sub-seabed penetration of the EM120 signal and the imaging of buried diapir material. The high backscatter area in turn is surrounded by a much larger low backscatter 'halo'. This origin of this halo is unknown.

Photographic transects across the diapirs show fractured blocky material at the seabed, often mantled with unconsolidated sediment or glacial dropstones (Fig. 6g, h). Most cores from the diapir areas recovered cohesive glacigenic mud, rather than more consolidated diapir material, which reflects the photographic observation that diapiric material outcrops only over limited areas of the seafloor. Preliminary analysis of cores which appear to have sampled the diapir sediment suggest that it is composed of silica-rich ooze of Miocene age (Achmetzhanov, pers comm; van Weering pers comm), similar to that recovered from other mud diapirs further north on the Norwegian margin (ref).

No evidence for recent mud flows or biological communities which might indicate active fluid flow were observed during SEA4-dedicated environmental surveys in the area. However, some box cores obtained by Dutch scientists in 2002 did contain an unusual fluid mud which could possibly be an indication of active fluid flow (van Weering, pers comm). Unfortunately, none of this material was preserved for analysis. Overall, the abundance of glacial dropstones on top of the diapirs, coupled with the lack of any observations of fluid flow or its effects, would suggest that the diapirs are not highly active structures or that the rate of activity is low and its areal distribution limited. However, fluid mud recovered in some recent box cores could be evidence for present day mud volcanism On the basis of the limited surveys carried out to date, we cannot rule out the existence of areas of active diapirism and/or fluid venting.

3.6. Deep water corals

No 'reefs' or concentrations of deep water corals were identified on sidescan sonar images from SEA4. Features similar to the 'Darwin' mounds, seen south of the Wyville Thomson Ridge (Masson et al, 2002) are absent. This is confirmed by photographic surveys, which failed to identify any significant occurrences of corals.

3.7. Holocene sedimentary processes

There is widespread evidence that the Holocene sedimentary regime beyond the shelf edge in SEA4 is dominated by erosion, non-deposition or very low sedimentation rates. Holocene sediments are typically <15 cm thick and often contain abundant gravel-sized material, even on the floor of the channel. The variety of sedimentary, igneous and metamorphic lithologies within the gravel clearly indicates an ice-rafted origin and thus reworking of pre-Holocene material (Stoker et al, 1991). In some places, such as in parts of the Faroe-Shetland Channel basin floor where post-glacial muddy sediments are <5 cm thick, it is evident that the surficial gravel is ice-rafted material that has remained unburied due to limited deposition in the Holocene. Mud-dominated surficial sediments and low levels of sorting in samples recovered from the basin floor in water depths >1300 m indicate weak bottom current influence, suggesting that low sediment supply to the basin floor, rather than non-deposition or erosion due to current activity, is the main reason for low Holocene sedimentation rates.

The post-glacial cover of much of the continental slope, of the Faroe Shetland Channel floor south of about 60° 45'N, and all but the deepest part of the Faroe Bank Channel floor comprises 10-15 cm of sand and gravel. These surficial sediments show abundant evidence for strong bottom-current activity, in the form of erosional and depositional bedforms at all scales (Figs. 4, 6, 8, 9, 11-13), considerably higher levels of sorting of the sand fraction relative to the basin floor sediments and a lack of silt and mud-sized material. Widely occurring areas of gravel-covered seafloor are interpreted as "gravel lag contourites" (Stoker et al., 1998), indicative of erosion and winnowing of glacial sediments. This reworked glacial material, with the addition of Holocene bioclastic carbonate material (Light and Wilson, 1998), forms the thin post-glacial veneer covering most of the slope area. Most cores show a sharp unconformity between coarse-grained surficial sediments and the underlying glaciomarine muds rather than a gradual coarsening up sequence, suggesting a relatively abrupt change from a low to high current regime.

The occurrence of superficial sand bedforms at scales from a few tens of cm (Figs. 6e, f) to 100 m or more (Fig. 14) shows that sand and finer-grained material is highly mobile under the Holocene current regime on most areas of the continental slope in SEA4. However, the patchy occurrence of sand and the occurrence of bedforms such as barchan-type sand dunes suggests that the supply of sediment to the slope is limited (Stride, 1982). This is compatible with evidence from the adjacent shelf, which shows net sediment transport towards the ENE/NE, onto the shelf (Stride, 1982) and with the likelihood that sediment input derived from seabed erosion by bottom currents is presently inhibited by the coarse-grained surficial veneer. Present-day sediment input may largely be restricted to carbonate debris of biogenic origin (Light and Wilson, 1998).

Areas of contourite sand deposition show significant net accumulation of Holocene sediments. The Holocene age of this deposit, inferred from the lack of gravel within it, has recently been confirmed by ^{14}C dating (Holmes et al., 1999). The thin sheet like nature of the sand body, its surface ornament of ripples, good levels of sorting and the uniformity of the sediment over the entire zone indicate that this is a thin contouritic sand sheet. Similar sediments are now recognised to cover large areas of the continental slope west of Scotland and appear to result from stronger bottom water flow and possibly lower sediment input in the Holocene relative to the last glacial period (Armishaw et al., 1998; Stoker et al., 1998; Masson et al, 2002).

3.8. Sediment transport contrasts between late glacial and Holocene

3.8.1. Late Glacial Sedimentation

It is clear that the sedimentary environment in SEA4 has varied enormously over the last glacial/interglacial cycle. During the last glacial, ice carried large amounts of glacigenic sediment to the West Shetland shelf edge, which then fed directly into glacigenic debris flow fans on the slope (Stoker, 1997a; Stoker et al., 1991; Stoker and Holmes, 1991). Considerable volumes of ice rafted material were also supplied directly to the deep basin (Stoker et al., 1998). Many of the features which characterise the present day continental slope, such as iceberg ploughmarks, glacigenic debris flows, and channels, were formed at this time. However, in the deeper basin, there is considerable evidence that contour currents were also active in redistributing at least some of this glacigenic input, forming sheet sediment drifts (Stoker et al., 1998; Stoker and Holmes, 1991).

3.8.2. Holocene Sedimentation

Overall, the glacial period was characterised by strong interaction between along- and down slope sediment transport, and that many of the characteristics of the present-day slope and basin morphology were formed at this time. This contrasts markedly with the post-glacial Holocene period, extending to the present day, during which sediment input to the continental slope has been very low and down slope sediment transport appears to be almost non-existent. Post-glacial sediment transport processes have been dominated by reworking and along slope transport of surficial sediment by bottom currents. Low sediment deposition rates over much of SEA4 appear to be due to several factors including:

(a) lack of delivery of sediment to the shelf edge, due to net regional ENE transport of sediment on the shelf by wave action and tidal currents

(b) high energy bottom currents on both the upper and lower slope, which prevent sediment deposition and ensure transport of any available mobile sediment out of SEA4

(c) low 'in situ' sediment production by seafloor erosion, even in areas of strong bottom currents, because of 'armouring' of the seafloor by a surficial layer of gravel.

3.9. Bottom current speeds indicated by bedforms

Sediment bedforms at all scales, seen on seabed photographs, sidescan sonar images and high-resolution profiles, can provide evidence for the velocity of the bottom currents which were responsible for their formation. It is a reasonable assumption that the evidence preserved in the geological record (e.g. the migration direction of sediment waves) will be representative of relatively long term net bottom current transport. On the other hand, superficial bedforms (e.g. sediment ripples), modified by frequent bottom current events, may record only the last significant or peak current event, and thus may be difficult to reconcile with both the long-term record and with measurements made using short-term instrument deployments. It is important to note that we have no direct evidence of how often and for what period 'peak current' events might operate. However, seafloor photographs show that almost all the superficial bedforms in SEA4 have a remarkably fresh appearance. For example we rarely see any 'temporary' deposits of fine-grained material (other than organic detritus) in the troughs between ripples, and areas of gravel seafloor are completely clear of fine-grained debris (Fig. 6). Ripples generally have a fresh appearance and have not been degraded by bioturbation and other biological activity. Thus we believe that the currents responsible for bedform generation are continuously or at least frequently active.

A summary of the velocities associated with bedforms in the deep ocean is given in Table 1. Most of the evidence is derived from analogous bedforms observed in shallow water on the continental shelf or upper continental slope, where information on currents is much more complete than in the deep ocean (see references in Table 1). The key bedforms in the SEA4 are rippled contourite sands, barchan dunes, comet marks and furrows. Rippled contourite sands occur widely on the mid to lower continental slope northwest of the UK, where they are associated with current velocities in the order of 0.3-0.4 m s^{-1} (Southard and Boguchwal, 1990; Baas, 1999; Masson et al, 2000; Masson, 2001; Masson et al, 2002). Coarser grained sandy gravel contourite lag deposits occur at shallower depths on the slope, where velocities may be 0.75 m s^{-1} or greater. Barchan and related dune forms indicate velocities in the order of 0.4-0.75 m s^{-1} (Kenyon and Belderson, 1973; Kenyon, 1986; Belderson et al, 1988). Isolated barchans are often indicators of a limited but continuous sand supply. The location of the barchan field in Faroe Bank Channel, on the edge of an area of gravel seafloor which passes down-current into sandy seafloor, is typical. Two types of furrows clearly occur in the deep ocean (Flood, 1983). Furrows in fine-grained cohesive sediments are associated with persistent bottom currents of < 0.3 m s^{-1}. The furrows found in the Faroe Bank Channel are of the second type, cut into gravel. These indicate bottom current velocities in the range 1.0-1.5 m s^{-1} (Kenyon and Belderson, 1973; Stride, 1982; Belderson et al, 1988). Seafloor erosion, as indicated by scarps and associated sand ribbons in the area of the sill between the Faroe-Shetland and Faroe Bank Channels, and by areas of bare rock on the lower slope of the Faroe platform, may indicate even higher velocities. Similar features in the Straits of Gibraltar correlate with peak currents up to 2.5 m s^{-1} (Kenyon and Belderson, 1973).

In the present study, all the data from the upper slope at depths <500 m, such as the barchans seen on sidescan data (Fig. 14) and comet marks on seafloor photographs (Fig. 6d; Table 1) indicate strong currents towards the NE (Fig. 18). Peak current velocities in excess of 0.75 m s^{-1} are indicated by the presence of comet marks (Kenyon, 1986). This is consistent with the oceanographic data, and indicates formation under the strong NE-directed slope current (Turrell et al., 1999).

Data from greater water depths on the lower continental slope present a less clear cut picture. North of 61°N on the West Shetland slope between 500 and 1000 m water depth, large scale features such as sediment waves and sheet sands, co-existing with erosional furrows, suggest significant current influence on sedimentation. Seabed photographs, however, show limited evidence for strong currents. Gravel covered seafloor at about 500 m depth typically gives way to mixed gravel/sand seafloor at greater depths but evidence for comet marks around boulders or even biological evidence for a preferred current direction is generally lacking. Erosional furrows are more common south of 61°N on the West Shetland slope than to the north, suggesting that currents are stronger, presumably because of the southward narrowing of the Faroe Shetland Channel which leads to constriction and acceleration of the flow. Here, evidence for strong currents in the form of comet marks or preferential deposition behind boulders is seen on some photographs taken at water depths of 800-1000 m.

Sediments in the eastern Faroe Bank Channel range from sand through to coarse gravel, with some areas of bare, scoured rocky seafloor; fine-grained sediments are largely absent, indicating a high-energy current regime. The observed bedforms confirm this, indicating peak bottom currents varying between < 0.3 and > 1.0 (perhaps > 1.5) m s^{-1} across the area (Table 1).

4. CONCLUSIONS

4.1. Summary and conclusions

This report describes the seabed sediments of SEA4 and the sedimentary processes which have shaped its present day morphology and sediment distribution. The main conclusions are:

(1) The present day sedimentary environment of SEA4, seaward of the continental shelf edge at about 200 m water depth, is dominated by low sediment input and deposition rates, and by reworking of surficial sediments by bottom currents.

(2) The large scale seabed morphology was shaped mainly during the last glacial, when high sediment input resulted in glacigenic debris fan formation.

(3) Seabed sediments show a general decrease in grain size with increasing water depth, from mixed gravel and sand on the upper slope to mud in the deeper Norwegian basin below about 1500 m. However, this simple pattern is modified by the pattern of bottom currents. In general, stronger currents (correlating with coarser sediment) occur at greater depths in the relative narrow southern Faroe Sheltand Channel and Faroe Bank Channel than in the more open basin further north.

(4) Sediment bedforms show that bottom currents are particularly active at water depths <500 m, under the NE directed slope current, where peak current velocities >0.75 m s^{-1} can be expected. In this area, mobile sand bedforms move over a predominantly gravel substrate. Gravel at the seabed and areas of seabed scour in the sill area between the Faroe Shetland and Faroe Bank Channels indicates local bottom currents > 1.0 m s^{-1}.

(5) On the lower slope and over parts of the basin floor in the southern Faroe Shetland Channel and Faroe Bank Channel, sand and muddy sand deposits, often with a pattern of ripples on the sediment surface, suggest peak currents in the order of 0.3-0.4 m s^{-1}.

(6) No large-scale patches of deep water corals have been found in SEA4.

(7) A field of mud diapirs occurs in the southern Norwegian Basin. No evidence for fluid escape (or possible associated biological communities) have been found to date. However, there remains a possibility that localised areas of fluid escape may be active in the mud diapir province.

4.2. Implications for hydrocarbon exploration

Ocean currents are the major factor controlling the present day sedimentary regime in SEA4. Over much of the area, particularly in water depths <1000 m, currents are strong enough to prevent deposition of any fine grained material and episodic peak currents may transport sand or even gravel. Some implications for hydrocarbon exploration are:

(1) Any particulate matter discharged from vessels operating in SEA4 is unlikely to settle on the seabed in the vicinity of the vessel, but will be carried out of the area (to the north if discharged above about 500 m water depth, to the south below 500 m). Note that high rates (up to 0.3 m/1000 yr) of fine-grained Holocene sedimentation characterise the Norwegian margin immediately north of SEA4, suggesting that this is the sink area for sediment eroded

from the upper west Shetland slope. The sink area for material carried to the southwest is unknown but is likely in the North Atlantic basin to the west of the Faroe Bank Channel.

(2) The occurrence of mobile sand (sand patches, dunes or ribbons) at the seabed will lead to a natural seabed variability over time as the sand is moved by the strong bottom currents. This has implications for the design and intepretation of repeat surveys. In particular, how do you distinguish between natural and anthropogenic changes?

