Holocene contourite sand sheet on the Barra Fan slope, NW Hebridean margin

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Abstract: Surficial sediment analyses, bottom photographs and current-meter data, coupled with studies of sidescan and 3.5 kHz echodata clearly show the imprint of a strong, seasonally-affected, slope current on the Hebrides shelf and slope. The present day shelf sediments are in fact relict, coarse-grained material (gravel with boulders) of Pleistocene glacial derivation, which have been modified during the Holocene by winnowing, sea-floor polishing and transport of the finer fraction across the shelf to the northwest. On the outer shelf and upper slope the sharp change from gravel to sand is marked by a physiographic-textural boundary, herein termed the *sandline*, which occurs at a depth of between 170 m and 300 m. Further down the continental margin on the lower slope, the lower limit of the sand-rich facies is marked by the *mudline*. This typically occurs at a depth of around 1200 m, and marks the depth of substantially increased clay-sized material. Above the mudline the long-term (Holocene to present), time-integrated signature of bottom current flow has resulted in the relatively slow accumulation of a mid-slope sandy contourite deposit, the Barra contourite sand sheet. This covers an area of 1000–1500 km^2 with an estimated sand volume of 30 000 m^3. Below the mudline the clay-rich deposits represent a hemipelagic drape with only minor bottom current influence and intense reworking by benthic organisms.

The Barra fan on the NW Hebridean slope apron is an important example of a glacially-fed, trough-mouth fan. Taken together with the contiguous Donegal fan, it forms the largest depocentre off NW Britain covering an area of about 7000 km^2 from the shelf-break to a depth of around 2000 m in the Rockall Trough (Fig. 1). This system has been the focus of detailed study by the authors

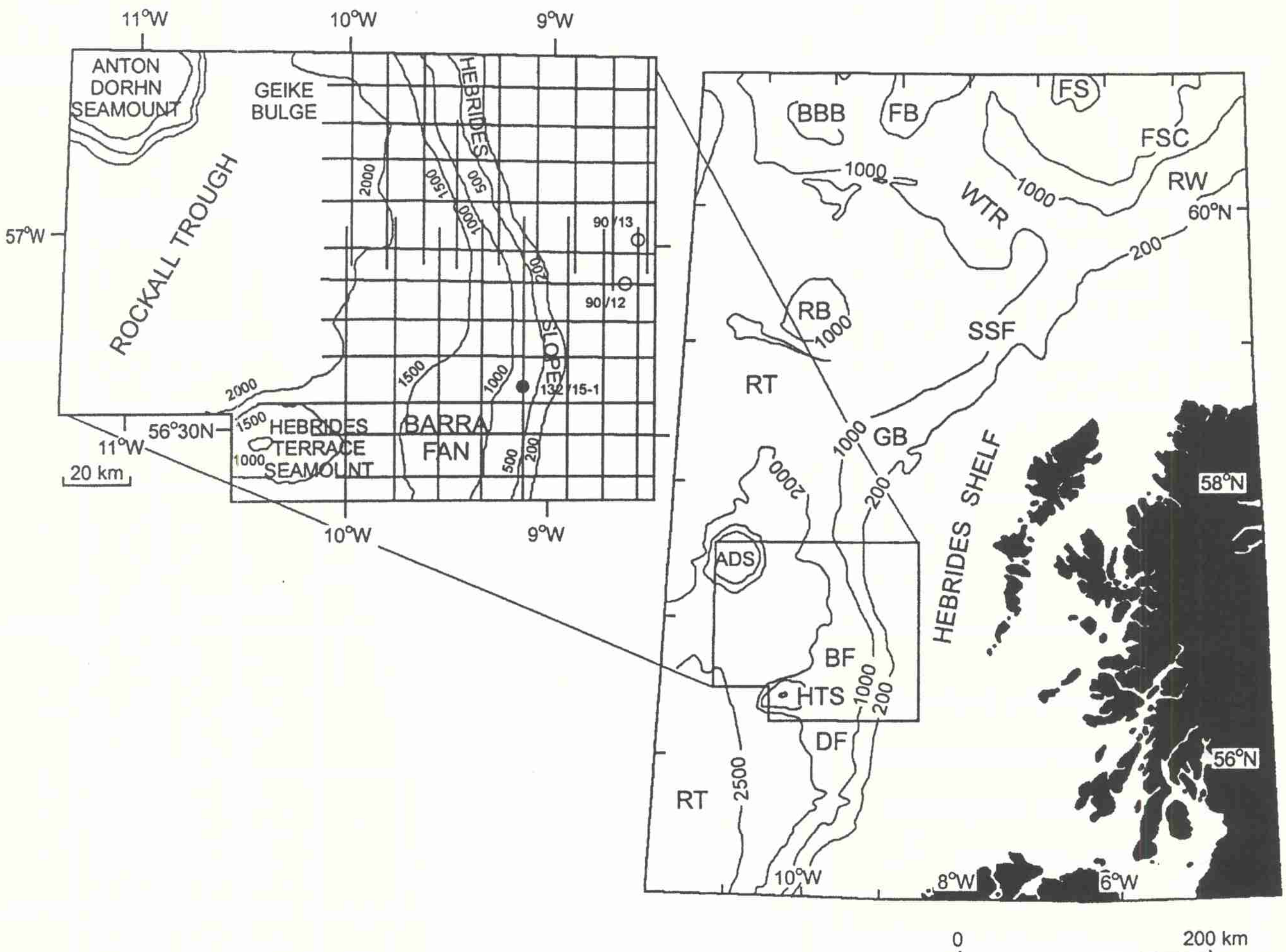

Fig. 1. Location of the study area, bathymetric setting (contours in metres) and track plots of regional 3.5 kHz seismic lines. South of *c.* 57°N, swath bathymetric data are available between 150 and 2000 m water depth for most of the study area. BBB, Bill Bailey's Bank; FB, Faroe Bank; FS, Faroe Shelf; WTR, Wyville–Thomson Ridge; RW, Rona Wedge; FSC, Faroe–Shetland Channel; RT, Rockall Trough; RB, Rosemary Bank; SSF, Sula Sgeir Fan; GB, Geike Bulge; ADS, Anton Dohrn Seamount; BF, Barra Fan; HTS, Hebrides Terrace Seamount; DF, Donegal Fan. (From Armishaw *et al.* 1998).

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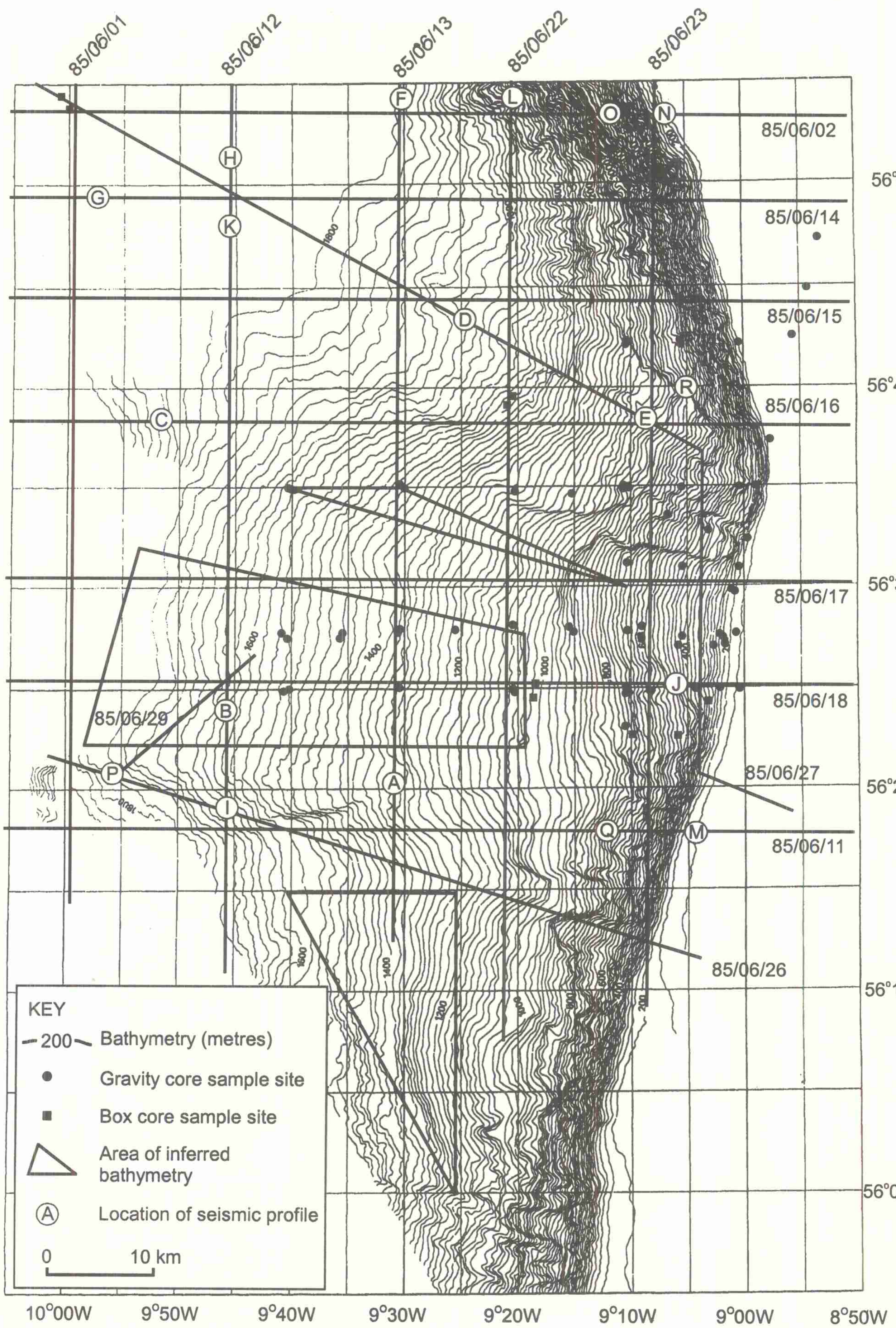


Fig. 2. Digitised bathymetry of the Hebrides Slope based on swath bathymetric mapping. Contours are at 20 m spacing. Black symbols mark the locations of core sites within the study area; dark lines show 3.5 kHz echosounder profiles. Boxed areas mark regions of inferred bathymetry, where survey data was of poor quality.

and other colleagues, that has particularly emphasized the interaction of alongslope, downslope and hemipelagic processes in deposition of the Quaternary–Recent succession (Howe 1995, 1996; Armishaw 1998; Armishaw *et al.* 1998, 2000; Holmes *et al.* 1998).

The present study briefly synthesizes some of this earlier work, and then uses detailed petrological analysis in conjunction with visual evidence from seabed photographs, geoacoustical properties of sediments and sedimentary structures to identify the long-term, time-integrated signature of the bottom current flow system on the Hebridean margin. The work also elucidates other active sedimentation processes, including offshelf spillover and downslope-delivery of sediment, and delineates the main sedimentary provinces on the margin that appear to be marked by the presence of a mudline on the mid- to lower-slope, and a sandline on the region between the shelfbreak and upper slope. The *in situ* observations from seabed photographs enables detailed seasonal changes in current flow and intensity to be recorded. The delineation of facies, in turn is used to define areas of erosion, non-deposition and winnowing, and deposition.

Sampling of cores was conducted over a two year period from 1994 to 1996 from 77 gravity core stations (0.10 to 2.7 m penetration depths) and 10 box core stations, yielding a suite of 102 core samples within the region (Fig. 2). Shipboard and laboratory logging followed standard procedures, including photography and x-radiography of all cores. Subsamples of each box core were collected for measurements of sonic velocity, grain size, carbonate content and total organic carbon content at 2 to 4 cm intervals down the core.

In the laboratory box-core subsamples and split gravity cores were analysed for texture, structure and composition. Textural characteristics of shallow subsurface deposits were determined from gravity core log descriptions and x-radiograph interpretations of half cores taken with a Scanray AC 120L device at settings of 65–75 kV for 2 to 2.5 minutes. Multiple particle size analyses at 2 to 4 cm intervals of silt and clay (<63 μm) fractions were undertaken using a Micrometrics Sedigraph 5000ET at the Department of Geography, University of Edinburgh. For the sand fraction (<4.0ϕ) a combination of wet- and dry-sieving was used.

Over 700 bottom photographs were obtained using the Proudman Oceanographic Laboratory UMEL deep-sea survey camera. A time series of shots were taken during a two year period, between March 1994 and May 1996 at stations along a southern transect between depths of 140 and 1500 m and stations along a northern transect between depths of 140 and 2000 m (Fig. 2). The seabed area photographed is trapezoidal in shape and about 3 m front to back. The width across the bottom frame is approximately 120 cm and that across the top is 250 cm (Humphery, pers. comm., 1996).

Remote survey data collected included Simrad EM12–120 (12 kHz) multibeam swath bathymetry, as well as 7.5 and 3.5 kHz echosounder seismic profiles.

Geological and oceanographic setting

The area of the continental shelf and slope considered in this study extends from a shoreward depth of about 120 m, to water depths in excess of 2000 m on the lower slope (Figs 1 & 2; Table 1). The shelf and slope system consists of a complex Neogene to Holocene sedimentary prism that extends oceanward between the structural highs of the Geike Bulge in the north and Donegal Platform to the south. The gently dipping shelf has an average gradient of < 0.5° with a somewhat irregular topography of deep inner shelf basins and ridges. The width of the shelf is typically 100 km or more. The slope system is dominated by the Barra Fan complex, prograding westward into the centre of the study region and encroaching on the Hebrides Terrace Seamount.

