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Sediment drifts and contourites on the continental margin off northwest Britain

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Abstract

Seismic reflection profiles and short cores from the continental margin off northwest Britain have revealed a variety of sediment-drift styles and contourite deposits preserved in the northeast Rockall Trough and Faeroe–Shetland Channel. The sediment drifts include: (1) distinctly mounded elongate drifts, both single- and multi-crested; (2) broad sheeted drift forms, varying from gently domed to flat-lying; and (3) isolated patch drifts, including moat-related drifts. Fields of sediment waves are locally developed in association with the elongate and gently domed, broad sheeted drifts. The contrasting styles of the sediment drifts most probably reflect the interaction between a variable bottom-current regime and the complex bathymetry of the continental margin. The bulk of the mounded/gently domed drifts occur in the northeast Rockall Trough, whereas the flat-lying sheet-form deposits occur in the Faeroe–Shetland Channel, a much narrower basin which appears to have been an area more of sediment export than drift accumulation. Patch drifts are present in both basins. In the northeast Rockall Trough, the along-strike variation from single- to multi-crested elongate drifts may be a response to bottom-current changes influenced by developing drift topography. Muddy, silty muddy and sandy contourites have been recovered in sediment cores from the uppermost parts of the drift sequences. On the basis of their glaciomarine origin, these mid- to high-latitude contourites can be referred to, collectively, as glacigenic contourites. Both partial and complete contourite sequences are preserved; the former consist largely of sandy (mid-only) and top-only contourites. Sandy contourites, by their coarse-grained nature and their formation under strongest bottom-current flows, are the most likely to be preserved in the rock record. However, the very large scale of sediment drifts should be borne in mind with regard to the recognition of fossil contourites in ancient successions.

Keywords: sediment drifts; contourite deposits; sediment waves; continental margin; Rockall Trough; Faeroe–Shetland Channel

1. Introduction

Bottom-current activity greatly influences both sediment accumulation and erosion on continental margins as well as ocean basins. The effects of these contour-following, deep geostrophic currents are particularly marked on slopes and basin plains within and adjacent to continental margins, where a variable sea-floor bathymetry may locally intensify and focus current activity. Sediment drifts are anomalous sediment bodies that commonly form positive fea-

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tures on the sea bed, and typically accumulate in areas swept by bottom currents and where there is a change in gradient of the sea bed, such as at the base of continental slopes. Fields of sediment waves may be developed in association with the drifts. Where particularly strong, bottom currents may cause erosion of the sea bed and the formation of channels, moats and furrows. Under this regime, sediment accumulation is likely to be more restricted and lack the mounded morphology generally associated with bottom-current deposits. Consequently, the resultant deep-water physiography of the continental margin may be locally complex.

The continental margin off northwest Britain is an area of varied bathymetry which flanks the oceanic Iceland and Norwegian basins (Fig. 1). Morphologically, it can be divided into an inner margin, consisting of the Hebrides and West Shetland shelves, and an outer margin, including the Rockall Plateau, Faeroe Shelf and intervening banks. Together, these form relatively shallow platform areas separated by the deeper-water basins of the Rockall Trough and Faeroe–Shetland Channel. Since the mid-Cenozoic, these basins have received an influx of bottom waters from several sources, and have experienced extensive redistribution of sediment via bottom-current activity. In the northeast Rockall Trough, sediment drifts and associated sediment waves, together with an erosional moat, are well-preserved (Stoker et al., 1993; Howe et al., 1994), whereas contourite sediments in the Faeroe–Shetland Channel display a more subdued stratal geometry, and the effects of major erosion are well expressed at the sea bed (Akhurst, 1991; Stoker et al., 1991, 1993).

The aim of this paper is to demonstrate the very varied depositional and erosional features associated with mid- to late Cenozoic bottom-current activity in the northeast Rockall Trough and Faeroe–Shetland Channel. In particular, we focus on the characteristics of contourites both at the regional scale, as recorded on seismic reflection profiles, and at the local scale as observed in sediment cores. From this, we are able to demonstrate the varied seismic character and sediment-body geometry of the contourites which, in turn, has implications for depositional processes and palaeoceanographic regimes. The inherent variability of the contourite sediments promotes a need for a revision and expansion of the contourite facies model, to include new styles of contourite deposits. Such refinement of models is particularly crucial in the search for examples of contourites within the rock record.

2. Regional setting

The Rockall Trough and Faeroe–Shetland Channel are deep-water intracratonic basins separating the Hebrides and West Shetland shelves from the Rockall Plateau and Faeroes Shelf (Fig. 1). The two basins are themselves separated by the prominent, northwesterly trending, Wyville–Thomson Ridge.

The Rockall Trough deepens to the southwest where it opens out into the Porcupine Abyssal Plain. Water depths in the trough increase from 1000 m in the northeast to 4000 m in the southwest. The width of the trough (at the 1000 m isobath) is between 200 and 250 km. The floor of the trough is relatively smooth and very gently inclined to the southwest. However, other features are noted towards the margins of the trough; a major depositional drift, the Feni Ridge, flanks the western side of the trough, whilst on its eastern side slope fans locally encroach onto the basin floor (Stoker et al., 1993; Stoker, 1997, 1998). In the central and northern part of the trough, the continuity of the basin floor is interrupted by the Rosemary Bank, Anton Dohrn and Hebrides Terrace seamounts. Intense scouring of the sea floor has occurred around these features. Slope angles across the northeastern margin of the trough (the Hebrides Slope) are mostly gentle being from 1.5° to 3°, but reach up to 10° at the junction with the Wyville–Thomson Ridge, and 28° in the area of the Geikie Escarpment (Fig. 1).

In contrast, the Faeroe–Shetland Channel is a smaller, narrower, more restricted basin. To the northeast, the channel widens and slopes down into the Norwegian Basin; to the southwest, the channel turns northwestwards and continues as the Faeroe Bank Channel, joining the Iceland Basin to the south of the Iceland–Faeroe Rise. Water depths in the channel increase from 1000 m in the southwest to 1700 m in the northeast. The width of the channel (at the 1000 m isobath) also increases northeastwards from 15 to 100 km. The floor of the channel is very gently inclined to the northeast, with a low (relief of <150 m) central ridge (Akhurst, 1991). An irregular, relict basin-

