Late Quaternary glacigenic contourite, debris flow and turbidite process interaction in the Faroe–Shetland Channel, NW European Continental Margin

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Abstract: The Faroe–Shetland Channel is an important conduit or gateway for the southward flow of cold bottom waters formed in the Norwegian Sea. This Norwegian Sea Overflow Water (NSOW) finds several spillover channels across the Wyville–Thomson Ridge, eventually descending into the northern Rockall Trough and Iceland Basin. The Neogene channel floor succession predominantly displays a broad sheeted drift geometry. Bottom current scours and channels were apparently inherited from an episode of enhanced bottom current activity in late Oligocene/early Miocene. The late Quaternary channel-floor succession is dominated by distal glaciomarine sediments, derived from the shelf and slope during glacial stages and mostly transported by ice-rafting. Glacigenic debris flows and minor turbidity currents were also active across the slope region. Consequently, the principal channel-floor facies are glacigenic contourites that show extensive bioturbation, rare primary structures, mixed composition and marked grain size variation. These features indicate the important influence of cyclical fluctuations in bottom current velocity throughout both stadial and interstadial or interglacial periods. However, the concentration of sandy contourites, erosive surfaces and top-only contourites during interstadials/interglacials and during phases of marked cooling or warming testify to the significance of climate-control on contourite deposition.

The Faroe–Shetland Channel is a NE trending, narrow, funnel-shaped, deep-water trough off NW Scotland, separating the West Shetland Shelf to the southeast from the Faroes Shelf to the northwest. The Channel opens out towards the Norwegian Sea in the NE and abuts against the Wyville–Thomson Ridge in the south where it turns to the NW and becomes the Faroe Bank Channel (Fig. 1).

The Faroe–Shetland Channel is the present-day bathymetric expression of an older sedimentary basin known as the Faroe–Shetland Basin, which has been at the centre of considerable exploration effort by the oil industry over the past 15 years. This followed early discovery of the Devono-Carboniferous Clair Field on the adjacent West Shetland Shelf, and has led more recently to the discovery of several Paleocene reservoirs near the southern end of the basin, including the Schiehallion, Foinhaven, Loyal and Suilven oil fields.

As a consequence of this economic interest, there is a plethora of data from the region, mostly from the pre-Quaternary section and much of which is still confidential. However, there have also been surficial mapping programmes, by the British Geological Survey (BGS) and the Geological Survey of Denmark and Greenland, and environmental surveys in relation to offshore exploration and production issues.

This paper presents a summary of some of these data from the

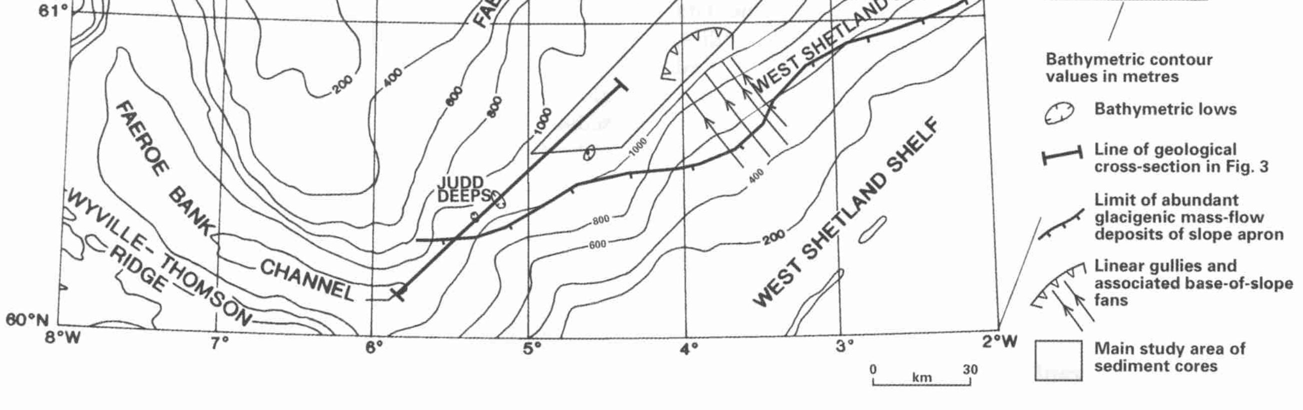

Fig 1. Location map and bathymetry of the SW Faroe–Shetland Channel region, showing the main area of study of the sediment cores. The limit of glacigenic mass-flow slope-apron deposits is taken from Stoker (1999), and the linear gullies and associated fans is adapted from Stoker *et al.* (1993) Masson (2001) and Bulat & Long (in press). Note that debris flows interbedded with the basinal section occur within the channel (e.g. see Fig. 7).

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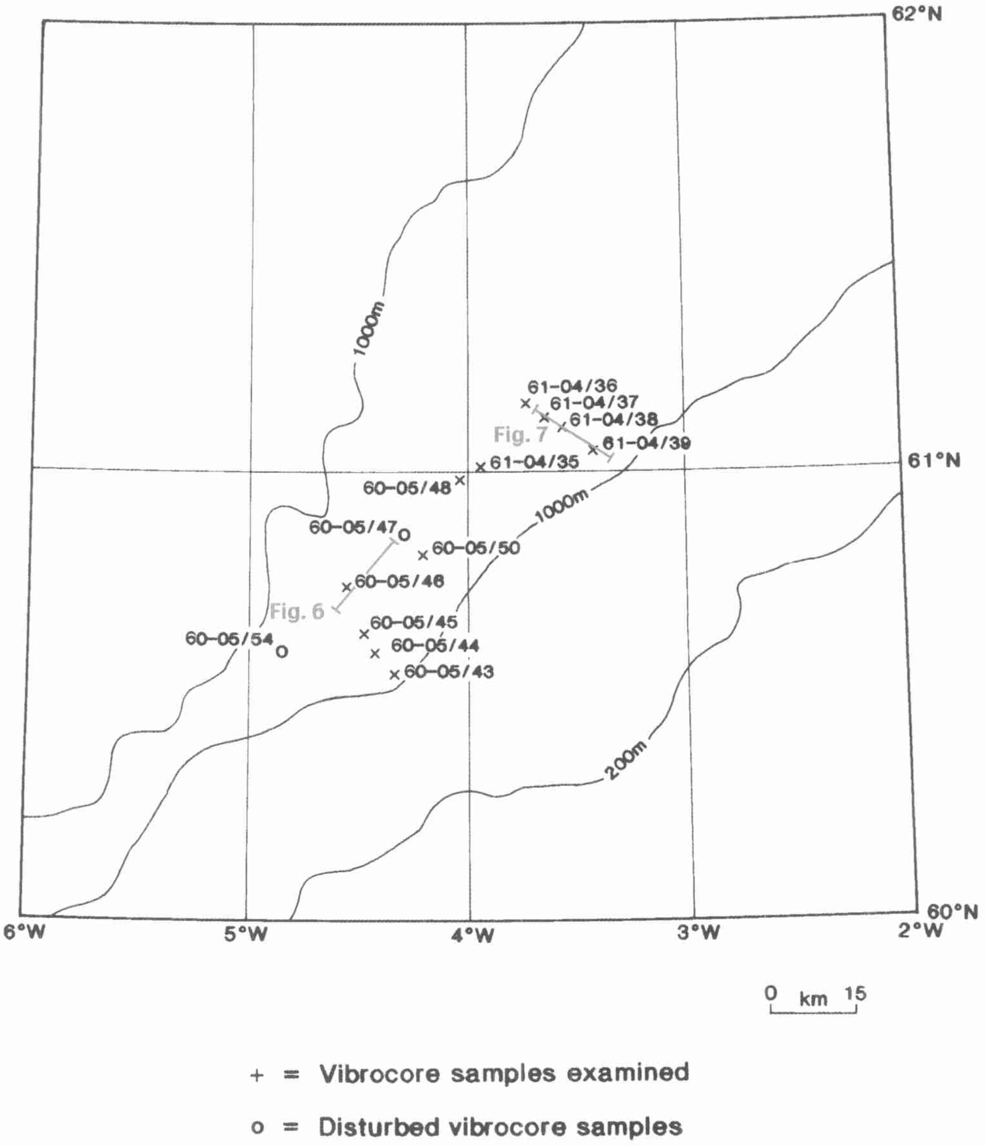

