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The Barra Fan: A bottom-current reworked, glacially-fed submarine fan system

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Abstract

On the basis of sedimentary structures, textures and ichofauna, seven depositional facies have been recognised in cores from the Barra Fan region of the Hebrides slope. Sedimentary facies are combined into three genetic groups A–C that represent their primary mode of deposition: (A) sandy to muddy contourite facies A, A1, and A2, which represent an overall coarsening upward sequence caused by an increase in bottom-current velocity over time; (B) disorganised glaciomarine deposits, including the glaciomarine dumpstone of facies B and facies B1 deposited as a result of ice-rafting and glaciomarine sedimentation; and (C) hemipelagite facies C and C1 which are the result of normal marine hemipelagic settling. It is most likely that all contourite facies (A–A2) identified in this study are Holocene (<10,000 y) in age and that the underlying glaciomarine and hemipelagite facies (groups B and C) were deposited during the last glacial period.

In terms of its diverse morphological elements and varied facies, this high latitude submarine fan is truly composite in nature. However, a broad three-stage glacial to post-glacial evolutionary system is recognised, during which different processes and process combinations were dominant. During the last glacial period (low stand system tract), downslope processes, including debris flows and minor turbidity currents, sculpted an irregular slope topography. Little in the way of bottom current activity was evident. Staged deglaciation was accompanied by rising sea level and high sedimentation rates across the region. This created an unstable margin prone to extensive sliding and slumping, that masked any effects of an incipient alongslope current. The present high stand system tract is dominated by a strong slope current that became fully active during the early part of the Holocene. Low sedimentation rates, diminished sediment supply and strong bottom current activity led to development of the sandy contourite sheeted drift system across the mid-slope region. Little downslope movement is evident during this period, so that the slope topography is being slowly smoothed and remoulded by active bottom currents. © 2000 Elsevier Science Ltd. All rights reserved.

1. Introduction

This paper forms part of a long-term multi-disciplinary programme, known as the Land Ocean Interaction Study (LOIS), that was designed to investigate material flux from the continents into the oceans. One

component of LOIS, the Shelf Edge Study (SES), is focussing on flux across the continental margin in selected areas around northern Britain, including the Outer Hebrides shelf-slope system. This is a relatively exposed continental margin that experiences moderate tidal currents, a persistent north-flowing slope current, sporadic upwelling and deep-water mixing. Within this area the Barra Fan represents a morphologically and sedimentologically distinct part of the continental margin dominated by both downslope-gravitational and alongslope-geostrophic processes. The whole region is currently one of active hydrocarbon exploration.

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The main aims of the present paper are: (1) to identify, classify and interpret the principal sedimentary facies across the Barra Fan region; and (2) to establish their relationship with the sedimentary processes that have been influential during their deposition. Within the morphological framework the main driving-mechanisms for the deposition of sediments have previously been established as being attributable to the interaction of both down- and alongslope processes (Armishaw, Holmes & Stow, 1998). This paper forms an extension of previous work and assesses the role of both down-slope and alongslope processes upon the vertical and lateral distribution of sedimentary facies, with particular emphasis on the presence and distribution of sandy contourites as well as upper slope/outer shelf sand bodies. These sand-prone bodies may provide important analogues for potential oil-bearing deposits.

The Hebridean continental shelf and slope have been strongly affected by Quaternary glaciation. Both the outer shelf and upper slope are characterised by a relict cover of boulders, gravels and coarse sand. Further down the slope there is a broad area covered by a thin layer of Holocene sands that has been interpreted as a contourite sand sheet (Armishaw et al., 1998). The mechanisms of sediment delivery to and transfer from the relict glacial deposits on the adjacent continental shelf are of key importance in understanding slope sedimentation. Preliminary dating of sedimentary facies identified in cores recovered from the study region together with a consideration of the relationship of sediments to changing oceanographic and climatic regimes allows us to construct a schematic model for late Quaternary sedimentation on Barra Fan.

2. Regional setting

The study area is located on the Barra Fan region of the Hebrides shelf and slope in water depths between 120 and 2100 m (Figs. 1 and 2), with a regional gradient of 1.2° . The shelf/slope system comprises 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 shelf region is characterised by a gently dipping ($<0.5^\circ$) topography dominated by deep inner shelf basins and shelf ridges. On a local scale, shelf topography is controlled by glacial ice relicts including ice scour and diamict lithofacies. Shelf width is typically 100 km or more.

Throughout the study area the shelf break is well defined and relatively sharp. It varies in depth from around 220 m in the south and 200 m in the north to between 160 and 180 m in the central region (i.e. head-wall of the Peach Slide). Outside the study area, both

to the south and particularly further north, it becomes a more poorly defined convex-upward ramp shelf-break. The Barra Fan system progrades westward into the central region and encroaches on the Hebrides Terrace Seamount which is enclosed by the 1800 m isobath to the east and the 2300 m isobath to the west (Fig. 1). The Barra Fan north of the Hebrides Terrace Seamount and Donegal Fan south of the Seamount, considered together, form the largest sediment depocentre off NW Britain, covering an area of over 7000 km².

The Barra Fan complex and similar depocentres west of the UK have been called 'slope-front fans' (e.g. Armishaw et al., 1998), the term being introduced by Stoker, Hitchen and Graham (1993) for glacially-fed sedimentary systems along the continental margin that received enhanced sedimentation with respect to the adjacent slope apron. Vorren, Hald and Lebesbye (1988), Vorren, Lebesbye, Andreassen and Larsen (1989) and Vorren and Laberg (1997) identified at least ten such systems around the margins of the Norwegian-Greenland Sea and called them 'trough-mouth fans'. These are fan-like bodies that form at the mouths of transverse troughs or channels that cut across glaciated continental shelves. However, for simplicity, we retain the name Barra Fan for the purposes of this paper.

A pronounced topographic feature in the central region (Fig. 2) is the Peach Slide, with an area of over 2000 km² and slide-transfer volume in the order of 80 km³ (Holmes, 1994; Holmes, Long & Dodds, 1998). North of the Peach Slide the regional slope is characterised by an average gradient of $4\text{--}5^\circ$, which locally exceeds 16° and a topography dominated by steep-sided canyons. There is a clearly defined steep upper slope down to about 600 m water depth, a less steep middle slope to about 1100 m and a slightly concave-upward lower slope to about 1700 m. Over the Peach Slide and the area immediately to the south where the lower slope banks up against the Hebrides Terrace Seamount, the gradients are less (typically $1\text{--}3^\circ$) and slope divisions less pronounced, although still observed at 600 m, 1000–1100 m and 1700–1800 m. The more southerly part of the study area is similar to the northern part, with steeper gradients, distinct upper-middle-lower slope divisions and a canyon-incised upper slope. Seaward of about 1800 m the slope passes into a narrow continental rise or directly into the flatter basin plain of the Rockall Trough.

The slope and rise are covered by a thin layer of Holocene sediments generally less than 50 cm and commonly less than 20 cm thick. Below this surface Holocene layer lies a 50–60 m layer of Upper Pleistocene (250,000–10,000 y BP) sediments, dominated by fine-grained, soft clays and silts (Stoker et al., 1993). There are two main Formations on the Barra Fan; the