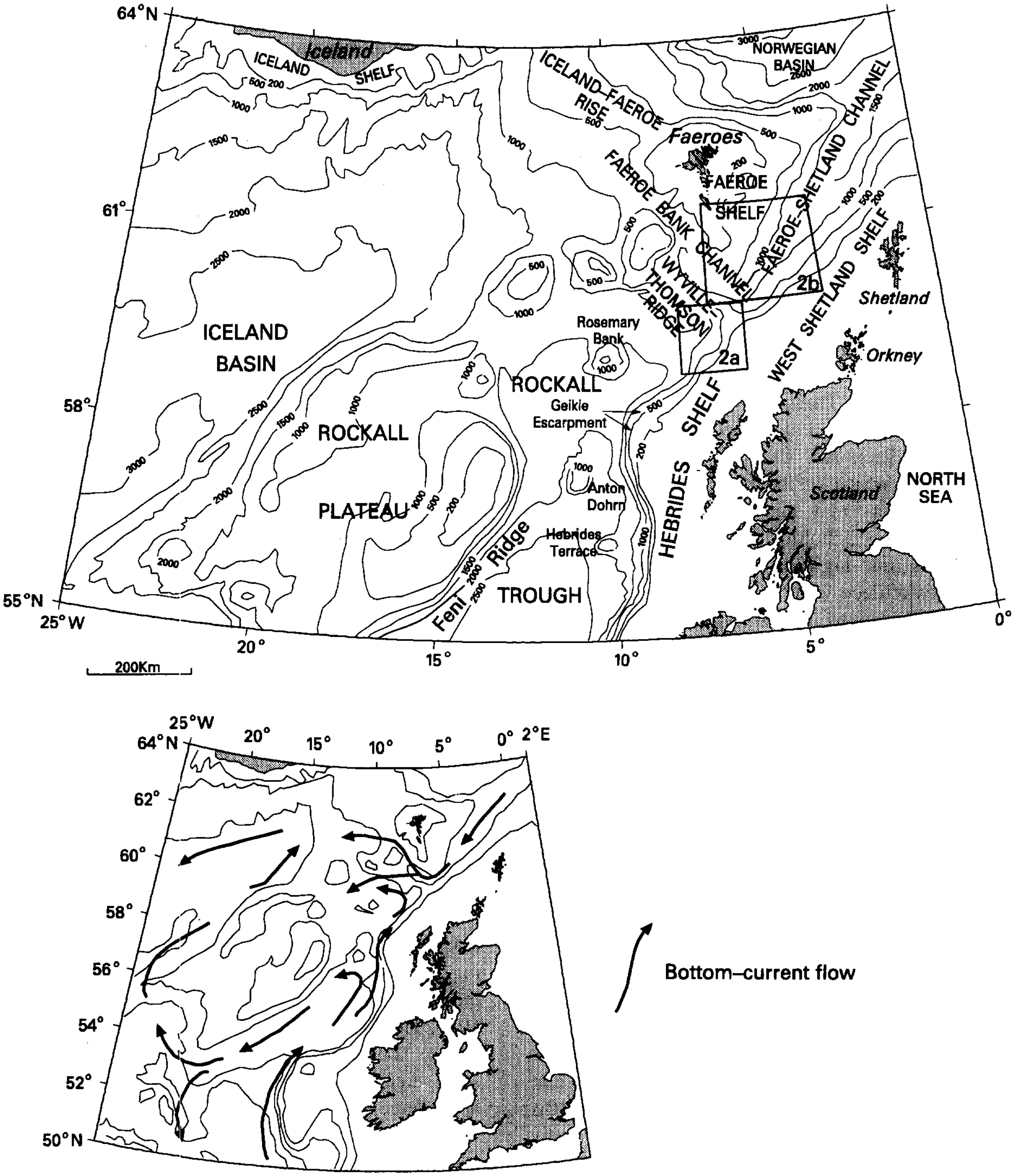


Fig. 1. Regional bathymetry of the continental margin off northwest Britain; contours in metres (after Roberts et al., 1977). Boxes show location of study areas which are expanded in Fig. 2. Small map shows present-day bottom-circulation pattern derived from a variety of sources (see text for references).

floor topography (see below) is locally preserved at its narrower southwest end (Stoker, 1990). Consistently gentle slope angles of 1°–3° flank the eastern margin (West Shetland Slope) of the channel, commonly steepest on the lower part of the slope.

Although depocentres may have existed in these areas since the late Palaeozoic, the present morphological expression of the basins is essentially a Cenozoic phenomenon, initiated by a major phase of subsidence in the mid-Cenozoic (Stoker, 1997, 1998). The increased amount of accommodation space generated within these basins far outstripped the rate of supply of sediment, and led to a significant deepening of the basins and, ultimately, the onset of bottom currents.

In the Rockall Trough, bottom-current activity has prevailed since Late Eocene/Oligocene time (Miller and Tucholke, 1983; Wold, 1994; Stoker, 1997, 1998), whilst in the Faeroe–Shetland Channel such activity may not have begun until latest Oligocene time (Eldholm, 1990; Damuth and Olson, 1993). This time lag most probably reflects different sources of deep-water masses, with inter-basinal mixing restricted by the Wyville–Thomson Ridge which has provided an effective barrier to deep-water exchange between the two basins.

In the Rockall Trough, bottom circulation was initially very vigorous and was accompanied by significant lateral migration of sediment by upslope accretion onto the flanks of the basin (Stoker, 1998), although a wide zone of erosion and/or non-deposition may have prevailed in the northeastern part of the trough, adjacent to the Wyville–Thomson Ridge. However, current strength gradually decreased and stabilised during the early to mid-Miocene (Stow and Holbrook, 1984). The effects of latest Palaeogene bottom-current erosion are also preserved in the Faeroe–Shetland Channel, in the form of a regional irregular erosion surface on the lower West Shetland Slope and in the channel, with a relief of up to 200 m (Damuth and Olson, 1993; Stoker et al., 1993). Although this surface is now mostly buried, several deeps or gullies on the present basin floor are partially infilled remnants of this erosion surface. In both basins, the bulk of the overlying Neogene–Quaternary strata accumulated under more-stable conditions. In the northeast Rockall Trough, this resulted in the development of a major, sediment-drift-complex (Howe et al., 1994), but in the Faeroe–Shetland Channel the basin-floor sediments are mostly flat-lying and largely devoid of any distinctive current-induced morphology (Akhurst, 1991; Stoker et al., 1991). On the lower part of the Hebrides–West Shetland Slope, these sediments interdigitate with, or are buried beneath, locally thick mass-flow deposits of the slope apron including the Sula Sgeir Fan (Stoker et al., 1993; Stoker, 1995) (Fig. 2). Since the Late Pliocene (about 2.48 Ma), the continental margin has accumulated ice-rafted debris, with more extensive shelf glaciation in the last 0.5 Ma, and the contourites retain a glaciomarine signature (Stoker et al., 1994).

The present deep-water circulation pattern on the continental margin involves a number of complex water masses (Fig. 1). Cold (−0.5°C), southwest flowing, Norwegian Sea Deep Water (NSDW) fills the bottom of the Faeroe–Shetland Channel up to a depth of approximately 500 m (Dooley and Meincke, 1981). Intermediate water masses of warm Atlantic Water flow to the northeast on the eastern side of the channel and to the southwest on the western side. The volume of NSDW funnelled southwestwards along the Faeroe–Shetland and Faeroe Bank channels exceeds that which overflows the broad Iceland–Faeroe Rise, to the north (Dickson et al., 1990). A small portion of NSDW flows across the western end of the Wyville–Thomson Ridge and south into the Rockall Trough; here it partially mixes with Labrador Sea Water and Antarctic Bottom Water to form North Atlantic Deep Water (NADW) which flows southwards along the western margin of the Rockall Trough (Stow and Holbrook, 1984; Dickson and Kidd, 1986). The eastern flank of the Rockall Trough is influenced by a northward-flowing slope current down to a depth of 1000 m on the Hebrides Slope (Booth and Ellett, 1983; Kenyon, 1986; Huthnance, 1986; D.J. Ellett, pers. commun., 1994). The origin of this slope current is disputed: some elements of Mediterranean Deep Water have been detected by its high silica and salinity values (Harvey, 1982; Hill and Mitchelson-Jacob, 1993), and some entrainment of the deeper NADW is possible. Termed North-East Atlantic Water (NEAW), this slope current continues north at water depths of less than 1000 m until it is deflected and accelerated to the west by the Wyville–Thomson Ridge.