Fig 2. Location of vibrocores, recovered by British Geological Survey, used in this study and seismic profiles shown in Figures 6 and 7.

southwest end of the Faroe–Shetland Channel in order to elucidate the nature of late Quaternary and Recent processes and sedimentation in the channel. Regional and oceanographic data are summarised from an extensive literature. Seismic studies, undertaken as part of a regional geological survey by BGS, used 40 cubic inch airguns, 1.5 and 2 kJ sparkers, 5 and 6 kV deep-tow sparkers, and 6 kV deep-tow boomer sources, together with an acoustic velocity of 1.6 km s^{-1} for interpretation of the Quaternary section. Sediment data are from a series of short vibrocores recovered from the Faroe–Shetland Channel (Fig. 2), which were then subjected to careful laboratory analyses. For the sedimentological information, we have drawn extensively on an earlier BGS report by the senior author (Akhurst 1991).

Geological and oceanographic setting

Geological setting and palaeoceanography

The Faroe–Shetland Basin is a narrow fault-bounded basin lying parallel to the northwest UK passive continental margin. It has probably existed as a depocentre since the late Palaeozoic following a Permo-Triassic rifting episode (Doré *et al.* 1999; Roberts *et al.* 1999), and has been a particularly important locus for sediment accumulation from the Mesozoic to Recent. The Mesozoic succession is some 7 km thick, of which up to 5 km are Upper Cretaceous deep-water sediments deposited as the basin subsided as a result of crustal extension.

During the Paleocene, basaltic volcanic lavas were extruded along the northwest margin whereas up to 2 km of deep-water sediments accumulated in the basin itself. A further 1.2 km sediment pile now represents the Eocene deposits, although the original thickness has been much reduced by synsedimentary tectonism and an episode of strong bottom current erosion during the latest Oligocene/early Miocene interval (Stoker 1990*a*; Stoker *et al.* in press). This intensification of bottom current circulation, which led to channel incision into the trough floor, followed the development of deep-water pathways linking the Arctic and Atlantic oceans *via* the Norwegian–Greenland Sea, and consequent southward flow of cold Arctic waters (Miller & Tucholke 1983; Zeigler 1988).

It is the plate-tectonic evolution of the Norwegian–Greenland Sea that strongly influenced the development of deep-ocean connections; specifically the opening of the Fram Strait (Northern Gateway), and the subsidence of the Greenland–Scotland Ridge (the Southern Gateway) (Jansen & Raymo 1996; Thiede & Mhyre 1996). It has been suggested that deep-water circulation in the Norwegian–Greenland Sea may have been initiated during late

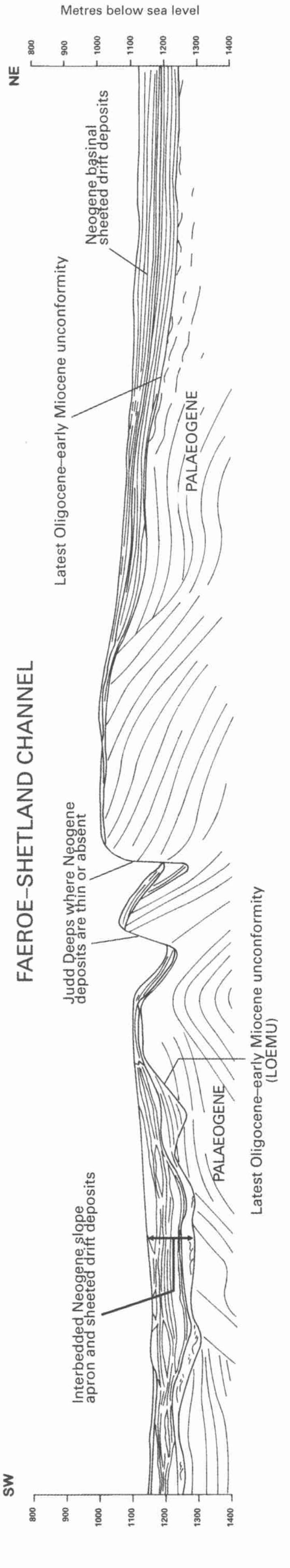

Fig 3. Interpreted geological cross-section across part of the Faroe–Shetland Channel (modified from Stoker 1990*b*). For location of section see Figure 1.

Eocene/early Oligocene time (Berggren & Schnitker 1983; Zeigler 1988; Davies *et al.* 2001). However, the modern pattern of deep-water exchange may be a Neogene phenomenon, initiated in the Miocene as the Fram Strait developed a true deep connection, and the Greenland–Scotland Ridge became fully submerged (Eldholm 1990; Jansen & Raymo 1996). The Faroe–Shetland Channel, with the Faroe–Bank Channel, lies at the southeast end of the Greenland–Scotland Ridge, and represents the deepest passageway across the Southern Gateway.

The effects of bottom current activity in the Faroe–Shetland Channel are manifest in the style of deep-water sedimentation associated with the Neogene succession. Overlying the latest Oligocene–early Miocene unconformity (LOEMU of Stoker 1999) is a sequence of Neogene sheeted drift deposits (Stoker *et al.* 1998) that range from about 100 m thick to locally absent over Palaeogene inversion structures on the basin floor at the southwest end of the channel (Fig. 3). This contrasts with the adjacent slope apron on the West Shetland Slope that locally exceeds 300 m thickness. The slope apron progrades into the basin from the West Shetland margin and interdigitates with the thinner basin-floor sheeted drift deposits (Fig. 3). There is clear evidence of non-deposition and local erosion throughout this part of the basinal drift sequence. Farther to the northeast, as the Channel deepens, the Neogene sequence appears to thicken substantially and may be several hundred metres thick (Davies *et al.* 2001).

Oceanographic setting (Fig. 4)

At the present day, cold (–0.5–1ºC), southward flowing Norwegian Sea water fills the Faroe–Shetland Channel to a depth of approximately 500 m. This is separated from warm (> 9ºC), northward-flowing Atlantic water at the surface by an intermediate layer 100–200 m thick. In fact, surface circulation in the Faroe–Shetland Channel forms an anticlockwise gyre, the core of Norwegian Sea Overflow Water (NSOW) is along the northwest side of the channel and deep eddy currents have been noted within 100 m of the seafloor (Dooley & Meinke 1981; Saunders & Gould 1989; Saunders 1990).