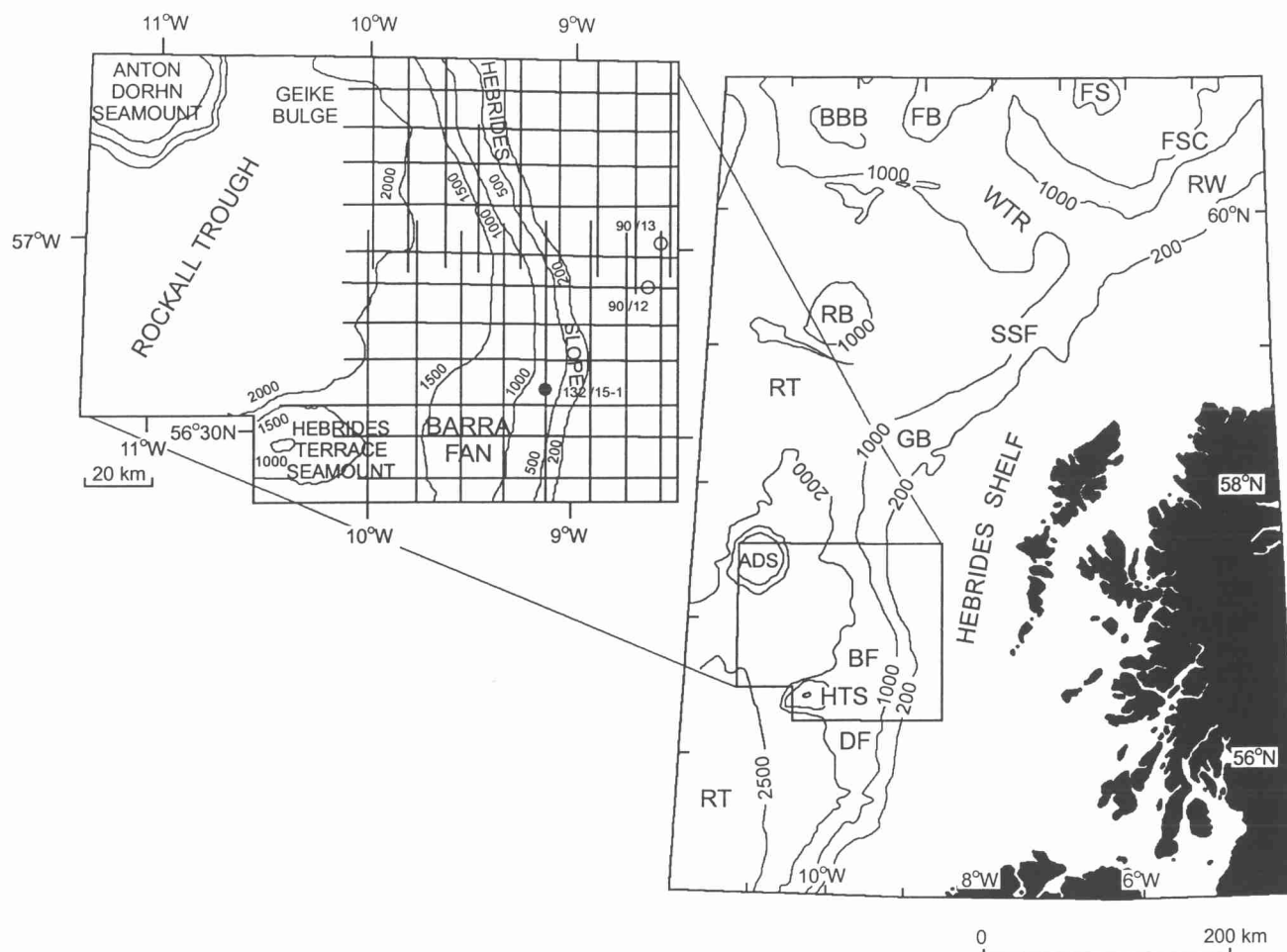


Fig. 1. Location of the study area, bathymetric setting (contours in metres) and track plots of regional 3.5 kHz seismic lines. South of about 57°N, swath bathymetric data are available between 150 and 2000 m water depth for most of the study area. BBB, Bill Bailey's Bank; FB, Faeroe Bank; FS, Faeroe Shelf; WTR, Wyville-Thomson Ridge; RW, Rona Wedge; FSC, Faeroe-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.

Gwaelo Formation on the slope and the Conan A Formation on the shelf and shelfbreak which is present down to depths of 300 m and below (Stoker et al., 1993). Sediments of the Gwaelo formation are characterised by very soft muds in contrast to the stiffer, pebble-rich muds of the Conan A formation. Upper Pleistocene sediments are underlain by the Upper and Lower Macleod Sequences of the Pliocene and Mid Pleistocene, which consist of firm mud and are probably underlain by sandstone and igneous basement rock.

Gross circulation in the region is dominated by a fast-moving north to north-easterly flowing slope current, carrying water of Atlantic origin to the western edge of the Norwegian Trench and into the Skaggeiak (Ellet, pers. commun., 1995). Modelling of the slope current suggests that it is chiefly driven by meridional pressure gradients with a minor influence of wind-dri-

ven processes. Measurements north of Scotland indicate typical speeds of 20 cm s^{-1} , with mean monthly speeds of between 13 and 30 cm s^{-1} along the shelf edge recorded west of the Hebrides (Turrell, 1992). In contrast, shelf circulation is exposed to moderate tidal currents and internal tides chiefly driven by near-diurnal clockwise rotating currents (Huthnance, 1986). During its passage northward along the shelf edge the slope current becomes entrained with shelf waters and some exchange of slope and shelf water occurs. The precise mechanisms whereby water is exchanged across the shelf edge and onto the slope are complex and not yet fully understood.

3. Data and methods

Sampling of seafloor sediment was carried out over

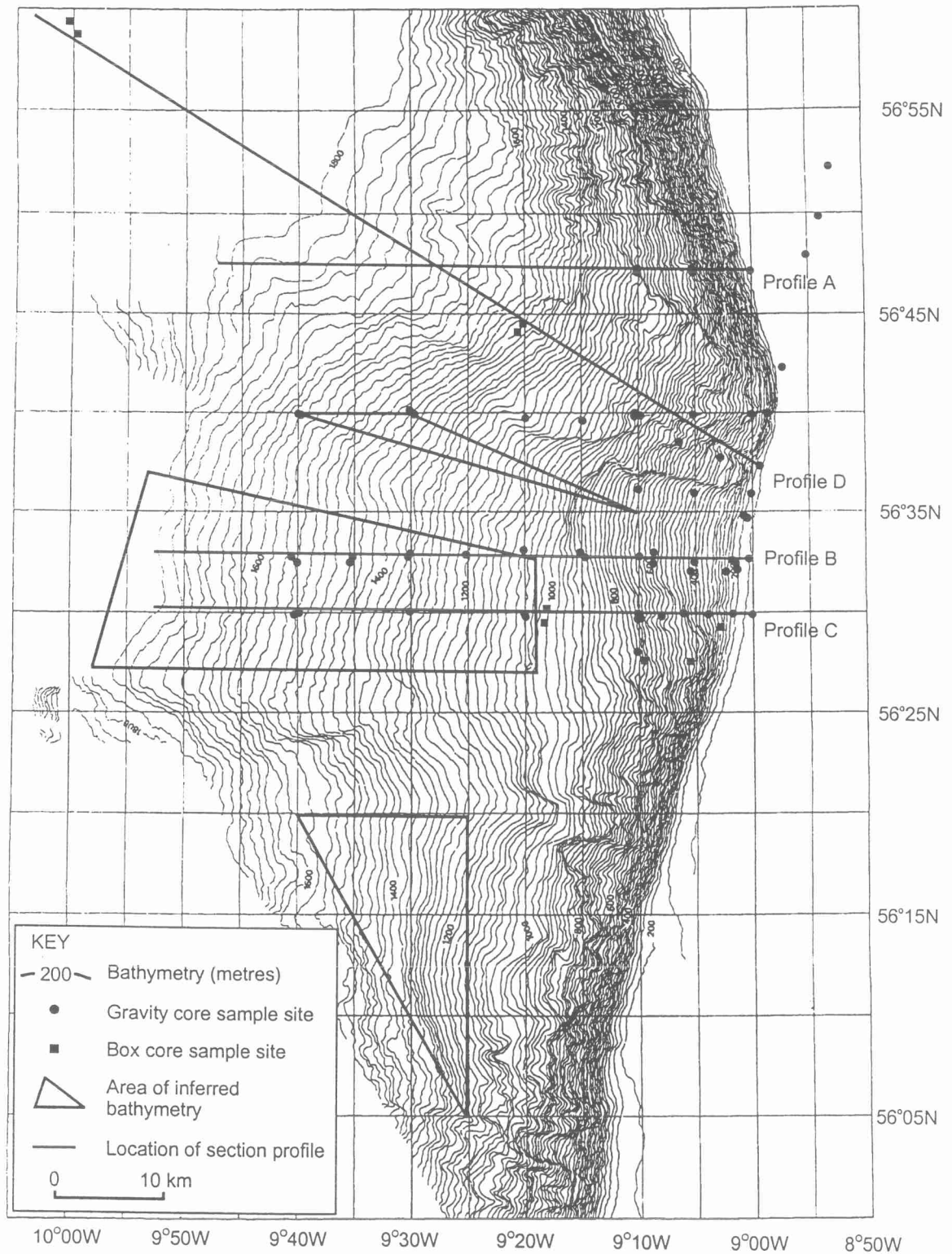


Fig. 2. Bathymetry of the Hebrides Slope based on swath-bathymetric mapping, showing the position of box and gravity core samples, and location of seabed profiles. Contour intervals are at 20 m spacing.

a two year period from 1994 to 1996. Samples were obtained at 77 gravity core stations and 10 box core stations, yielding a suite of 102 sediment cores (from 0.10 to 2.7 m in length) across the study region (Figs. 2–6). Core stations were aligned along four sections running approximately perpendicular to the shelf edge (Figs. 2–6). Four sub-samples of each box core were collected for measurements of acoustic velocity, particle size, carbonate content, and total organic carbon at approximately 2–4 cm intervals down the core. Gravity cores were obtained using a weighted gravity core with a 3 m barrel with a one tonne weight. Penetration depths ranged from 0.30 to 2.7 m; the average core length was 1.6 m. Sample locations were taken when the corer hit the seabed, using a global positioning system (GPS).