Within the region the gross hydrography may be distinguished by three main circulatory systems (Booth & Ellett 1983). The outer shelf is characterized by seasonally variable southeasterly weak residual currents (2–4 cm s^{-1}) in spring and summer and stronger northerly flowing currents (4–10 cm s^{-1}) in autumn and winter (Ellett *et al.* 1986), reflecting the a broadening of the slope current across the shelf during autumn and winter. The circulation over the shelf appears to be chiefly driven by near-diurnal, clockwise-rotating currents, internal tides and wave-induced currents (Huthnance 1986; Gordon & Huthnance 1987).

Table 1. *Principal characteristics of the Barra Contourite Sand Sheet*

Location	Hebridean margin, NE Atlantic
Setting	mid-slope setting, 300–1200 m water depth
Age	Holocene
Drift type	thin contourite sand sheet forming most recent part of mixed facies sheeted drift system
Dimensions	sand sheet 80–100 km × 15–25 km, 0.05–0.4 m thick in study area but more extensive along slope, sheeted drift complex of indeterminate size along slope
Seismic facies	thin sand sheet not fully resolved on seismic records, but gives moderate amplitude subparallel reflectors on 3.5 kHz records, mixed sheeted drift shows interlayered variable seismic facies
Sediment facies	thin sandy contourite facies, over silty and muddy contourites hemipelagites and glaciomarine sediments

A broad region of the mid-slope is dominated by a 36 km wide, fast-moving, north to northeasterly flowing slope current, carrying water of Atlantic origin to the Norwegian Sea (Fig. 3). The principal driving forces of the slope current are meridional pressure gradients, with minor effects of wind-driven processes. Current meter measurements of the current north of Scotland indicate typical speeds of 20 cm s^{-1}, with mean monthly speeds of 13 and 20 cm s^{-1} (Turrell *et al.* 1992) recorded from along the shelf edge west of the Hebrides.

Although the occurrence of shelf-slope exchange of water is not uncommon the precise mechanisms whereby water is exchanged are highly complex and are not yet fully understood (Ellett, pers. comm., 1995). West of Scotland, little exchange seems to occur during the summer months, as water near the sea floor becomes isolated and so remains cool and dense. However, with the onset of autumnal gales there is an increase in mixing of shelf waters (Edelsten *et al.* 1976; Booth & Ellett 1983). Cross-slope exchange velocities are generally slow, with an average velocities of 2 cm s^{-1} (Huthnance 1986).

The lower slope is affected by the northerly flow of the North Atlantic Deep Water which forms a continuation of the cyclonic loop that circulates in the southern trough, although it may include elements of North East Atlantic Water from the mid- and upper-slope. Part of this latter water mass derives from the influence of Mediterranean outflow (Harvey 1982). Current activity above the deep water mass is very variable in strength and direction.

Bathymetry

A detailed bathymetric chart of the Barra fan slope region has been constructed from multibeam swath-bathymetry echosounder data (Simrad EM12–120, 12 kHz). High quality data were collected for most of the area allowing contours to be drawn at 10 m intervals (Figs 2 & 3, contours shown at 20 m intervals for greater clarity).

Average slope angles across the region vary from 4–5° north of the Peach Slide to 1–3° on the uninterrupted seaward-dipping plain south of the Slide. Where the slope is highly incised by a network of steep-sided canyons in the north of the study area, slope angles may locally exceed 16°, although this is relatively rare. In the central region the most pronounced topographic feature is the Peach Slide (Holmes 1994; Holmes *et al.* 1998) which has an area of over 2000 km^2 and slide-transfer volume in the order of 80 km^3. Much of the mid and lower slope in the central and southern parts of the study area appear to be relatively smooth.

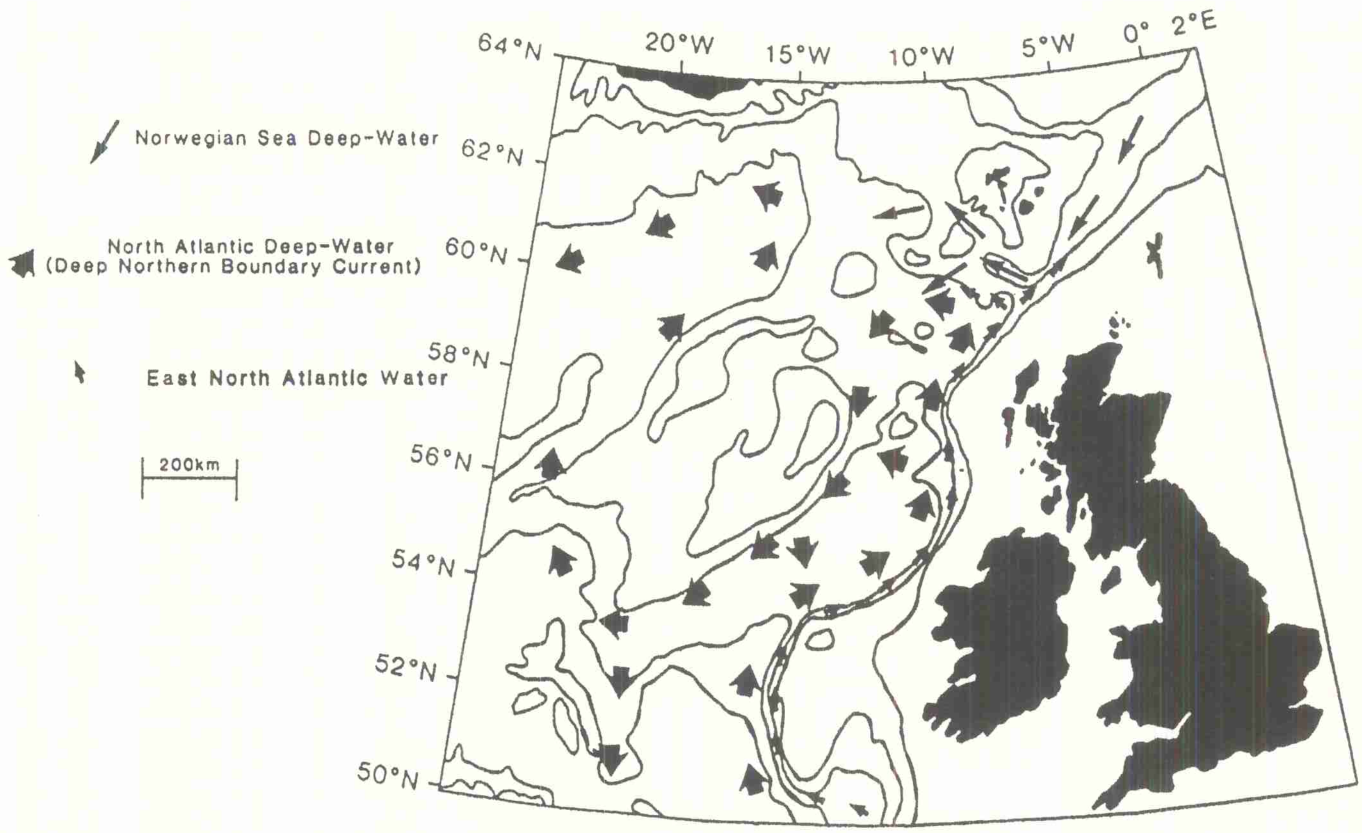


Fig. 3. Present day bottom water circulation pattern in the Rockall Trough and surrounding area, with Norwegian Sea Deep-Water overflowing across the Wyville–Thomson Ridge, North Atlantic Deep-Water flowing as an anticlockwise gyre in the basin, and a slope-current of Eastern North Atlantic Water.

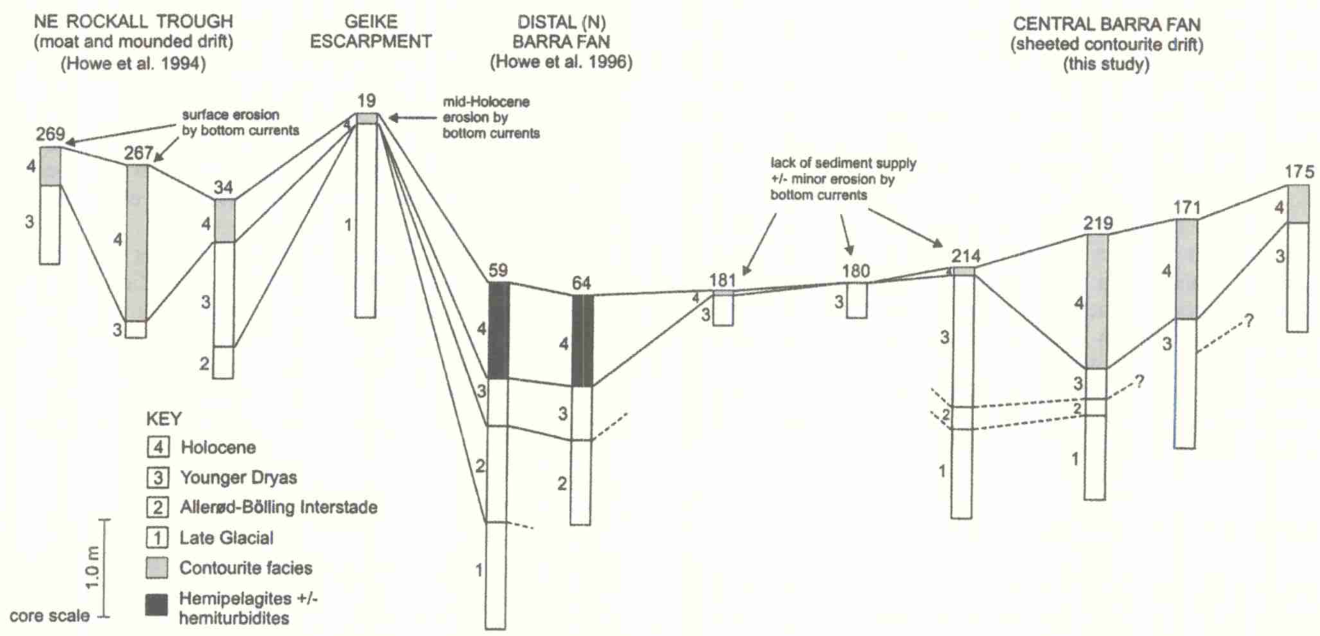


Fig. 4. Stratigraphic correlation panel for the NW Hebridean margin from the NE Rockall Trough to the central Barra fan, based on Howe *et al.* (1994), Stoker *et al.* (1993) and Armishaw *et al.* (2000).

Stratigraphic context

All the slope cores from the study area lie within the topmost part of the Mid-Pleistocene to Holocene seismostratigraphic unit, that generally shows strong basinward progradation during the glacial intervals (Stoker *et al.* 1993, 1994; Stoker in press). The thin Holocene drape and drift section cannot be resolved on seismic records but has been extensively cored. Provisional dating and correlation of the cores has been attempted by combining limited Pb210 and C14 radiometric analyses, the study of microfossil assemblages (foraminifers, nannofossils and dinoflagellate cysts) and the relative abundance of ice-rafted debris (IRD) (Armishaw *et al.* 2000).

On this basis, the sandy layer of variable thickness that occurs at the top of most cores can be assigned a Holocene age (Fig. 4). This is similar to cores from further North on the Rockall Trough

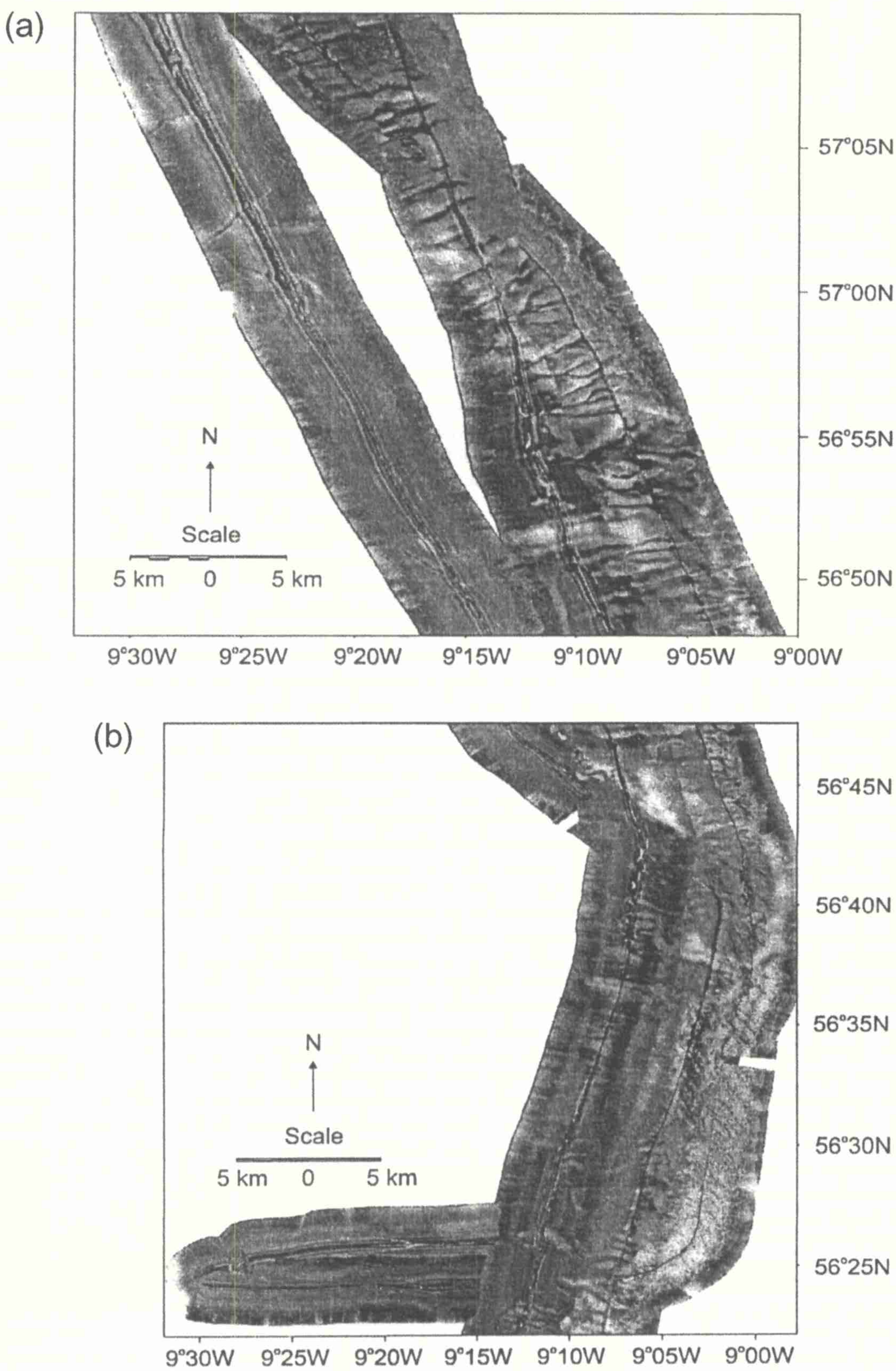


Fig. 5. TOBI side-scan mosaic of the Barra fan. (**a**) Northern region highlighting the dissected nature of the upper slope by erosive canyons. (**b**) Southern region incorporating the Peach Slide and showing the NE–SW trending irregular, variably degraded ice scour marks on the shelf and upper slope. Both regions show a broad mid-slope zone of relatively uniform medium-grey backscatter in some parts apparently masking original underlying elements. This uniform zone is the Barra contourite sand sheet.