(3) The strong currents are likely to create scour and/or deposition around any seabed installation (e.g. wellhead or pipeline), depending on current strength.

(4) The considerable heterogeneity of surficial sediments, particularly in the upper slope iceberg ploughmark area, needs to be taken into account when planning seabed operations. Precise navigation must be used in all environmental survey work (e.g. to ensure that geophysical survey data and samples are exactly co-registered)

(5) The occurrence of large areas of gravel substrate on the continental slope and even in places on the basin floor is relatively unusual. The wider importance of this substrate needs to be fully understood.

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Bedform	Sediment type	Peak current velocity	Reference
mud waves, contourite drifts	Fine-grained, often pelagic or hemipelagic	0.05-0.20 $m\ s^{-1}$	Manley and Flood, 1993
furrows	fine-grained, cohesive	< 0.30 $m\ s^{-1}$	Flood, 1983
contourite sheet	sand, often rippled	0.3-0.4 $m\ s^{-1}$	Southard & Boguchwal, 1990 Baas, 1999 Masson, 2001 Masson et al, 2002
barchan dunes	foraminiferal sand clastic sand	> 0.3 $m\ s^{-1}$ 0.4-0.75 $m\ s^{-1}$	Lonsdale & Malfait, 1974 Kenyon & Belderson, 1973 Kenyon, 1986
comet marks	sand/gravel lag deposit	> 0.75 $m\ s^{-1}$	Kenyon, 1986 Masson et al, 2000
sand ribbons	sand	1.0 $m\ s^{-1}$	Kenyon & Belderson, 1973 Belderson et al, 1988
furrows	gravel	1.0-1.5 $m\ s^{-1}$	Flood, 1983 Belderson et al, 1988 Stride, 1982
erosional scours	gravel, rock	1.0-2.5 $m\ s^{-1}$	Kenyon & Belderson, 1973

Table 1. Bottom current velocities associated with various types of bedforms observed in the deep ocean.

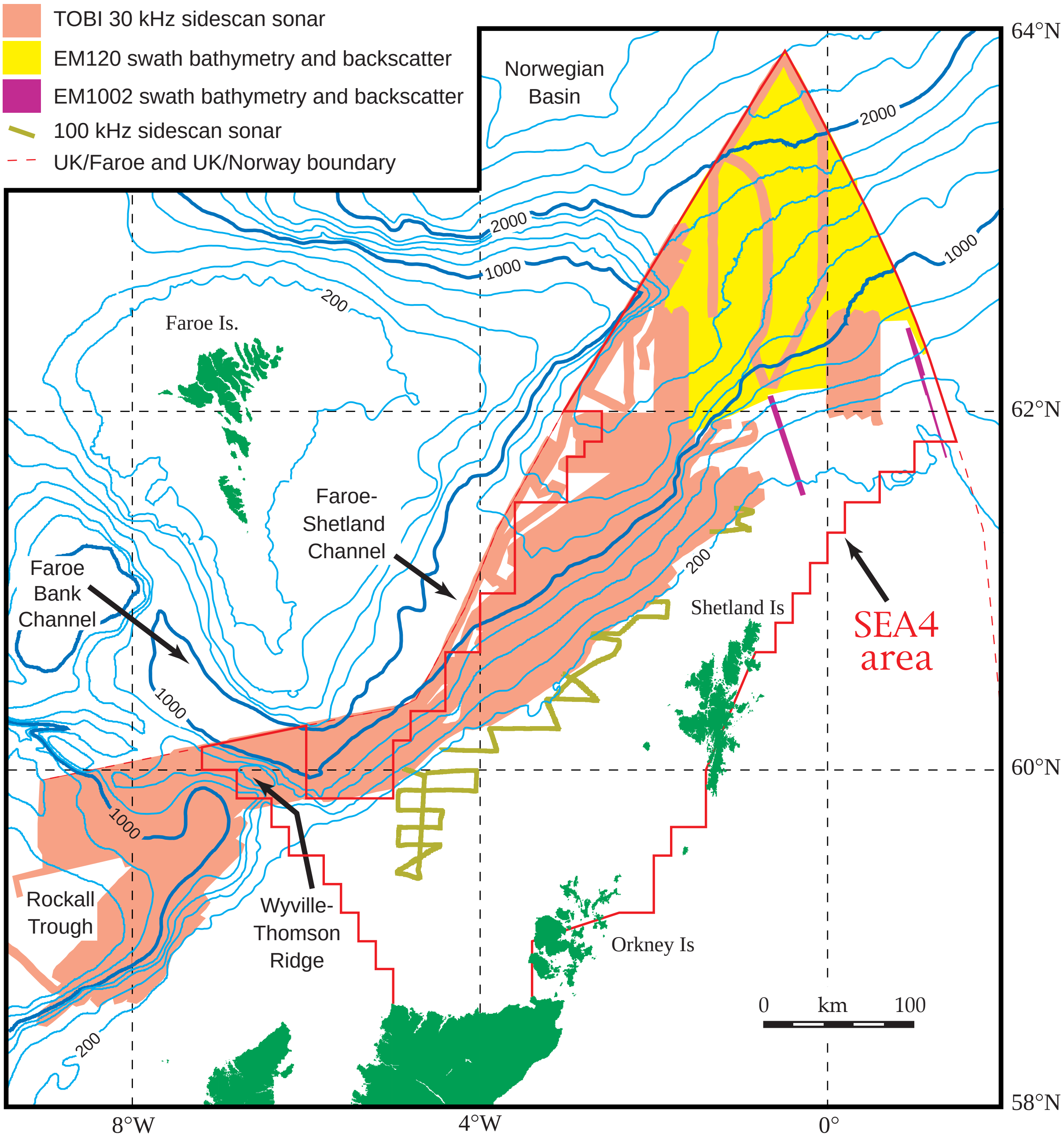

Figure 1. Summary of sidescan sonar and swath bathymetry survey data in SEA4.

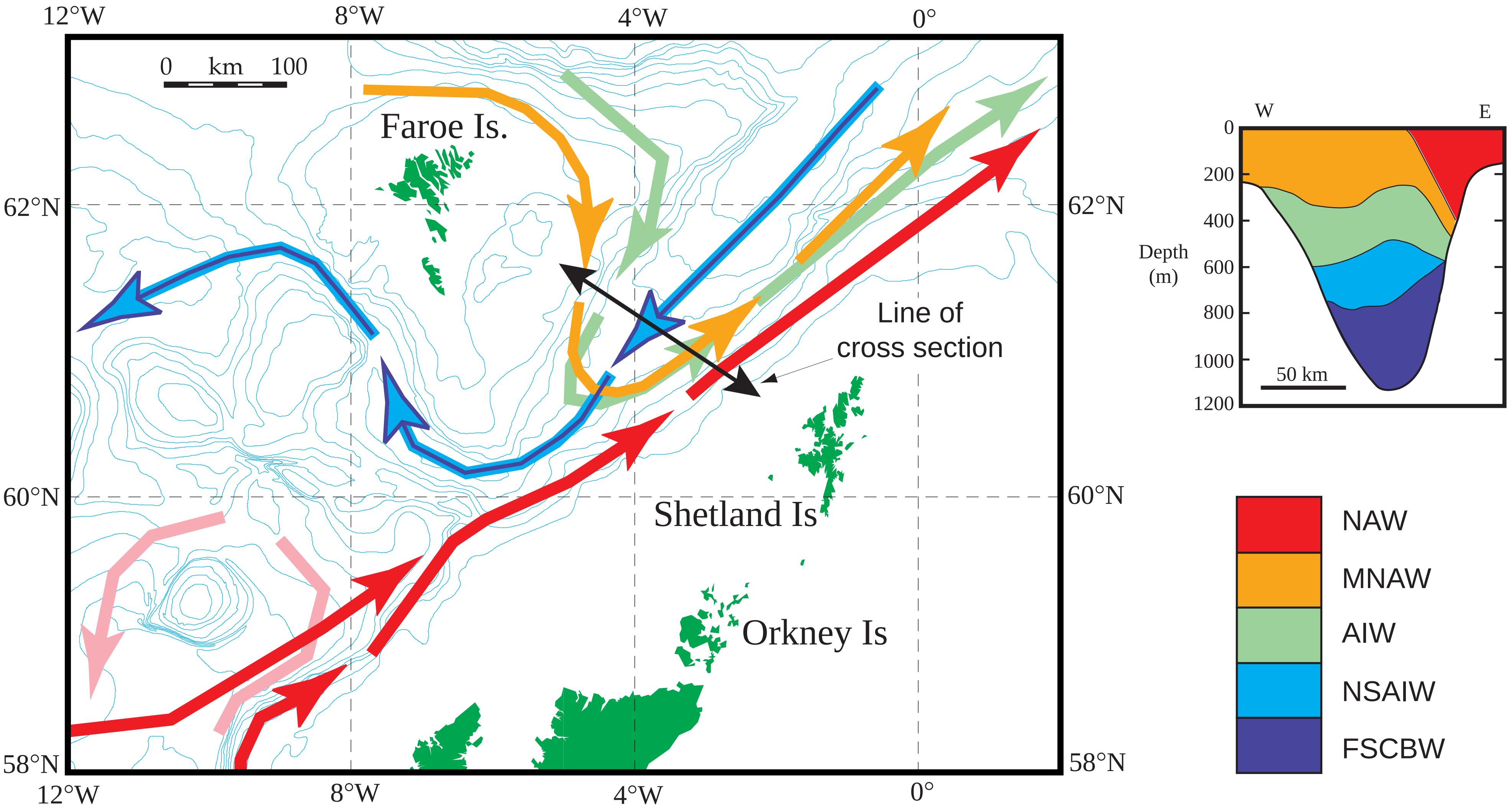

Figure 2. Left - summary of oceanographic regime to the north and west of Scotland. Right - section across the Faeroe-Shetland Channel (located by black arrow) showing water column structure in the vertical plane

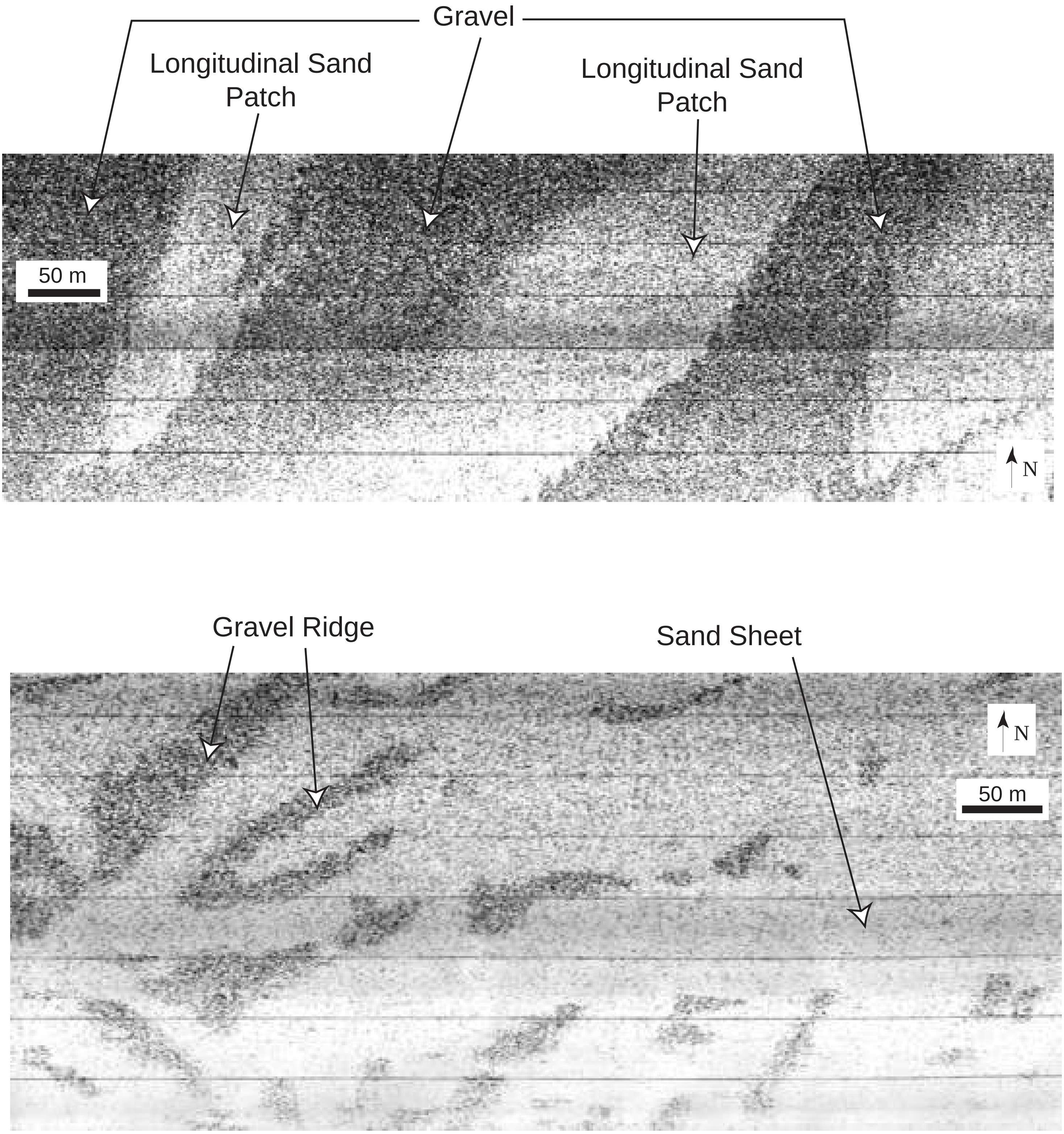

Figure 3. Examples of 100 kHz sidescan sonar data from the continental shelf west of Shetland (dark tones = high backscatter). (a) longitudinal sand patches on a gravel substrate. (b) sand sheet overlying iceberg ploughmarks.