In the laboratory, box core sub-samples and split gravity cores were analysed for texture, structure and composition. Structural characteristics 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 min. Particle size analysis of the silt and clay (<63 μm) fraction on all box core samples and selective gravity core samples was undertaken using a Micrometrics[®] Sedigraph 500ET. For the sand fraction (>63 μm) a combination of wet and dry sieving was used. Total carbonate content was determined by use of a 'Karbonate Bombe' following the procedure of Muller and Gastner (1971); samples were taken to correspond with particle size analysis intervals at 2 and 4 cm intervals. Compositional properties of sediment samples were observed by means of smear slides and semiquantitatively determined by visual estimation. Radionuclide concentration levels were determined at the Scottish Universities Research and Reactor Centre from a series of shelf and slope cores (MacKenzie, pers. commun., 1996). Radionuclides analysed include Sellafield waste ¹³⁷Cs and ²⁴¹Am which provide information on sediment mixing and accumulation and input of material from water of Irish Sea origin. ²¹⁰Pb provides accumulation rates and mixing depths for nearshore cores, and ¹⁴C provides sediment accumulation rates.

4. Sedimentary facies

The various lithologies recovered from the cores show that the nature of sedimentation on the Barra Fan is variable both spatially and temporally (Figs. 3–6). This heterogeneity is particularly noteworthy on both the upper and lower continental slope, and indicates a range of processes active within the study region. On the basis of their structural, textural, compositional and bioturbational properties (Table 1), the sedimentary facies described have been interpreted as belong-

ing to three major depositional groups: (1) contourite deposits; (2) glaciomarine sediments with ice-rafted debris (IRD); and (3) hemipelagites. The principal descriptive characteristics of each of seven distinct facies are summarised in Table 1 and illustrated in Figs. 7 and 8 (grain size) and Fig. 9 (structures visible in X-radiographs). Further details are given in Armishaw (1998). This section now focuses more on our interpretation of the depositional processes involved.

4.1. Facies A, A1 and A2: Contourites

4.1.1. Facies A: Sandy contourites

The most common occurrence of facies A is as a thin surface layer deposit between 0.05 and 0.40 m thick from upper and middle slope cores (Figs. 3–6). It is mainly structureless with a variable degree of bioturbation and, in some cases, shows negative grading. It rarely encroaches onto the lower slope, but in cores taken from the Peach Slide it is found in cores as deep as 1540 m. Facies A has been interpreted as a sandy contourite, and is equivalent to those described from the northern Barra Fan and north-eastern Rockall Trough (Howe, 1995, 1996; Howe, Stoker & Stow, 1994). The mixed biogenic-terrestrial composition, fragmented bioclastic particles, common iron-staining, bioturbation, lack of structure and negative grading to a gravel lag surface are all features directly comparable with the sandy contourite models of Stow and Lovell (1979), Stow (1982, 1985) and Gonthier, Faugeres and Stow (1984).

According to recent work by Viana, Faugeres and Stow (1998a), facies A could be described as mid-depth sandy contourites, formed under major geostrophic flows in depths of 300–2000 m. On the Barra Fan they form as a thin sheeted-drift accumulation that reflects the present day slope current regime, where the surface sands are moulded into current ripples or winnowed away to leave coarse lag deposits on the upper slope. The formation of such contourite drifts 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., 1998a). The slope current flowing along the edge of the continental shelf west of Britain is a persistent, predominantly non wind-driven current (Huthnance, 1984, 1986) that flows with a mean monthly speed of between 13 and 30 cm s^{-1} . It is most active at depths of between 300 and 500 m and is constantly reworking and redistributing the surface sands.

The supply of sediment to these mid-depth sandy sheet drifts on the Barra Fan is from a variety of sources, both internal and external, including bottom-

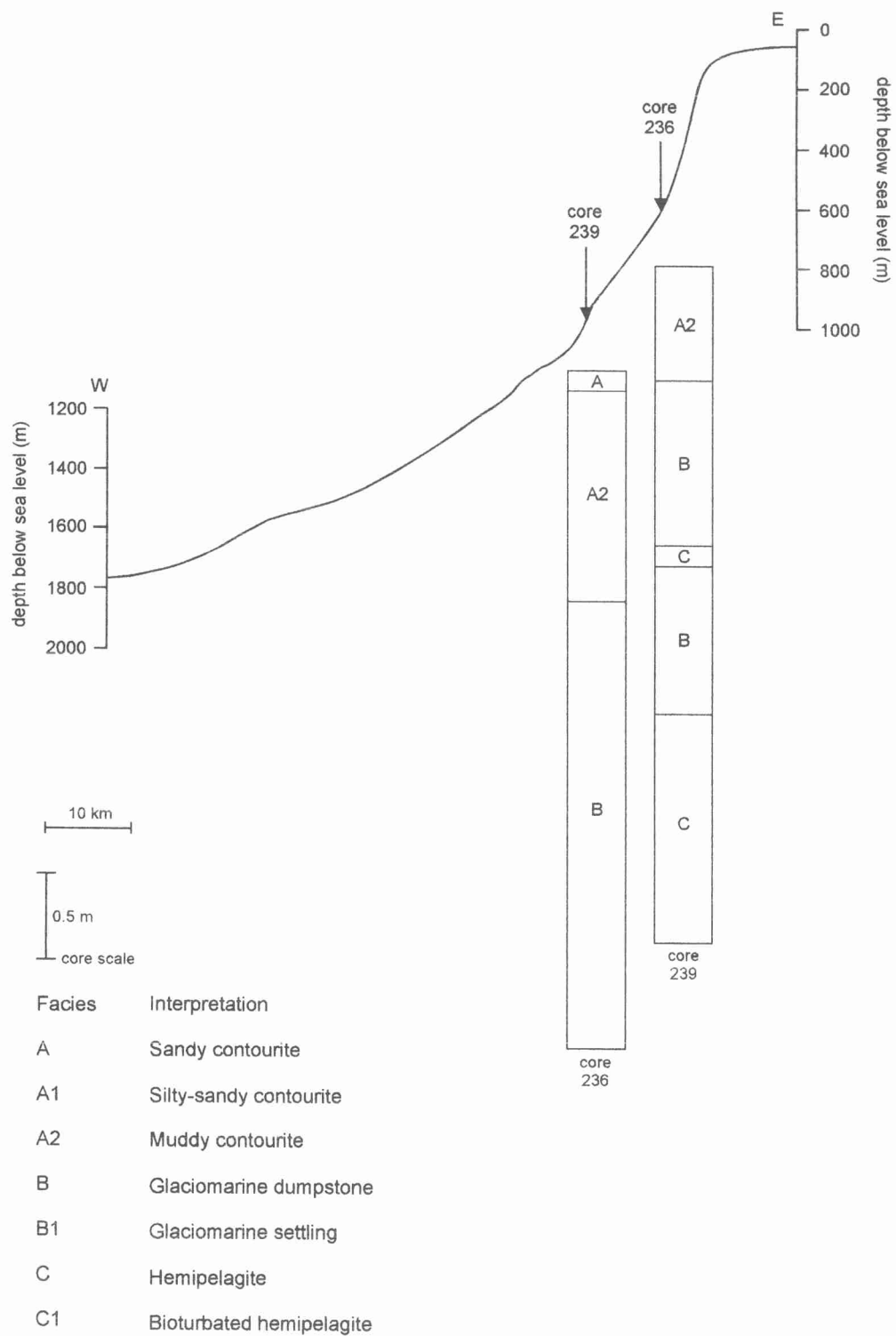


Fig. 3. E–W seabed profile A, showing the location and facies of gravity cores 236 and 239 from the Peach Slide. Location of profile shown in Fig. 2. Full description of facies can be found in the text.