Current meter data available from deep moorings in the Faroe–Shetland Channel, provided by the British Oceanographic Data Centre, typically show mean weekly velocities of 20–40 cm s^{-1} directed towards the southwest or west-southwest. Individual readings can be much greater, and reverse flow interpreted as large eddies is also noted.

Bathymetry

The Faroe–Shetland Channel separates the West Shetland and Faroes margins. The shelf break of the West Shetland Shelf lies at about 200 m water depth, whereas the principal gradient change south of the Faroes Shelf is closer to 300 m (Fig. 1). Slope angles on both flanks are relatively shallow, from 1–3º.

The Faroe–Shetland Channel slopes very gently from a depth of just over 1000 m in the southwest (Fig. 1) to some 1700 m in the northeast, a distance of just less than 450 km. It presents an elongate funnel shape, opening from a width of some 25 km (between the 1000 m isobaths) in the southwest to over 120 km at the northeast end where it merges with the Norwegian Sea. At its southwest end it abuts the Wyville–Thompson Ridge, where it turns sharply towards the northwest and becomes the Faroe–Bank Channel (Fig. 1).

Detailed bathymetric study of the floor reveals that north of about 60º 30′N it has a relatively flat cross-sectional profile, with a low central ridge along part of the axial region as well as trough-parallel bathymetric lows or minor channels in both axial and marginal positions. South of 60º 30′N, the bathymetry is more

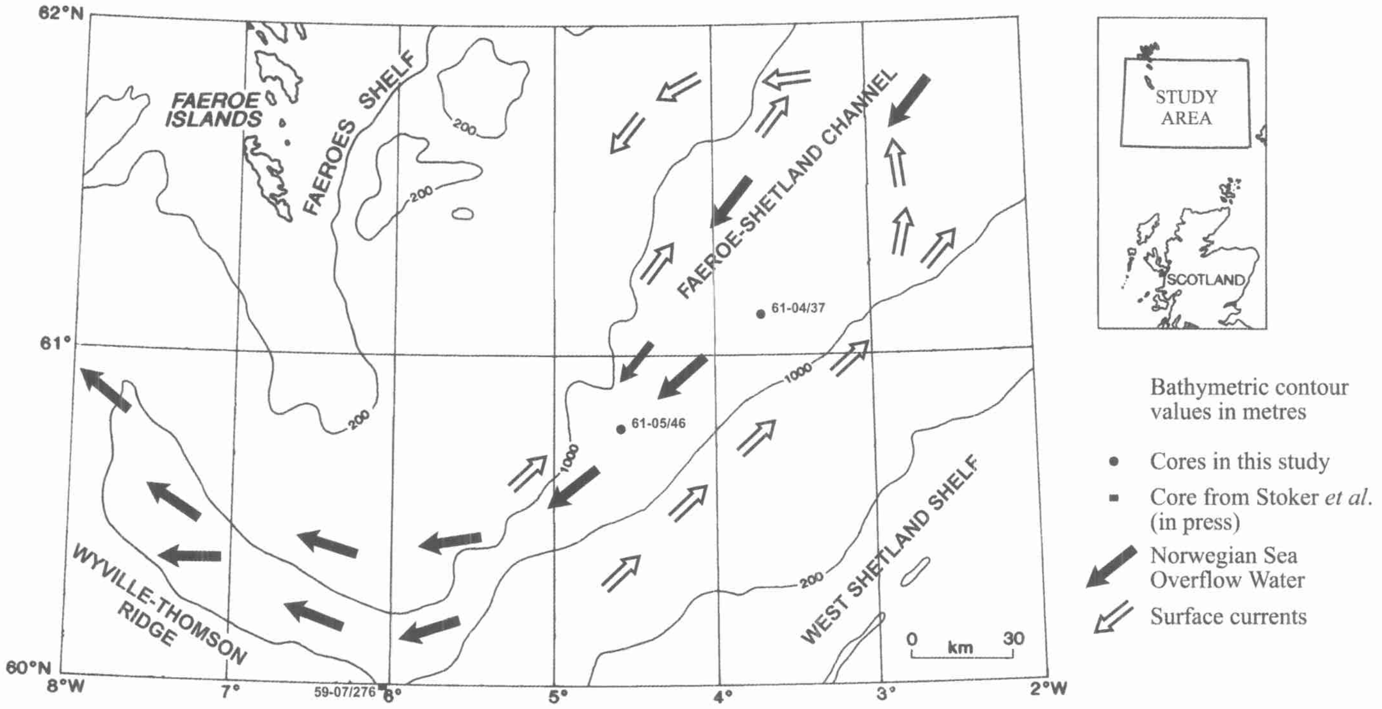

Fig 4. Present-day deep-water and surface circulation in the Faroe–Shetland Channel region.

complex and several enclosed deeps, the Judd Deeps, form a highly sculpted channel floor (Figs 1 & 3). The formation of these deeps may be linked to very strong bottom current erosion in late Oligocene–early Miocene time (Stoker *et al.* in press).

Stratigraphic context

The Neogene succession on the West Shetland margin has been assigned to the Nordland Group (Stoker 1999). On the shelf and slope, the Nordland group has been divided into Lower, Middle and Upper Nordland units that represent, respectively, Miocene, Pliocene to middle Pleistocene, and middle Pleistocene to Holocene deposits. However, the recognition of these units in the basinal succession remains problematic, particularly at the southwest end of the Channel where the Neogene strata are relatively thin. Thus, for the purpose of this study, especially with respect to their seismic characteristics (see Figs 6 & 7), the basinal strata are here referred to as Neogene (Nordland Group) undivided.

By way of contrast, the sediment cores used in this study have provided a high-resolution subdivision of the uppermost layers of the Neogene succession. Short (< 6 m long) vibrocores recovered from the Faroe–Shetland Channel have been accurately dated using a combination of oxygen isotopes, carbon 14 analysis and microfossil assemblages (Fig. 5; Akhurst 1991). The oldest material recovered for this study is considered to be from the last interglacial (Eemian).

Seismic characteristics of the Neogene basinal succession

In the Faroe–Shetland Channel, the Neogene basinal sequence is mostly characterized by high-frequency, laterally continuous, parallel, sub-horizontal reflectors on both airgun and sparker profiles (Figs 6 & 7), that reflect an overall sheeted drift geometry (Stoker *et al.* 1998). The base of the sequence locally onlaps the underlying Palaeogene strata where the LOEMU forms an irregular surface (Fig. 6*a*, *b*). Such basin-floor onlap is most spectacularly demonstrated in the area of the Judd Deeps (Fig. 3). Within the Judd Deeps, the Neogene reflectors display a downlapping relationship indicative of lateral accretion. Farther to the northeast, internal convergence of reflectors over Palaeogene highs and over the flanks of the low central ridge is indicative of depositional thinning and, more rarely, very low-angle truncation of reflectors suggests localised short-lived erosive episodes (Fig. 7).