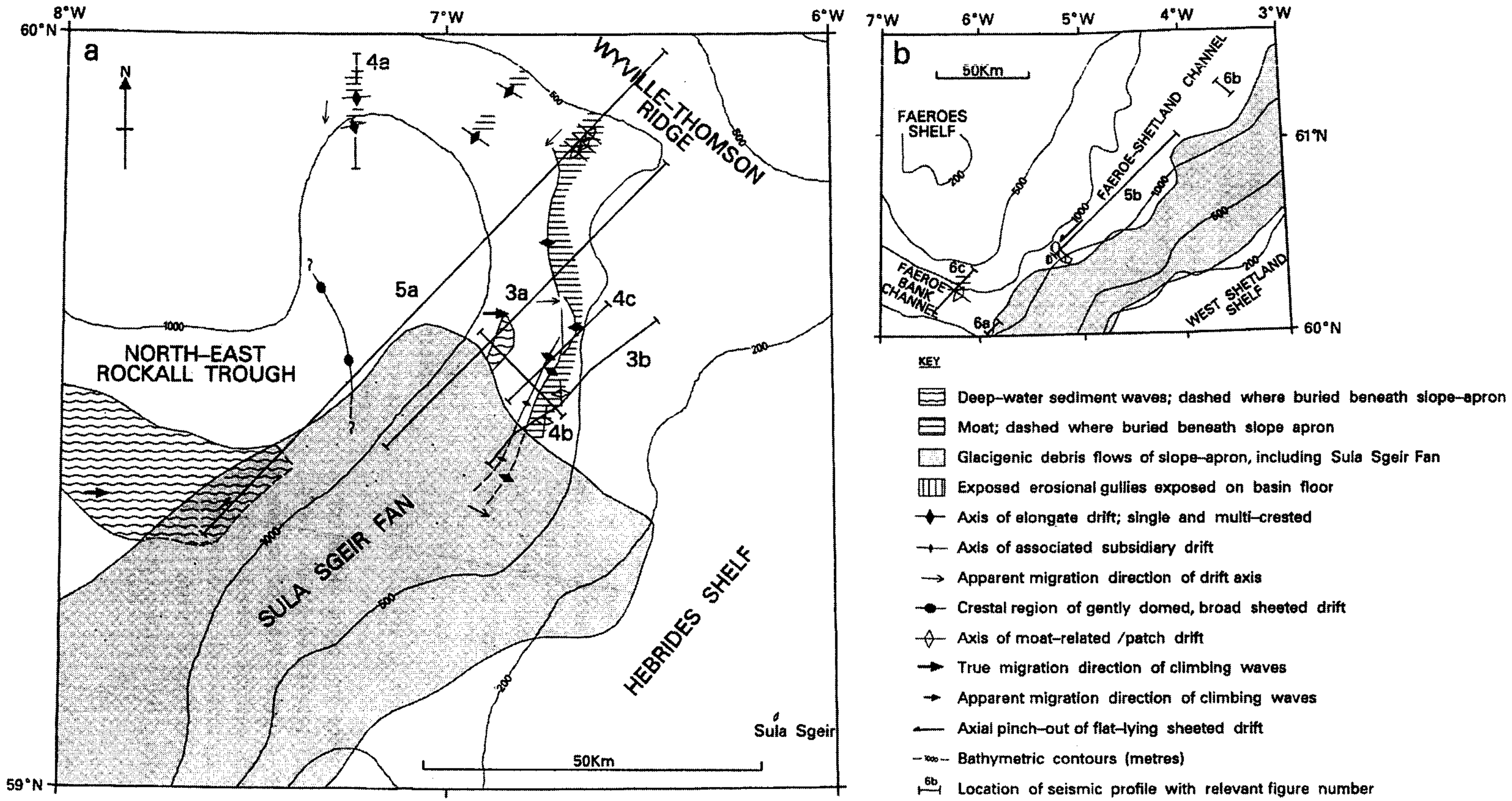


Fig. 2. Schematic maps showing main morphological features of sediment drifts in (a) northeast Rockall Trough (modified after Howe et al., 1994), and (b) Faeroe–Shetland Channel, together with locations of seismic profiles illustrated in Figs. 3–6. Maps are presented at different scales because of the variable complexity of the two areas. Maps are located in Fig. 1.

Current-meter observations have provided some indication of the velocities of the water masses circulating within the area. Flow of NSDW at the centre of the Faeroe–Shetland Channel in a water depth of 900 m has been recorded between 13 and 22 cm s^{-1}, although peak flows of 33 cm s^{-1} have been measured (cf. Akhurst, 1991). On the northern Hebrides Slope, in water depths of 403 m and 468 m, velocities between 26 and 48 cm s^{-1} have been detected for the NEAW slope current, whilst farther south, in the region of the Geikie Escarpment, peak flows of 15 to 25 cm s^{-1} have been monitored in water depths 1035 m and 457 m, with consistent flows along the bathymetric contours to the northeast (cf. Howe and Humphrey, 1995).

3. Contourite deposits

3.1. Seismic characteristics

On a regional scale, seismic reflection profiles have revealed significant differences between contourites preserved in the northeast Rockall Trough and the Faeroe–Shetland Channel. The trough is primarily an area of sediment accumulation, and several types of sediment drift have been identified on the profiles. In contrast, the funnelled morphology of the Faeroe–Shetland Channel resulted in stronger currents, greater winnowing and erosion of the sea floor, and a condensed sequence of sheet-form contourites has accumulated. The main characteristics of the contourite successions in seismic profiles are illustrated in Figs. 3–6; these are described in more detail below.

3.1.1. Northeast Rockall Trough: sediment-drift complex

A sediment-drift complex has been identified in the northeast Rockall Trough (Howe et al., 1994). This complex consists of three types of sediment drift: (1) elongate drift and associated sediment waves; (2) broad sheeted drift and associated sediment waves; and (3) moat-related drifts. An erosional moat is present along the northeast margin of the drift complex.

3.1.1.1 Elongate drift. The elongate drift displays a mounded, asymmetric profile, is up to 300 m thick and up to 20 km wide, with a maximum relief above seabed of 150 m (Figs. 3–5a). The drift axis can be traced along the base of the Wyville–Thomson Ridge and northernmost Hebrides Slope for about 60 km, but is buried beneath the glacigenic slope apron to the south (Fig. 2). The distal edge of the slope apron is illustrated in Fig. 3a and Fig. 5a, where debris flows overlie and therefore post-date the bulk of the contourite deposits.

On the seismic profiles, the drift exhibits a layered reflection pattern, the reflections ranging from parallel and continuous to divergent or convergent resulting in non-uniform thickness of the component layers. A smaller, subsidiary drift is locally developed on the lee-side (west) of the main drift (Fig. 3b, Fig. 4b). Locally, the axis of the elongate drift splits and the subsidiary drift displays enhanced development to a similar geometry and dimension as the elongate drift; the result is a *multi-crested drift* with several contemporaneously active crestal regions (Fig. 4c). This along-strike variation may be rapid as is illustrated by the intersecting profiles in Fig. 4b and c which image the same drift in adjacent locations (Fig. 2). Inspection of the sparker profile in Fig. 4c indicates that the multi-crested drift-form developed out of a single drift that is now buried. A change in sea-floor topography preserved in the middle part of the sequence indicates the onset of multi-crested drift development. This may have resulted from a change in palaeoceanographic circulation during deposition. Farther west, an apparently multi-crested drift (Fig. 4a) may have similarly resulted from a change in the bottom-current regime adjacent to the Wyville–Thomson Ridge, with the result that the elongate drift has shifted laterally, basinward (away from the Wyville–Thomson Ridge), remaining as a single drift. This differs from the above multi-crested drift in that only one drift axis is actively developing. A less dramatic basinward-shift in the drift axis, illustrated in Fig. 5a, reinforces the variable along-strike character of this elongate drift.