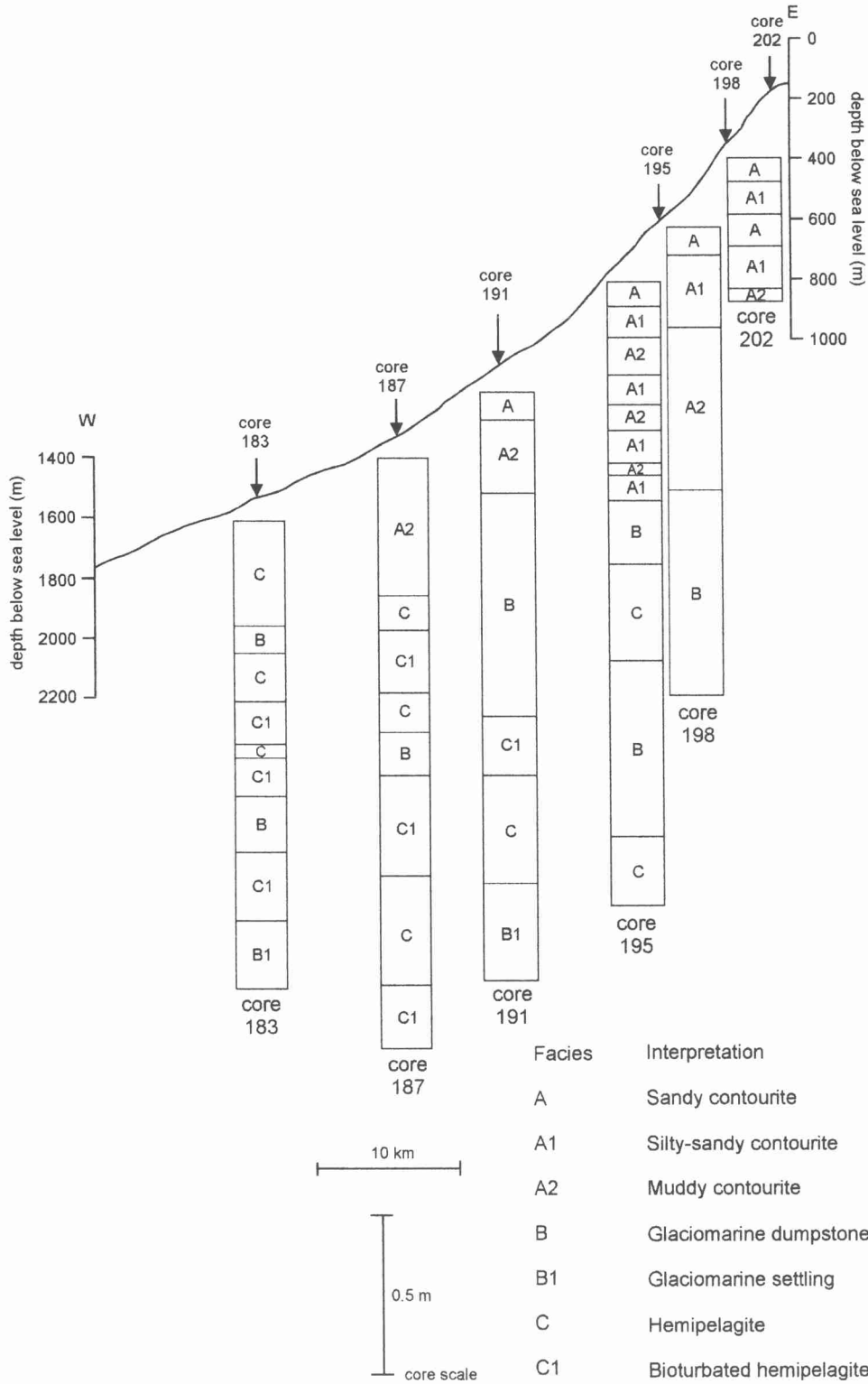


Fig. 4. E–W seabed profile B, showing the location and facies of gravity cores from the upper and lower slope sections of the Barra Fan. Location of profile shown in Fig. 2. Full description of facies can be found in the text.

current erosion upstream of the drift, the pirating of offshelf spillover, pelagic biogenic fallout and in situ winnowing. We suggest that offshelf spillover has been particularly important for the following reasons:

1. the high percentage of terrigenous grains, including detrital carbonate, and minor glauconite imply a shelf source for the contourite sands;
2. regional trends in particle-size distribution show a

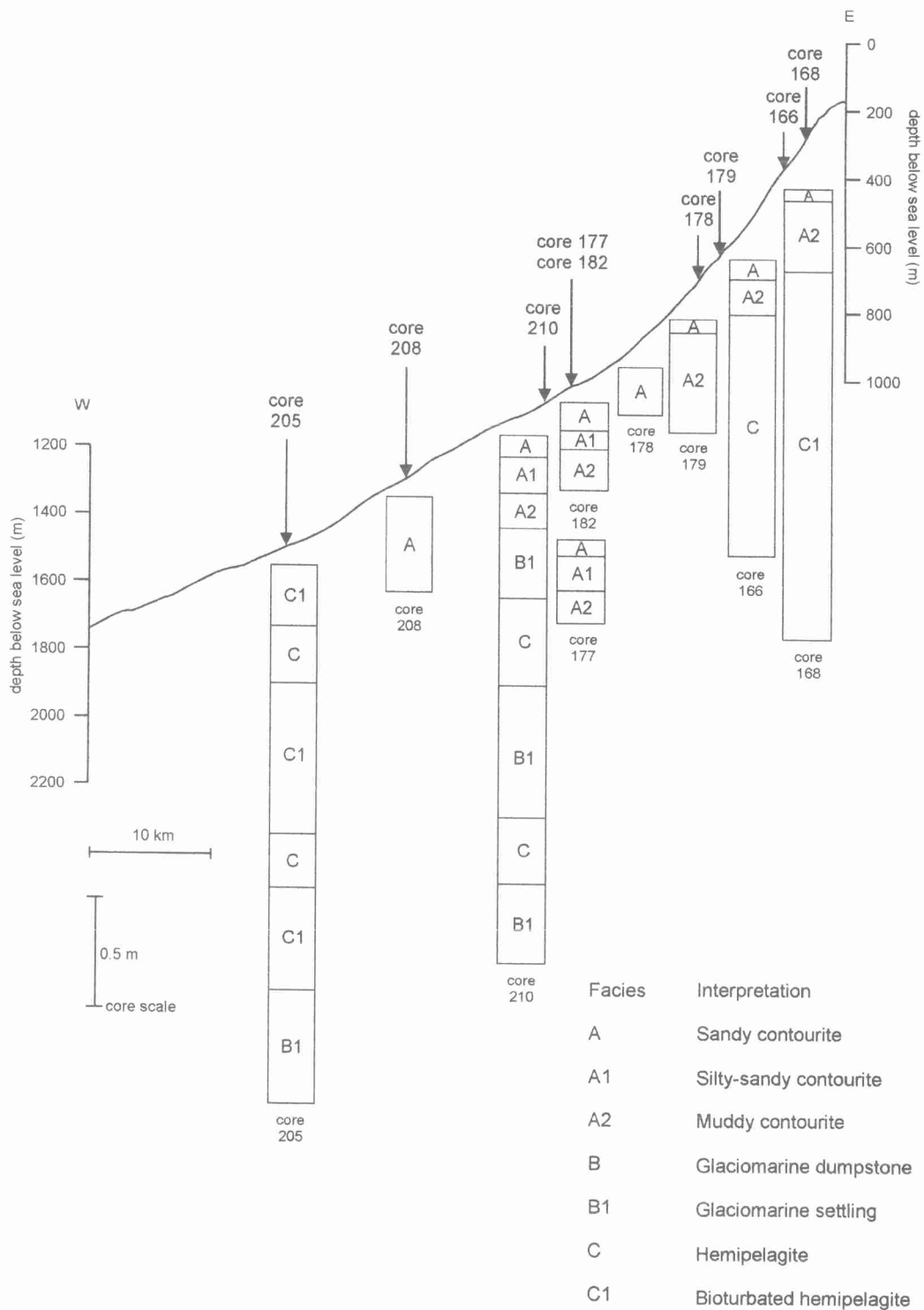


Fig. 5. E–W seabed profile C, showing the location and facies of box and gravity cores from the upper and lower slope section of the Barra Fan. Location of profile shown in Fig. 2. Full description of facies can be found in the text.