On the West Shetland slope, the Neogene slope apron deposits are locally > 300 m thick over parts of the slope south of 60° 30′N. The bulk of the slope apron displays a seismic character indicative of slope progradation and downslope movement (Stoker 1995, 1999; Bulat & Long in press), although eroded remnants of formerly more extensive, Miocene, elongate mounded drifts are buried beneath the prograding wedge on the middle and lower slope (Stoker 1999). The prograding deposits generally comprise transparent and chaotic seismic units bounded by laterally continuous, high amplitude reflectors (Fig. 3). High-resolution profiles show characteristic lensoid units (Fig. 7), which commonly display irregular tops and locally erosive bases. These sediments are interpreted as debris flow deposits (Stoker 1990*a*, *b*; Holmes 1990; Stoker *et al.* 1991; Stoker 1995), the most recent of which were derived from late Pleistocene ice sheets located at the edge of the West Shetland Shelf (Stoker 1995). The debris flows interdigitate downslope with the, seismically well-layered basinal sequence and, locally, extend onto the channel floor (Fig. 3). Where the debris flows and basin-floor sediments are interbedded, the former tends to increase the thickness of the basinal succession (Figs 3 & 7). High-resolution seafloor mapping has revealed areas of downslope-oriented linear gullies associated with base-of-slope debris-flow fans between 60° 30′ and 61° 0′N (Masson 2001; Bulat & Long in press). These linear, highly erosive features are most probably the result of turbidity currents (Fig. 1). Thus, material transported by ice-rafting, debris flow and turbidite processes was delivered onto the channel floor in the area of study.

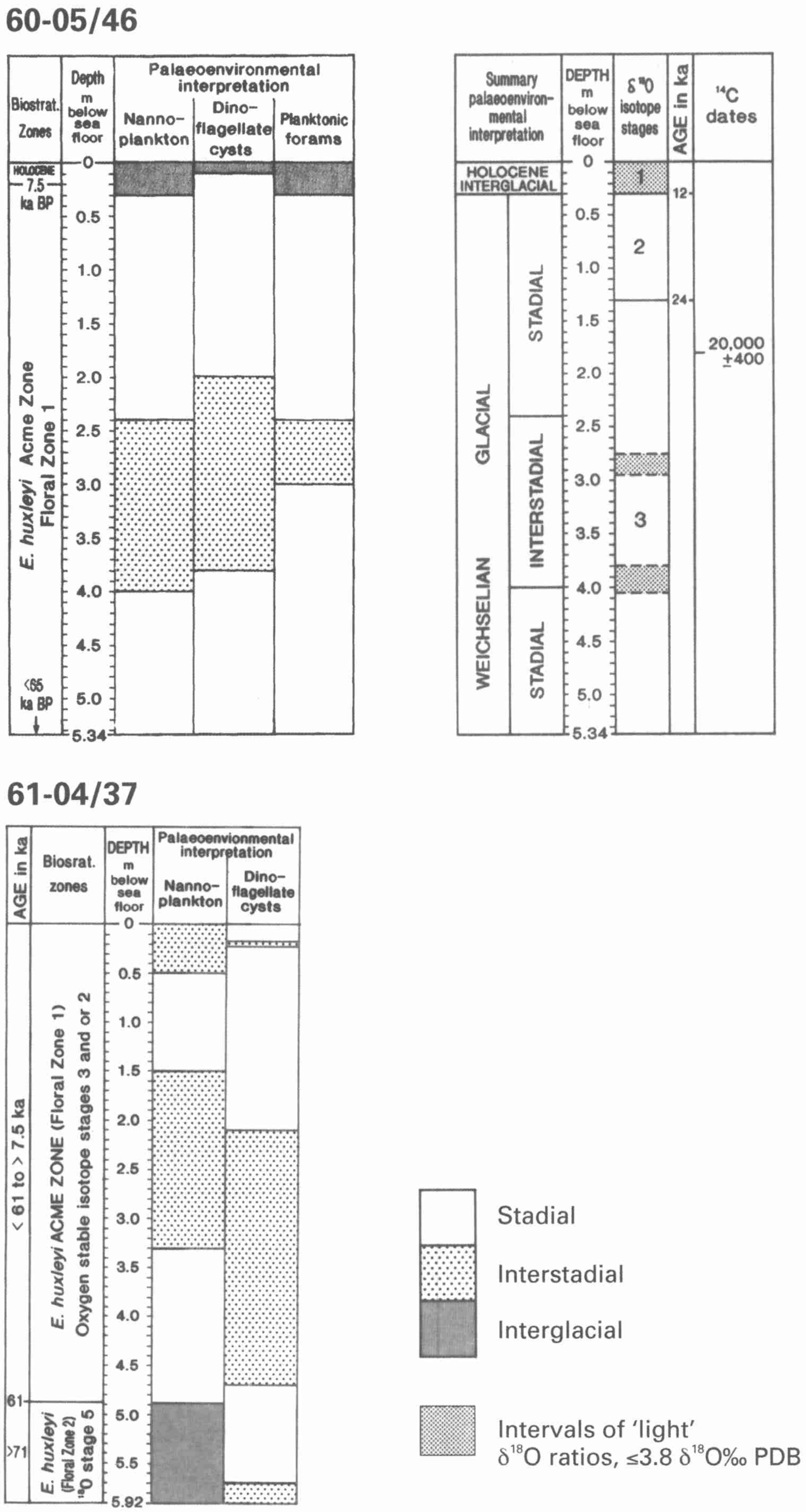

Fig 5. Detailed late Quaternary–Holocene stratigraphy of cores 46 and 37 from the Faroe–Shetland Channel.