Well-developed sediment waves are locally preserved on the basinward side of the elongate drift; these have a wavelength of about 2 km and a height above sea bed of about 20 m (Fig. 4b). The internal geometry of the waves displays alternating asymmetric and sinusoidal units indicative, respectively, of active upslope migration and passive suspension

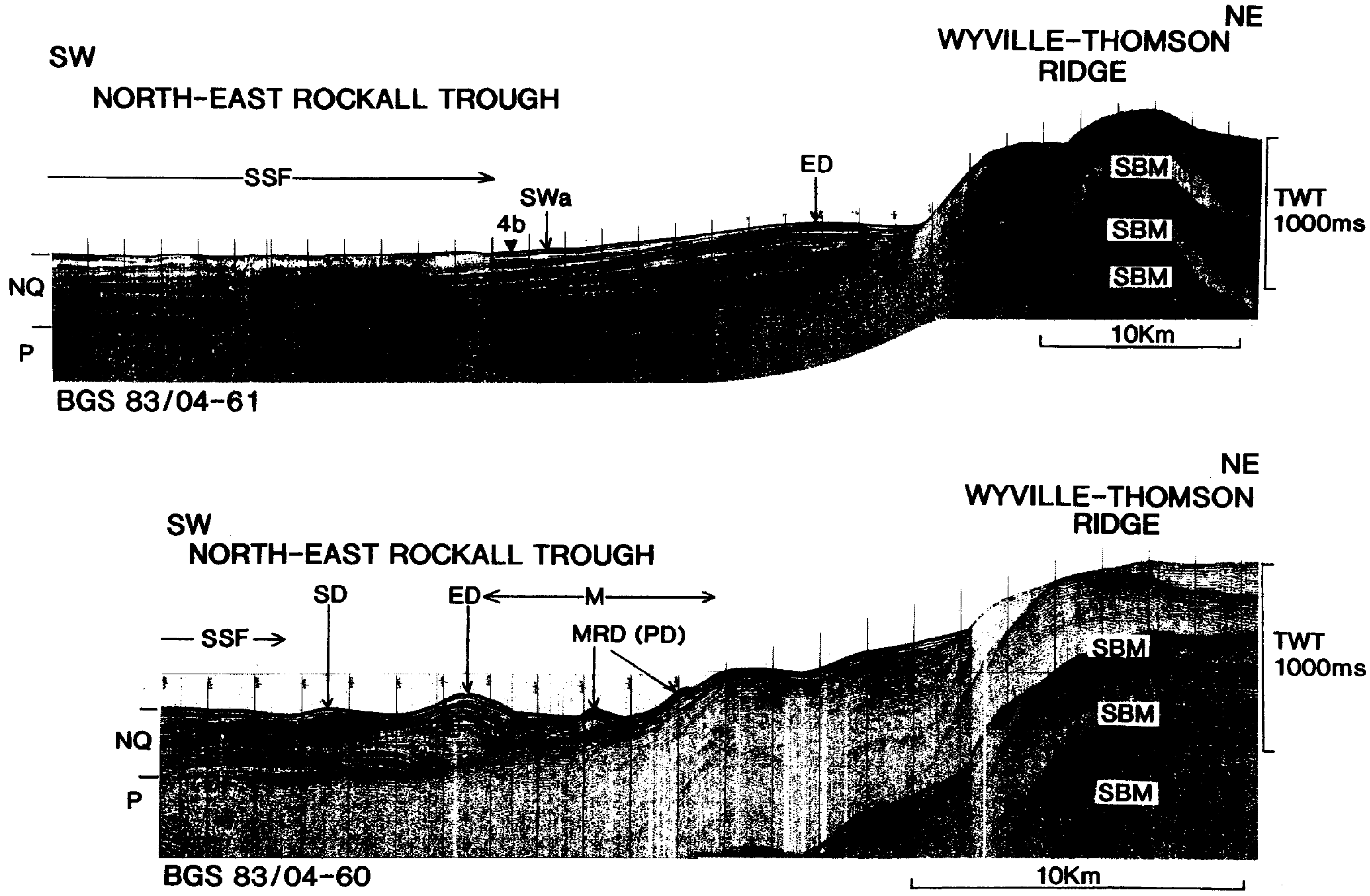
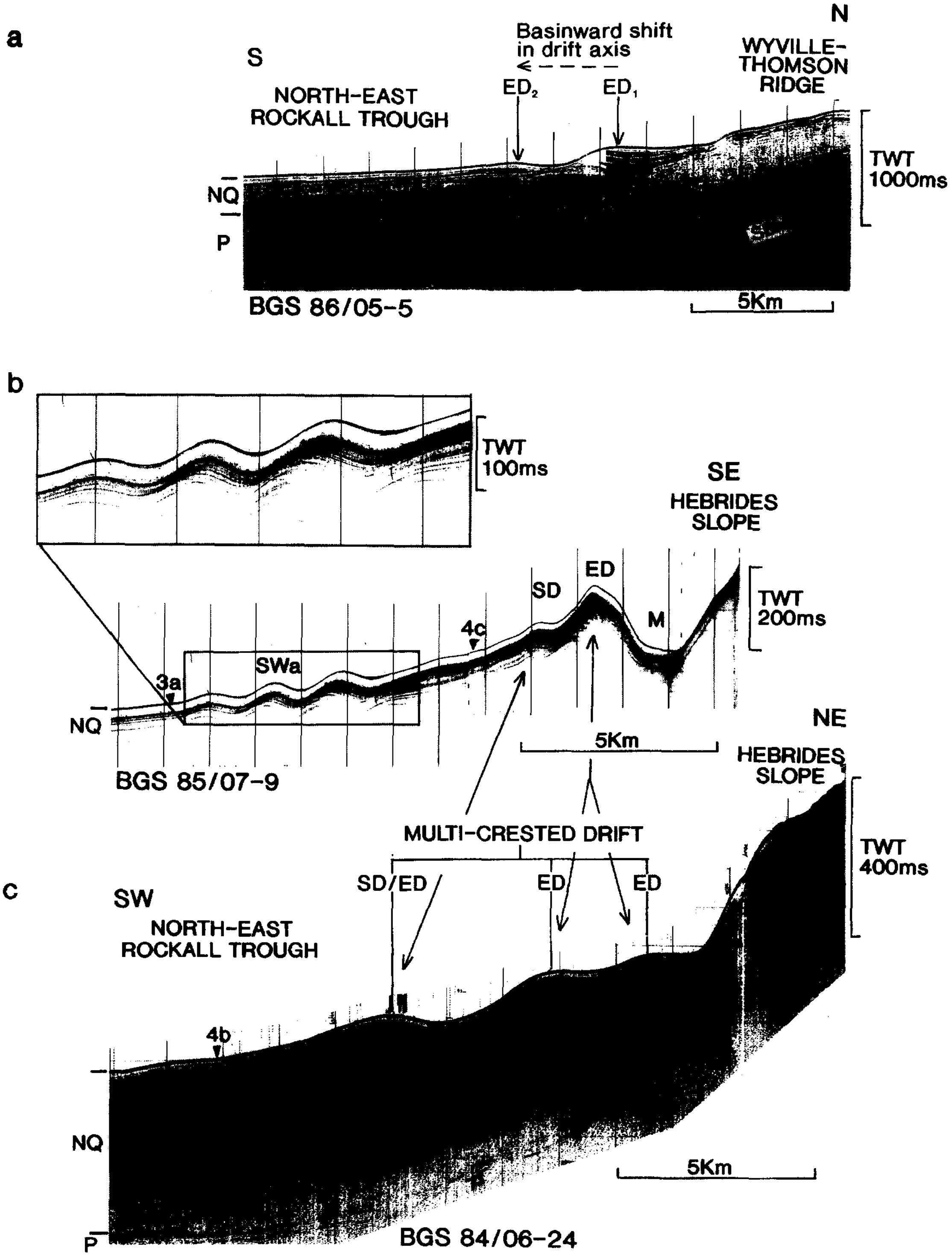


Fig. 3. Single-channel airgun profiles illustrating the seismic characteristics of (a) the elongate drift and sediment waves, and (b) the elongate, subsidiary and moat-related drifts in the northeast Rockall Trough, adjacent to the Wyville–Thomson Ridge. In both profiles, the drift complex is partially buried below the distal edge of the Sula Sgeir Fan. Abbreviations: *ED* = elongate drift; *SD* = subsidiary drift: *MRD* = moat-related drift; *PD* = patch drift; *M* = moat; *SSF* = Sula Sgeir Fan; *NQ* = Neogene–Quaternary; *P* = Palaeogene; *SBM* = sea-bed multiple; *TWT* = two-way time. Profiles are located in Fig. 2; intersection with Fig. 4b is indicated in Fig. 3a. Estimates of scale on the seismic profiles are calculated by assuming the velocity of sound in water is 1.45 km s^{-1}, and in sediments from 1.55 km s^{-1} to 1.8 km s^{-1}, based on increasing compaction with depth (Hamilton, 1985).


a
S
NORTH-EAST ROCKALL TROUGH
Basinward shift in drift axis
ED$_2$
ED$_1$
N
WYVILLE-THOMSON RIDGE
NQ
P
TWT 1000ms
BGS 86/05-5
5Km
b
TWT 100ms
SE
HEBRIDES SLOPE
SD
ED
M
4c
SWa
3a
NQ
TWT 200ms
5Km
BGS 85/07-9
NE
HEBRIDES SLOPE
MULTI-CRESTED DRIFT
SD/ED
ED
ED
c
SW
NORTH-EAST ROCKALL TROUGH
4b
NQ
P
TWT 400ms
5Km
BGS 84/06-24

draping (Howe, 1996). An overall upslope direction of sediment accretion is evident from the profiles; the asymmetry of the uppermost sediment layers indicates that the waves are currently in an active phase.