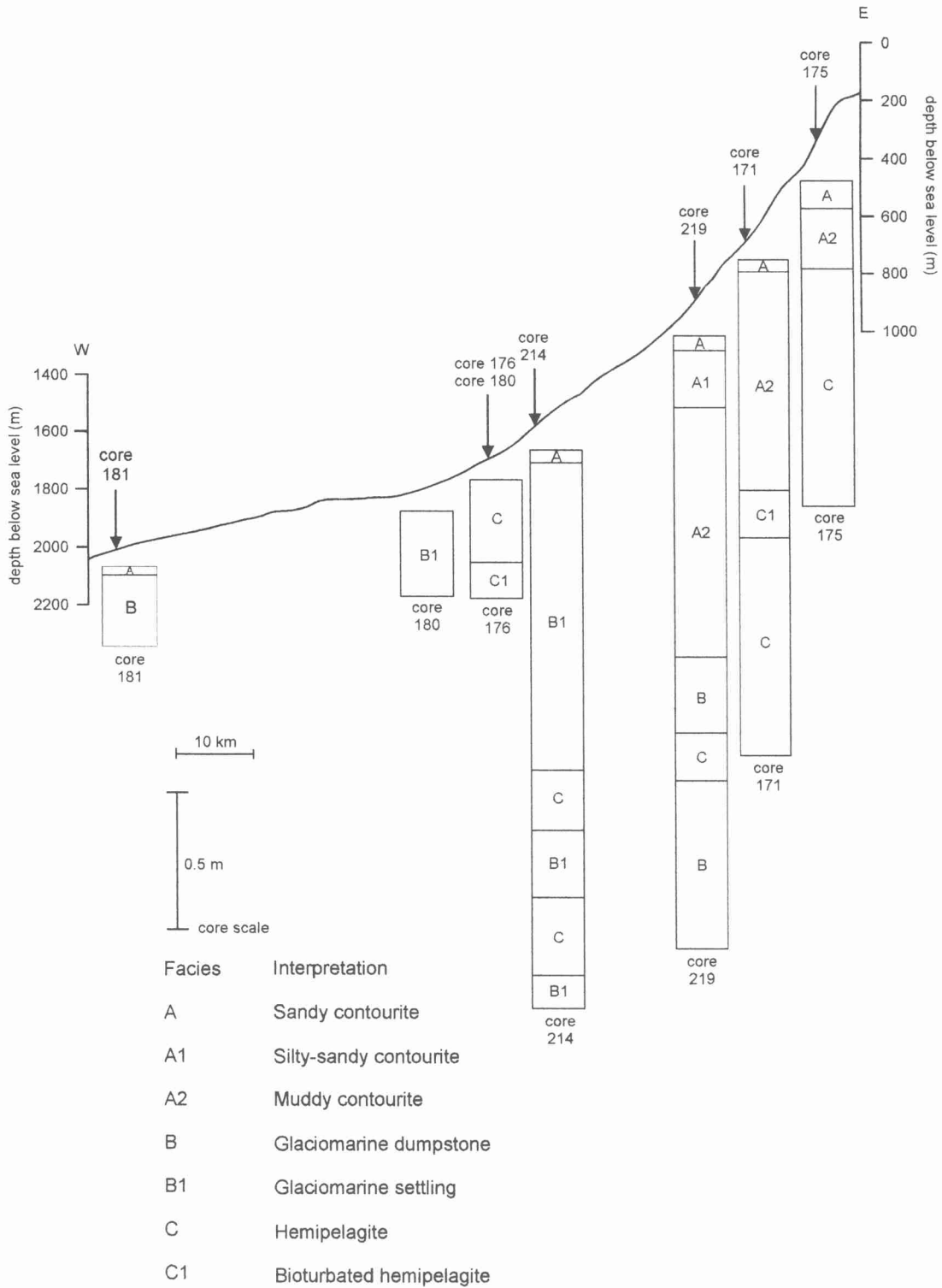


Fig. 6. SE–NW profile D, showing the location of and facies of box and gravity cores from the upper and lower slope section of the Peach Slide. Location of profile shown in Fig. 2. Full description of facies can be found in the text.

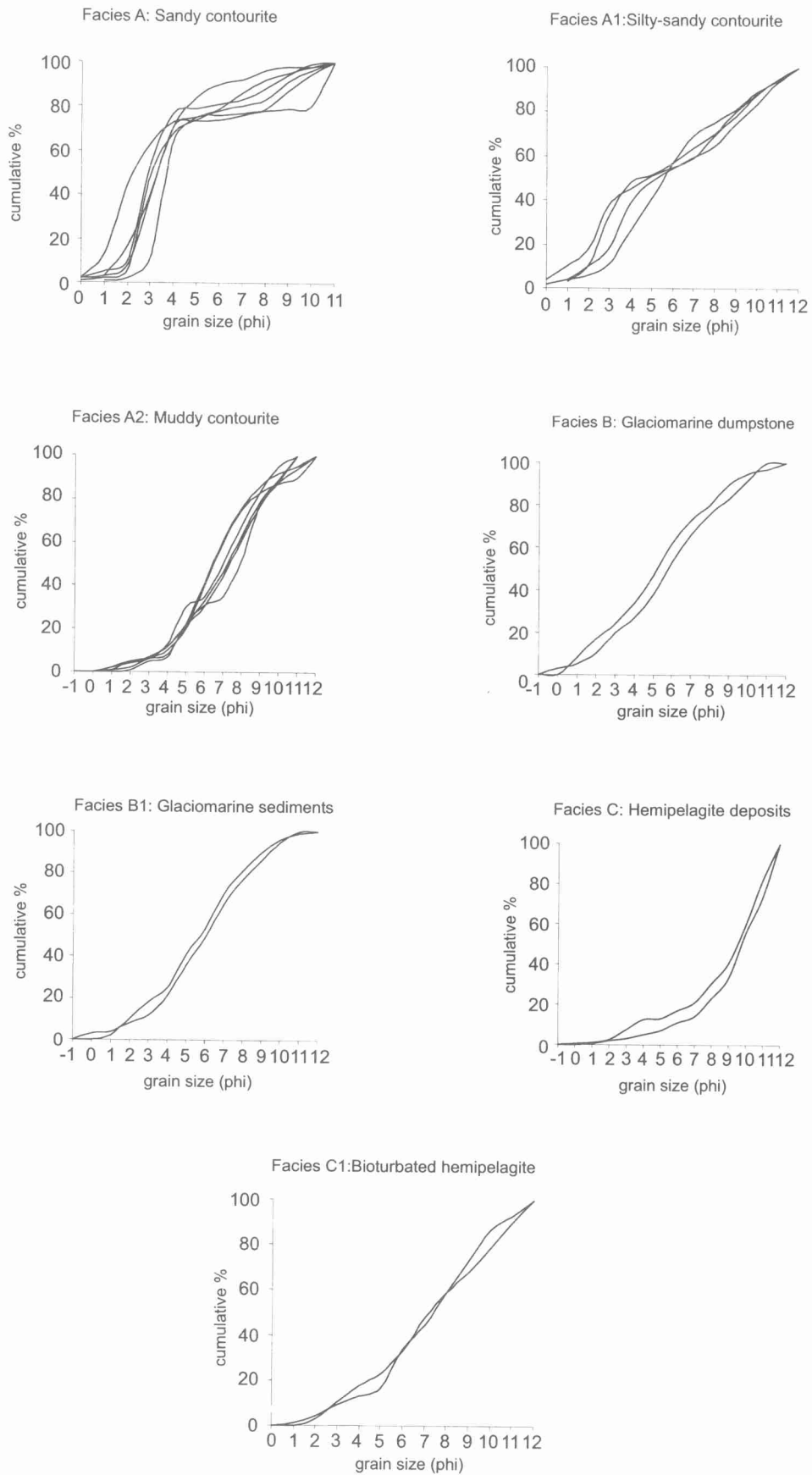


Fig. 8. Cumulative frequency grain-size distribution curves for facies identified on the Barra Fan. Figures are based on averages of 5–8 samples for each facies.