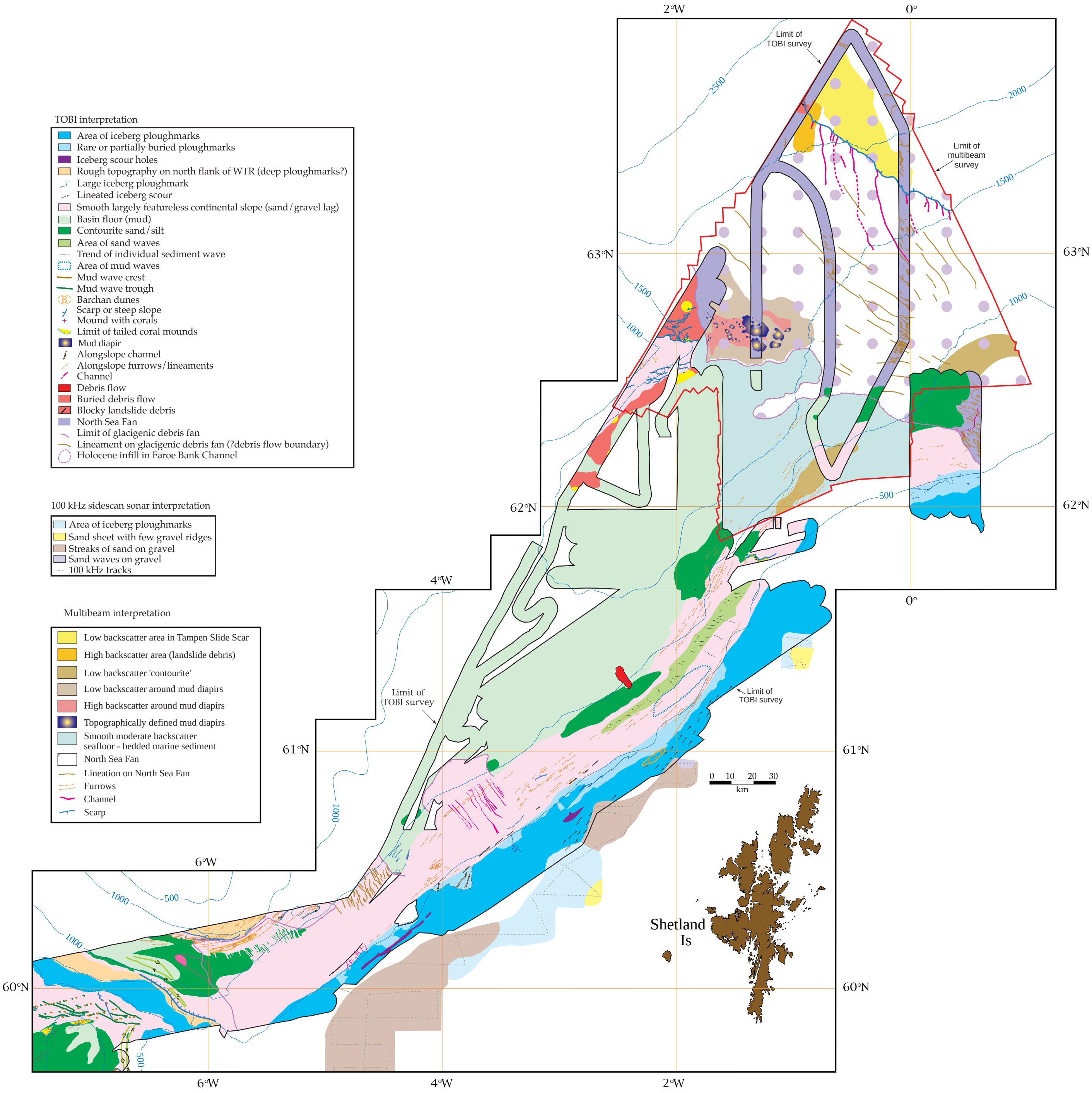

Figure 4. Summary interpretation of SEA4 based on sidescan sonar, swath bathymetry, profiles and sediment cores. Areas of no data are left blank.

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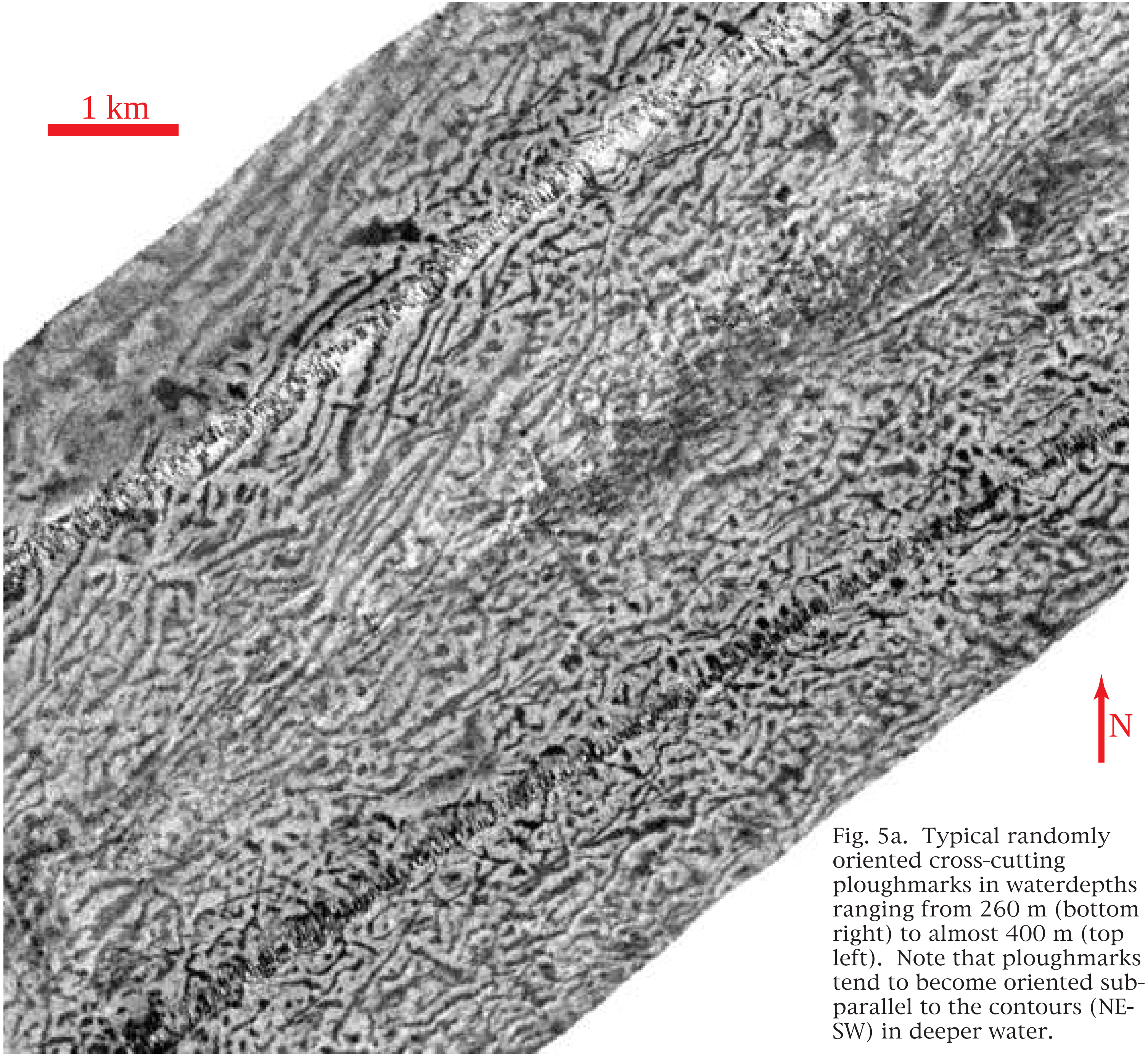

Fig. 5a. Typical randomly oriented cross-cutting ploughmarks in waterdepths ranging from 260 m (bottom right) to almost 400 m (top left). Note that ploughmarks tend to become oriented subparallel to the contours (NE-SW) in deeper water.

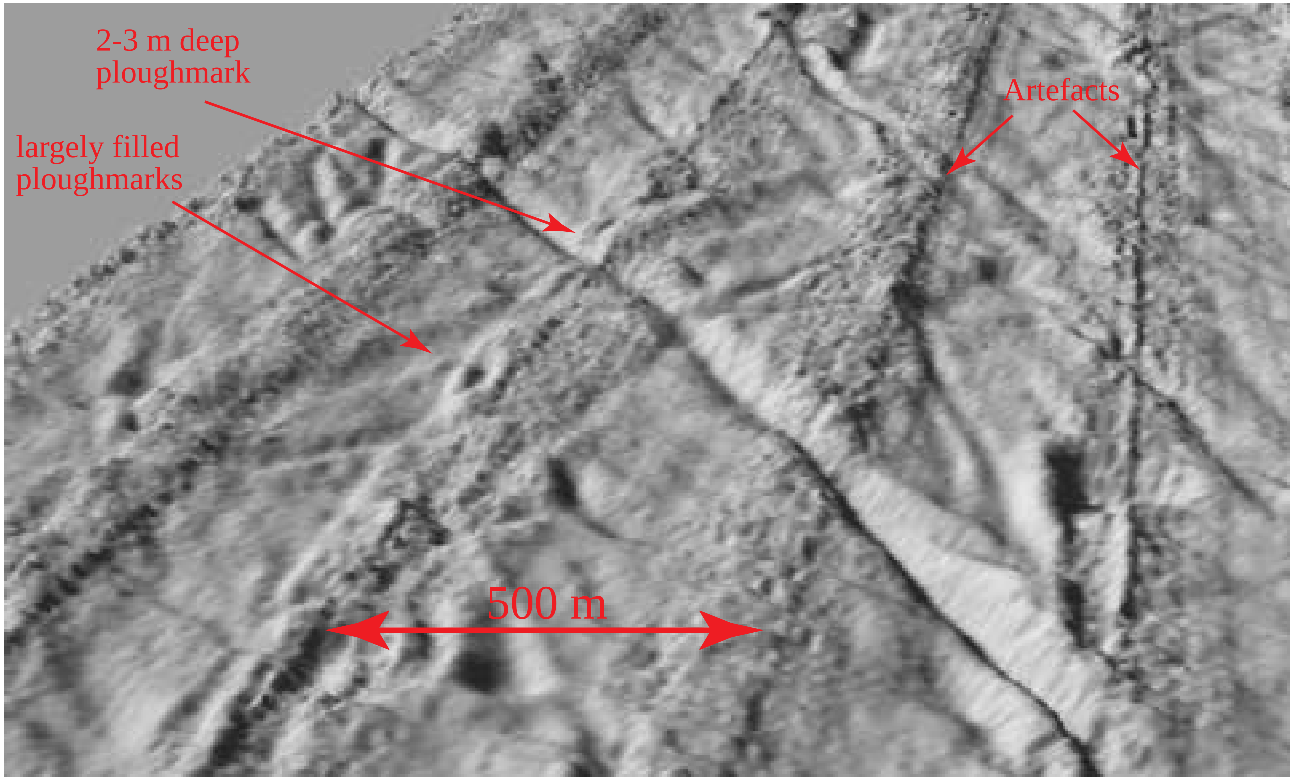

Figure 5b. 3D perspective view, based on EM1002 swath bathymetry data, of iceberg ploughmarks on the upper slope north of Shetland. Most of the ploughmarks in this area are largely infilled. The single obvious open ploughmark is 2-3 m deep. Note that it cross-cuts several infilled ploughmarks. Track parallel artefacts are due to slightly noisy data in far range of each swath.

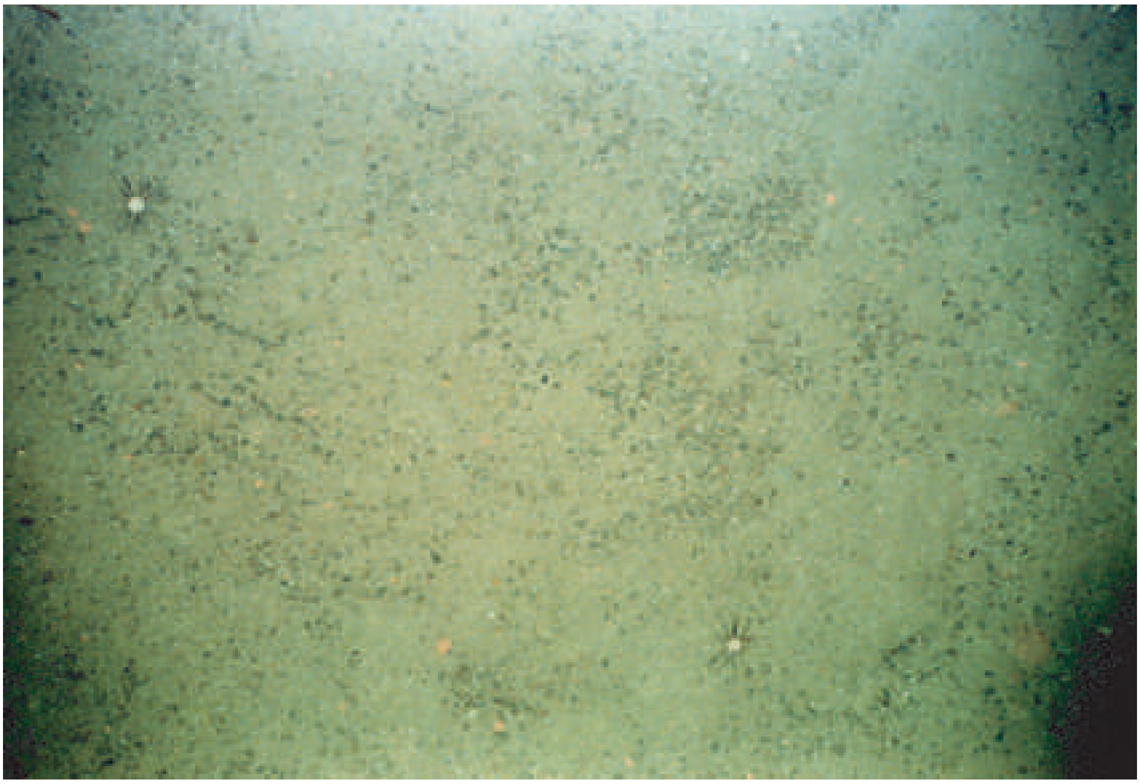

Figure 6a. Seabed photograph showing coarse sandy sediments with abundant small pebbles, typical of iceberg ploughmark troughs. Water depth 300 m.