3.1.1.2 Broad sheeted drift. The broad sheeted drift occupies a large part of the basin floor to the west of the elongate drift (Fig. 5a) (Howe et al., 1994). This sediment accumulation is up to 490 m thick, several tens of kilometres across, and displays a relief of up to 60 m above the general basin floor. Its western extent is unknown but is beyond the limit of the data set; to the south, it is buried beneath the glacigenic slope apron of the Hebrides Slope (Fig. 2, Fig. 5a). The sediments display a layered character in seismic profiles, the reflectors are parallel and laterally continuous with low-angle downlap to the northeast observed at the base of the drift. This is related to a slopeward migration of the drift; the broad crestal region of the drift has migrated approximately 10 km to the northeast during the late Cenozoic.

A large field of sediment waves occurs on the southwest flank of the broad sheeted drift (Fig. 5a). These extend over an area of about 550 km^2, and form a sediment package of up to 200 m thick. Richards et al. (1987) divided the package into a basal set of climbing sediment waves, up to 105 m thick, passing upwards through a transitional unit into an upper unit characterised by sinusoidal waves, some of which have heights of 18 m and wavelengths of over 1 km. These waves were likened by Richards et al. (1987) to shallow-water sandy climbing ripples moving by traction. However, it should be noted that (1) the size of these deep-water waves is considerably greater than that of sediment ripples, and (2) that sediment transported to such marginal deep-water areas is predominantly in suspension and is, therefore, usually very fine-grained. Howe et al. (1994) demonstrated an upcurrent/oblique current migration direction towards the Hebrides Slope, consistent with the migration direction of the drift complex. The sediment waves retain some sea-bed expression except where locally overlain by the distal edge of the glacigenic slope apron. Their present sinusoidal morphology and partial burial beneath the glacigenic deposits suggests that they are not presently active.

3.1.1.3 Moat-related drifts. The moat-related drifts are a relatively small-scale component of the drift complex. Their size and geometry vary from small, isolated, asymmetric drifts, 30 m thick and, 1 to 2 km wide, on the slope side of the moat (Fig. 3b), to larger drifts, up to 100 m thick and 4 km wide, plastered on the flank of the elongate drift, on the basinward side of the moat, and displaying a more subdued relief (Fig. 5a). In the latter example, despite the local basinward shift of the elongate drift, the contourite sediments have continued to onlap the flank of the Wyville–Thomson Ridge due to the development of the associated moat-related drifts. On seismic profiles, the moat-related drifts are acoustically well-layered and characterised mainly by semi-continuous, parallel reflectors, but with occasional discontinuous erosional horizons. Because such small drifts are not exclusively related to an erosional moat (see below), the more generic term patch drift (cf. Carter and McCave, 1994) may be applicable.

3.1.1.4 Moat. An erosional moat is evident at the base of the Hebrides Slope and on the flank of the Wyville–Thomson Ridge. In profile, this varies, commonly over short distances, from a broad shallow depression to a deeper well-defined depression (Figs. 3–5a). The width of the moat varies from 2 to 6 km, with depths of up to 100 m relative to the crest of the adjacent elongate drift. Locally, the moated area has migrated westwards away from the flank of the Wyville–Thomson Ridge (Fig. 4a).

Fig. 4. (a) Single-channel airgun profile showing an apparent double drift in the northeast Rockall Trough, adjacent to the Wyville–Thomson Ridge, resulting from the basinward shift in location (ED_1 to ED_2) of a single-crested elongate drift. (b) Deep-tow boomer profile illustrating the characteristics of the elongate and subsidiary drifts, and associated sediment waves, at the foot of the Hebrides Slope; inset shows detail of sediment waves, particularly the alternation of asymmetric and sinusoidal units. (c) Sparker profile showing multi-crested drift development at the foot of the Hebrides Slope. This represents the along-strike development of the elongate and subsidiary drifts shown in Fig. 4b, into three separate, but contemporaneously active drifts of broadly equal dimension (see text for details). Abbreviations as in Fig. 3. Profiles are located in Fig. 2; intersection of profiles indicated by figure numbers.