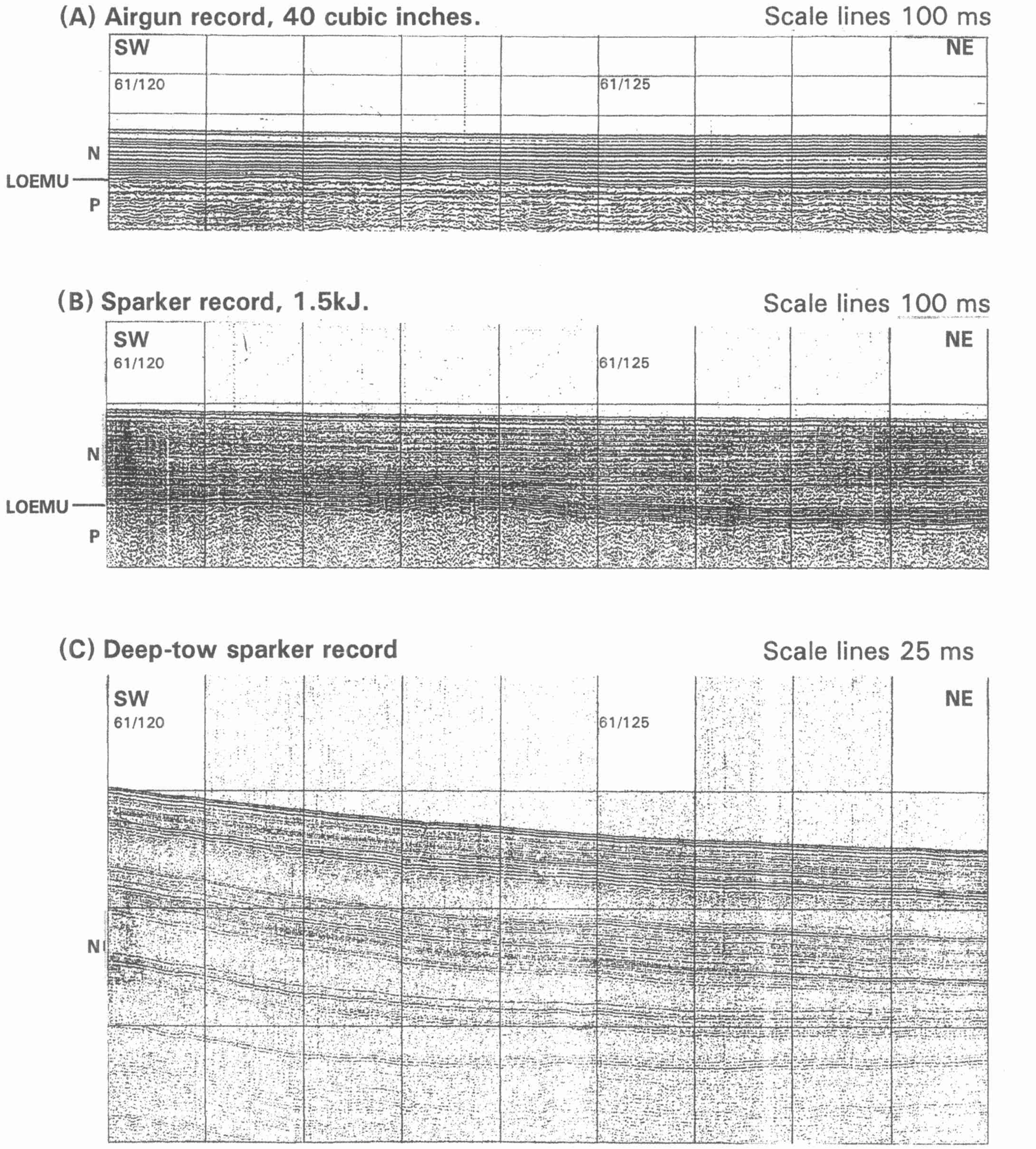

Fig 6. Typical seismic profiles from the floor of the Faroe–Shetland Channel (BGS Survey 83/04, line 61, fixes 120–128), showing characteristic airgun, sparker and deep-tow sparker sources. Note onlap of Neogene strata onto irregular basal unconformity (LOEMU) in profiles A and B. Profile is located in Figure 2.

Sedimentary characteristics of Upper Neogene (Quaternary) basinal deposits

Sediment facies

Five distinct facies have been identified in the Faroe–Shetland Channel based on observations from the eleven vibrocores used for this study. These are listed below with their relative abundance (%) in the sections examined, and illustrated in Figure 8. Gravel clasts and coarse sand grains are common throughout, and can be readily interpreted as glacial Ice Rafted Dropstones (IRD).

Mud	*26%*
Sandy mud – unsorted	*50%*
– sorted	*10%*
Muddy sand and gravelly muddy sand	*8%*
Dark grey mud	*1%*
Pale laminated mud	*5%*

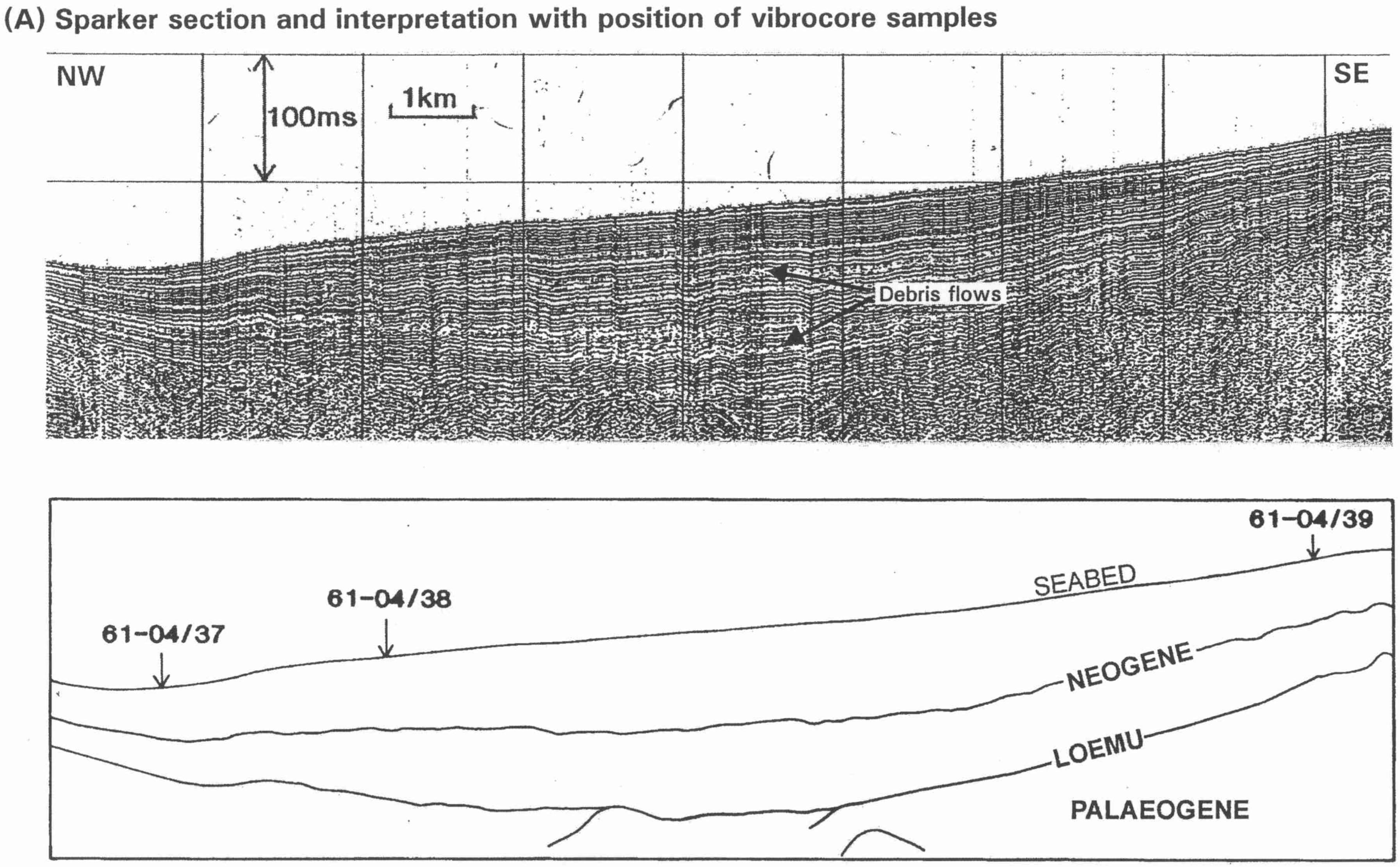

Fig 7. Sparker seismic section (BGS Survey 84/05, line 43) across part of the Faroe–Shetland Channel. Note broad lenticularity of the Faroe–Shetland Channel sequence over the Upper Tertiary section, indicative of a contourite sheet-drift geometry. Note also: 1) the marked thinning of the sedimentary section in the central portion of the Faroe–Shetland Channel, related to non-deposition and erosion under an active bottom current system; and 2) the general thickening of the basinal section where interbedded, lensoid, debris flows are present. LOEMU, latest Oligocene–early Miocene unconformity. Profile is located in Figure 2.