slope (Howe *et al*. 1994; Howe 1996), and correlates with a muddy or silty facies typical of the lower slope (Knutz *et al*. 2002) and basin floor. In some cases, the sandy section probably represents a condensed Holocene sequence or part of the early Holocene only, as a result of winnowing and erosion under high bottom current activity. However, we do not yet have adequate stratigraphic control from the study area to confirm this.

Seismic characteristics

Seafloor morphology (Fig. 5)

Combined use of swath bathymetry, high resolution seismic profiles and sidescan sonar images has allowed detailed characterisation of seafloor morphology. Armishaw *et al*. (1998) identified seven principal morphological elements on the outer shelf and slope:

- Ice scour features
- Canyons and channels
- Slides
- Debris-flow masses
- Lobes
- Elongate to wavy bedforms
- Smoothed sediment surfaces

It is only the last two of these that we attribute to bottom current activity. Narrow elongate features characterized by light to dark alternations in TOBI backscatter intensity extend a few kilometres alongslope over parts of the mid and upper slope. Possible sediment waves with across-slope crest orientation are less clearly observed. More distinctive are broad areas of uniform speckled grey, medium intensity backscatter that extend in a somewhat discontinuous, mid-upper slope belt over the much of the study area (approximately 500 km^2). Pale ghosts of other elements are in some places discernible beneath this uniform pattern, whereas just outside the main uniform zone, other elements become dominant with a slightly blurred form. We interpret this uniform backscatter zone as typical of the Barra sand sheet covering a large area of the mid-upper slope. Where it thins markedly the sidescan images of other elements are slightly blurred.

3.5 kHz echocharacter (Figs 6 and 7)

Fourteen distinct seismic facies have been recognised in the study area and their distribution mapped (Armishaw 1998). For the purposes of this paper, we focus only on the four major classes that are broadly based on the earlier echo-character classification schemes of Damuth (1975, 1978, 1980) and Pratson & Laine (1989), and modified according to our own observations.

Class I. Distinct, acoustically stratified seismic facies are characterized by sharply defined, laterally continuous, acoustically layered seafloor reflectors underlying a distinct seabed reflector. This seismic facies class can be further subdivided into four echofacies on the basis of number and clarity of acoustic strata.

Class II. Irregular seismic facies are characterized by a distinct, or indistinct seabed surface reflector and lenticular subbottom reflectors around acoustically unstratified transparent to semi-transparent zones. Two sub-divisions have been recognised and although they are classified separately according to differences in underlying acoustic characteristics the two facies are intergradational and are not always clearly distinguished.

Class III. Wavy echoes are based upon a geometric classification in which the term 'wavy-echo' should not be confused with sedimentary bedforms or processes. The class includes regular to irregular, low to high amplitude overlapping hyperbolae, standing and migrating waves and single mounds or grouped levees.

Class IV. Prolonged seismic facies are characterized by a very prolonged to semi-prolonged seabed reflector underlain by a diffuse blackened zone caused by very high acoustic backscattering with negligible or no subbottom reflectors.

These seismic facies have all been observed by previous investigators in similar continental margin regimes, and the interpretations put forward in those studies are generally applicable to the West Hebridean slope apron system. However, our sedimentary interpretations (below) have been further calibrated by comparison with detailed study of more than 100 cores, extensive bottom photographic coverage, bathymetry and side-scan sonar data.

The distinct seismic facies (Class I) are very widespread throughout the region especially the mid-lower slope and mostly show a drape morphology. All cores recovered from these facies are dominated by hemipelagic sediments. We therefore interpret these seismic facies as mainly fine-grained hemipelagites, with minor interbedded turbidites and/or more coarse-grained glaciomarine input, especially where the reflectors are of higher amplitude and penetration is. Slight changes in apparent thickness and broad lenticularity of subbottom reflectors indicate the influence of bottom currents during deposition, so that sediments in these areas will be partly contouritic.

The irregular seismic facies (Class II) are also very widespread especially on the upper-mid slope, showing transparent to semi-transparent layers and lenses intercalated with acoustically stratified deposits. Cores from the study area include fine hemipelagites, sandy contourites and mixed grade glaciomarine deposits. Elsewhere on the margin cores that penetrate the lenticular transparent zones have recovered debrites (Stoker *et al.* 1992). We therefore interpret these seismic facies as representing a variety of interbedded facies including hemipelagites, contourites, glaciomarine sediments and debrites.

The wavy seismic facies (Class III) are less widely distributed and more varied in nature than either Class I or II. The regular, migrating waves are best interpreted as either contouritic or turbiditic in origin (see also Howe 1996), whereas the less regular waves are more probably isolated contourite waves or patch drifts. The low relief ridges that parallel cross-slope channels are clearly low-relief levees with one or more back-levee turbidite sediment waves in some cases. Thickness variations of the thin upper seismic unit represents differential sediment accumulation probably caused by the interaction of bottom currents with an irregular slope topography.

The prolonged seismic facies (Class IV) are also varied in nature but of restricted occurrence. They include coarse-grained (sand and gravel) relict glacial deposits on the shelf and uppermost slope that have been subject to intense shelf reworking and spillover processes during the Holocene; slide and slump deposits restricted to steep slopes, showing little acoustic penetration and a semi-prolonged seafloor reflector because of the steep angles involved; and an irregular seafloor (probably coarse-grained) caused by intense bottom current flow and erosion.

The seismic facies map (Fig. 6) shows that the acoustic character of the sea floor throughout the study area is highly variable. This heterogeneity is particularly noteworthy on both the upper and lower continental slope, and indicates a diversity of sea-floor deposits and processes in an area of complex bathymetric relief. The overall trends of the facies are perpendicular to the continental margin; however specific evidence for trends parallel to the continental margin are also displayed. Further evidence for alongslope trends does not directly come out in the seismic facies map but is expressed as thickness variations (drifts and sheets), erosive zones, moats and lag zones and rare bottom current waves and drifts. These features are observed in cores, bottom photographs and side-scan sonar data. The Holocene Barra sand sheet alone is not resolved at this scale of study, but when combined with the late Pleistocene bottom current affected unit can be seen as a thin sheeted drift (Fig. 5).

Sediment facies

Seafloor photography

Photographs of the seafloor illustrate a variety of features attributable to current activity, normal marine hemipelagic sedimentation, and benthic fauna. Observations of the seafloor across a northern and southern slope transect provides clear evidence for: (a) a seaward-fining sequence of surface sediment facies; (b) seasonally affected bottom current flow and erosion between depths of 140 and 1000 m; and (c) deposition at depths below 1500 m evidenced by non-current induced features and a densely populated and variable benthic community.

There is a clear decrease in mean grain-size of the surface sediment cover with depth downslope. Sediments on the outer shelf and upper slope down to 300 m are composed of up to 50% coarse gravelly sand to large cobbles and boulders (2–20 cm diameter, maximum 50 cm) (Fig. 6a). Sand cover with less gravel