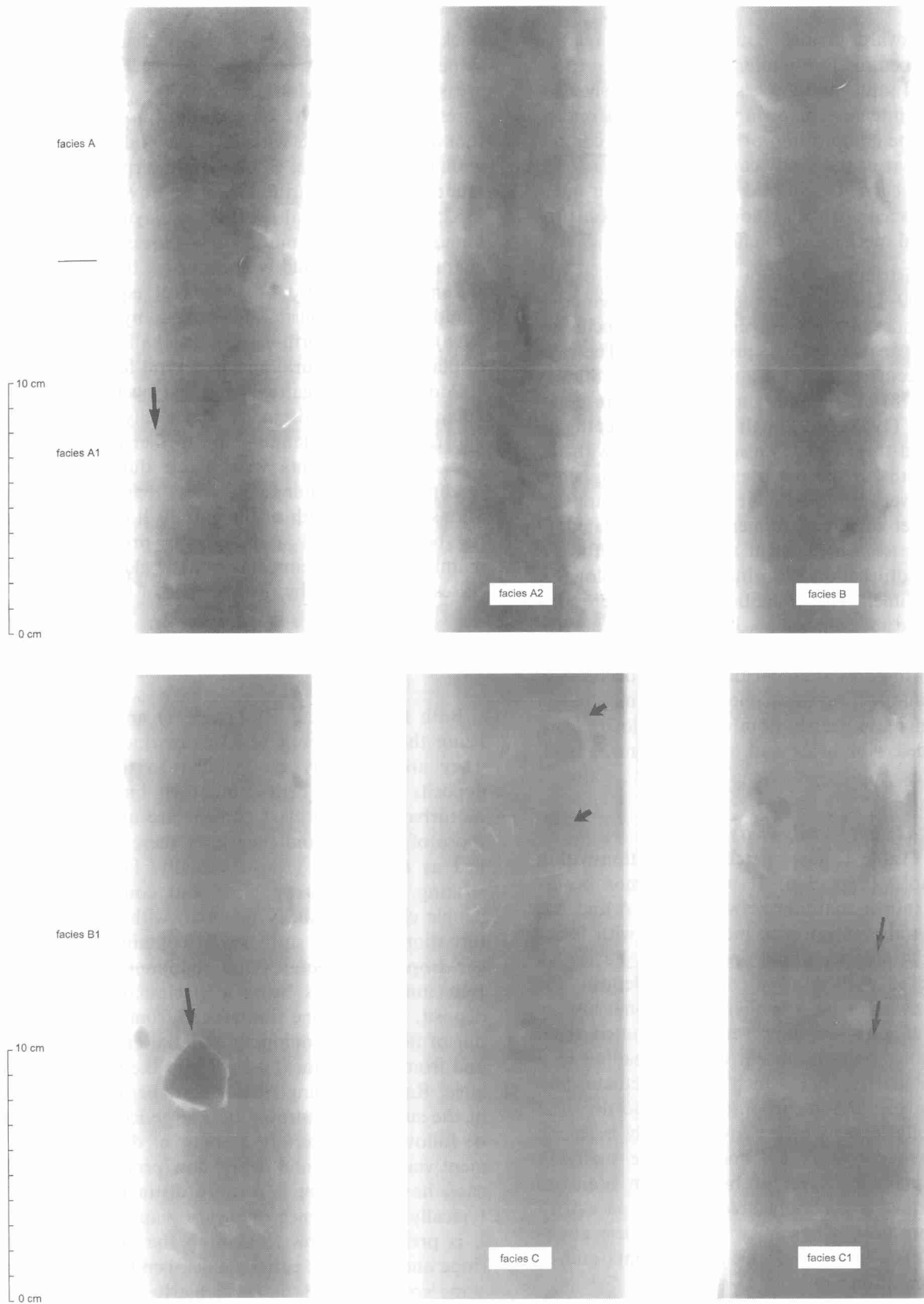


Fig. 9. X-radiograph prints of main sediment facies. (A) Sandy contourites (facies A), dark, top 10 cm, overlying silty-sandy contourites (facies A1) with intermittent shell fragments (arrow) and traces of bioturbation. (B) Muddy contourite facies (A2), core 198, 70–110 cm, moderate bioturbation throughout the unit. (C) Glaciomarine dumpstone (facies B), core 198, 130–170 cm, moderately bioturbated clayey-silt with abundant pebble clasts distributed randomly throughout the unit. (D) Facies B1, core 191, 100–140 cm, highly bioturbated with abundant traces of *mycelia* and intermittent ice-rafted dropstones (arrow). (E) Hemipelagite facies C, core 195, 220–260 cm, homogeneous silty-clay unit with minor traces of bioturbation. Artifacts are remnant from where geotechnical properties have been taken (arrows). (F) Bioturbated hemipelagite (facies C1), core 205, 65–100 cm, sediments are thoroughly disturbed with abundant *Zoophycos* burrows (arrows) crossing the column.

- gradual seaward fining, coupled with a relative increase in benthic foraminifera;
3. relict glacial sands and gravels on the outer shelf indicate that intense winnowing has occurred on the shelf, and the composition of these sands is compatible with that of the sandy contourites; and
 4. strong tidal currents, coupled with the known interchange between shelf and slope water masses, provide an ideal mechanism to effect spillover.

The further distribution of sand downslope to depths of around 1200–1300 m is presumably due to winnowing and transport in the main slope current, including eddy transport seaward of the principal axis. The relatively deep occurrence of the mudline (*sensu* Stanley and Wear, 1978) on this margin is discussed in detail by Armishaw (1998). Although the water depths to which the sand-sheet extends also correspond with the maximum depths of the persistent north-flowing slope current; however, the dominant composition appears to reflect a net offshore sediment delivery related to on-going processes on the shelf and at the shelfbreak. The intense bioturbation is an indication of a slow, or negligible sediment accumulation rate, where the infauna is able to keep pace with deposition or erosion. Decreasing p-wave velocities recorded from the upper 0.16 m of cores are coincident with a decrease in particle size and sorting down the core and may reflect an upward increase near-bottom current velocity leading pronounced winnowing and, in some cores, gravel-lag contourites.

4.1.2. Facies A1: Silty-sandy contourites

Facies A1 (Table 1) has a patchy distribution within the core samples (Figs. 3–6). Its most common occurrence is as a transitional unit between facies A and A2, although it is also rarely seen interbedded with facies A, particularly in upper slope cores (Fig. 4). Facies A1 is interpreted as a silty-sandy contourite deposit, for similar reasons and with a similar depositional history to facies A. Facies A1, however, has resulted from generally weaker bottom current activity, leading to a finer-grained matrix, but which may fluctuate and therefore lead to the incorporation of mottles and sand and shelly lenses where current activity is strong enough to winnow away silt and clay-size material. The slight to intense level of bioturbation indicates that the infauna is generally able to keep pace with sediment deposition; where trace fossils are less abundant this implies periods of stronger currents and/or higher sedimentation rates.

4.1.3. Facies A2: Muddy-silty contourites

In terms of the stratigraphic thickness within the core samples, facies A2 is clearly the thickest of all the contourite deposits (Figs. 3–6), and is over a metre

thick in some cores. It is widely distributed on the slope apron and is common in upper and mid-slope areas across the region and, with the exception of two cores (where it is the only contourite unit), is always found in association with facies A and less commonly with facies A1 (Figs. 3–6). It is interpreted here as a muddy-silty contourite (Stow & Lovell, 1979; Stow, 1982; Gonthier et al., 1984) displaying fine-grained, homogeneous and moderately bioturbated sediment characteristics of muddy contourites from many slope systems. It may also be the direct equivalent of the muddy-silty contourites described by Howe (1995, 1996) from the north-eastern Rockall Trough, which display similar textural and structural features.

Poor sorting, negative skew and occurrence of irregular coarse-grained, sandy and shelly concentrations and rare indistinct laminae are further indications that weak bottom-currents were active during deposition; grading of the laminae possibly representing fluctuations in the strength of the current flow. The material for both facies A1 and A2 was probably supplied mainly through hemipelagic and glaciomarine processes as evidenced by the presence of lithic clasts.

4.2. Facies B and B1: Glaciomarine deposits

Both facies B and B1 (Table 1) are interpreted as being the direct result of glaciomarine sedimentation. They are texturally very similar to the hemipelagic deposits described below, but their internal structure, bioturbational and clast content are quite different to those of facies C and they have therefore been classified as a separate group. Visually, facies B is quite striking, clearly disorganised and contains abundant pebble clasts and shelly material, with very weak bioturbation. In contrast, facies B1 contains fewer but larger dropstone structures and abundant *mycelia*. Facies B is interpreted as being a glaciomarine dumpstone deposit, which is one that results from the rapid melt-out of floating ice dumping material eroded from land and from the continental shelf into the slope hemipelagites. Rapid dumping of this sort, perhaps as a result of the sudden overturning of a large iceberg, may then be followed by a certain amount of downslope movement via slumping and debris flow processes. In such a case, however, there is a more distinct basal contact, typically with evidence of shearing and erosion. Facies B is present in cores from both the upper and lower slope and is seen as either a thick-bedded unit in upper slope cores (Figs. 3–6), particularly those taken from the Peach Slide, or as a thin unit, interbedded with facies C or C1 further downslope, suggesting that units may thin oceanwards.

The massive homogeneous nature, intense bioturbation and abundant clasts in the poorly sorted silty

clays suggest that facies B1 is also the result of direct ice-rafting and glaciomarine sedimentation. Similar poorly sorted deposits are described by Howe (1996), from the north-east Rockall Trough, and Pickering, Hiscott and Hein (1989), and are attributed to rain-out from icebergs. They are, in effect, glaciomarine hemipelagites. The distribution of facies B1 over the slope is limited to the middle and lower slope areas (Figs. 3–6) and is commonly found as a 0.30–0.40 m thick unit interbedded with facies C near the base of the cores. With the exception of two cores, facies B and B1 are never found in the same core, and it is possible that facies B1 is the distal element of facies B. Since ice-rafting and surface current activity are only possible in a completely or partially open sea environment, facies B1 have probably been deposited either during periods of deglaciation or summers of glacial periods (Wang & Hesse, 1996). The high to intense bioturbation throughout the facies B1 reflects a relatively low sedimentation rate (Yoon, Chough, Thiede & Werner, 1991).

4.3. Facies C and C1: Hemipelagites

The structural and textural analyses of facies C and C1 (Table 1) indicate that both have been deposited as a result of hemipelagic settling, but are described as individual facies on the basis of their distinctive textural and bioturbational characteristics. Facies C is the most widespread of the two hemipelagic facies although both are common in cores from all slope areas (Figs. 3–6), where they underlie the contourite facies A2 or are interbedded with glaciomarine facies B or B1.

Facies C1 is generally more intensely bioturbated than facies C, and typically includes *Zoophycos* burrows as well as irregular sand lenses. The intense bioturbation may indicate relatively slower rates of sedimentation for facies C1. Ice rafted debris is very limited or absent but rare patches in facies C, in particular, indicate at least some degree of glaciomarine sedimentation within the facies. Hemipelagites from both the northern Barra Fan and north-eastern Rockall Trough have been described by Howe (1995, 1996) and are very similar to those described here. They also compare well with the muddy hemipelagites of Stow and Tabrez (1998).