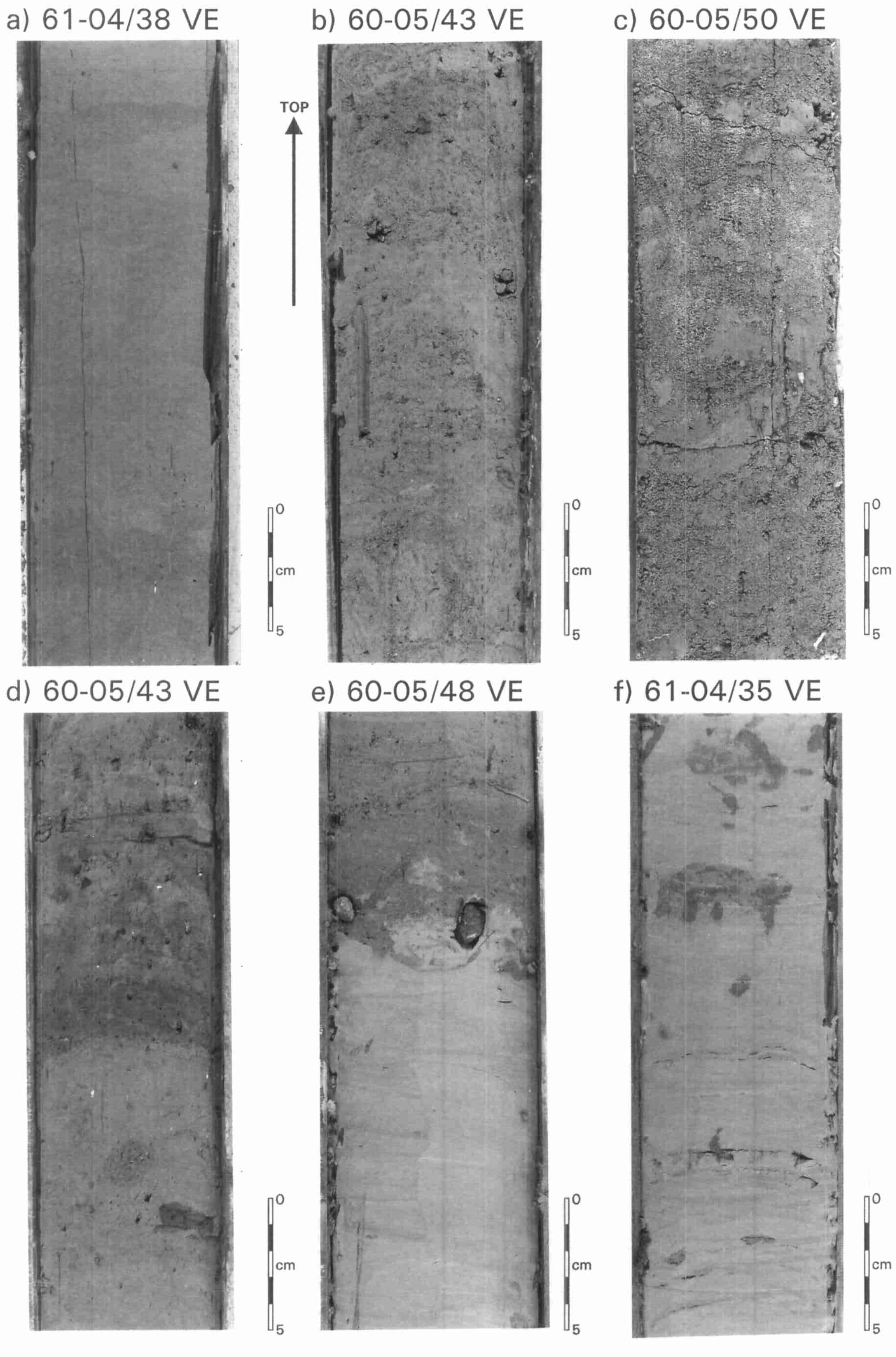

Fig 8. Core photographs of typical sediment facies from Faroe–Shetland Channel cores. See Figure 2 for core locations and abbreviations. (a) Mud Facies, vibrocore 61-04/38VE, 3.88 to 4.12 m below sea floor; (b) Sandy Mud Facies, vibrocore 60-05/43VE, 2.41 to 2.64 m below sea floor; (c) Muddy Sand Facies, vibrocore 60-05/50VE, 4.34 to 4.57 m below sea floor; (d) Dark Mud Facies, vibrocore 60-05/43VE, 4.73 to 4.97 m below sea floor; (e) Pale Mud Facies, vibrocore 60-05/48VE, 0.68 to 0. 91 m below sea floor; (f) Pale Mud Facies, vibrocore 60-05/35VE, 1.18 to 1.41 m below sea floor.

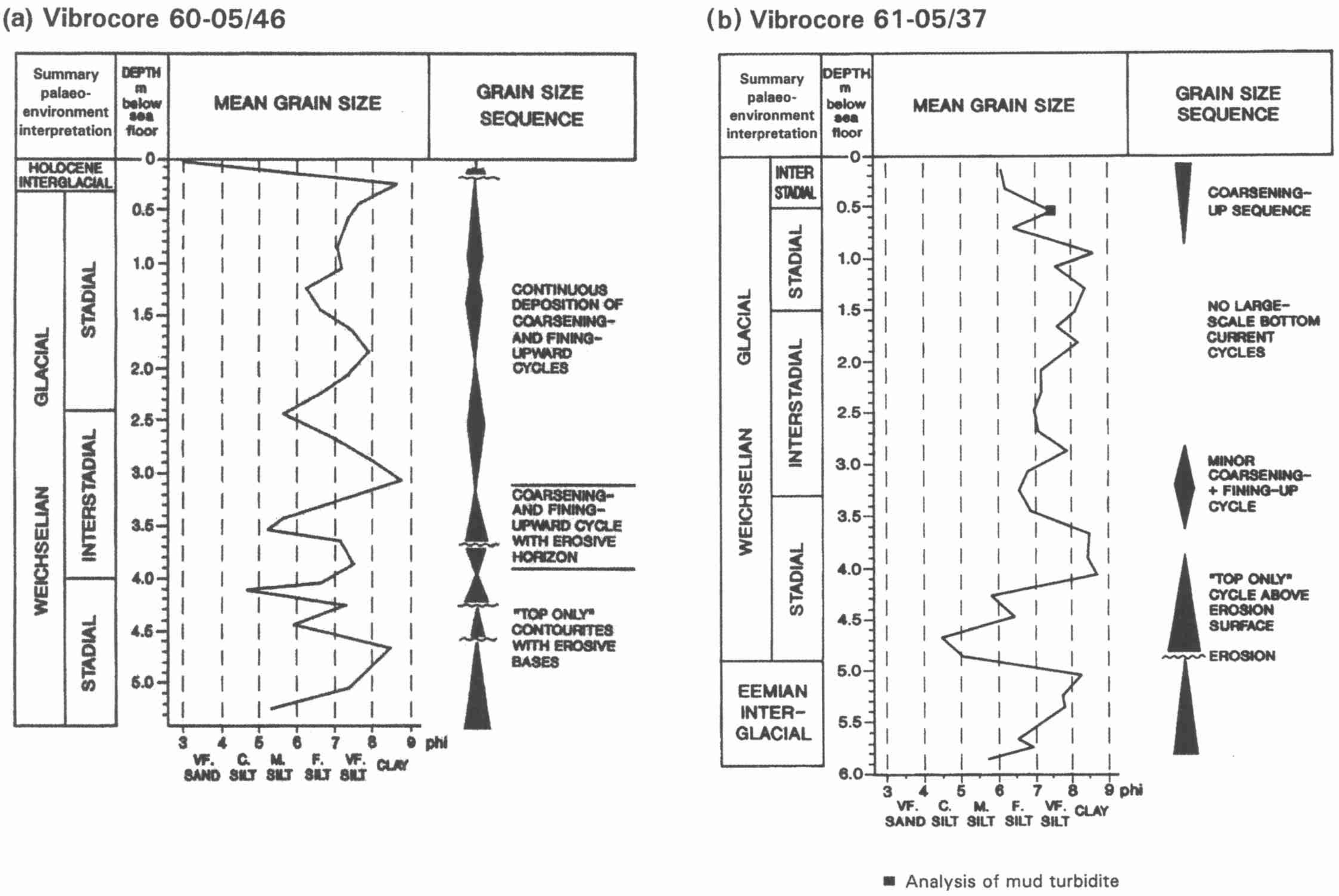

Fig 9. Mean grain-size variation, grain-size sequences and erosive horizons together with best interpretation of vibrocore stratigraphy noted in a) vibrocore 61-05/46VE and b) vibrocore 61-04/37VE. See Figure 2 for core location.