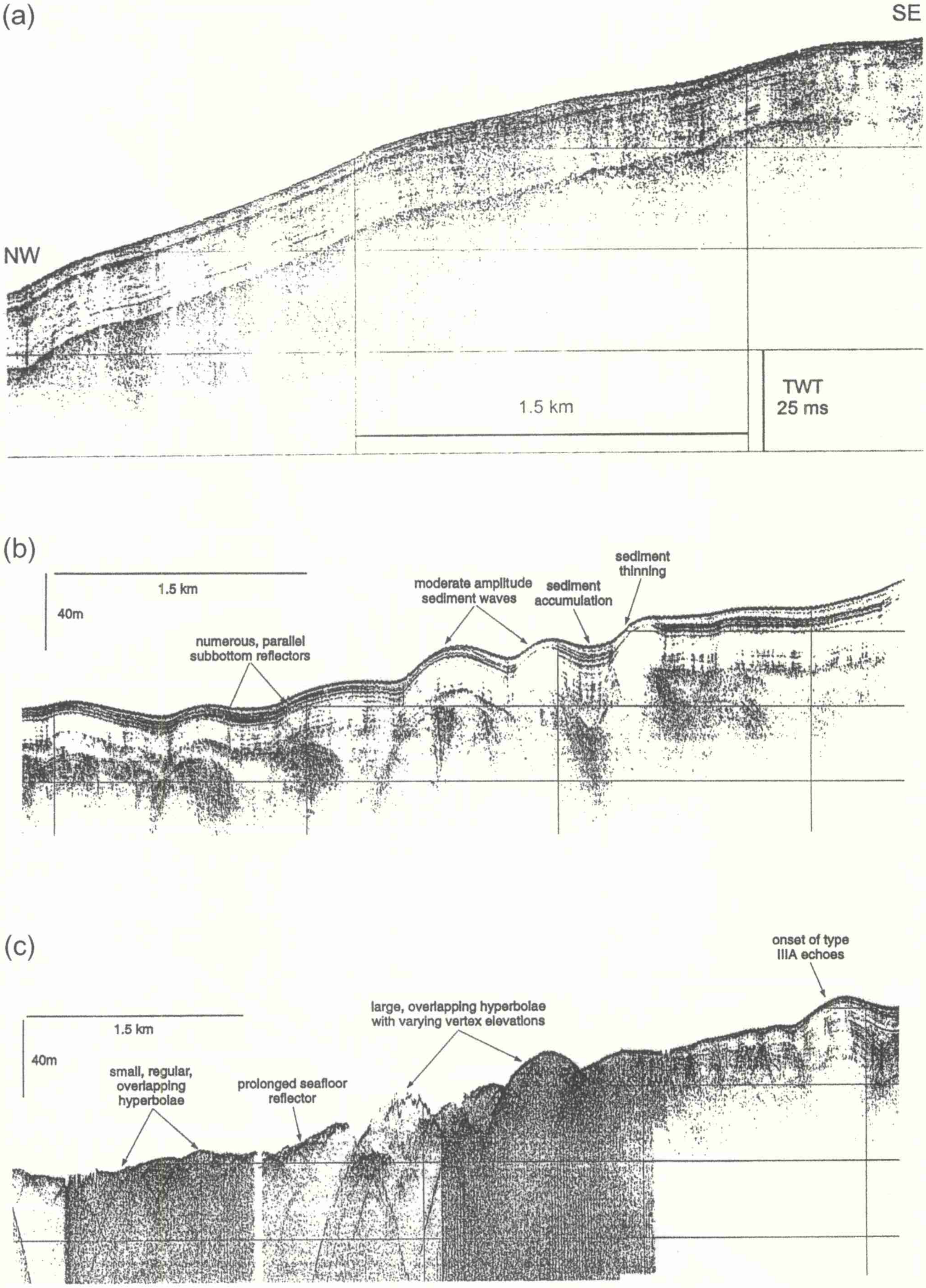
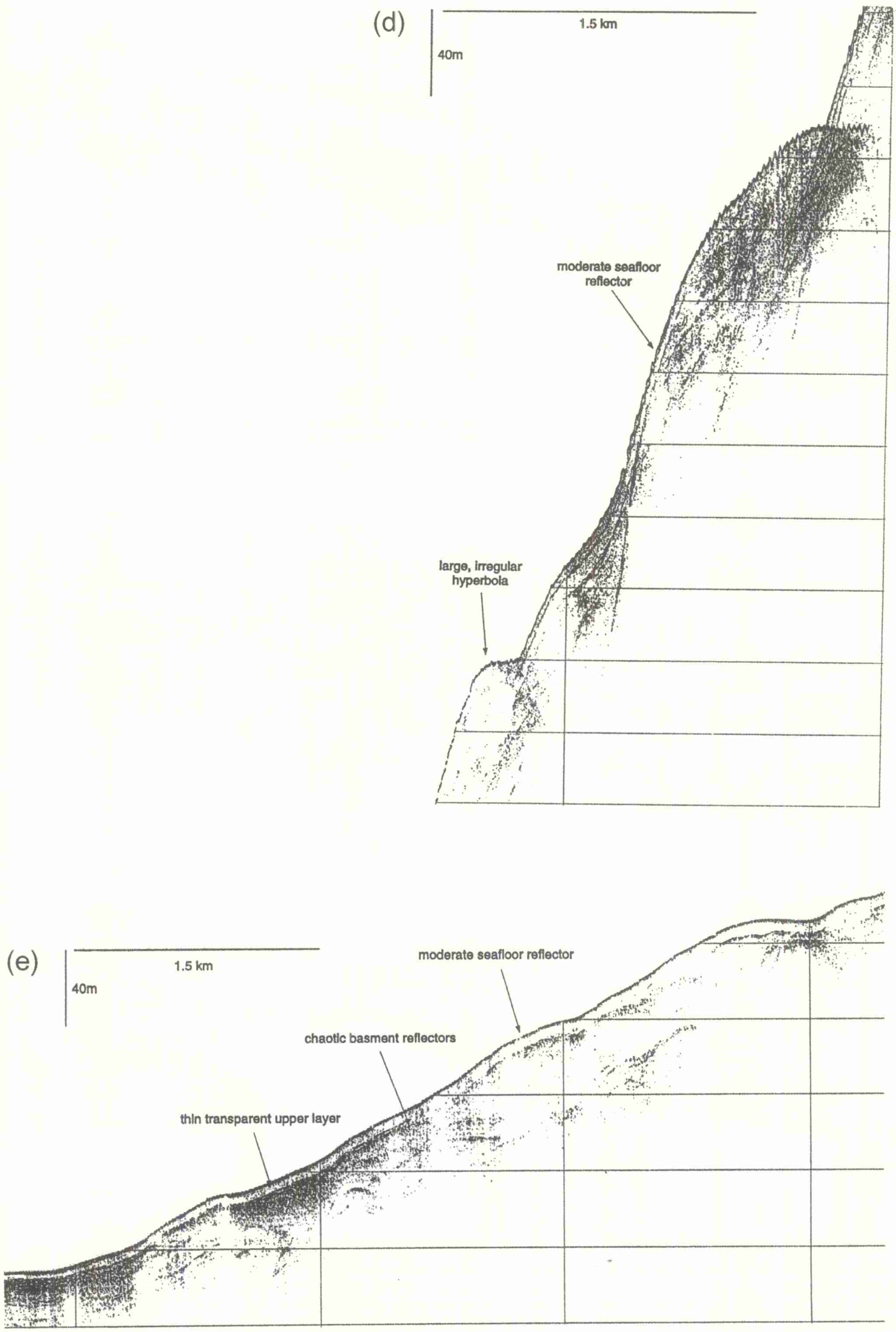
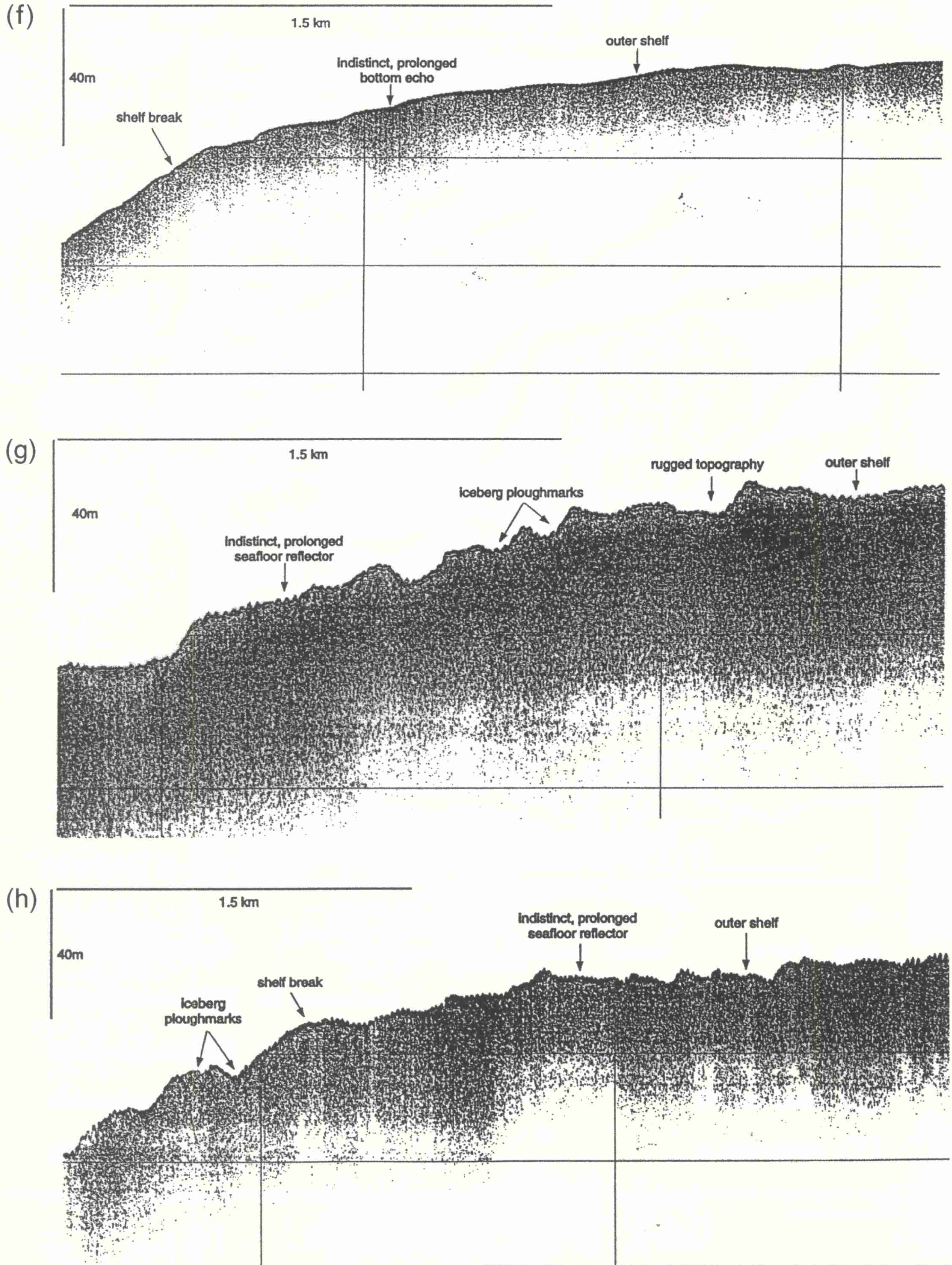


Fig. 6. Selected 3.5 kHz seismic profiles showing features of alongslope sedimentation on the mid and lower slope (profiles A, B, C); downslope sedimentation on the upper to mid slope (profiles D, E); and the effects of seafloor polishing and spillover on the outer shelf to upper slope (profiles F, G, H). Profiles are located on Figure 2, and show examples of seismic facies as follows: A, facies IB; B, facies IIIA; C, facies IVD; D, facies IVC; E, facies IIA and IIB; F, facies IVA; G and H, facies IVB.


(d)
1.5 km
40m
moderate seafloor reflector
large, irregular hyperbola
(e)
1.5 km
40m
moderate seafloor reflector
chaotic basment reflectors
thin transparent upper layer


(f)
1.5 km
40m
shelf break
indistinct, prolonged bottom echo
outer shelf
(g)
1.5 km
40m
indistinct, prolonged seafloor reflector
iceberg ploughmarks
rugged topography
outer shelf
(h)
1.5 km
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iceberg ploughmarks
shelf break
indistinct, prolonged seafloor reflector
outer shelf

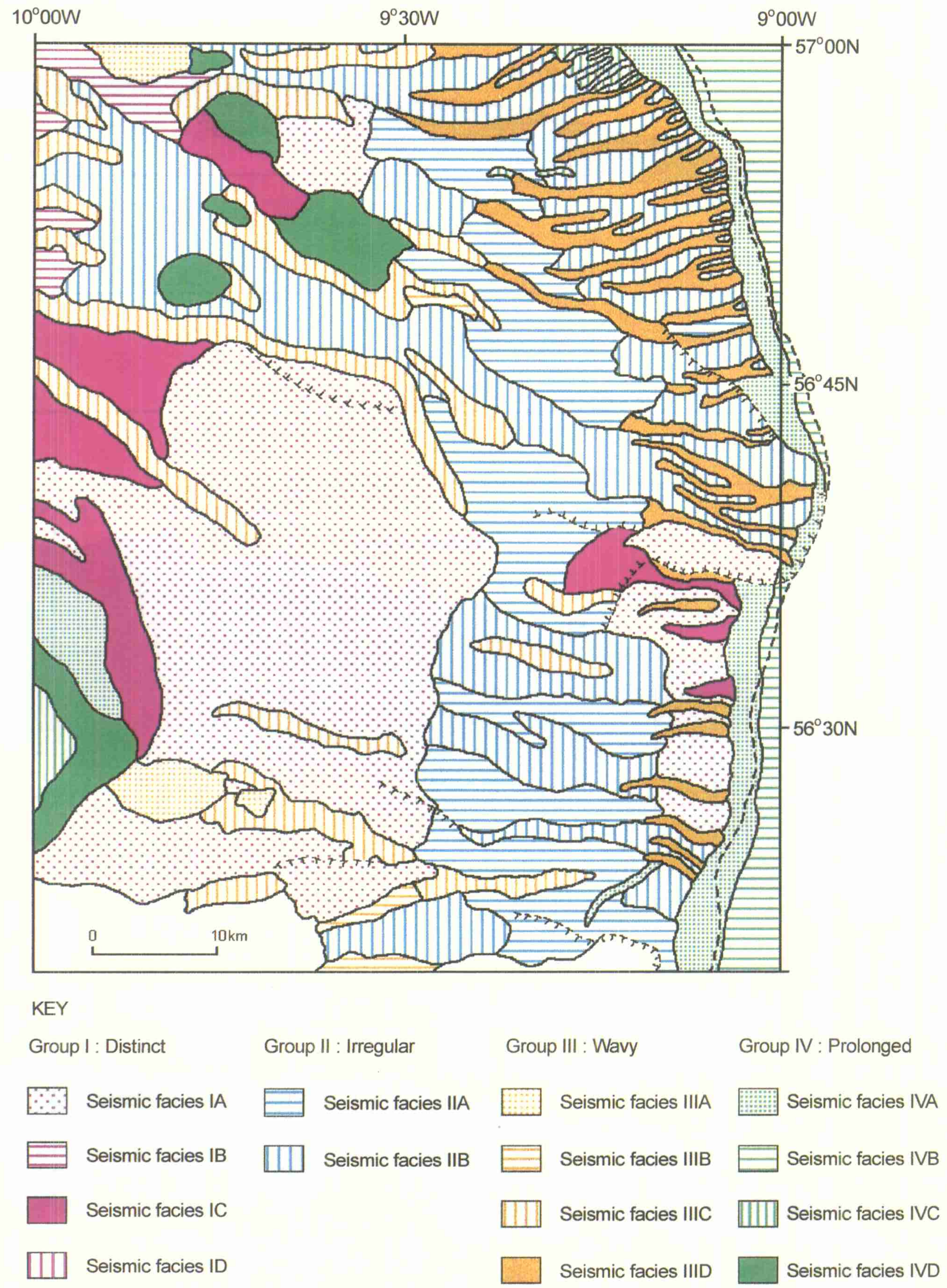


Fig. 7. Map of 3.5 kHz seismic facies over the Barra fan and slope region. Selected examples of the seismic facies are shown in Figure 6. Location and track lines are shown in Figure 2.

persists to a depth of approximately 700 m (Fig. 6b). From 700 m the sand becomes notably siltier to depths of 1000 m (Fig. 6c) with rare gravel patches and boulders (maximum 30 cm diameter). Photographs from the deepest stations shows a muddy sediment cover which is distinctly granular in parts (Fig. 6d).

Current induced features are characteristic of sites between 140 and 1000 m, including sand and silt ripples, sand waves, and obstacle marks. The most common and extensive current features observed are sand and silt ripples. These range from patterns of confused, asymmetric sand ripples on the shelf and upper slope (Fig. 7a) to well-aligned straight crested sandy-silt ripples at 1000 m (Fig. 7b). Ripple crest orientation is variable, depending on the position and depth at which they are found. The majority indicate a north to north–northeast flowing current (Fig. 7a), or more rarely northeast or northwest flow. On the upper slope between water depths 140 to 200 m the presence of a well developed field of sand waves (Fig. 7c) is strong evidence for high velocity currents within the shelfbreak region. On the outer shelf and upper slope less extensive scour crescents and crag-and-tail structures are good indicators for persistent current conditions at the seabed, with velocities of at least 12–15 cm s^{-1} required for their formation (Lonsdale & Hollister 1979).

Observations from photographs at depths of 1500 m and below (Fig. 7d) show features that can be attributed to processes other than current activity. Photographs show a fine-grained homogeneous sediment with an intensely bioturbated surface and an associated fauna, that can be interpreted as a hemipelagic drape.

Principal sediment facies

On the basis of short cores collected from the study area, Armishaw *et al.* (2000) identified seven principal facies (Table 2). These were named on the basis of an interpretation of the major processes involved in their deposition and included:

Facies Group A: A, sandy contourite; A1, silty sandy contourite; A3, muddy contourite.

Facies Group B: B, glaciomarine dumpstone; B1, glaciomarine hemipelagite.

Facies Group C: C, hemipelagite; C1, hemipelagite with rare dropstones.

We would add a further facies group comprising two facies to this list to include the upper slope and outer shelf gavels and gravelly sands observed in seafloor photographs as well as from previous studies of surface grab samples (Figs 8 and 9).

Facies Group D: D, relict gravels; D1, relict coarse gravelly sands.