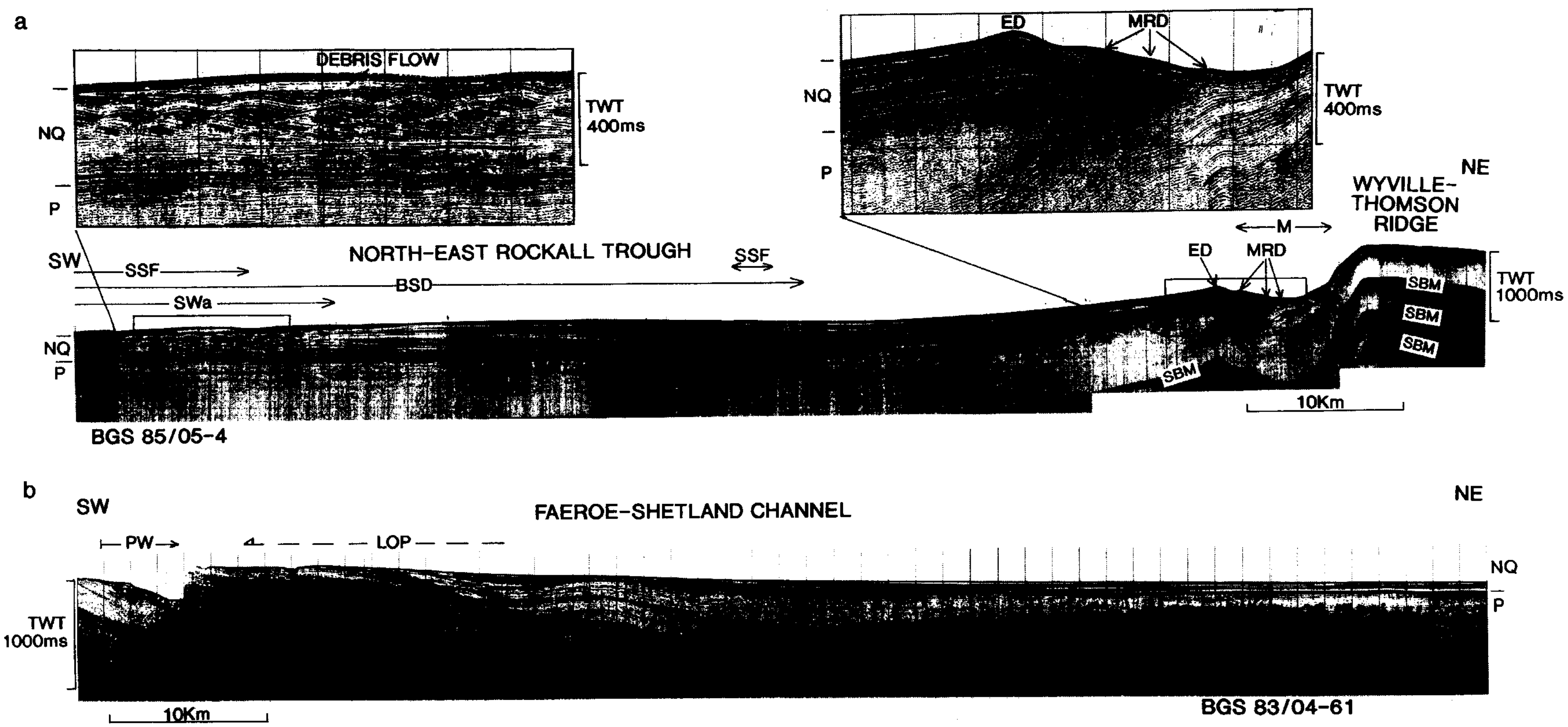


Fig. 5. (a) Single-channel airgun profile showing the seismic characteristics of the elongate and moat-related drifts adjacent to the Wyville–Thomson Ridge, together with the gently domed, broad sheeted drift and associated sediment waves in the northeast Rockall Trough. Insets: (top left) buried sediment-wave field with upward change from asymmetric to sinusoidal waves; (top right) despite southwestward (basinal) migration of elongate drift axis, contourite sediments progressively onlap the Wyville–Thomson Ridge due to moat-related drift development. (b) Single-channel airgun profile along the axis of the Faeroe–Shetland Channel showing the seismic characteristics and flat-lying nature of the sheet-form contourites in the channel, and their progressive southwestward onlap and pinch-out onto the underlying, gently folded, Palaeogene strata which may be locally exposed at the sea bed. An erosional gully at the southwest end of the profile has been partially infilled by a thin prograding wedge of Neogene–Quaternary sediments. Abbreviations as in Fig. 3 except: *BSD* = broad sheeted drift; *PW* = prograding wedge; *LOP* = low-angle onlap and pinch-out. Profiles are located in Fig. 2.

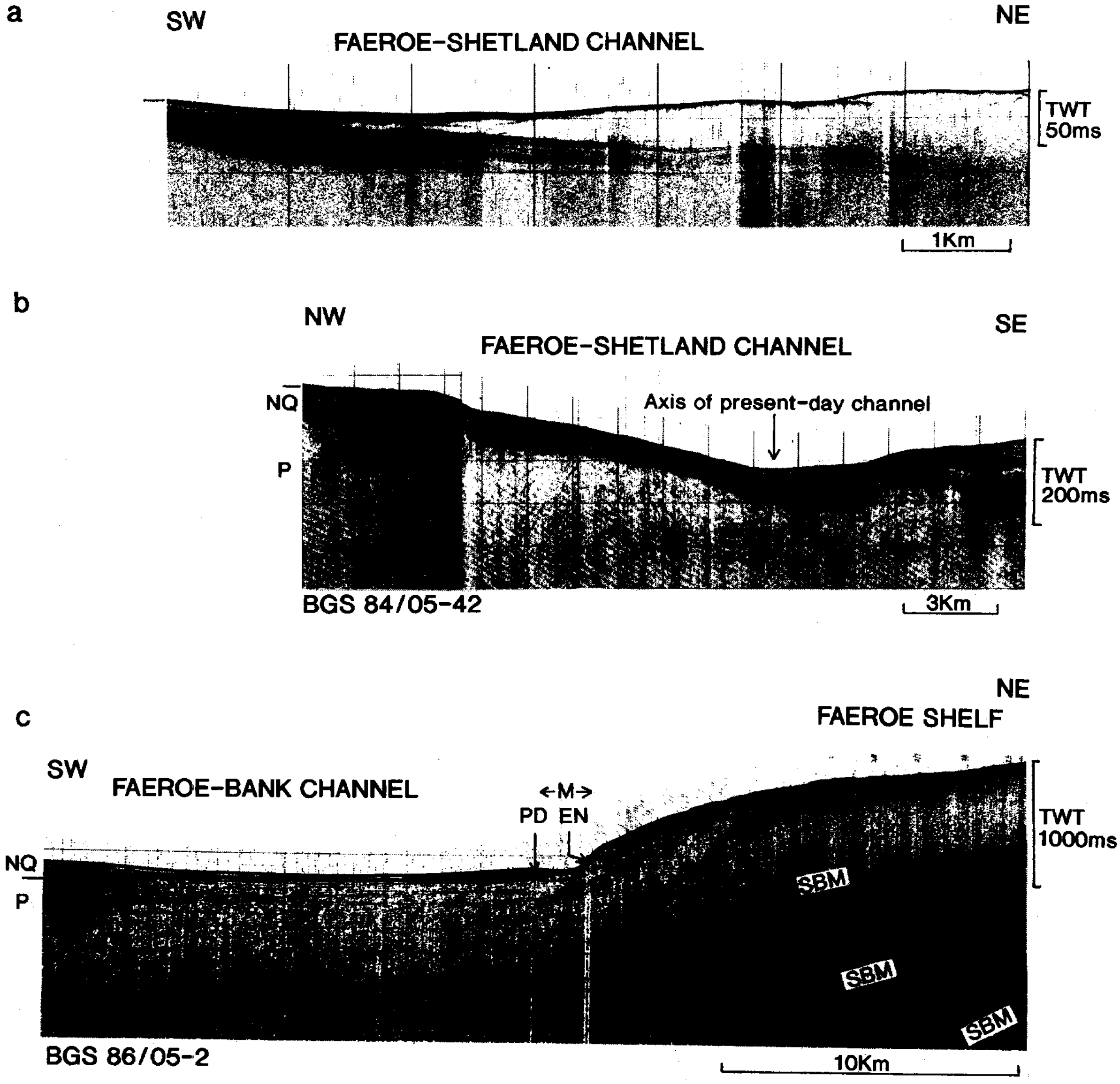


Fig. 6. (a) Deep-tow boomer profile from the Faeroe–Shetland Channel showing the pinch-out of acoustically layered, sheet-form contourites onto the exhumed upper surface of a debris-flow package. (b) Sparker profile across the Faeroe–Shetland Channel showing acoustically layered sheet-form contourites overlying folded and eroded Palaeogene strata. Note the variable thickness of the contourite sequence and the truncation of reflectors by sea-bed erosion along the axis of the present-day channel. (c) Single-channel airgun profile across part of the Faeroe Bank Channel showing a predominantly thin, sheet-form character to the Neogene–Quaternary contourite section, but with a small patch drift developed adjacent to the southern Faeroe Slope. Note also the steep erosional notch cut at the base of the slope. Abbreviations as in Fig. 3 except: *EN* = erosional notch. Profiles are located in Fig. 2.

3.1.2. Faeroe–Shetland Channel: sheeted drifts

The basin-floor sediments in the Faeroe–Shetland Channel display a predominantly sheet-form geometry and are characterised by parallel, laterally continuous seismic reflectors (Fig. 5b, Fig. 6). Strong bottom currents have largely maintained a flat-lying sea bed, although very subtle, open undulations may be present (Fig. 5b, northeast end). At its maximum extent, the sheeted drift is up to 80–100 m thick (Stoker et al., 1993).

Locally, reflectors in the basal part of the contourite sequence display evidence of downlap and onlap onto the latest Palaeogene unconformity, and internal convergence over palaeotopographic highs (Fig. 5b, Fig. 6b). The latter is interpreted as depositional thinning over the highs and is a feature of the entire channel-floor succession. Truncation of reflectors at very low angles is observed within the succession in the central part of the channel, suggesting local, short-lived, erosive episodes (Akhurst, 1991). However, the effects of such erosion are most clearly illustrated at the present sea bed where there is erosion and downcutting into the channel-floor succession (Fig. 5b, Fig. 6b). At the southwest end of the channel, where the currents are strongest, erosion of the sea bed is evident where the acoustically well-layered sediments pinch out onto the exhumed upper surface of glacigenic debris flows (Fig. 6a) (Stoker et al., 1991). Low-angle onlap and progressive pinch-out of the sheet-form contourites along the axis of the Faeroe–Shetland Channel is illustrated in Fig. 5b, as the channel floor shallows to the southwest.