1 m

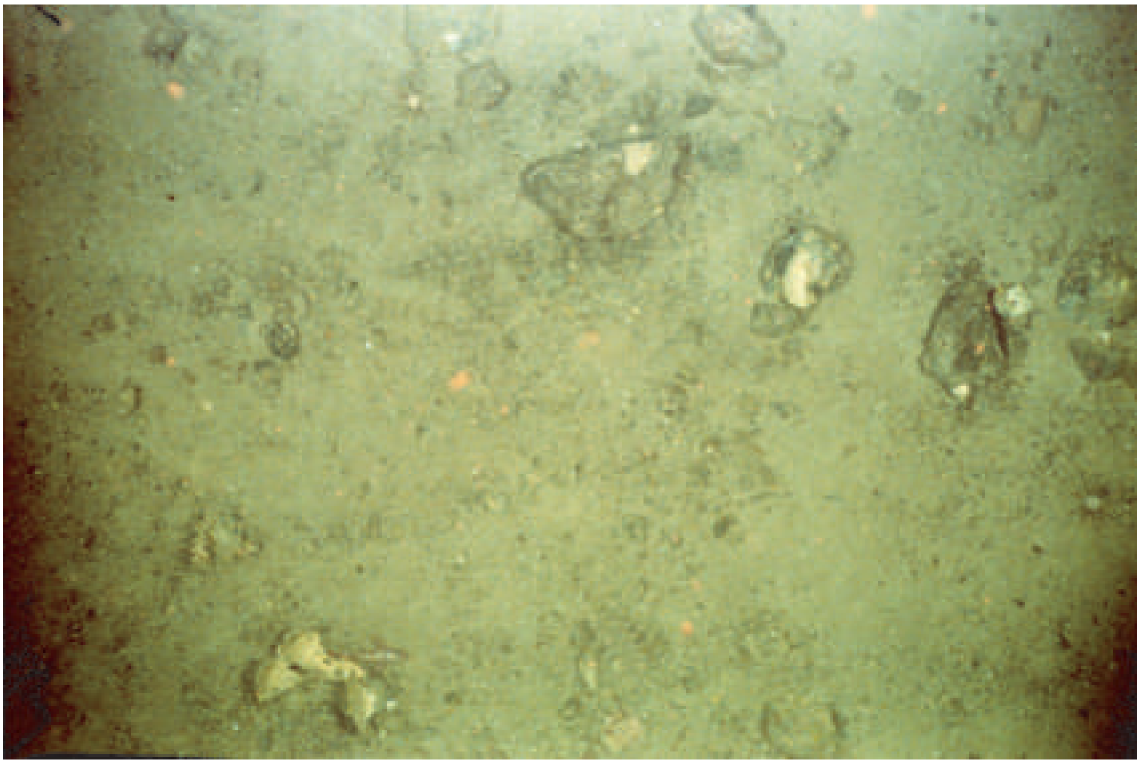

Figure 6b. Seabed photograph showing coarse sandy sediments with abundant boulders up to 50 cm in size, typical of iceberg ploughmark ridges. Water depth 300 m.

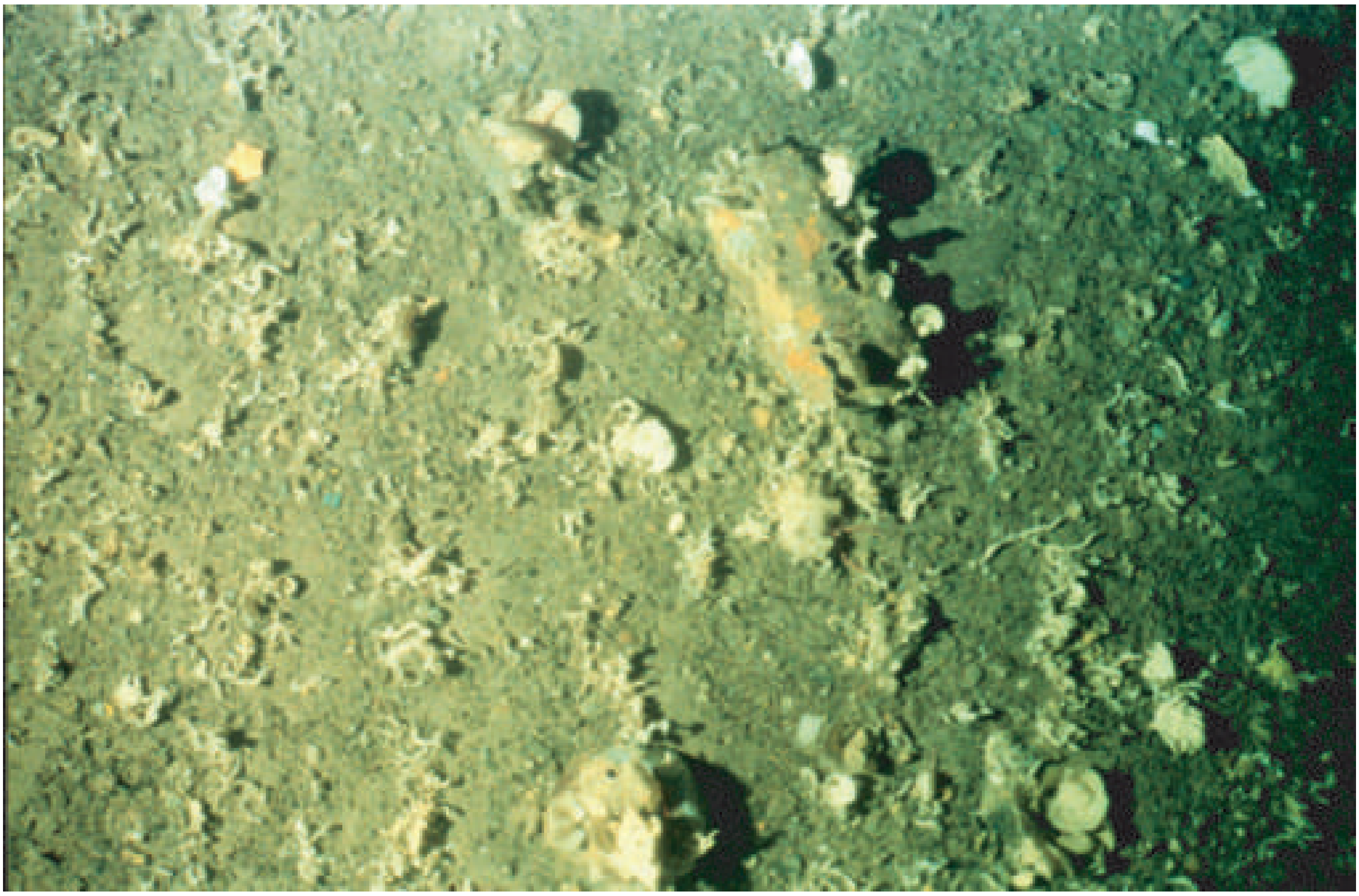

Figure 6c. Seabed photograph showing gravel covered seafloor with abundant epifauna, mainly sponges. Water depth 486 m.

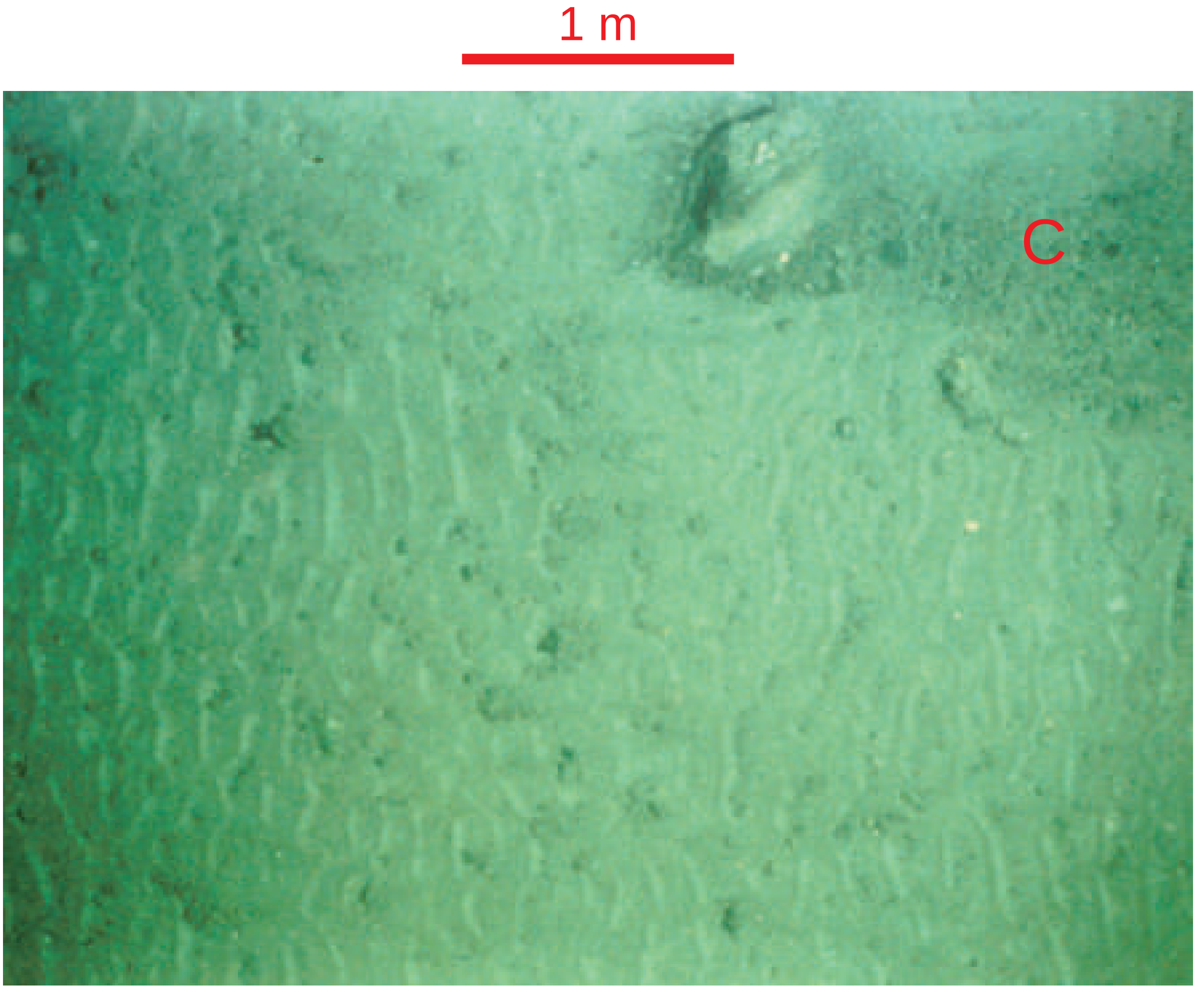

Figure 6d. Sand ripples on a gravel pavement. Ripple asymmetry and comet mark (C) behind boulders indicate bottom currents from left to right (towards the NE). Water depth 510 m.

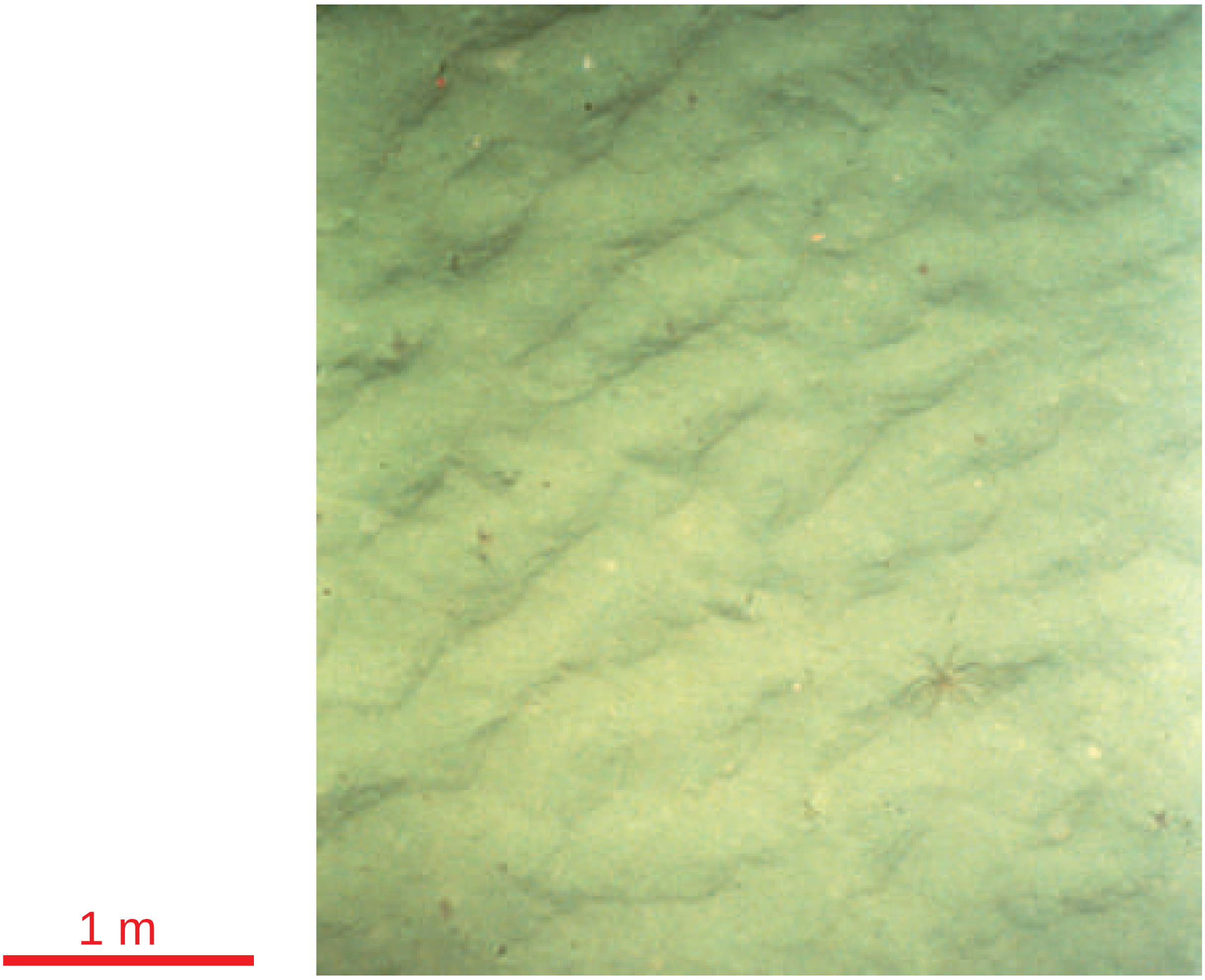

Figure 6e. Seabed photograph showing rippled fine sand in about 900 m water depth on the west Shetland slope.