The Barra sand sheet is made up of *Facies A* sandy contourites that occur as a thin surface layer between 0.05 and 0.40 m thick in mid-upper slope cores (Fig. 10). In cores from the Peach Slide, the sandy facies has been displaced to depths as much as 1540 m. The sand is mainly structureless and bioturbated, in some cases with a more or less well-developed reverse grading to the surface. It is a poorly sorted, mainly very fine-grained sand, with a mixed biogenic-terrigenous composition, fragmented bioclastic particles and common iron-staining. Fuller details of facies groups A–C are provided by Armishaw *et al.* (1998, 2000) and their distribution across the slope illustrated in Figure 11. Further details of the surface facies are given below.

Surface facies – Petrology and texture

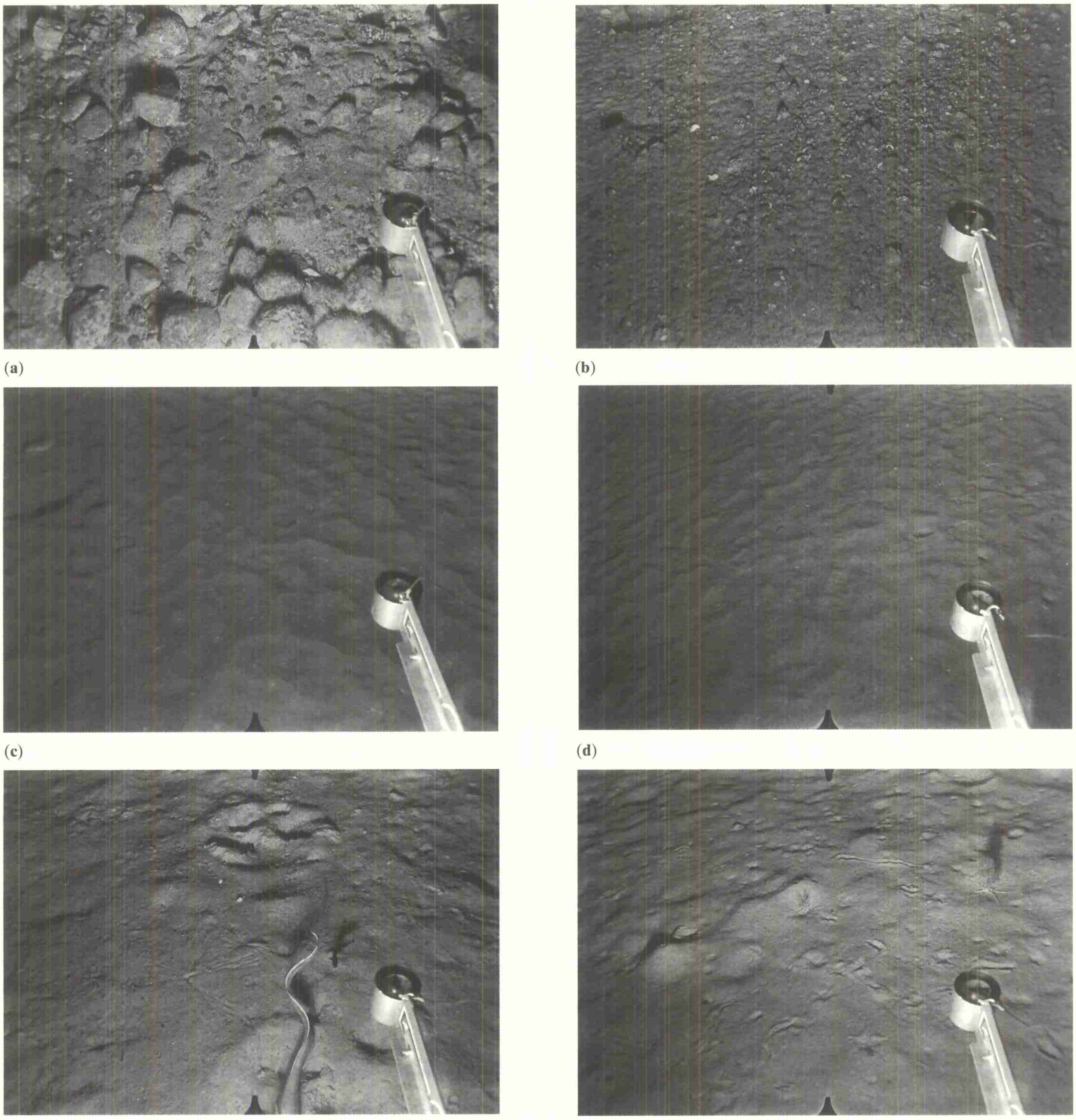
Grain size analyses reveal four major textural components (gravel, sand, silt and clay) on the outer shelf and slope (Fig. 12). The regional sedimentation pattern across the slope shows that the margin is texturally graded from a coarse gravel-rich shelf cover to a predominantly clay-rich sediment on the lower slope (Fig. 13). The proportion of gravel-sized material decreases sharply seaward from the shelf (10% with patches of > 50% gravel) to about 300 m (<1%), below 300 m the proportion of gravel remains relatively constant to the lower slope. The most extensive sediment cover on the middle slope is sand. The greatest proportion of sand-sized material is found between the outer shelf and mid-slope region (70–85%) down to about 1000 m water depths, where the proportion drops to 10–20%. Below 1000 m the proportion of sand remains relatively constant to over 2000 m. Silt is the most variable textural component on the shelf and slope and varies in proportion to as little as 10% on the upper slope to 40–50% at depths of 1500 m. Below 1500 m the proportion decreases to between 10 and 30% . Clay increases rapidly from negligible amounts on the upper slope to over 40% at about 1500 m, unlike that of silt, the proportion of clay then continues to increase gradually to over 60% exceeding 2000 m on the lower slope.

Sediment collected at depths between 140 and 300 m is texturally classified as gravelly sand, that between 300 and 1000 m as sand, that between 1000 and 1500 m as a silt-sand-clay mixture, and deeper than 1500 m as a silty clay. Trends shown in the textural variations are generally similar to the contemporary boundaries mapped on the British Geological Survey 1:250 000 seabed sediment map (James *et al.* 1990). Textural variations in the present study also reveal some important north–south contrasts (Figs 12 and 13). On the northern Barra Fan the presence of sand is recorded down to a depth of at least 1500 m. In contrast on the southern Fan region the presence of sand is seen to a maximum depth of 1200 m. Detailed particle size analyses of the present data reveal that the proportion of sand-sized material in the surface sediments on the northern Barra Fan is up to 25% at depths of about 1500 m, whereas the proportion of sand-sized material in cores from 1500 m on the southern Barra Fan is on average less than 10%. Similarly the proportion of silt- and clay-sized material is also different from north to south. Samples from the northern Barra Fan at depths of 1500 m contain on average 45% silt and <35% clay-sized material, whereas those from similar depths on the southern Barra Fan contain on average 20% silt and >60% clay. The median grain-size shows a diminution from gravel intermixed with coarse and medium sand (0.5 to 3.0 ϕ) on the outer shelf and upper slope to depths of about 300 m, to fine and very fine sand (2.0 to 4.0 ϕ) and coarse to medium silt grades (4.0 to 6.0 ϕ) to depths of 1000 m, with the predominance of clay-sized (>8.0 ϕ) material below.

Surface facies – Composition and mineralogy

The general seaward fining trend is consistent with a gradual change in composition with depth, as shown by the analysis of the sand and silt fraction (Fig. 14). The proportion of terrigenous material decreases from 60–75% on the shelf and upper slope to 15–30% on the lower slope which is broadly coincident with a decrease in the sand and silt fractions. This gradual change in the proportion of terrigenous material is coupled with an associated increase in the proportion of planktonic material from 25–40% on the upper slope, to 80% on the lower slope. Terrigenous/planktonic ratios range from 0.88 to a maximum of 4.16, with an average of greater than 2.0 over most of the study region. Regional trends consist of increasing terrigenous/planktonic ratios seaward, with a significant increase in the ratio in depths greater than 2000 m. The only areas of approximately equal proportions of sand-sized terrigenous and planktonic grains are on the outer shelf and upper slope, in depths down to about 700 m.

Compositional changes with depth are also well illustrated by the distribution of foraminiferal tests and the proportions



(a) (b) (c) (d) (e) (f)

Fig. 8. Seafloor photographs depicting a seaward fining sequence of coarse gravels and sands on the outer shelf and upper slope to fine silt and clay on the lower slope. (**a**) Camera station N200. Seafloor composed of large cobbles and boulders with interstitial coarse and medium grained sand. (**b**) Camera station S300. Seafloor composed of coarse to fine gravel with interstitial sand. (**c**) Camera station N700. Seabed composed of fine sand. Symmetrical sand-ripples suggest oscillating currents in a NNW–SSE trend. (**d**) Camera station S1000 depicting silty sands reworked by weak NW-flowing currents indicated by small-amplitude ripples. (**e**) Camera station N1500. Seafloor is composed of silty clay and clay and is reworked by a mixed benthic population, giving it a granular texture. (**f**) Camera station N2000. Seafloor is composed of silty clay and clay and is reworked by a mixed benthic population, giving it a granular texture. The seabed area photographed is trapezoidal in shape and *c*. 120 cm across the bottom and *c*. 250 cm across the top of the frame (Humphery, pers. comm., 1996).

of iron-stained, silt- and sand-sized material. The percentage of foraminiferal tests increases from less than 10% on average on the upper slope at 700 m to 20–30% at about 1000 m depth where the proportion remains constant down to 2100 m. Seaward changes in the proportions of iron-stained and glauconitic material are broadly similar and reveal a gradual decrease from up to 10% on the outer shelf and upper slope to <0.5% at depths below 2000 m. Across the slope depth-related compositional associations are predominantly parallel to the shelfbreak and slope isobaths. Simple graphic plots illustrate that (a) the relative proportion of

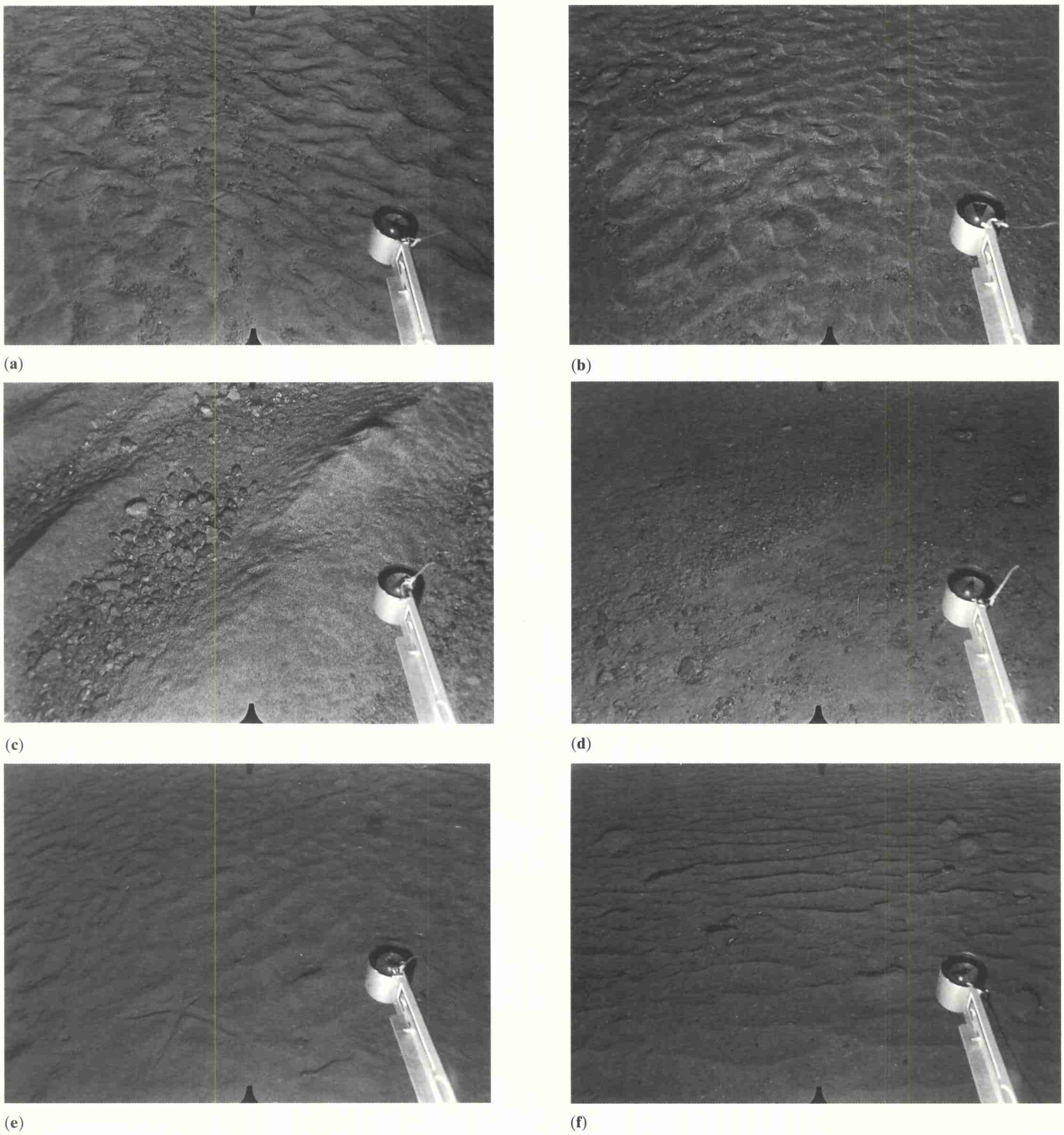


Fig. 9. Bottom photographs indicating bottom-current flow on the shelf and slope. (**a**) Camera station S140 depicting asymmetric and confused sand ripples under the influence of a north to north–northeast flowing current. (**b**) Camera station S200 (August 1995) depicting mainly asymmetric sand ripples under the influence of a northwesterly flowing current, and a weaker set of interference ripples from a more northeasterly flowing current. (**c**) Camera station S200 (March 1995) showing N–S aligned deep, sand waves on the upper slope. (**d**) Camera station S300 depicting a mixed gravel and sand substrate, with evidence of some alignment under the influence of a NNE flowing current. (**e**) Camera station S700 depicting a fine sandy substrate with asymmetric to symmetrical ripples under the influence of a north to north–northwest flowing current. (**f**) Camera station S1000. Field of symmetrical, straight-crested sand ripples, interspersed with small (1–3 cm) and large (up to 20 cm) pebbles and boulders causing the development of crag-and-tail structures. The seabed area photographed is trapezoidal in shape and *c.* 120 cm across the bottom and *c.* 250 cm across the top of the frame (Humphery, pers. comm., 1996).

terrigenous fragments and water depth are inversely correlated; (b) the relative proportion of planktonic material and depth correlate positively; and (c) the total proportion of sand-sized particles and terrigenous material correlate positively.