A slightly different sediment package occurs locally at the shallower southwestern end of the Faeroe–Shetland Channel. A thin prograding wedge of Neogene–Quaternary sediment has accumulated on the southern flank of a discrete, partially infilled, erosional gully associated with the latest Palaeogene erosion surface (Fig. 5b) (Stoker, 1990). On the steeper side of the gully, little or no sediment has accumulated since the mid-Tertiary and Eocene strata may locally crop-out at the sea bed. Mounded sediment drifts (or patch drifts), although atypical of the channel in general, are also locally present. One example is preserved at the junction of the Faeroe–Shetland and Faeroe Bank channels, where a drift up to 100 m thick and about 5 km wide encroaches onto the northern flank of the channel (Fig. 6c). A steep erosional notch is also observed on the slope side of the associated moat. However, in the central part of the channel a sheet-form geometry is maintained.

3.2. Lithological characteristics

Recent studies of numerous short cores recovered from both the northeast Rockall Trough (gravity cores, to 2 m length) and the Faeroe–Shetland Channel (vibrocores, to 5 m length) indicate that the uppermost part of the drift succession is dominated by fine-grained muds and sands of a glaciomarine origin (Stoker et al., 1989, 1991, 1993; Akhurst, 1991; Howe et al., 1994; Howe, 1995, 1996). Three facies can be distinguished within these sediments on the basis of grain-size characteristics, sedimentary structures and composition (using the classification of Folk, 1974). These are muddy sand, sandy mud and mud facies (Table 1), each of which may include lithic clasts of glaciomarine origin, in more- or less-concentrated horizons. The nature and interpretation of these facies are summarised below.

3.2.1. Northeast Rockall Trough contourites

The sea-bed layer in all of the cores examined from the northeast Rockall Trough consists of a muddy sand facies, up to 28 cm thick, which is moderately well sorted, greyish yellow, intensely bioturbated, and with comminuted shell material. Cross-bedding is only rarely preserved. A similar muddy sand layer has also been noted in the lower section of a single core from the moated area adja-

Table 1
Characteristics of contourite deposits (summarised from Stoker et al., 1989; Akhurst, 1991; Howe et al., 1994; Howe, 1995)

Sediment facies	Grain size	Sedimentary structures	Thickness	Interpretation
Mud facies	Mud with <1% lithic clasts	Small-scale (<5 mm) homogenising bioturbation and larger burrow structures	Up to 2.28 m thick	Muddy contourites
Sandy mud facies	Slightly sandy mud and sandy mud with <1% lithic clasts	Small-scale (<5 mm) homogenising bioturbation and larger burrow structures	Up to 3 m thick	Silty muddy contourites
Muddy sand facies	Muddy sand or slightly gravelly muddy sand with 3% lithic clasts	Small-scale (<5 mm) homogenising bioturbation and larger burrow structures. Cross-bedding rare.	Less than 0.5 m thick	Sandy contourites

cent to the elongate drift (Howe et al., 1994). This facies is interpreted as a sandy contourite with 30–80% medium- to fine-grained sand and <45% mud.

The sandy mud facies underlies the sea-bed muddy sand layer in all of the cores. It is up to 55 cm thick, poorly sorted, olive brown, and with sporadic gravel clasts. Only in some intervals there is lamination in cores and X-radiographs. Small-scale fining- and coarsening-upward units, a few tens of centimetres in thickness, are common. Bioturbation is intense throughout. This facies is interpreted as a silty muddy contourite with up to 70% silt and 10–40% sand and minor gravels.

A poorly sorted, intensely bioturbated, homogeneous mud facies occurs in the lower sections of the cores. The mud is composed of up to 95% silt–clay, <5% sand and variable but low amounts of gravel. In most cases, the mud lacks any evidence of bottom-current influence and is best interpreted as being of hemipelagic origin (Howe, 1995). Subtle grain-size variation and indistinct lamination in parts may suggest the influence of weak bottom currents and hence the development of muddy contourites, although the evidence is equivocal.

Interbedded with the contourite and hemipelagite facies are thinner (<10 cm), poorly sorted, sandy pebbly muds and muddy gravels, composed of 10–40% fine- to coarse-grained sand, 50–90% mud and 10–60% gravel. These sediments are interpreted as ice-distal glaciomarine deposits. Any evidence for bottom-current influence is generally masked by the dominance of the ice-rafted component. However, in some parts, coarsening- to fining-upward sequences are present, together with probable erosive contacts, which implies that winnowing and erosion has taken place.

3.2.2. *Faeroe–Shetland Channel contourites*

Sediment cores from the Faeroe–Shetland Channel have a poorly sorted glaciomarine character (Akhurst, 1991). Lithic dropstone clasts and fine-scale homogenising bioturbation are ubiquitous. Larger (>5 mm) biogenic burrow structures are also common, cutting through the earlier bioturbated network.

A muddy sand facies, in beds from 15 to 50 cm thick, forms a minor (8%) but distinctive component of the cored sediments. Although some samples show >50% fine-grained sand, the mean grain size of most of these olive-grey sediments is medium- to coarse-grained silt, and they are therefore more correctly termed silts. No relict of primary lamination or cross-bedding is present, but lithic clasts are common throughout. Upper bedding surfaces are always gradational into the sandy mud facies; lower bedding surfaces may be gradational or are relatively unbioturbated, with evidence of erosion. The muddy sand facies is interpreted to be sandy (and silty) contourites.

The sandy mud facies comprises 60% of the cores examined. Beds of this facies are grey to olive grey and up to 3 m thick. Bedding contacts are gradational, bioturbation is common, and burrow types are diverse. The facies has a mean grain size of fine- to very fine-grained silt, and typically forms part of coarsening- to fining-upward sequences between muddy sand and mud facies. The sandy mud facies is interpreted as muddy and silty contourites.

Mud facies sediments are dark olive to olive grey and comprise 26% of the cores examined. These very fine-grained sediments may include distinctive *Zoophycos* burrows. Beds of the mud facies, up to 2.28 m thick, appear homogeneous. However, cyclical variation in mean size, between fine-grained silt and clay, demonstrates bottom-current influence during sediment accumulation. In most cases, bed contacts are gradational, although there is an erosive contact where directly overlain by muddy sand facies. The mud facies is interpreted as muddy contourites.

Coarsening-upward to fining-upward sequences of sandy, silty-muddy and muddy contourites are relatively common in Quaternary sediments of the Faeroe–Shetland Channel, in addition to the background glaciomarine sedimentation. Correlation of these facies sequences for more than 50 km along the floor of the Faeroe–Shetland Channel (Akhurst, 1991) emphasises the regional scale of bottom-current influenced deposition and demonstrates the accumulation of contourites with a sheet-form geometry. Subtle cyclical variation in mean grain size within the muddy contourites from the channel illustrates that the influence of bottom currents may be quite cryptic.