Figure 6f. Seabed photograph showing the edge of a barchan dune (rippled sand) on a smoother sandy seafloor with some gravel. Faroe Bank Channel, water depth 1150 m.

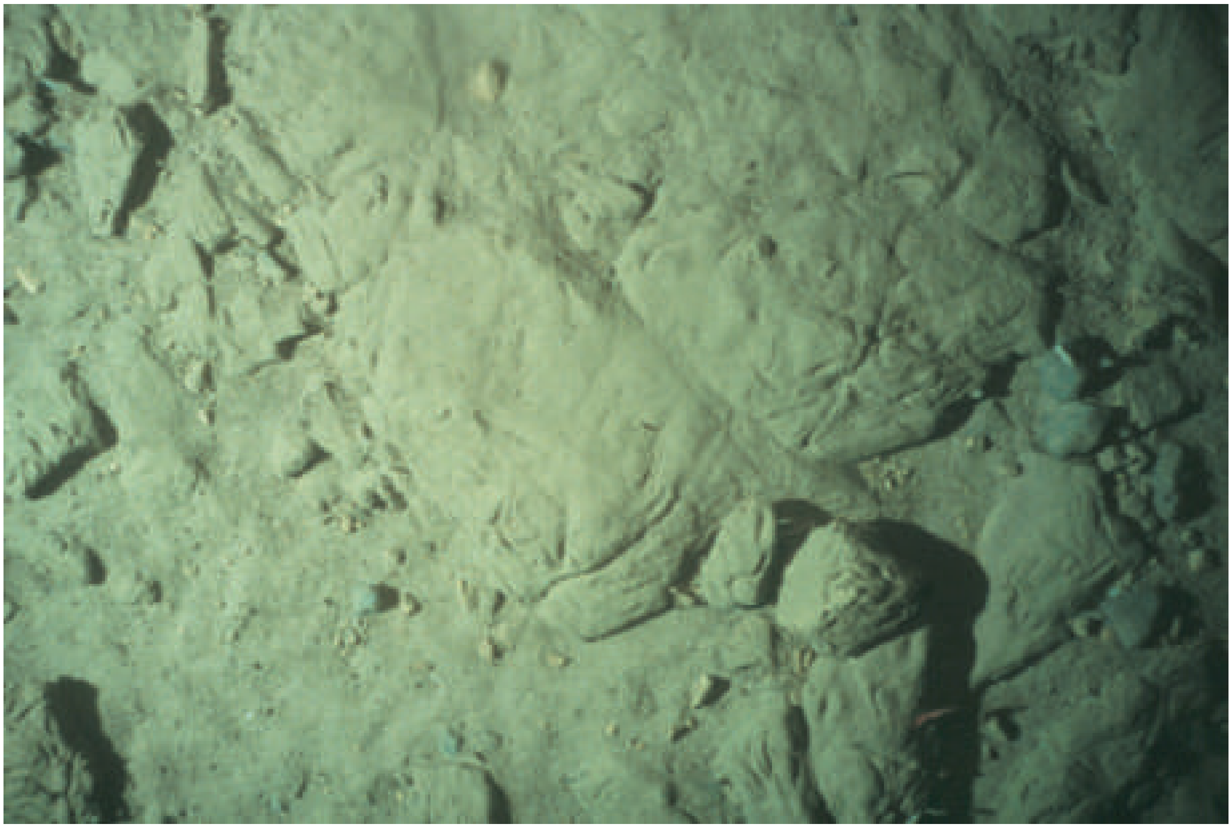

Figure 6g. Surface of fractured mud diapir material (?Miocene ooze) in the Norwegian Basin.

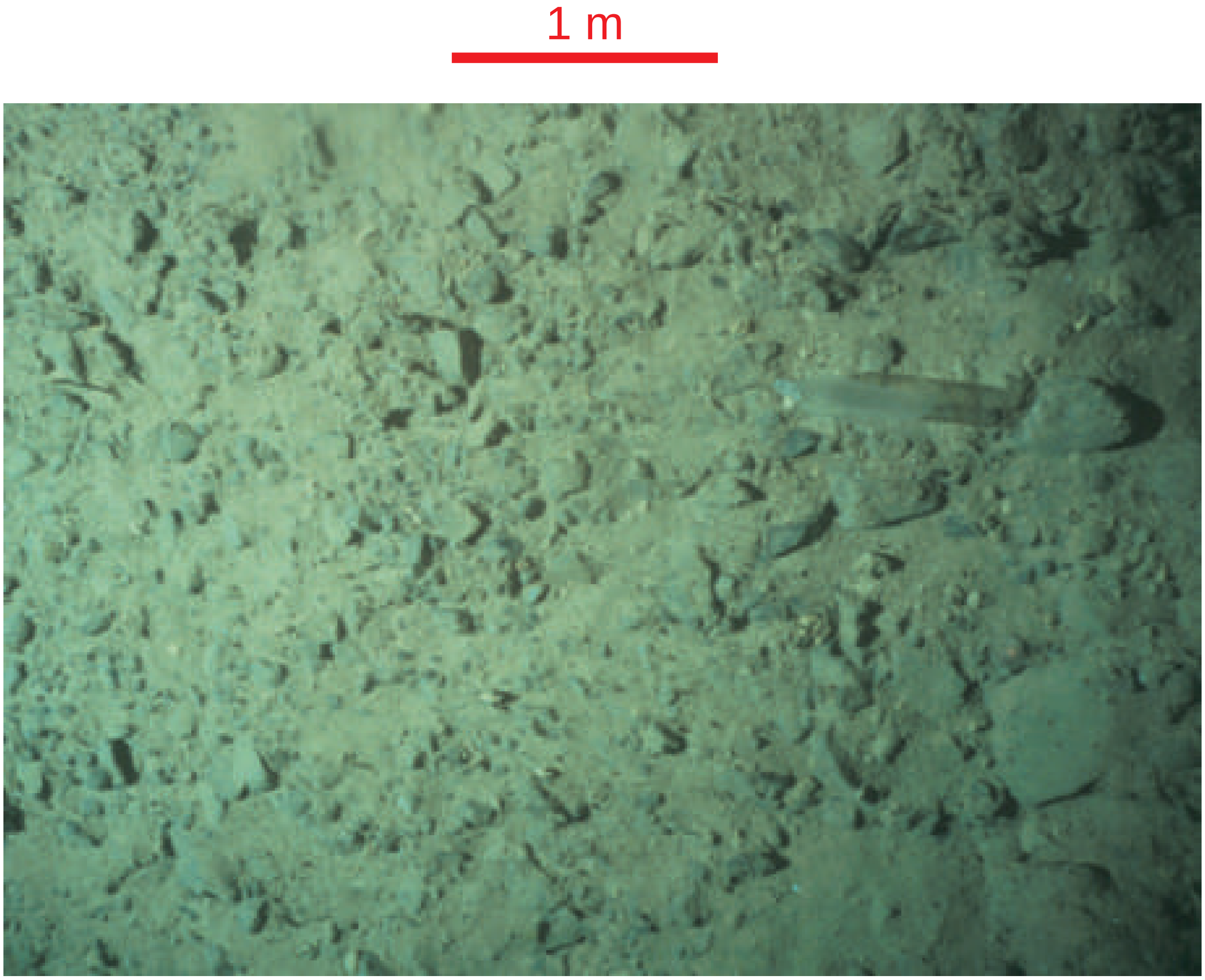

Figure 6h. Elevated area on mud diapir covered with gravel (iceberg dropstones) in the Norwegian Basin.

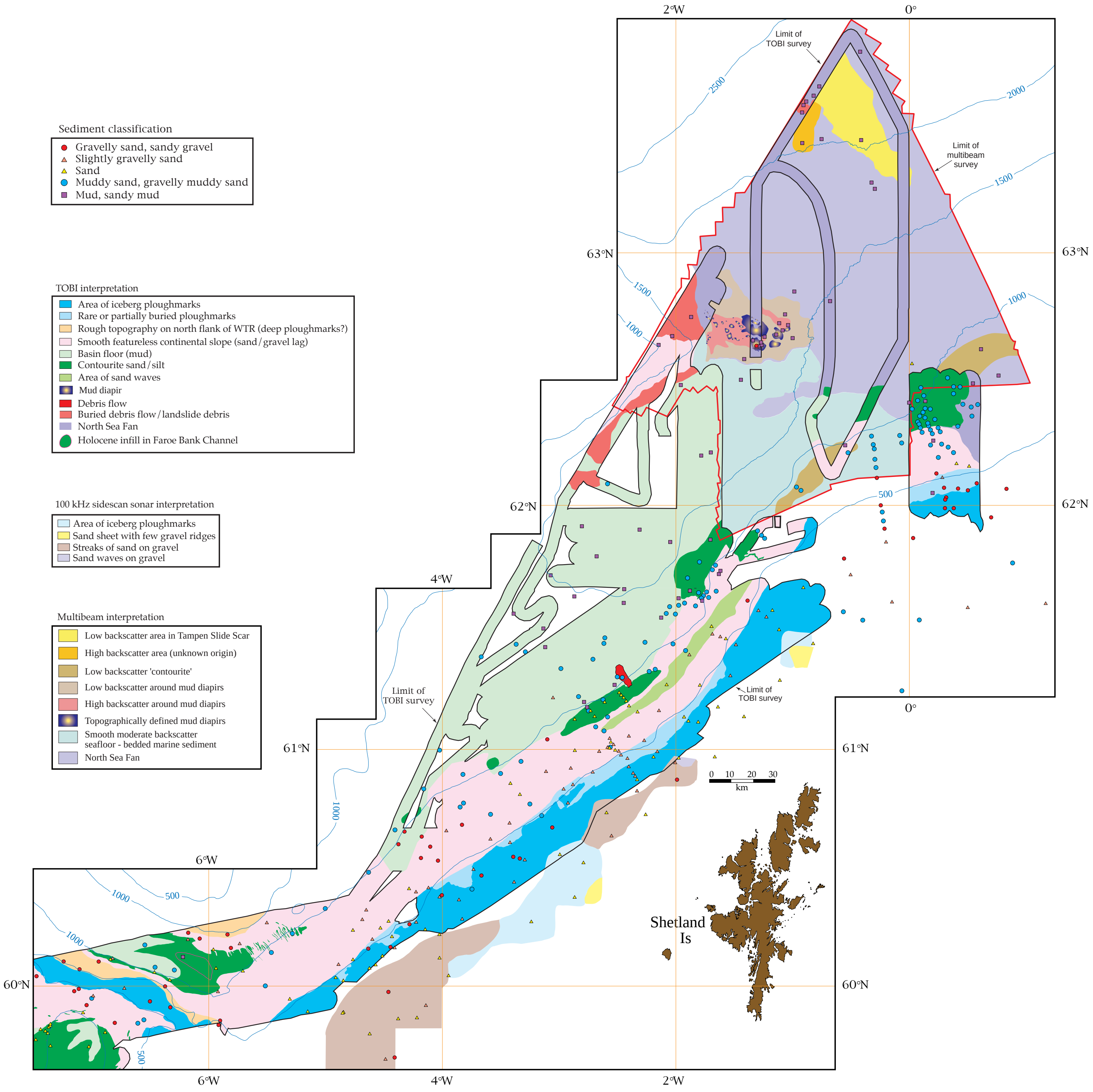

Figure 7. Summary of seabed samples collected in SEA4 superimposed on a simplified version of the facies interpretation map.

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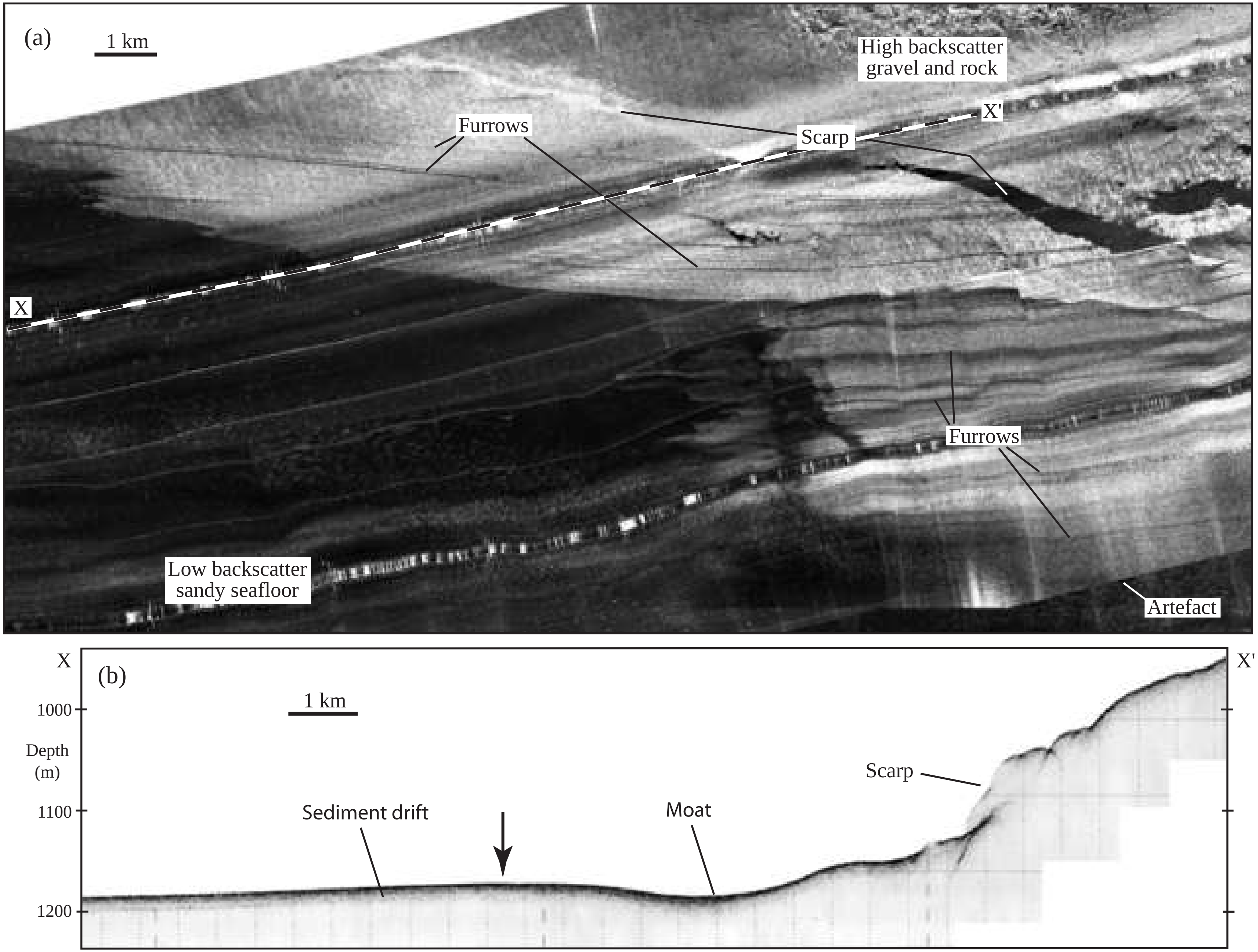

Figure 8. (a) Sidescan sonar image from the Faroe Bank Channel showing low backscatter contourite sands, furrows cut into a gravel seafloor and a large erosional scarp. Profile x-x' (b) shows that the major change in sediment type coincides with the crest of a sediment drift and that gravel seafloor coincides with the moat that separates the sediment drift from the Faroes slope. This implies that the strongest bottom currents are confined to a narrow belt along the lower slope of the Faroe Platform.