5. Discussion

5.1. Process interaction

Based on our careful interpretation of facies identified in the recovered cores, the principal processes of

deposition on the Barra Fan have been contouritic, hemipelagic and glaciomarine. However, it is important to recognise that none of these processes is mutually exclusive of the others and that process interaction is most probably the norm. A hemipelagic contribution of mixed biogenic and terrigenous sedimentary particles has been present throughout the time period represented and, at times, appears to have been the only process operating. Where bottom currents were active then this hemipelagic rain has been an important or dominant contributor to the contourite deposits. There is thus considerable overlap between the muddy and silty contourites (Facies A1 and A2) and the hemipelagites (Facies C and C1). The sandy contourite facies (A) must have been subject to stronger bottom currents in order to winnow away much of the finer hemipelagic component. In the case of sheeted contourite drifts, as are typical of this margin, then the interpretation is clearly more speculative than where an elongate mounded drift is present. Nevertheless, the observed sediment features coupled with the known present-day slope current system strongly favour a contourite origin (or component) for facies group A, and there seems to be little viable alternative for the sand-rich facies A.

Alternative processes known to introduce sands into deep water include turbidity currents and sandy debris flows. However, there is a complete absence of turbidite sedimentary structures, even those associated with deep-water massive sands from high-density turbidity currents (see, for example, Stow et al., 1996, and this volume). The presence of bioturbation to a greater or lesser extent throughout the bed thickness is a feature not readily compatible with a sandy debris flow deposit. The less understood process of sand spillover from the outer shelf onto the upper and middle slope is, indeed, believed to be responsible for supplying at least part of the material for facies A. However, this process is probably caused in part by eddying associated with a strong slope current and would not in itself explain the reverse grading and patchy gravel lag surface observed. We remain confident in the interpretation of the facies as a sandy contourite.

The glaciomarine interpretation of facies group B is strongly supported by the presence of ice rafted debris and the known occurrence of shelf ice during the last glacial period. The glacial dumpstone facies B could be interpreted as the result of downslope debris flow processes only where there is a distinct bed with a sharp base and associated features of shearing and erosion. In the study cores, this does not occur. Both glacial facies are considered to have had a strong element of hemipelagic sedimentation such that facies B1, in particular, is regarded as a glaciomarine hemipelagite.

In fact, the absence of any clear debrites or turbidites from the study cores is somewhat surprising,

given the strong evidence of downslope processes from slope morphology (canyons, channels, lobes, slide masses, etc.), and from interpretation of both 3.5 kHz seismic records and TOBI sidescan images (Armishaw et al., 1998). We can only conclude that the short cores recovered were of insufficient length to penetrate re-sedimented facies that were much more common in past glacial times. Longer cores described by Howe (1996) and Knutz (1999) from the northern part of Barra Fan do contain both turbidites and debrites, albeit as a relatively minor component of the section.

5.2. Facies correlation and dating

Little in the way of dating has been completed on cores taken from the study region, although some ^{210}Pb and ^{14}C radionuclide analyses for a series of cores from the shelf and slope are available (MacKenzie, pers. commun., 1996). These data have been used here in conjunction with dinoflagellate cyst and nannofossil analyses taken from cores north of the present study area on the northern Barra Fan and north-eastern Rockall (Howe, 1995, 1996; Howe et al., 1994). In addition, we can use the presence/absence of ice rafted debris as an indication of glacial to post-glacial conditions and so attempt a correlation of sedimentary facies identified in cores from the study region.

There is little doubt that the top sandy contourites of facies A are equivalent to the sandy contourites described by Howe (1995, lithofacies A; 1996, lithofacies 1). Nannofossils taken from their northern counterparts have been assigned to the early Holocene (Harland, 1993; Hine, 1993) and are therefore younger than 10,000 y BP. However, without better age resolution in this area we are unable to ascribe the fivefold subdivision of the Holocene found by Howe et al. (1994), that suggests non-linear warming into the Holocene, but it is likely that a similar subdivision is present and therefore that non-linear warming has had an affect on the Holocene sedimentation pattern on the Barra Fan. The sharp erosive contact found, in some cases, at the base of facies A suggests that between the deposition of finer-grained contourite facies A1 and A2 and coarse sandy contourites of facies A, there may have been a significant phase of very strong bottom-current activity.

We are less certain about the age of contourite facies A1 and A2 but do note that they are completely devoid of IRD. Furthermore, similar muddy contourite deposits have been recognised from both the northern Barra Fan and north-eastern Rockall Trough by Howe (1995, 1996) and Howe et al. (1994), and have been dated as Holocene in age. The deposition of these muddy contourites is attributed to the onset of sluggish bottom-currents brought about by the changeover from glacial to interglacial conditions. Further

increases in velocity through time is evidenced by the overlying coarser-grained silty-sandy contourites of facies A1.

It is most likely, therefore, that all the contourite facies (A, A1, A2) in the study area are Holocene in age (i.e. <10,000 y), whereas the underlying facies (both B and C groups) were deposited during the past glacial period. Assuming this is the case, then contourite accumulation during the Holocene is seen to have occurred at very different rates across the region, ranging from about 0.5 cm/ky on the lower slope to 14.5 cm/ky on the middle slope. Where facies C or C1 occur at the surface on the lower slope, then either the upper parts of these facies are also Holocene in age or there has been significant seafloor erosion. This latter interpretation appears most likely where glaciomarine facies B1 occurs at the surface.

The lower rates of sedimentation are compatible with the Holocene rates of 1.2 cm/ky determined from ^{14}C analysis of cores in the study region (MacKenzie, pers. commun., 1996). Marked seafloor erosion has been noted by Howe (1995, 1996) from further north. The higher rates of sedimentation are also within the range noted by Howe et al. (1994) for drift deposits in the northern Rockall Trough. His rates for mounded drifts are up to 64 cm/ky, whereas our rate of 14.5 cm/ky refers to sedimentation on a much lower relief sheeted drift deposit (Figs. 7–9).

A provisional correlation panel for the NW Hebridean margin is presented in Fig. 10, combining earlier work of Howe (op. cit.) and others with data from this study. Several important points can be made:

1. contourite sedimentation is mainly restricted to the Holocene and is very variable in its distribution;
2. both mounded and sheeted drifts occur and these show variation in thickness and hence rates of accumulation from the axial zones to the margins;
3. bottom current erosion is inferred at the present seafloor for the NE Rockall Trough drifts and between thin surficial sandy contourites and underlying late glacial facies on the Geike Escarpment;
4. the reduced contourite thickness on the lower part of the Barra Fan is here interpreted as being due primarily to reduced offshore sediment supply into the path of the slope current;
5. facies variation through the Barra Fan cores studied here can be tentatively correlated with Late Glacial, Allerød Bölling Interstade, Younger Dryas Stade and Holocene subdivisions identified on the distal fan by Howe et al. (1996);
6. although these subdivisions await confirmation by dating, we can further infer that the oldest sediments recovered in this study (e.g. base of core 214) are around 20,000–30,000 years old, assuming sedi-

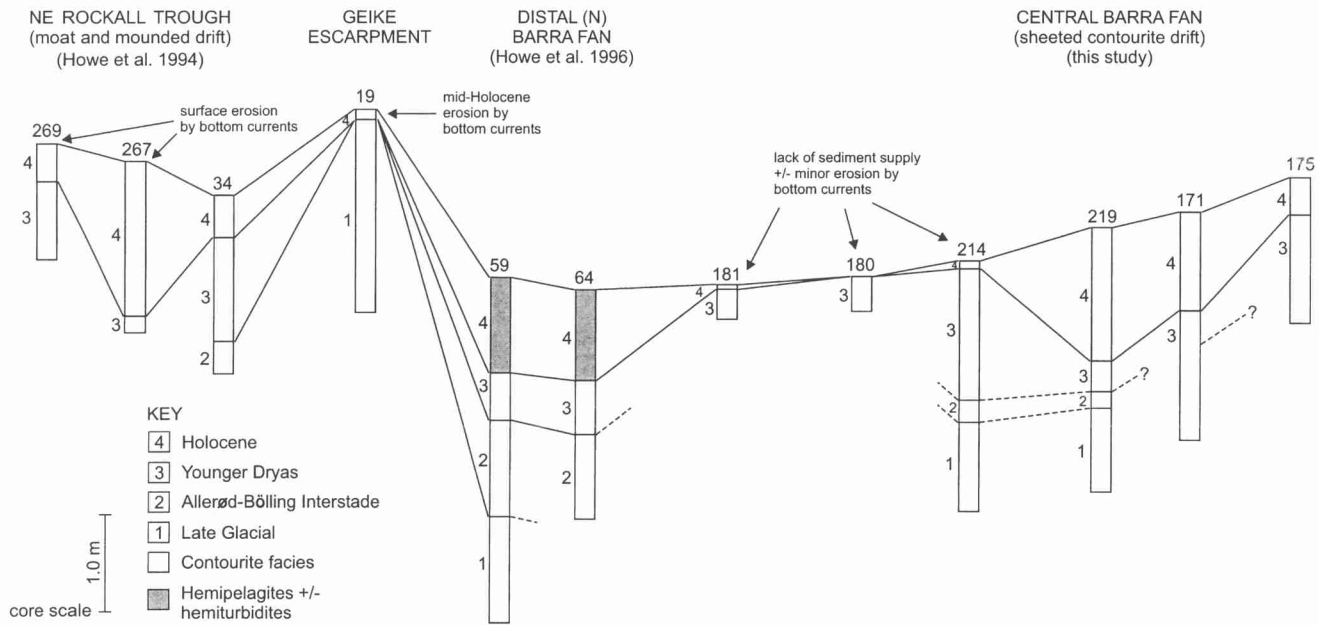


Fig. 10. Correlation panel for the NW Hebridean margin from the NE Rockall Trough to the central Barra Fan based on Howe et al. (1994, 1996), Stoker et al. (1993) and this study.

mentation rates of 10–20 cm/ky during the late glacial period.