Discussion

Seafloor polishing and sand spillover

From seabed photographs within the study area outer shelf gravels and gravelly sands are seen to be present between depths

Table 2. *Principal sediment facies of the Barra fan study area (modified from Armishaw* et al. *2000)*

Sedimentary characteristics	**Facies A sandy contourite**	**Facies A1 silty-sandy contourite**	**Facies A2 muddy contourite**	**Facies B glaciomarine dumpstone**	**Facies B1 glaciomarine hemipelagite**	**Facies C hemipelagite (much bioturbation)**	**Facies C1 hemipelagite (+dropstones)**	**Facies D relict gravel**	**Facies D1 relict coarse gravelly sand**
Colour	olive grey to dark greyish brown	olive grey to dark greyish brown	olive grey to dark olive grey	light olive grey to olive grey	dark grey to dark greyish brown	dark olive grey to dark grey	olive grey to dark olive grey	olive grey to dark grey (variable)	olive grey to dark grey (variable)
Contacts: top	sharp	sharp-gradational	sharp or bioturbated	bioturbated	gradual or bioturbated	grad/sharp/bioturbated	sharp or gradational	Sharp (seafloor)	Sharp (seafloor)
base	sharp	sharp-gradational	gradual or bioturbated	sharp or gradational	gradual or bioturbated	grad/sharp/bioturbated	gradual/bioturbated	Sharp-gradational	sharp-gradational
Sedimentary structures	rare negative grading	coarse lenses and pockets, rare negative grading	rare lenses, pockets, laminae and grading	structureless, chaotic with coarse lenses and clasts	structureless, chaotic with coarse lenses and clasts	homogeneous and bioturbated	mostly homogeneous and bioturbated	Structureless (negative grading)	Structureless (negative grading)
Ice-rafted debris	generally absent	rare dropstones	rare dropstones	abundant dropstones < 5 cm diameter	intermittent dropstones < 10 cm diameter	very rare dropstones	rare dropstones	Relict IRD	Relict IRD
Bioturbation type	*Chondrites Mycelia*	*Planolites Mycelia*	*Planolites Mycelia*	*Zoophycos, Planolites Mycelia*	*Mycelia*	*Mycelia*	*Zoophycos*	Unknown	Unknown
Bioturbation intensity	slight to intense 5–99%	slight to high 5–90%	slight to moderate 5–60%	moderate 30–60%	slight to intense 5–99%	moderate 30–60%	moderate to high 30–90%	Unknown	Unknown
Carbonate content	biogenic 5–10%	biogenic 5–10%	biogenic 10–20% detrital 25–50%	biogenic 5–30% detrital 5–30%	biogenic 20–40%	biogenic 5–30%	biogenic < 5–10% detrital 30–65%	< 10%	< 10%
Total organic carbon	0.1–0.6%	0.3–0.75%	0.35–0.75%	not known	not known	not known	0.25–0.6%	0 %	0 %
Grain size: mean	4.5–4.7	5.9–7.1	8.1–8.4	6.9–9.5	7.2–8.6	9.6	6.9–7.4	No data	No data
median	2.8–2.9	6.1–9.0		4.9–9.1	8.9–9.5		8.1–9.4		
sorting	2.7–3.0	3.0–3.5	0.9–2.4	2.4–3.0	1.4–2.9	2.9	1.6–4.2		
modes	2 (9)	2–3 (8–9)	6–7 (8–10)	2–7 (9–11)	9–11	8–10	5–6 (2–3)		
skewness	0.8–0.81	–0.1– –0.9	0.68	–0.6	–0.8–3.9	–0.8	–0.5– –0.9		
(all data in phi units)									
Interpretation	sandy contourite strong bottom currents sheeted drift deposit	silty – sandy contourite moderate bottom currents	muddy contourite weak bottom currents	glacial dumping from rapid meltout of floating ice	glacial fallout from floating ice and hemipelagic dispersion	hemipelagic sedimentation at very low rates	hemipelagic sedimentation and minor glacial input	Glacial to glaciomarine + shelf reworking	Glacial to glaciomarine + shelf reworking

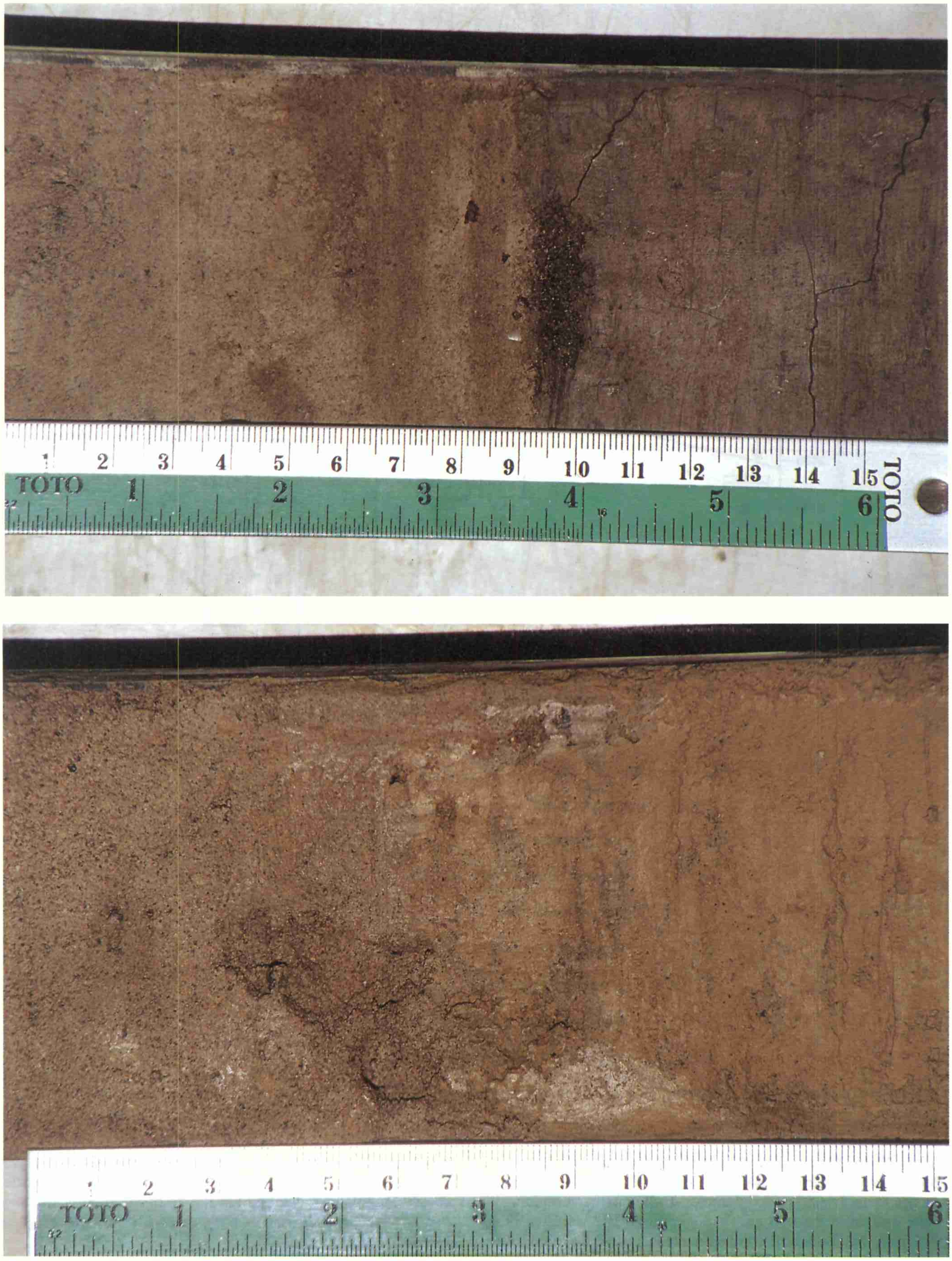


Fig. 10. Selected core photographs from the Barra contourite sand sheet – sandy contourite facies. Top to left.

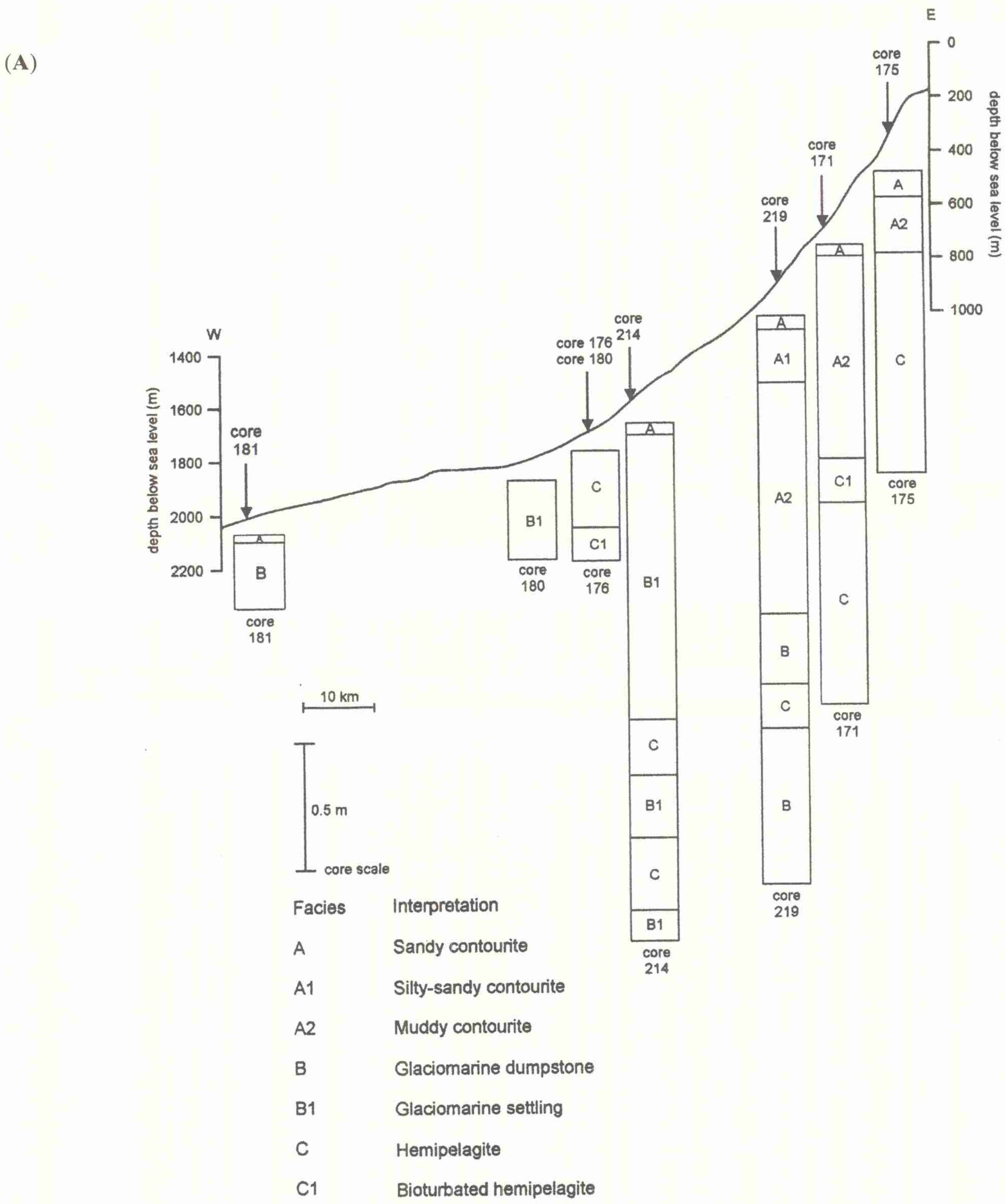
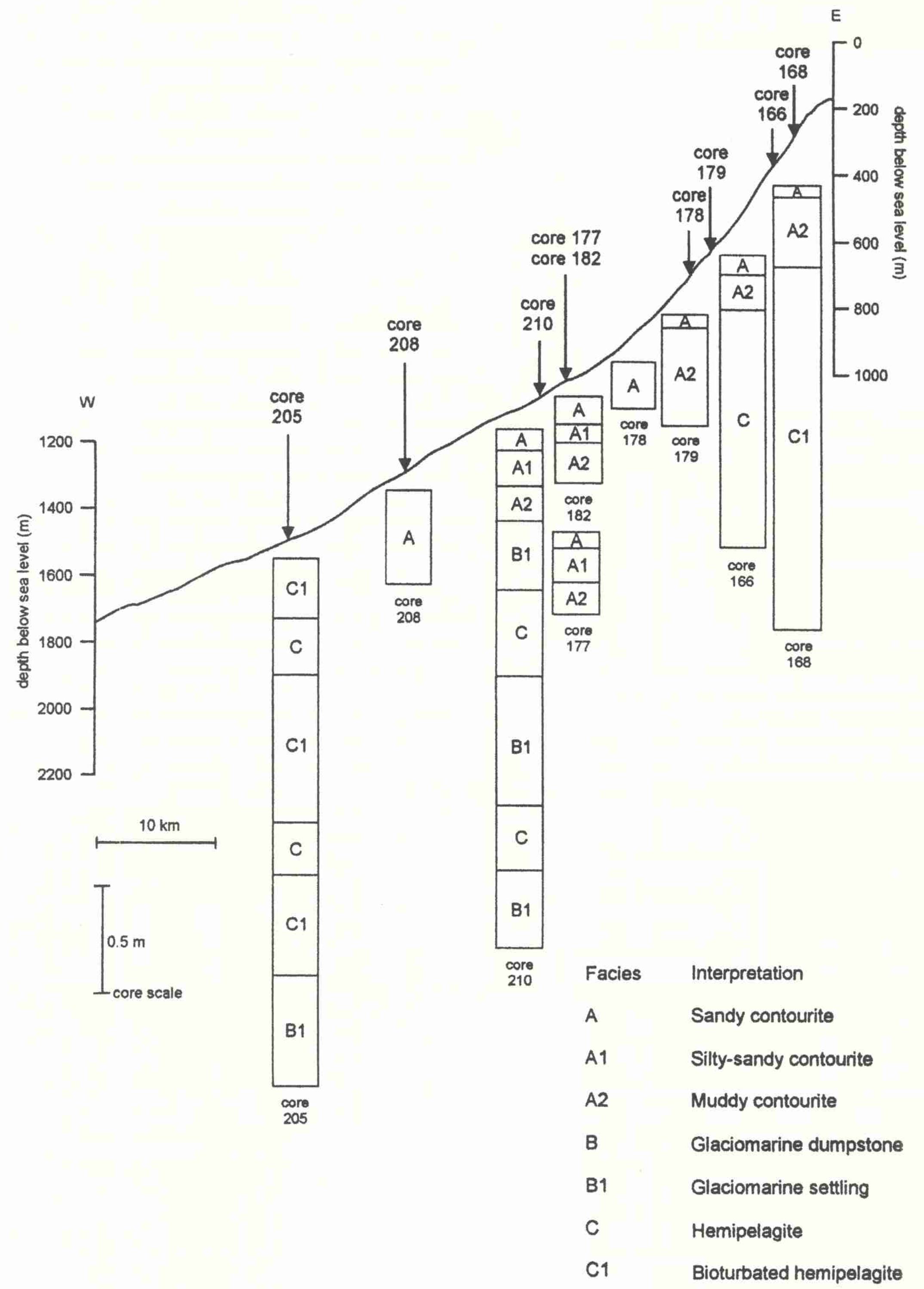