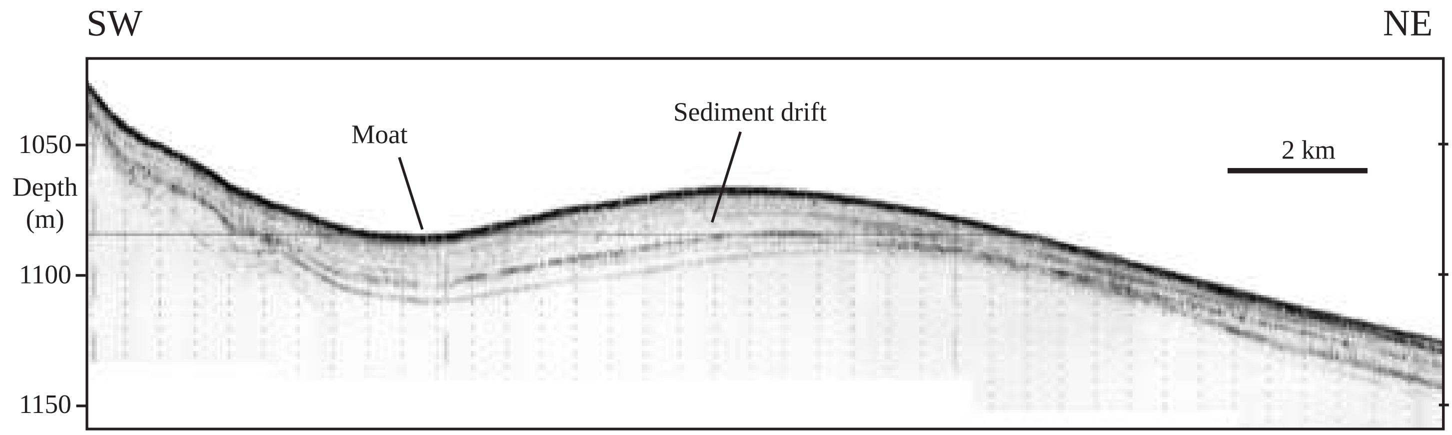

Figure 9a. A 3.5 kHz profile from the Faroe Bank Channel floor, showing a bedded sediment drift adjacent to the northern slope of the Wyville Thomson Ridge. Note asymmetric deposition across drift crest.

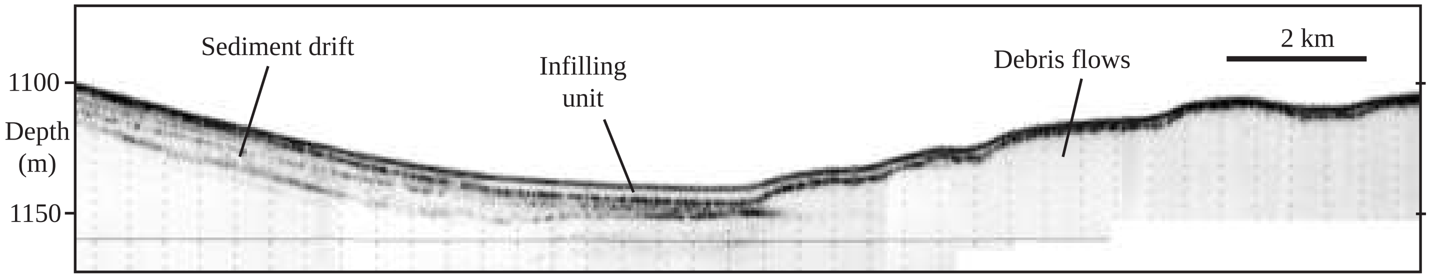

Figure 9b. A 3.5 kHz profile from the Faroe Bank Channel floor, showing the boundary between parallel bedded sediment drift and mounded, transparent glacigenic debris flows. Note late stage (?Holocene) unit filling topographic low in centre of profile.

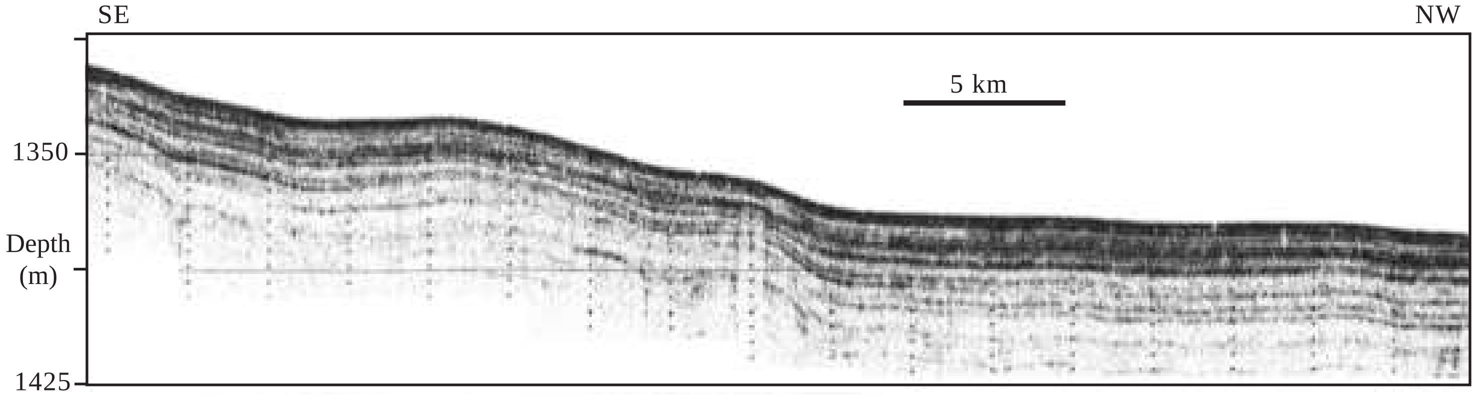

Figure 9c. A typical 3.5 kHz profile from the Faroe-Shetland Channel floor, showing parallel bedded acoustically layered sediments and penetration of about 50 m sub-seabed. Note high vertical exaggeration (approx 95 :1) on this compressed profile.

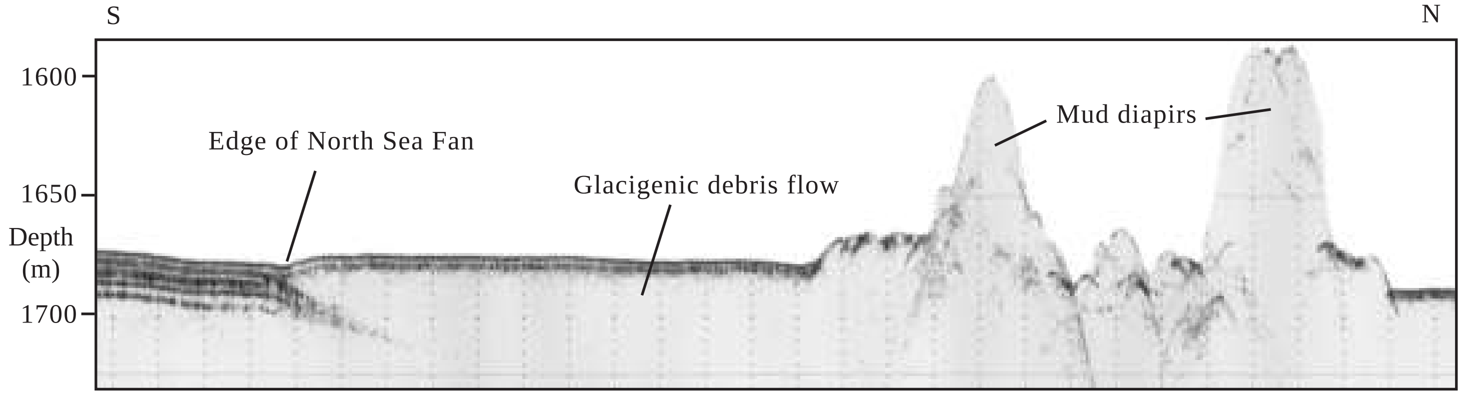

Figure 9d. A 3.5 kHz profile from the Norwegian Basin floor Floor, showing the relief associated with the mud diapirs. profile also crosses the boundary of the North Sea fan (parallel bedded glaciomarine sediments to the south and tranparent glacigenic debris flows to the north)

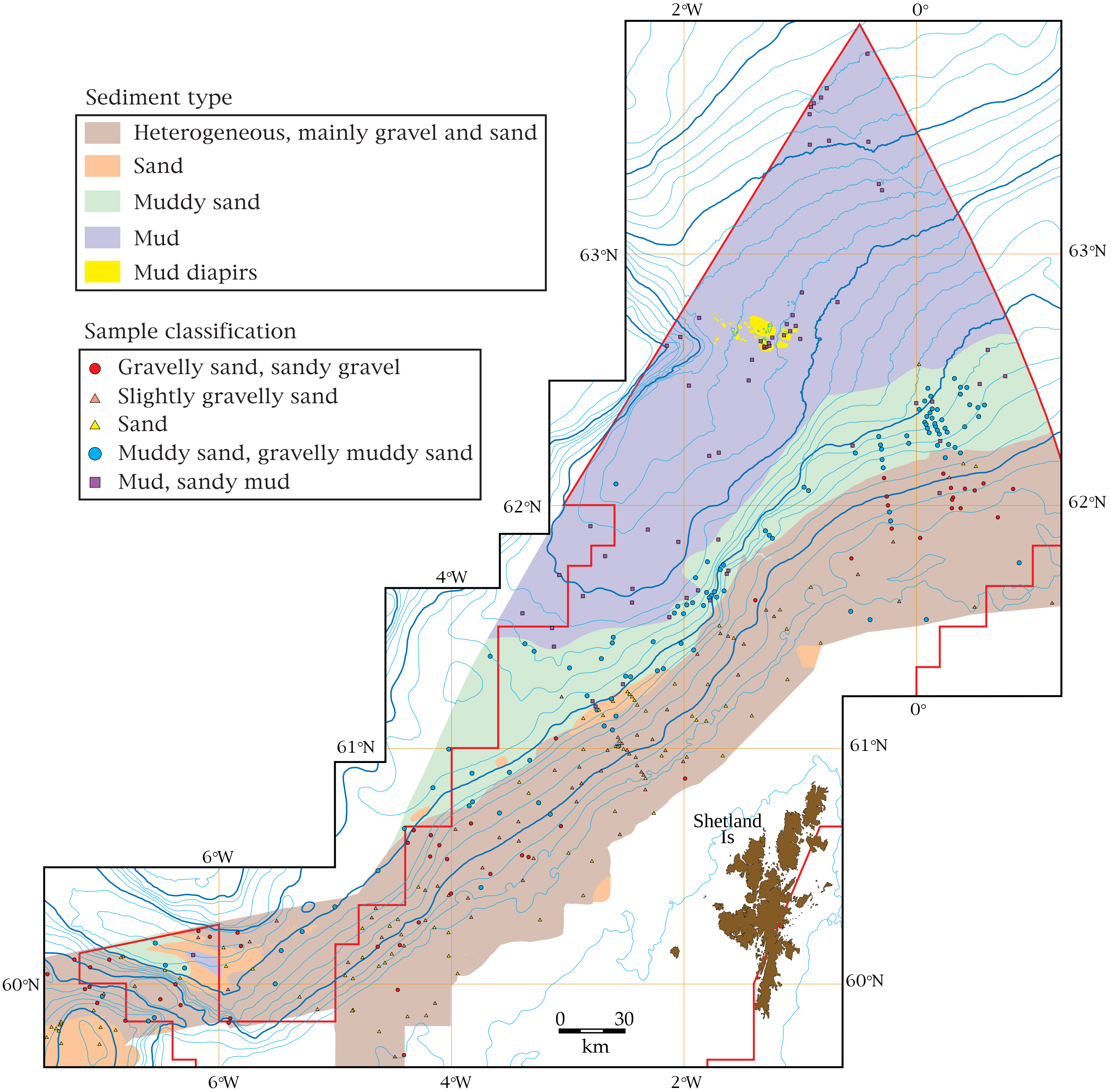

Figure 10. Generalised distribution of seafloor sediment type in SEA4, based on sidescan sonar, sample and profile data. Coloured symbols show location of sample stations.