5.3. Glacial to post-glacial margin development

The Barra Fan is composite in terms of its diverse morphological elements (Armishaw et al., 1998) and in terms of its varied facies and processes as detailed above. However, its development since the last glacial period from an estimated 30,000 y BP show three distinct episodes during which different processes and process combinations have been dominant. These are illustrated in Fig. 11A–C.

The last glacial period (Fig. 11A, low-stand system tract) was characterised by grounded ice that extended practically to the edge of the present day shelf, building up terminal moraines of poorly sorted glacial debris on the outer shelf. Iceberg calving, though relatively minor at the glacial maximum, contributed ice rafted debris to glacial hemipelagites and caused some scouring on the outer shelf and upper slope. Downslope mass movements dominated, including debris flows and turbidity currents that cut deep canyons and channels across the upper and middle slope regions. Slides and slumps further helped to sculpt an irregular slope topography. There is no evidence of an active slope current at this stage and the North Atlantic Deep Water bottom current, if it existed, was only very sluggish.

Deglaciation (Fig. 11B) took place in several stages

of rapid warming, alternating with cooler periods concomitant with sea-level rise. The margin was in transition and probably saw even greater seaward flux of material than during glacial maxima. Icebergs and ice flows continually broke free from the receding shelf and greatly increased the rate of glaciomarine sedimentation. Sudden melting and overturn of icebergs led to glaciomarine dumpstone facies. Rising sea level, coupled with rapid sedimentation, created an unstable slope prone to slides, slumps and debris flows. We suggest that the composite Peach Slide event was triggered during this period (see also Holmes et al., 1998). Bottom water circulation was most likely beginning to increase in intensity and an early version of the slope current may have been established at this time. However, any effects of this bottom current activity were masked by other processes.

Present day conditions (Fig. 11C, high-stand system tract), established in the early part of the Holocene, were markedly different. High sea-level and the lack of glaciers on the shelf or over the mainland led to a much diminished sediment supply. Tidal currents actively reworked the poorly sorted glacial debris over the shelf and upper slope, winnowing away fines that ultimately contributed to hemipelagic sedimentation over the deeper margin. A strong slope current (the Northeast Atlantic Water flow) was established and, partly as a result of the irregular indented shelf edge, this current was prone to large-scale meanders and eddies, as shown by Viana et al. (1998b) for the Campos margin off Brazil. We suggest that these served to

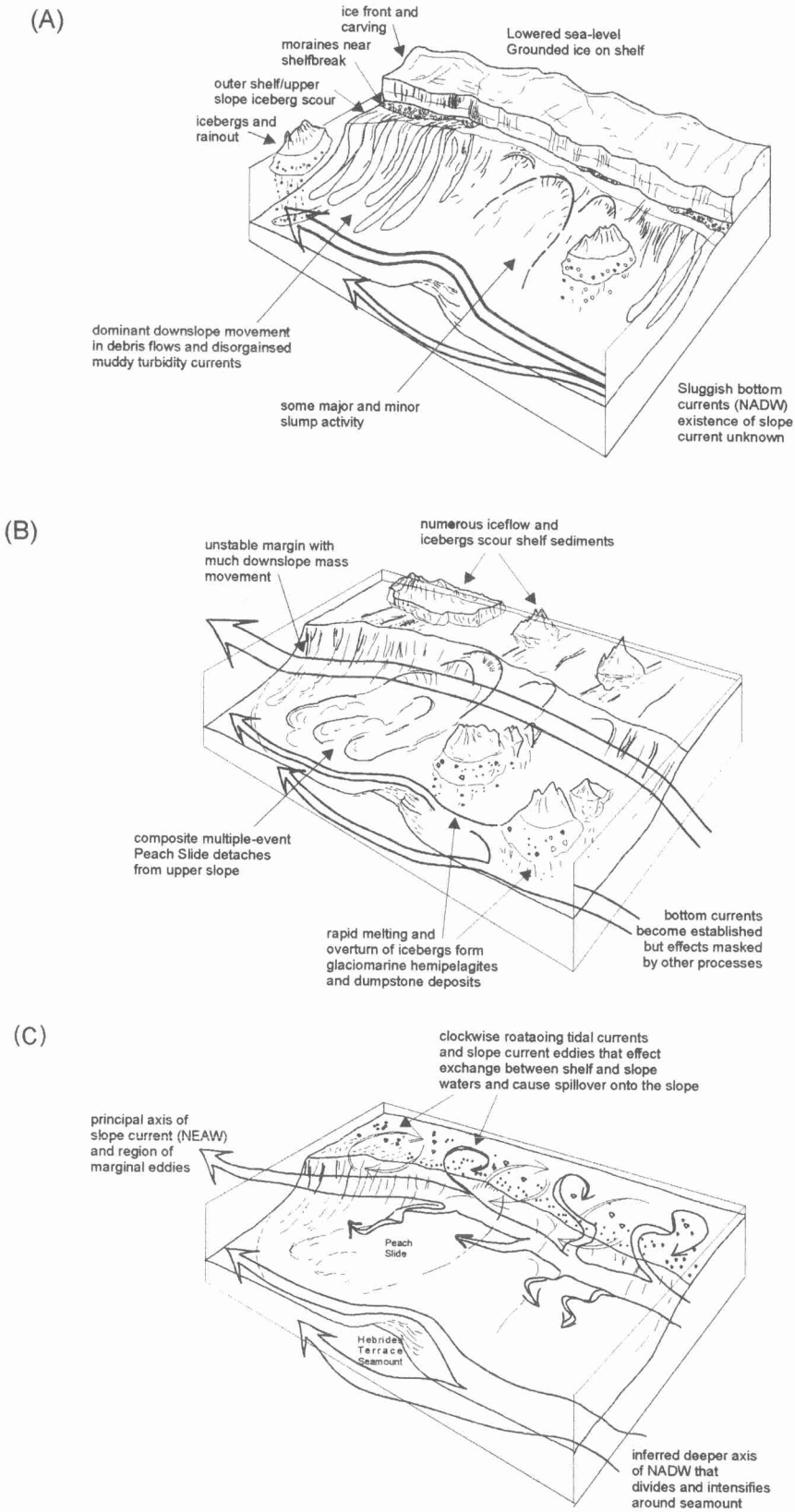


Fig. 11. Model for the development of the Barra Submarine Fan, see text for detailed discussion. (A) Last glacial low-stand system tract. (B) Deglaciation with rising sea level. (C) Holocene high-stand system tract.

increase shelf winnowing of fines and to transport sandy material across the outer shelf and over the shelf edge, thus effecting significant offshelf spillover. Alongslope reworking of this material as well as in situ winnowing created the sandy contourite sheeted drift that characterises the middle slope.

The deeper flow of North Atlantic Deep Water was also stronger such that it picked up the hemipelagic rain of fine terrigenous and sandy biogenic material, forming these into muddy and silty contourites. Locally, interaction with bottom topography such as the Hebrides Terrace Seamount divided and intensified flow, creating a moat around the base of the seamount floored with more sandy contourites. There has been very little downslope mass movement during this period and, at the present day, active bottom currents are slowly smoothing and remoulding an irregular sea-floor.

6. Conclusions

In many respects, the Barra Fan can be considered as typical of high-latitude glacially-fed slope depocentres — the so-called trough-mouth fans of Vorren et al. (1989) and Vorren and Laberg (1997). The results of this study, therefore, showing the detailed nature and distribution of sediments as well as the late Quaternary-Recent evolution of the Barra Fan, have much broader application to our understanding of such sedimentary systems. High rates of mixed grade sediment supply characterise the low-stand system tract as well as periods of deglaciation and rising sea-level. At times, downslope processes dominate, with debris flows being more common than turbidity currents, and large-scale sliding/slumping indicative of margin instability during glacial lowstands. At other times, glaciomarine sedimentation is the dominant process, including both chaotic dumpstone deposits, which result from the rapid meltout of floating ice, and more uniform glaciomarine hemipelagites.

The Barra Fan has also been markedly influenced by bottom current activity, most likely throughout its history (Knutz, 1999), but becoming more evident during highstand system tract. Low sedimentation rates, coupled with a strong mid-depth bottom current, have led to the smoothing of topography and the reworking of sediment, leading to an extensive sandy contourite sheeted drift deposit. Current induced shelf spillover processes are believed to keep this contourite drift supplied with sand grade material. The nature and origin of such contourite sands are of further interest to the hydrocarbon industry in their consideration of deepwater exploration plays.

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