The main characteristics that distinguish each of these facies are their colour, grain size, sedimentary structures, ichnofacies and nature of bedding. They are all dominantly siliciclastic in composition, with a very minor foraminiferal/nannofossil component. The IRD gravel clasts include an assortment of sedimentary, igneous and metamorphic rocks consistent with derivation from the Scottish mainland. Akhurst (1991) provides a detailed overview of the ichnofacies and further work on this topic is in progress (A. Wetzel and others), although we do not consider it further in this paper.

Mud facies: olive grey to dark olive grey when fresh; mainly fine-grained (clay-silt size) with < 1% IRD; mostly structureless and thoroughly bioturbated with distinctive burrow traces common (Fig. 8a); bedding typically gradational (0.10–2.28 m thick), but with sharp contacts in places. *Interpretation* – glaciomarine hemipelagites and muddy contourites.

Sandy mud facies: grey to olive grey when fresh; slightly sandy to sandy muds with variable % IRD; mostly structureless and thoroughly bioturbated with distinctive burrow traces common (Fig. 8b); bedding typically gradational (0.08–3 m thick), but with sharp contacts in places. *Types* – unsorted sandy muds in which the sand fraction shows the full range of grain size; sorted sandy muds in which the sand fraction has a distinct mode in the fine-very fine sand size; sandy muds with micro-shale clast horizons. *Interpretation* – glaciomarine hemipelagites, mottled silt-mud contourites, and micro-shale clast contourites.

Muddy sand facies: dark grey to greyish brown when fresh; poorly sorted very muddy sand size with variable % IRD (in some cases relatively high); mostly structureless and thoroughly bioturbated with distinctive burrow traces common (Fig. 8c); bedding typically gradational (0.10–0.68 m thick) with bioturbated contacts, basal contact generally more distinct than upper, and some erosion evident. *Types* – muddy sand and gravelly muddy sand. *Interpretation* – glaciomarine sandy hemipelagites and sandy contourites.

Dark mud facies: very dark grey brown to dark grey when fresh; mud or slightly sandy mud size with rare IRD and micro-shale clasts (Fig. 8d); structureless to diffuse planar laminated, with little bioturbation; thin distinct beds (3–10 cm thick). *Interpretation* – unclear.

Pale laminated mud facies: pale brown to greyish brown when fresh; mainly fine-grained (silty clay to slightly sandy mud size) with < 1% IRD and soft textured; well laminated (Fig. 8e) and graded laminated units, some contorted lamination, overall normal grading, bioturbation near the tops of beds, sharp at bases, with some distinctive burrow traces (Fig. 8f); isolated thin to medium thick beds (< 0.30 m thick). *Interpretation* – fine-grained turbidites.

Vertical and horizontal distribution

The dominant facies making up some 94% of the section examined are the muds, sandy muds and muddy sands. These are typically arranged in a broadly cyclic manner from mud to sandy mud to sand facies and then back through sandy mud to mud facies (Stoker *et al.* 1998). This pattern is clearly visible on grain size profiles (Fig. 9), where the grain size oscillation cycles are between 0.3 and 1.2 m thick, and is very typical of the standard contourite facies model (Stow *et al.* 1986, 1996).

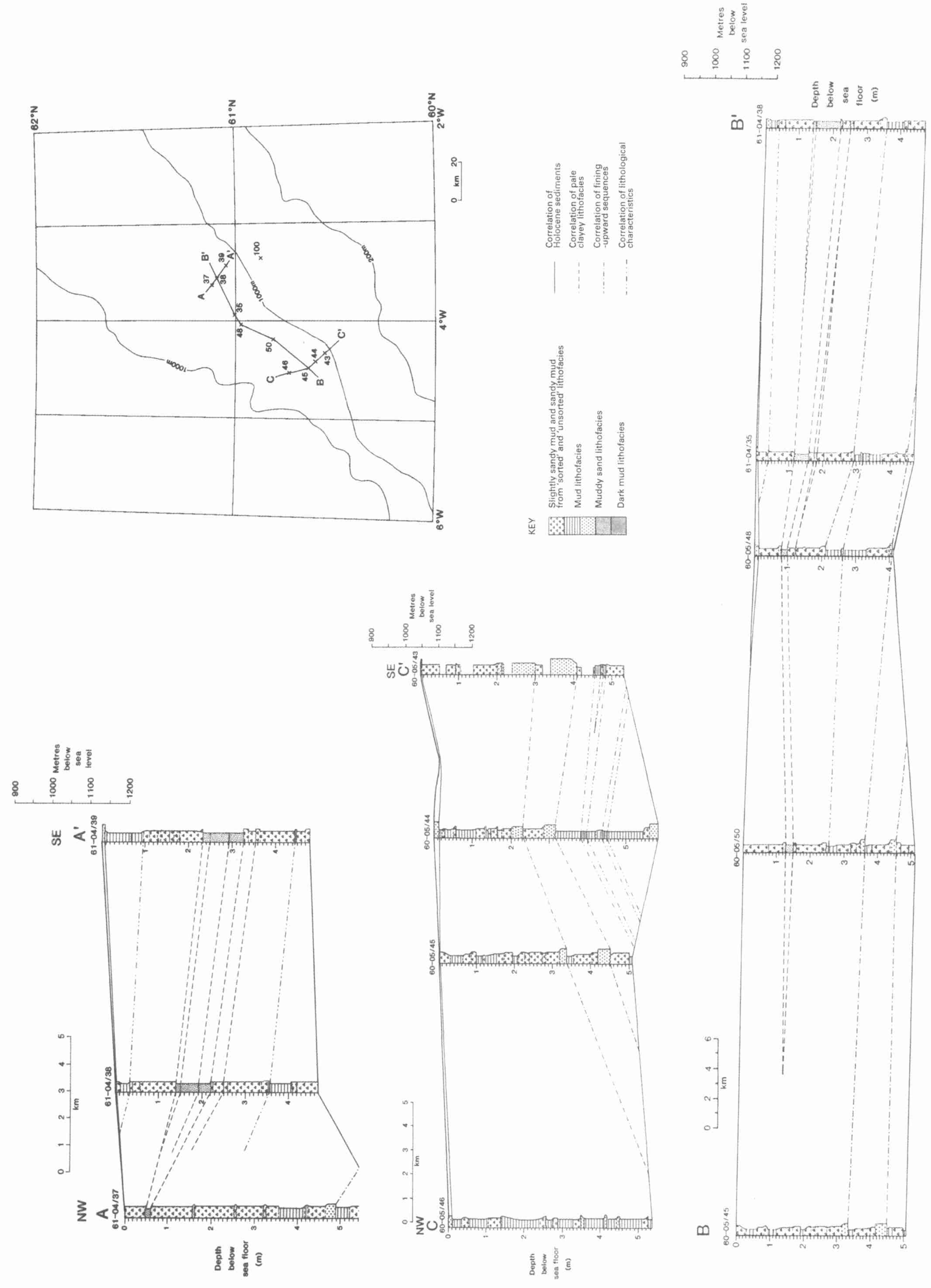

Fig 10. Panel cross-sections showing lateral correlation and vertical distribution of facies from the studied cores.