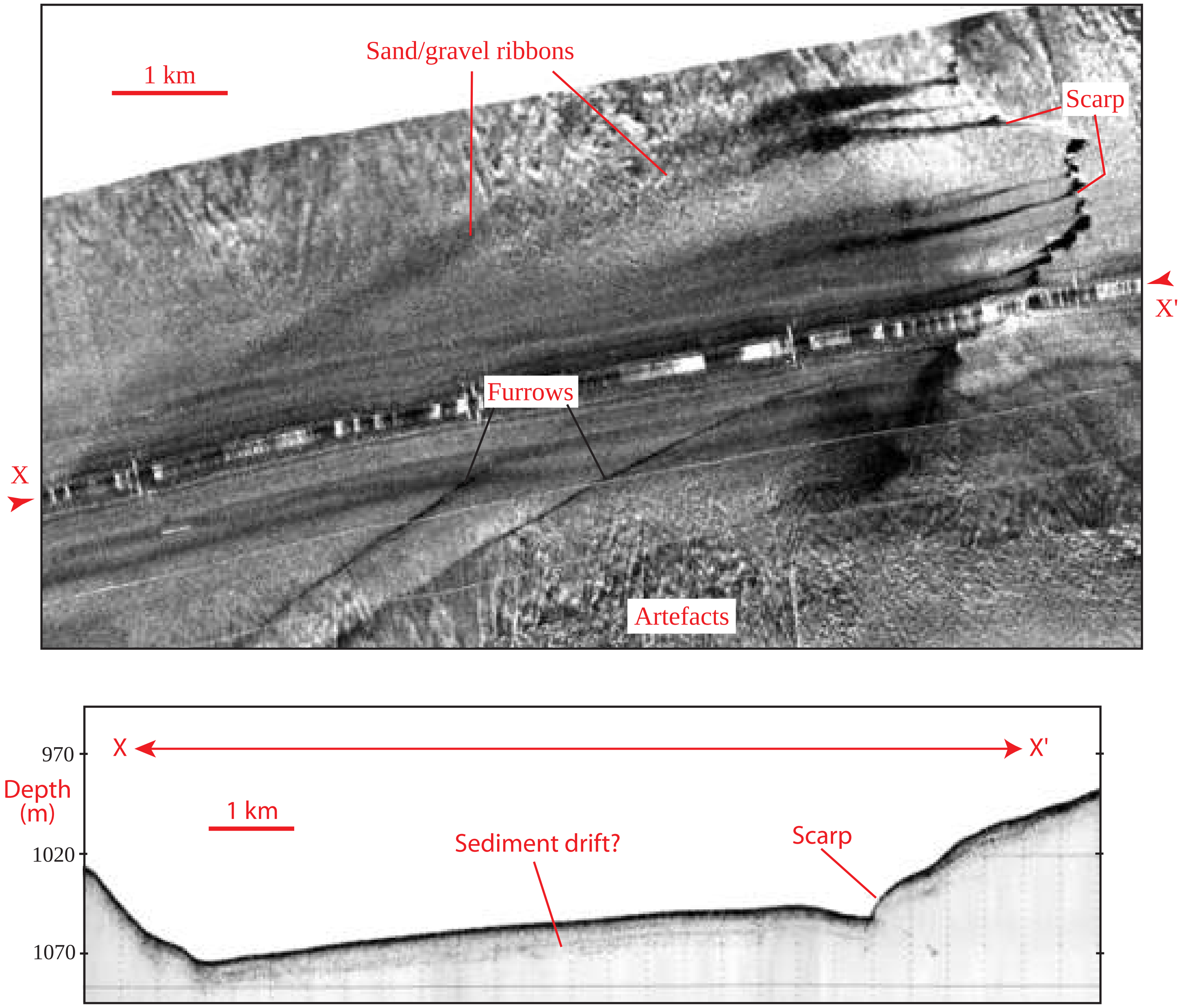

Figure 12. Sidescan sonar image (above) and profile (below) of a large-scale erosional scour in the Faroe Bank Channel. A thickness at least 50 m of sediment appears to have been eroded from the scoured area. The profile suggests partial filling of the scour by a sediment drift. However, the sidescan image shows furrows and sand/gravel ribbons at the present day seafloor, indicating that strong bottom currents and erosion are active at the present day.

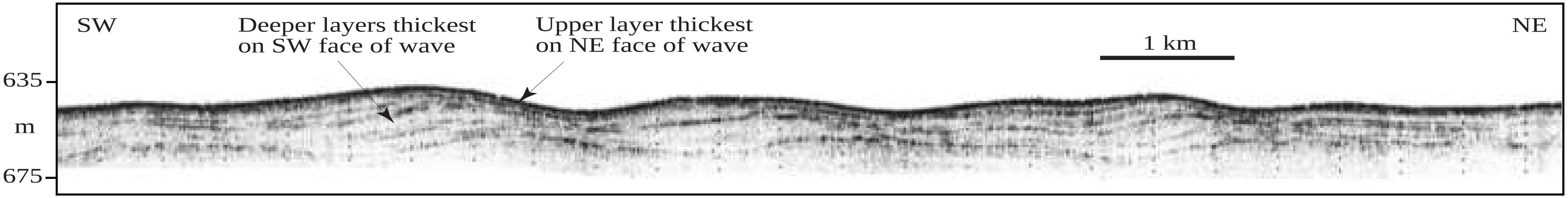

Figure 13a. 3.5 kHz profile showing low amplitude mudwaves. Internal structure of mudwaves generally suggests migration towards the SW and formation under a current flowing towards the NE. However, there is a suggestion that the uppermost layer is thickest on the NE wave face, indicating a possible reversal of wave migration and current direction.

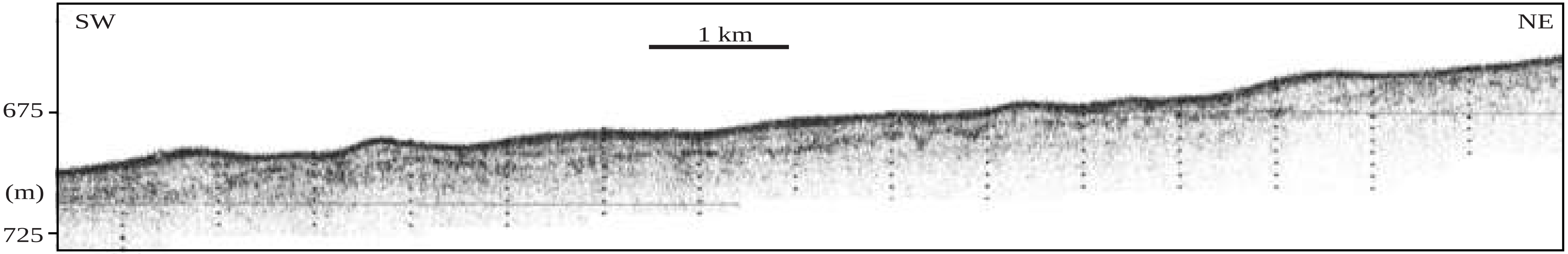

Figure 13b. 3.5 kHz profile showing low amplitude sandwaves. Lack of penetration and sub -bottom reflectors indicates coarser grained sediments relative to the mudwaves shown in (a).

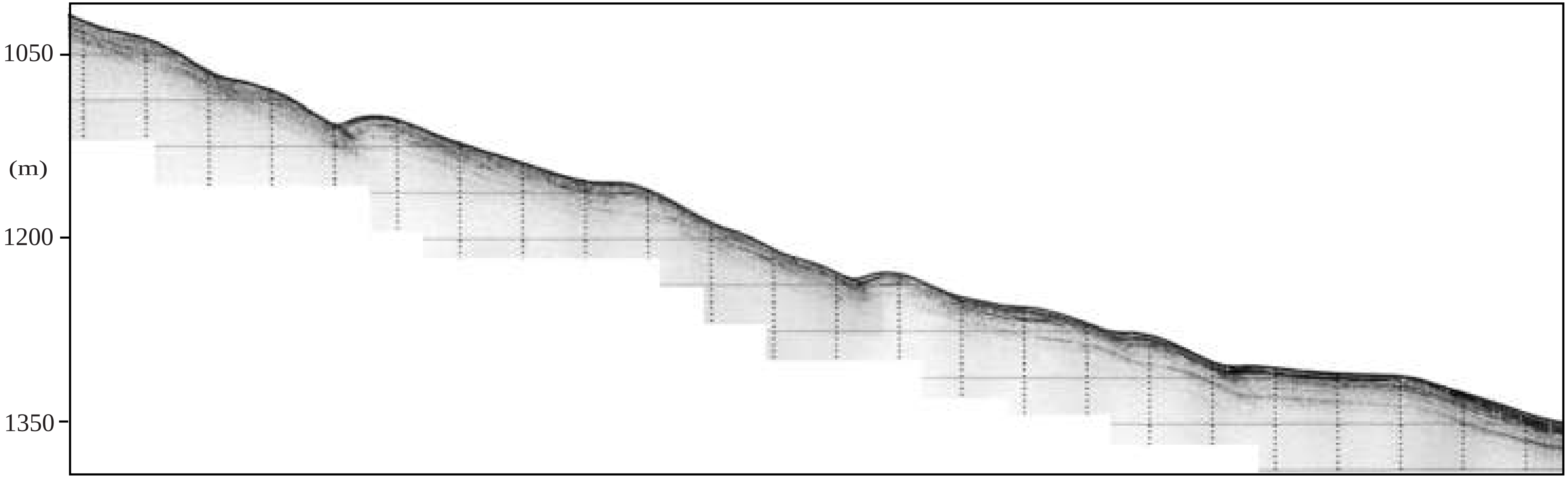

Figure 13c. 3.5 kHz profile perpendicular to the west Shetland slope at 61° 50'N showing a complex elongate drift. Furrows occur with each topogrpahic depression, showing that these are erosional areas, in effect 'moats' between a series of subsidiary drift crests.

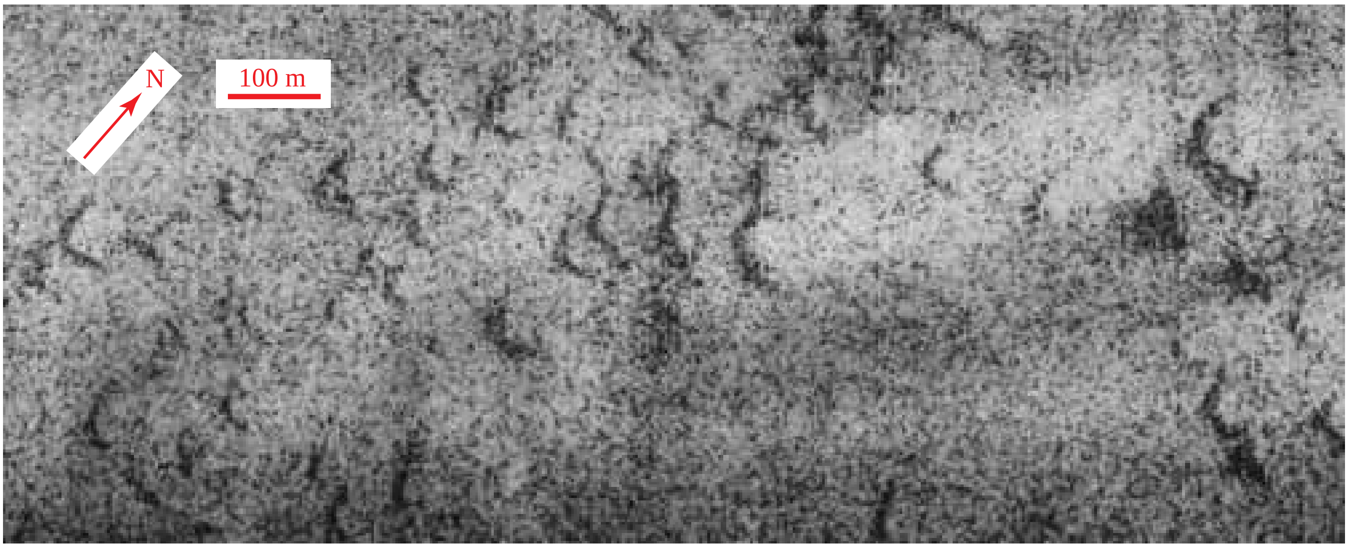

Figure 14. Sidescan sonar image of barchan dunes on the west Shetland slope, water depth 350 m

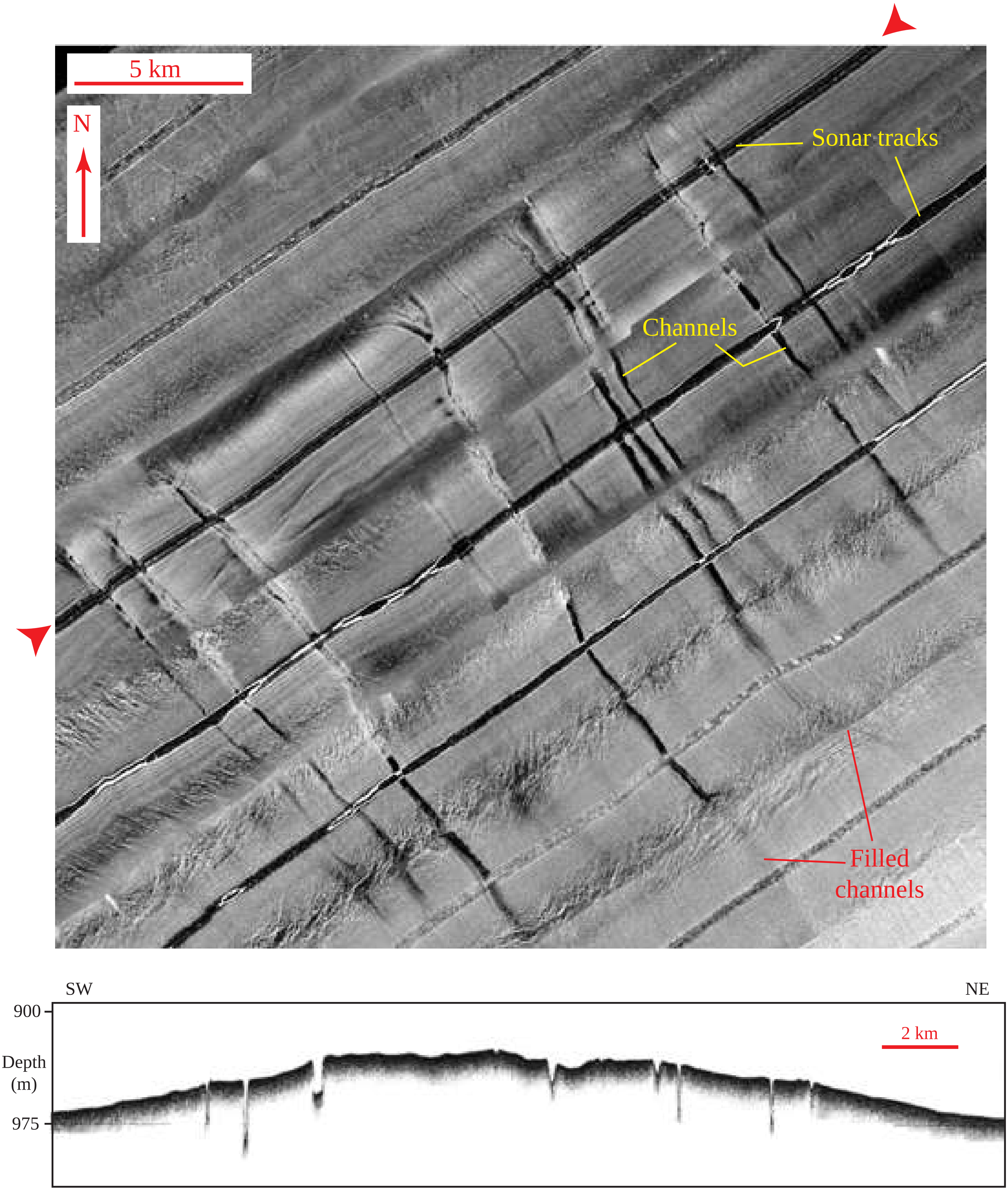

Figure 15. Sidescan sonar image (above) showing a group of sub-parallel straight-sided channels. Most channels start abruptly at about 650 m water depth and end at 1000 m water depth. Some, however, have poorly defined extensions upslope of 600 m which may mark filled channel segments. Large arrowheads locate 7 kHz profile shown below. Channels are typically 50-250 m wide and up to 40 m deep. Note that channels are incised into a positive topographic feature, interpreted as the upslope edge of the debris fan fed by the channels.