Fig. 11. Slope profiles showing core sections and facies distribution across the central (**A**) and northern (**B**) Barra fan. (From Armishaw *et al.* 2000).

of about 140 to 300 m. These comprise a mixture of cobbles, boulders, gravel with minor sand and shell detritus; the cobbles vary in size from 5 to 50 cm in diameter in the northern region of the slope and from 2 to 30 cm in diameter to the south of the region. Given the depth of the gravel deposits below sea level, and the limited extent and strength of the shelf circulatory system it is unlikely that the present day hydraulic and morphologic regime is actively delivering coarse-grained sediment to the outer shelf region. Consequently the outer shelf facies represents the modern overprint on a relict Pleistocene shelf environment. The presence of cobbles and boulders is related to glacial, fluvial and coastal processes that prevailed when the coastline extended seaward to a position close to the shelf edge during Pleistocene eustatic low stands. A similar gravel band at the lip of the shelf is also seen on the Norwegian shelf and is a characteristic feature of glaciated margins.

The formation of the outer shelf sand and gravel facies in the present study is very similar to that of the outer shelf/slope sands described by Viana *et al.* (1998) from several other continental margins including those from the USA Atlantic margin (Stanley *et al.* 1981; Blake & Doyle 1983) and the Scandinavian margin (Kuijpers *et al.* 1993; Yoon & Chough 1993) where they are

(B)



described as bottom current reworked sand accumulations. The combination of processes and relatively shallow water depths involved in their deposition precludes them from being described as contourite or even shallow water contourite deposits. Typical bedforms range from sand and gravel wave fields to smaller-scale, randomly-oriented sand ripples which are believed to result from the passage of a geostrophic outershelf/slope current, combined with the action of large current eddies, storm waves, tides and internal waves. This process combination can be referred to as *seafloor polishing* (Viana *et al.* 1994, 1998).

The removal of sands and some gravel from the shelf and their redistribution to the slope is related to the onshelf penetration of surficial geostrophic currents and associated eddies and is known as shelf *spillover* (Stanley *et al.* 1981). The controlling factors for the formation and preservation of such deposits requires a complex combination of elements. The principal hydrodynamic regime requires the combined effects of a relatively strong geostrophic upper slope current with a marked element of cross-shelf exchange of water, along with the effects of tide-induced bottom currents and the downward propagation of shelf eddies. In the present study the gross circulation is dominated by the strong, persistent north to northeasterly flowing slope current, and

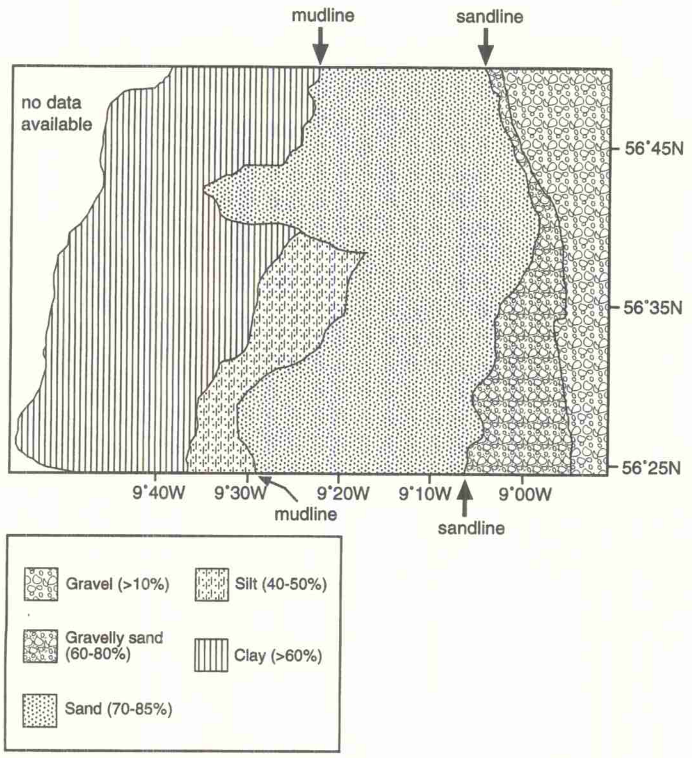


Fig 12. Map of surficial sediment grain size class from the Barra fan region based on grain size analyses of core top samples. The broad sand belt between the sandline and mudline is referred to as the Barra contourite sand sheet. The marked offset in the position of the mudline at around latitude 56°40′ is due to downslope lateral displacement in the Peach Slide.

although the precise mechanisms of cross-shelf exchange are not yet fully understood from the region, there is a marked increase in the mixing on the shelf during autumn and winter due to autumnal gales (Edelsten *et al.* 1976). In light of the lack of modern sediment input from external sources the chief supply of spillover sediment is the relict shelf deposits from Pleistocene sea-level low stands and transgressive episodes (Ferentinos 1976) and the winnowing of glaciomarine sediments on the outer shelf which has led to significant reduction in the original sediment thickness.

Barra contourite sand sheet

Below about 300 m water depth and up to around 1500 m on the northern Barra Fan and 1200 m on the southern Barra Fan, there is a broad area of sandy facies covering the slope surface. This we have termed the *Barra contourite sand sheet*, and interpret it as a mid-depth sandy contourite. Such deposits, as reviewed by Viana *et al.* (1998), are formed under major geostrophic flows in water depths in excess of 300 m and up to about 2000 m. The Barra contourite sand occurs as a thin (3–40 cm) surface sheet over an area of between 1000 and 1500 km^2 within the study region. We estimate its total volume in this area alone at approximately 30 000 m^3.

The presence of symmetric and asymmetric sand-silt ripples on the slope down to depths of 1000 m on the surface of the contourite sheet indicate a persistent, fast-moving alongslope current flow, with flow velocities of over 30 cm s^{-1}. The accumulation of such contourite deposits requires the presence of either relatively strong, semi-permanent geostrophic currents flowing at intermediate depths within the water column, or very strong surficial geostrophic currents that are able to influence the seafloor at these depths (Viana *et al.* 1998). The supply of sand to the slope

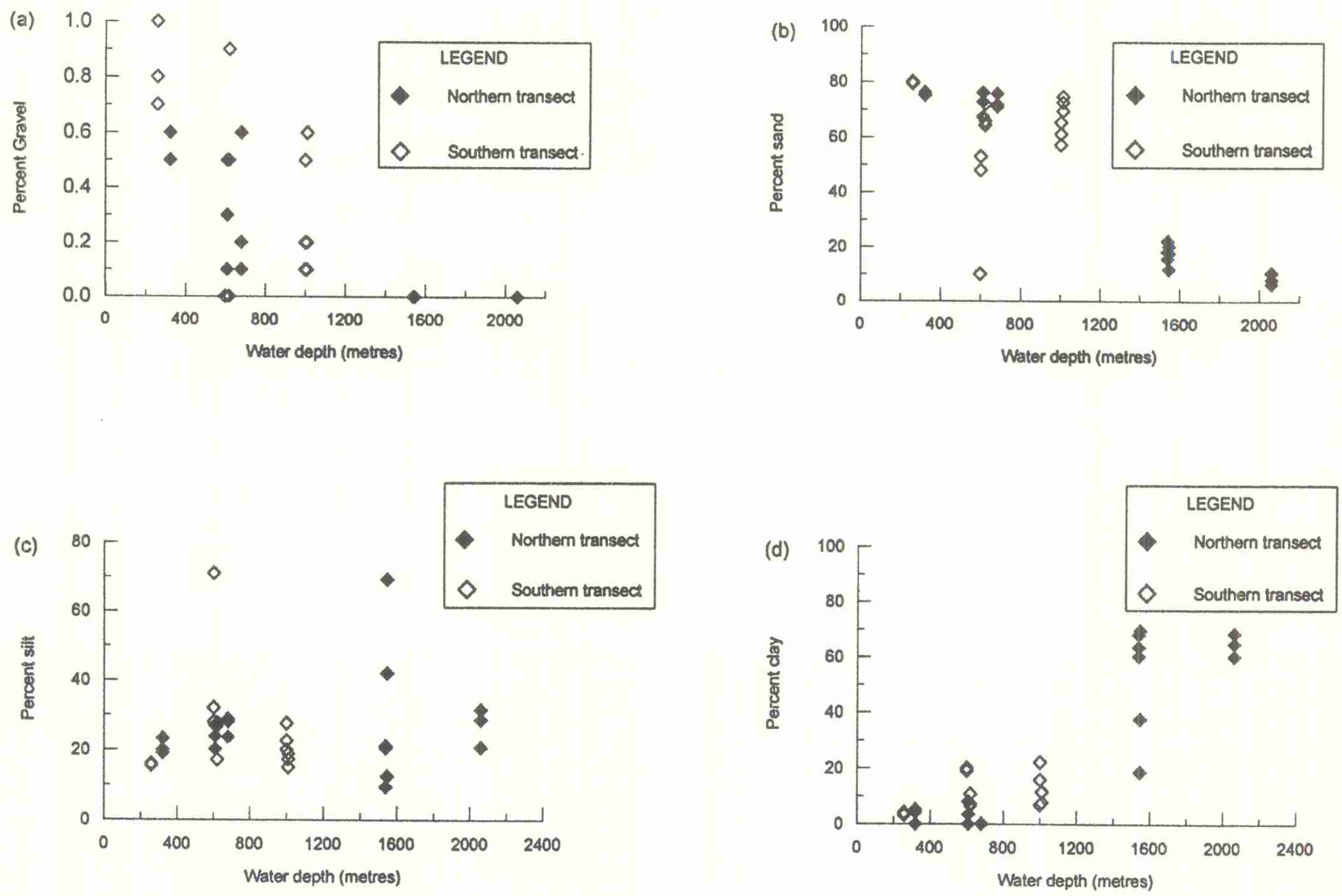


Fig. 13. Graphic plots showing the four major textural classes v. depth. Each point represents at least two analyses from a core top sample.