Some variability in sequences is observed with the fining-up portions of the cycles (i.e. top-only contourites) being common towards the base of the cored section and a coarsening-up cycle (i.e. base-only contourites) occurring at the top of most cores. This latter is capped by the thin Holocene muddy sand unit. Erosive horizons commonly occur coincident with the coarsest grain size and at the base of the fining-up cycles.

Lateral correlation between ten of the study cores has been possible to a limited extent over the study area (Fig. 10). Principal aspects of the lateral distribution of facies are:

- Regional correlation of the surficial Holocene sandy facies as a thin veneer (in places either very thin and non-recovered or absent, e.g. cores 37 and 50).
- The pale-brown laminated turbidite facies can be correlated between cores in the northeastern part of the study area, being thickest in core 39 and decreasing in thickness both across the channel (to cores 38 to 37) and along the channel (to cores 35, 48 and 50), this is consistent with lateral supply from the southeast probably close to core 39, and has been correlated with a debris flow event on the slope (Akhurst 1991).
- Only local correlation of the dark grey mud facies, i.e. between the two cores (43 and 44) in which it occurs.
- Two prominent sandy contourites at the base of the fining-up units (top-only contourites) can be correlated between cores 43, 44 and 45 in the southern transect, and further north to cores 50, 48, 35 and possibly 37 (for the top sand only).
- Correlation of the sandy mud facies and grain size cycles is much less definitive and not attempted here (but see Akhurst 1991, for a fuller discussion).

Sedimentation rates

Dating of selected cores used in this study has been carried out using a combination of biostratigraphic analysis (nannofossils, planktonic foraminifers and dinoflagellate cysts) and limited oxygen isotope data. Average sedimentation rates for the upper 5 m of section vary from about 3 cm ka^{-1} (core 46) to 7 cm ka^{-1} (core 37). Even removing the turbidite beds from the calculation, the highest rates (about 10 cm ka^{-1}) are found in core 37. Taking the Holocene section alone, the mean accumulation rates are from 2–5 cm ka^{-1}.

Discussion

Depositional processes and evidence for contourites

Glaciomarine sedimentation is clearly prevalent through most of the Quaternary section studied in the cores. IRD are everywhere present apart from in the thin Holocene veneer and in localised turbidites. The cores studied from the Faroe–Shetland Channel are mostly, therefore, within the distal glaciomarine environment, where glaciomarine hemipelagic sedimentation dominated and, in this case, was clearly modified by the action of strong bottom currents. Other non-glacial processes are more minor in their contribution.

Although seismic evidence suggests that debris flow processes constructed much of the slope succession, minor turbidity current input is evident locally as indicated by the linear gullies (Fig. 1). Akhurst (1991) has interpreted the thin dark grey clay facies as the distal component of a glacigenic debris flow, partly based on the presence of micro-shale clasts. However, we now suggest that these clasts, as well as those observed as thin horizons within the sandy mud facies are more likely to result from bottom current erosion and local redeposition. Certain other pebbly mud beds with sharp bases might be interpreted as distal debrites, but it is difficult to distinguish these from glacigenic hemipelagites with increased IRD.

The action of bottom currents has been a much more important influence on sedimentation throughout the interval examined for this study. The evidence for this is manifold:

- The known presence of a strong bottom current flow through the Faroe–Shetland Channel throughout the Neogene period at least.
- Seismic patterns that indicate widespread deposition of sheeted drifts, as well as broad areas of erosion.
- A range of sediment facies typical of (glacigenic) contourites including continuous bioturbation with very rare primary sedimentary structures, grain size cyclicity, winnowing of fines and sorting of fine sands, mixed composition and reworking of microfossil assemblages.
- Clear cyclic arrangement of facies and grain size in vertical section yielding both complete and partial contourite sequences, together with clearly erosive boundaries.
- Good lateral correlation of facies cycles, particularly the sandy contourite intervals, over at least 50 km along the Faroe–Shetland Channel.

Drift geometry and sediment export

The SW Faroe–Shetland Channel is characterized principally by the development of sheeted drifts coupled with widespread erosion (see also Stoker *et al.* 1998). The sheet-like drift geometry formed as a result of vigorous bottom current flow maintained across the whole channel floor as it narrows towards the southwest. The sheeted drift thins towards the southwest and over highs in the channel floor, due to non-deposition, winnowing and erosion. Local scours are evident over an otherwise smooth surface. Elongate mounded drifts, largely buried beneath the slope apron, are only locally preserved along the Faroe–Shetland Channel margins (Stoker 1999). These largely relict (Miocene) features contrast markedly with the flanks of the Channel farther to the northeast, beyond the limit of the study area, where elongate mounded drifts of Plio-Pleistocene age are commonly preserved on the West Shetland slope (Stoker 1999).

The principal role of bottom currents in developing the sheeted drift geometry in the SW Faroe–Shetland Channel basin-floor succession has been one of restricted and/or non-deposition throughout the Plio-Pleistocene interval. Although glaciomarine sediment input across the West Shetland slope would have been relatively large at times during the Plio-Quaternary period, the finer fraction of any glaciomarine hemipelagic and IRD material was effectively maintained in suspension in the southward flowing bottom currents. At times of enhanced bottom current activity, the floor of the Faroe–Shetland Channel was subject to erosion as well as non-deposition. Consequently the Faroe–Shetland Channel has served as an important region of sediment export to the south.

Contourites and climate

In trying to relate fluctuation in bottom current activity to climate change through the late Pleistocene to Holocene period, it is apparent that the relationship is not a simple one. In addition, dating of the cores is still patchy and incomplete so that the relationships outlined below must be considered preliminary.

The most recent warm period (the Holocene) is characterised by a thin sandy contourite veneer as well as by seafloor erosion. This suggests enhanced bottom current activity during the most recent interglacial period, as has been proposed from many other studies in the North Atlantic (Stow *et al.* 1986; Stoker *et al.* 1989; Faugères & Stow 1993; Stoker *et al.* 1998; Armishaw *et al.* 1998, 2000). Careful analysis of the cores used in this study show a similar increase in bottom current activity during earlier interstadial and interglacial periods (e.g. core 36, Duan *et al.* 1994), but also a marked increase in top-only contourites and erosive horizons during both rapid warming and cooling phases. This is in line with several earlier studies (e.g. Duplessy *et al.* 1988; Dowling & McCave 1993).

Grain size cyclicity together with other evidence for contourite deposition is also apparent through the clearly glacial periods. We therefore concur with Akhurst (1991), Stoker *et al.* (1991) and Knutz *et al.* (2001) that bottom current activity persisted through the glacial NE Atlantic, but was less intense during glacial stages.

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