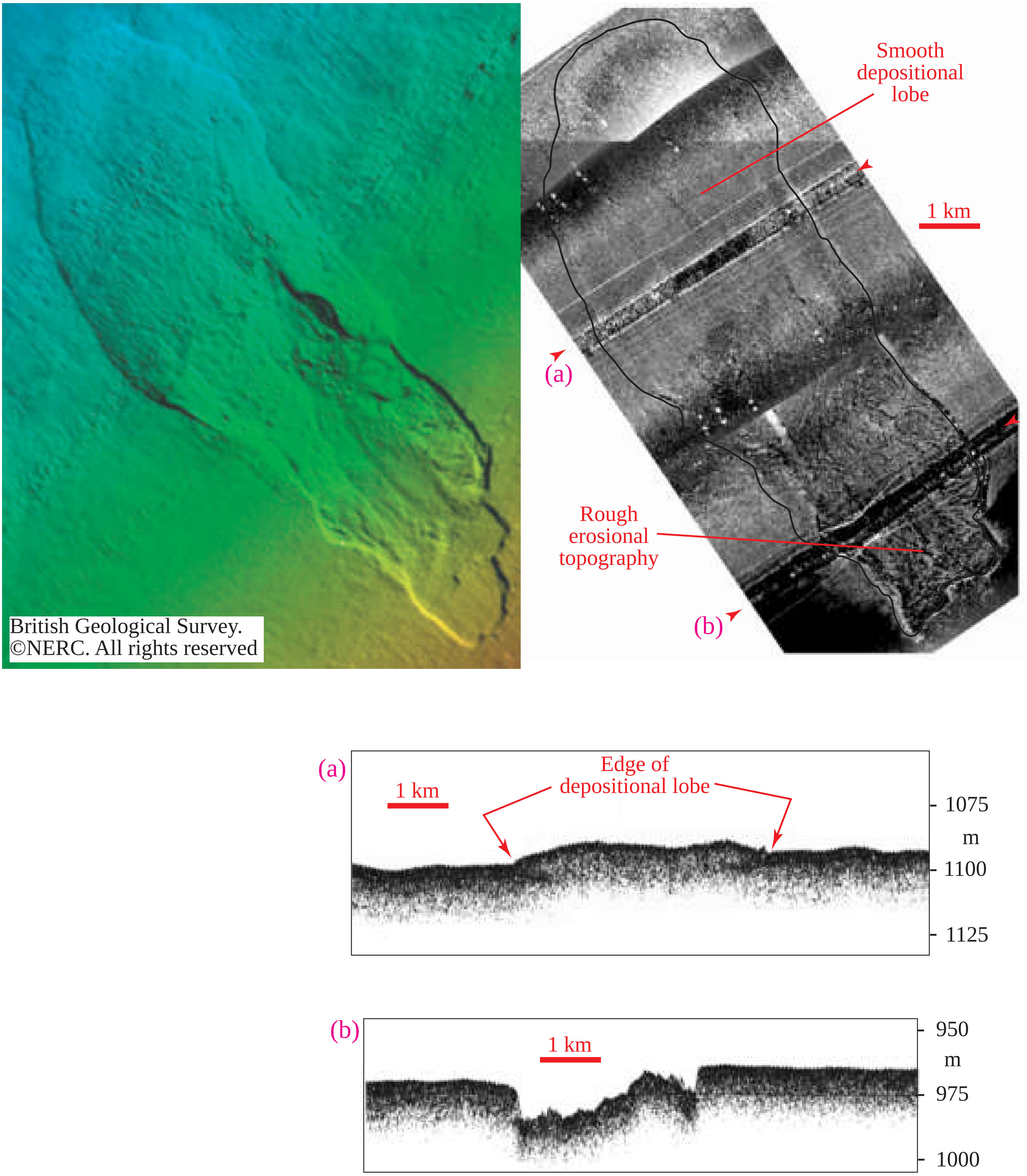

Figure 16. The AFEN Slide, a small sediment slide in the Faroe-Shetland Channel in 900 to 1100 m water depth. Top left: shaded relief bathymetry derived from 3D seismic data (courtesy of Dave Long, BGS). Top right: Sidescan sonar image, with location of profiles (below). Bottom: 7 kHz profiles showing the transition from rough erosional terrain in the area of the slide headwall (b) to a smooth depositional lobe downslope (a).

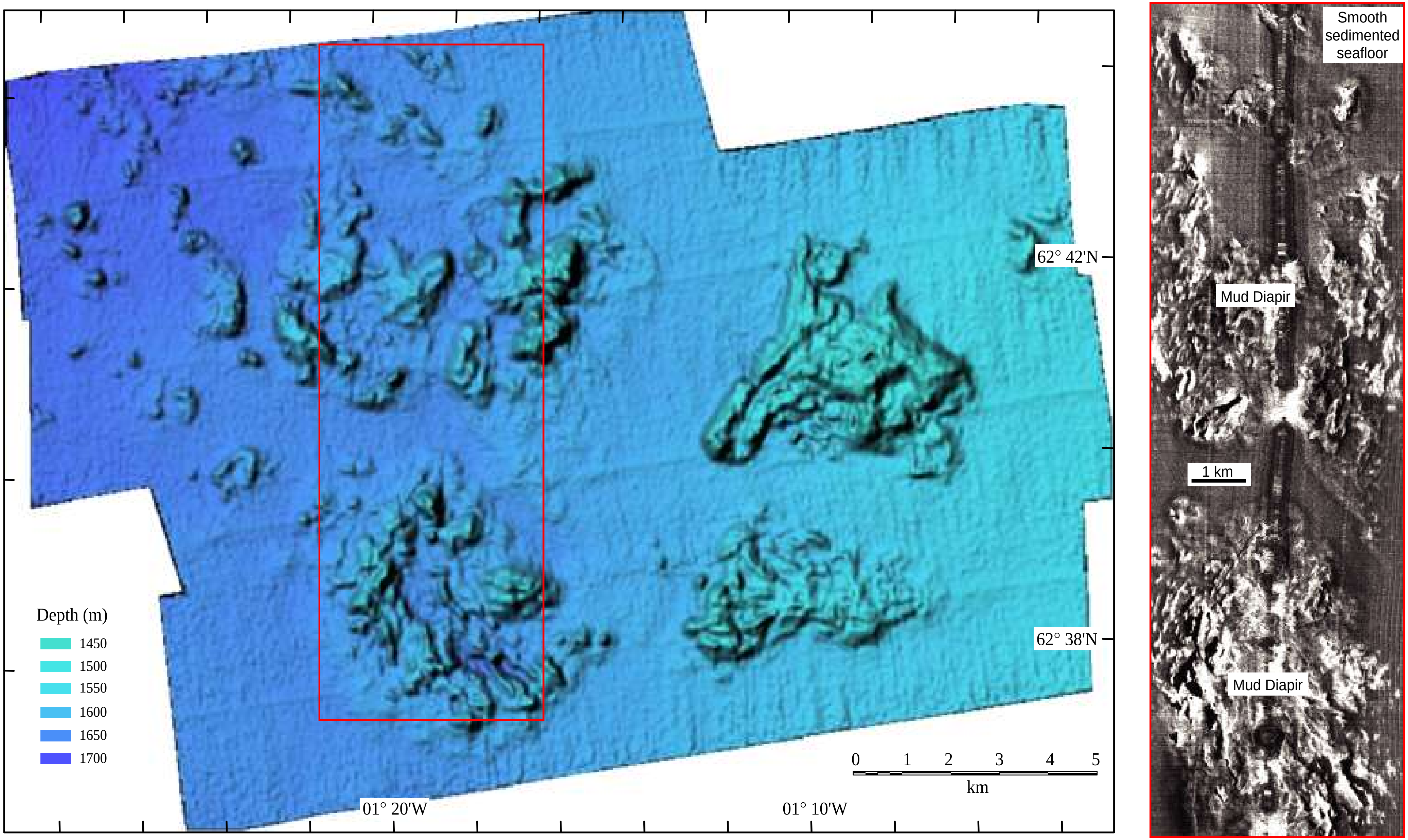

Figure 17. Left: shaded relief bathymetry of the mud diapir province in the southern Norwegian Basin. Note that indivdual structures seem to be more fragmented (or possibly partially buried) towards the west. This may suggest that the eastern structures are younger and more likely to be active. Right: sidescan image of diapirs (located by red box on bathymetry image) showing that these structures have much rougher topography that is apparent from the bathymetric map.

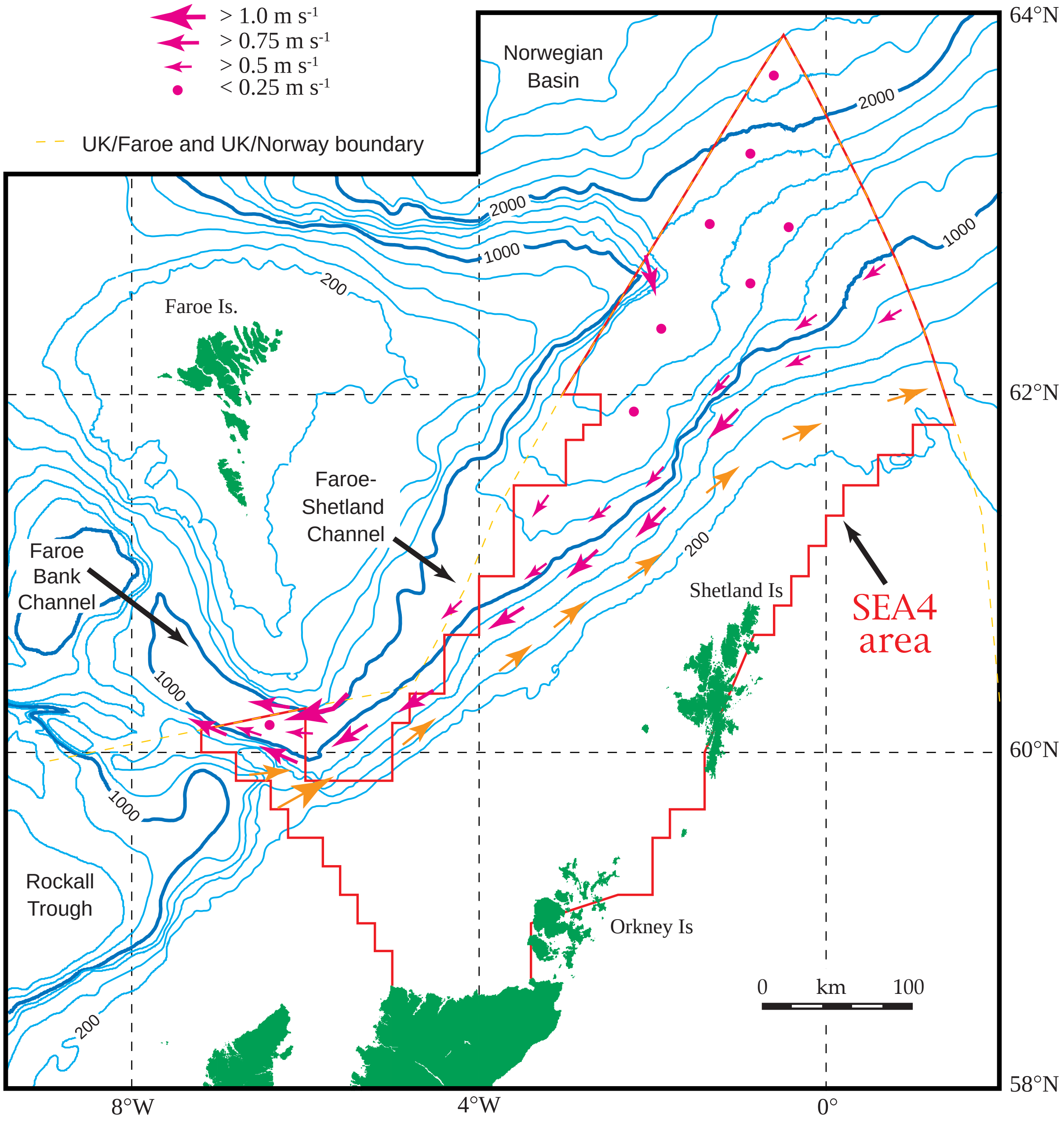

Fig. 18. Estimates of maximum bottom current velocity, based on sedimentary bedforms, in SEA4. Note that current velocities may be variable on a variety of time scales. Northward movement of warm North Atlantic water is shown by orange arrows, magenta arrows show cold water moving south from the Norwegian Sea. The strongest currents, probably reaching > 1.5 m s^{-1}, occur in the area of the sill between the Faroe Shetland and Faroe Bank Channels. In areas where no indicators of current velocity are seen (mainly areas of muddy seafloor) the maximum bottom current is estimated at < 0.25 m s^{-1}.