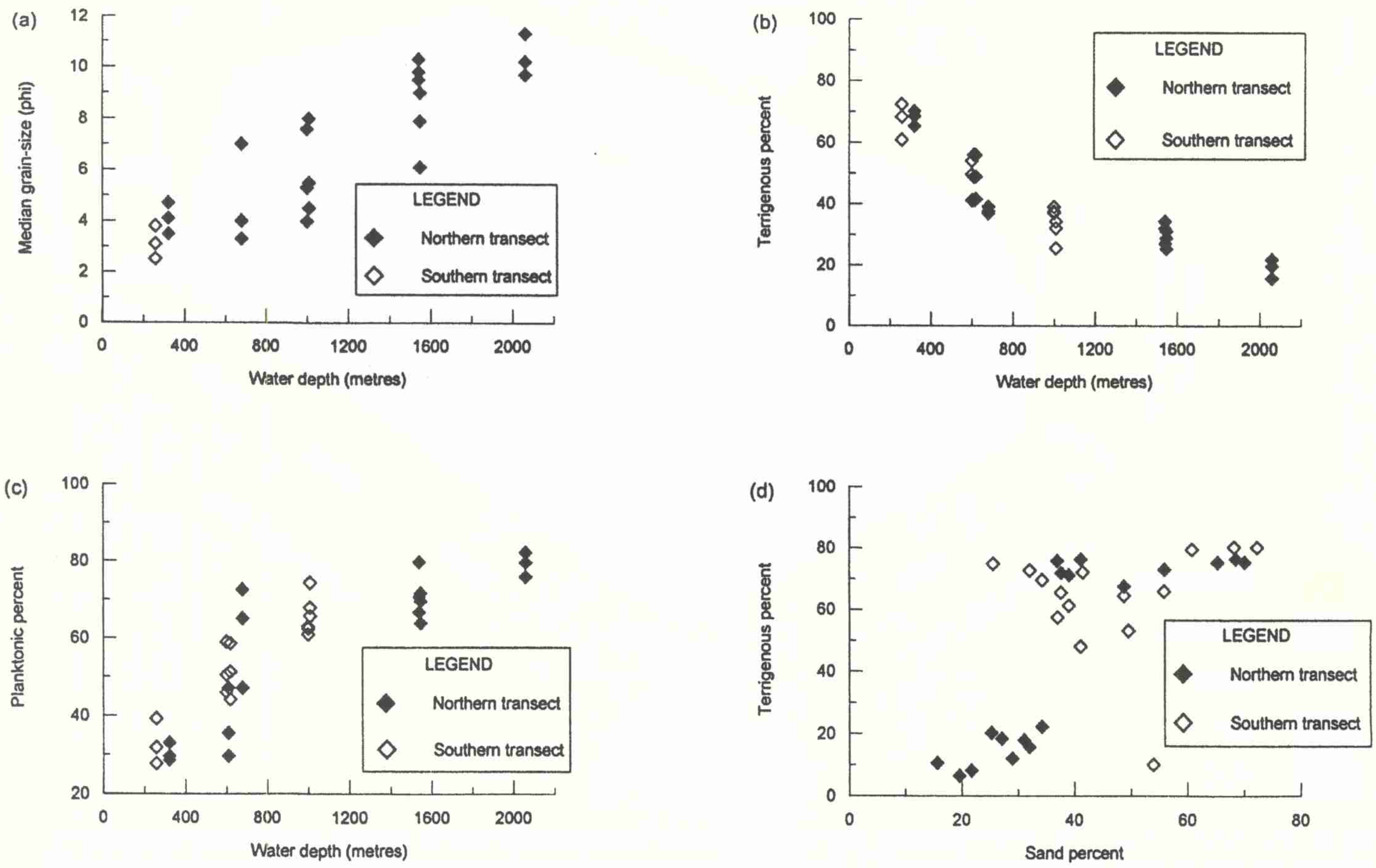


Fig. 14. Graphic plots showing trends of selected petrologic and compositional parameters: (**a**) median grain size v. clay content; (**b**) terrigenous content v. depth; (**c**) planktonic content v. depth; (**d**) terrigenous content v. sand content.

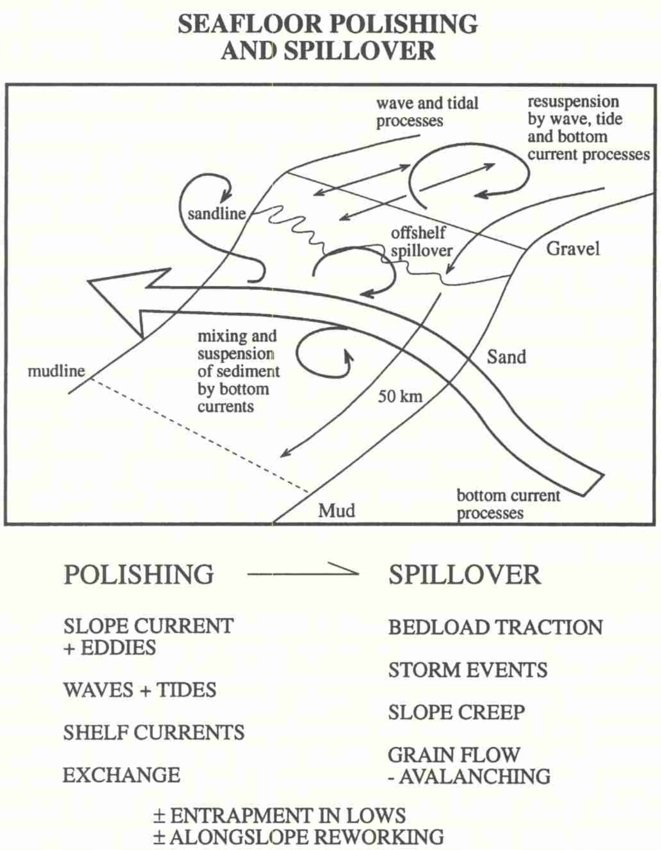


Fig. 15. Model of seafloor polishing and offshelf sand spillover under the influence of a variety of bottom current and downslope gravity processes. (From Stow & Mayall 2000, after Viana *et al.* 1998).

comes from a variety of sources both internal and external including bottom current erosion upstream of the drift, the pirating of offshelf spillover, pelagic biogenic fallout and *in situ* winnowing. The present day hydraulic regime is clearly evidenced by photographs of the seafloor surface. The time series of shots taken over a period of over two years quite clearly shows the seasonal effects on the generally northerly advecting slope current on the Hebrides Slope, and also the fluctuation in both current strength and orientation with depth and location on the slope. Over a two year period photographs indicate a NNW–SSE oscillating flow effective during the winter and spring months and a much reduced flow during the summer. Booth & Ellett (1986) attribute the decrease of a slope current during the summer months to the notable lack of cross-shelf water exchange during the summer and autumn.

Petrologic parameters of the Barra sand sheet also provide an effective means of recognizing the more subtle, long-term (Holocene to recent) influence and interaction of bottom current activity and downslope delivery of sediment on the Hebridean margin that are not otherwise apparent in direct observations of the seafloor. On-going, off-shelf spillover processes on the outer shelf and beyond the shelfbreak, and the influence of bottom current activity, are reflected in the intermediate texture (between shelf gravels and lower slope muds) and mixed terrigenous-biogenic composition of the surface sands. Between depths of approximately 300 and 1200 m the terrigenous sand component is largely attributed to shelf spillover. By contrast, the presence of diverse assemblages of fragmented benthonic and planktonic tests, coupled with an overall upward increase in grain-size through the sand sheet, are characteristic of vertical supply, followed by alongslope transportation and reworking of the surface sediment by vigorous bottom currents.

The lower limit of the transitional facies is delineated by the mudline (Stanley & Wear 1978; Stanley & Freeland 1978; Stanley

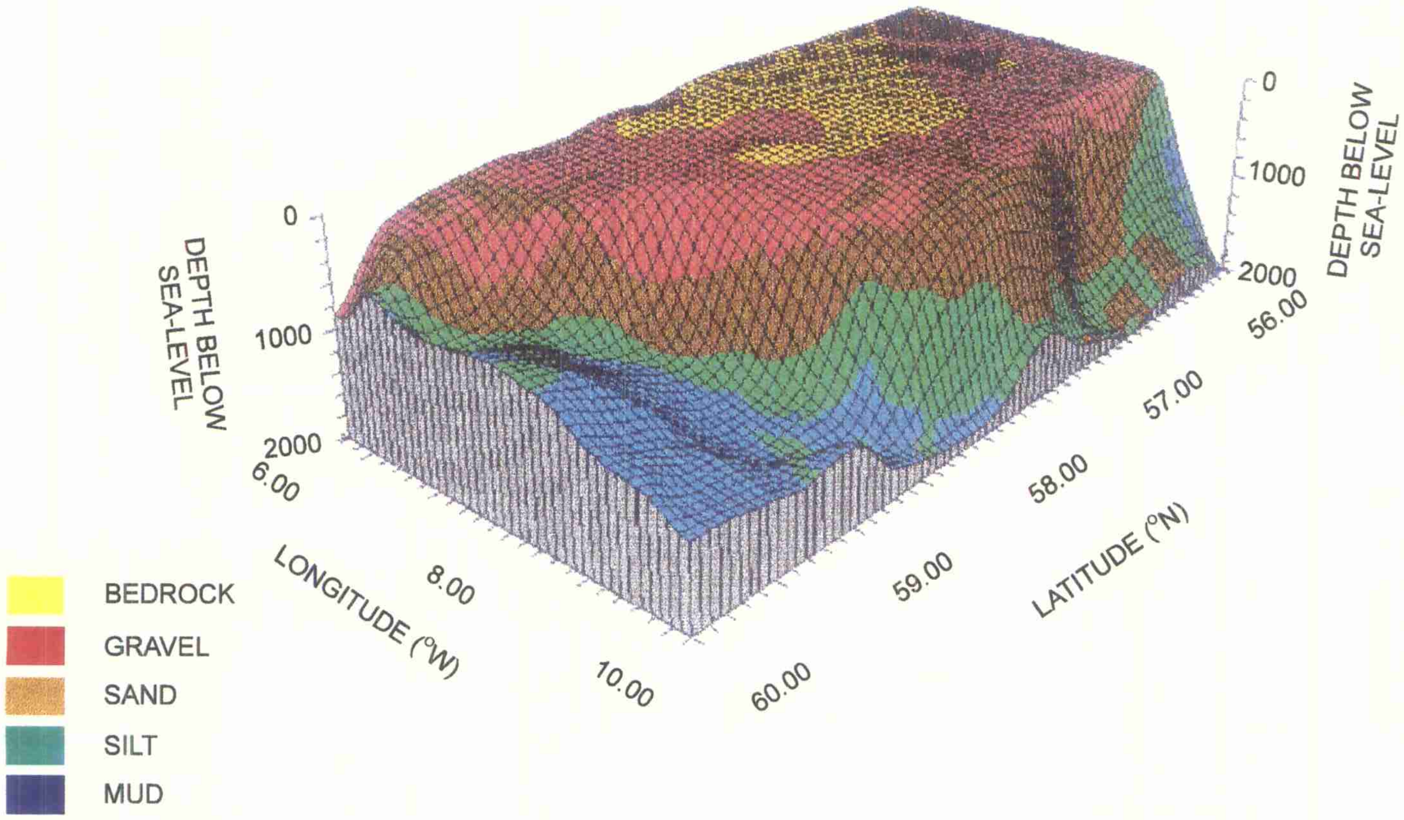


Fig. 16. 3D perspective image of the sea-bed topography derived from processed bathymetric data from the Hebrides Slope between 56°N and 60°N, including data from the study area between 56°N and 57°N. The colour overlay shows surface sediment types (grain size classes) derived from detailed sediment analysis of core top samples. The data show a seaward-fining sequence from gravel on the shelf and upper slope to mud on the lower slope. The broad area of sand lies between an upper slope sandline and lower slope mudline – and is known as the Barra contourite sand sheet.

et al. 1983) (Figs 12 & 13), where the amount of clay no longer increases significantly with depth. At this depth the clay content generally exceeds 60% and the median grain size of samples is generally finer than 8 phi. The presence of non-current-induced features on the seabed are largely attributed to normal marine hemipelagic settling. Observations from photographs clearly indicate a high benthic population which has resulted in an intensely reworked surface and granular texture in some parts. The decrease in the amplitude of current induced bedforms passing down through the transitional facies is attributed to the progressive decrease in current velocity down the lower slope, and the onset of the slope facies marks the decrease in frequency of currents exceeding threshold velocities needed to erode fine sediment. The present limit of the mudline it seems is therefore likely to identify a separation of energy zones; above the mudline marks an erosive or winnowing zone for fine grained sediment whereas sediments below mark a zone of non-erosion/deposition.

Recognizing a Mudline and Sandline

The transition from a gravel-rich outer shelf to a clay-rich lower slope is marked by the presence of two significant facies boundaries that result principally from a combination of hydrological and physiographic conditions. The boundary between the outer shelf/upper slope gravels and mid-slope sands is defined here as the *sandline*. The sandline is the first major facies boundary to be encountered as we progress down the slope and represents the level to which a coarse grain size (gravel) spike is present on the slope. Above the sandline the outer shelf/upper slope facies is dominated by coarse sands and gravels up to boulder size; below it the proportion of gravel-sized material is <1% and the major grain-size component is sand (70–85%). The position of the sandline across the region varies between 170 and 300 m. It is rarely coincident with the shelfbreak and tends to be present at a greater depth on the northern Barra Fan, particularly where it is associated with the presence of a canyon-incised steep upper slope.

The second of the two facies boundaries is the *mudline* as previously defined by Stanley & Wear (1978). The mudline marks the lower limit of the Barra sand sheet below which the amount of clay no longer increases significantly with depth. At this depth the clay content generally exceeds 60% and the median grain size of samples is generally finer than 8 phi. Across the region the mudline is present on the northern Barra fan at depths in excess of 1500 m, and on the southern fan to a maximum depth of 1200 m. The mudline here reflects an important boundary between an area of long-term winnowing and non-deposition of fines and their net accumulation in the absence of a strong bottom-current system. By comparison with earlier studies of the mudline on the North American continental margin (Stanley & Freeland 1978; Stanley & Wear 1978; Stanley *et al.* 1983), we note that its depth on the Hebridean margin is generally greater, reflecting the presence of a persistent mid-slope, high-energy, bottom current system along this margin.

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