Lateral correlation of a coarsening-upward to fining-upward couplet to a fining-upward sequence with an erosive base within the channel, demonstrates pe-

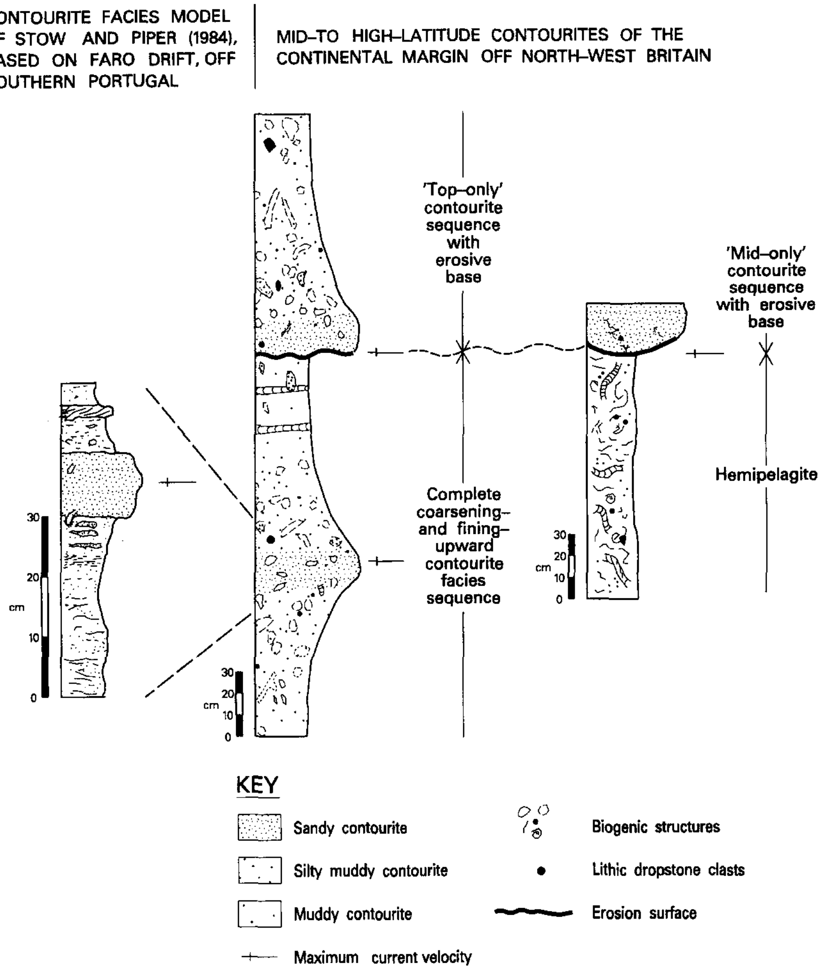


Fig. 7. Schematic logs illustrating the comparison of the standard contourite facies model of Stow and Piper (1984) with the contourite sequences recovered off northwest Britain; see text for details.

riods of very vigorous bottom-current flow. Where the erosive effects were locally intensified, coarsening-upward sequences, deposited as bottom-current velocity increased, were eroded as current velocity reached a maximum. The resulting fining-upward sequences with an erosive base are termed top-only contourite sequences (Akhurst, 1991) and have been identified in both the northeast Rockall Trough and Faeroe–Shetland Channel (Fig. 7). In the latter area, top-only contourites are noted where the sedimentary sequence is thinned over palaeotopographic heights. Sediment accumulation was, therefore, condensed by increased winnowing and non-deposition where currents were locally restricted over these highs.

4. Discussion

In the preceding sections we have presented an overview of bottom-current sedimentation on the continental margin off northwest Britain, as well as a comparison between the processes and deposits of the northeast Rockall Trough and Faeroe–Shetland Channel. The data presented raise several interesting aspects of broader relevance to contourite studies.

4.1. Seismic patterns of drift deposits

The northwest margin of Britain presents an area of varied morphology (gentle to steep slopes, semi-enclosed basins, topographic obstacles and barriers, etc.), that is influenced by several different water masses and associated bottom-current systems. It is this complexity that has promoted the development of varied drift types: mounded elongate drifts, broad sheeted drifts and moat-related drifts. These types conform with those described by Faugères et al. (1993) and synthesised as drift models by Stow et al. (1996). In addition, small-scale patch drifts occur at various locations on the margin, not necessarily specifically related to a channel or moat topography.

Certain specific features of these drifts appear to be indicative of the bottom-current regime under which they formed.

(a) Distinctly mounded drift forms, such as elongate drifts of the northeast Rockall Trough, have accumulated where there is a lateral gradient of decreasing velocity away from the core of a relatively strong, high-velocity bottom-current system. The development and migration of sediment-wave fields, together with slow migration of the drift as a whole, attests to the long-term stability of the current system in the region. However, the reasons for the precise location and extent of a sediment-wave field and their mechanism of formation are still largely unresolved (e.g. Flood and Shor, 1988; Howe, 1996).

(b) Broad sheeted drift forms, such as those of both the northeast Rockall Trough and Faeroe–Shetland Channel, are generally associated with large areas swept by currents of lower velocity than those which form the mounded drifts, in some cases where major bottom-current gyres develop in a semi-enclosed basin. Whereas this appears to be the case for the sheeted drift and associated sediment-wave field in the northeast Rockall Trough, that in the Faeroe–Shetland Channel probably formed under a more active current system resulting from the shallowing and narrowing of the Channel in the direction of the flow and funnelling of bottom currents that are thus able to maintain relatively high velocity across the whole channel floor. The sheeted drift in this case is relatively thin as a result of non-deposition, winnowing and erosion, most notably over highs on the basin floor. The surface of the drift is generally smooth, but with evidence of some irregular scour features in parts, and covered with a thin sandy contourite layer. Although some mounded drifts and associated moats are found in the Faeroe–Bank Channel, the region appears to have been more an area of sediment export than drift accumulation.

(c) Multi-crested drifts are indicative of a progressively more complex bottom-current pattern. They may form in response to a slight change in the bottom-current pathway and/or, splitting of the current into two or more strands, perhaps influenced by developing drift topography itself. Drift complexes result from the action and interaction of several different water masses, different bottom currents and associated gyres and strands, together with a varied topography. These conditions pertain in the northeast Roekall Trough.

(d) Erosion and non-deposition are equally characteristic of areas under the influence of bottom-current systems. Localised erosion beneath the cores of well-constrained currents is generally clearly expressed on seismic records as moats and scours associated with elongate mounds, patch drifts and pre-existing topographic features. More widespread erosion and non-deposition can occur where high bottom-current velocities are maintained over a broad area for a significant period of time. Erosive/non-depositional boundaries of this sort can be recognised as subparallel discontinuities within a contourite mound or sheet, that separate units of normal drift accumulation and/or slow lateral migration.

4.2. Sandy contourites and top-only contourites

The standard facies models for contourites show muddy, silty and sandy contourites, of either siliciclastic or biogenic composition, typically co-occurring in a coupled coarsening-upwards to fining-upwards sequence over a few tens of centimetres to a few metres in thickness (Fig. 7) (Stow, 1986; Stow et al., 1996). These are generally explained as the result of long-term variations in bottom-current velocity, but can be complicated by variations in sediment supply to the current system. As with the analogous Bouma sequence in turbidites, partial contourite sequences are the norm rather than the exception, as exemplified by the Faro Drift contourites (Gonthier et al., 1984; Stow et al., 1986). Sequences without the middle sandy division are explained by the bottom current never attaining the velocity for sand transport and deposition, whereas sequences with a missing lower or upper division are likely to

Table 2
Comparison between thin-bedded sandy turbidites and top-only contourite sequences

Thin-bedded sandy turbidites	*Top-only* contourite sequences
Flute casts may be present at the base of the sandy bed generated by the incursion of a high-velocity current	Erosion at the base is the result of a gradual increase in current velocity
Biogenic structures preserved at the base of the bed are casts of pre-existing horizontal burrows in the underlying bed	Large, post-depositional burrow structures transfer sandy contourite sediment down into the underlying mud
Sandy turbidites are deposited as turbidity currents wane in velocity	Sand-sized grains are concentrated by winnowing and non-deposition of finer-sized grains
Coarser grains or clasts usually concentrated at the base of the bed	Coarser grains or clasts, including ice-rafted debris, can be present throughout the sequence
All or part of the Bouma (1962) sequence of sedimentary structures may be distinguished	Fine-scale homogenising bioturbation is common; lamination or cross-bedding may be preserved if bioturbation is less intense
Post-depositional bioturbation may penetrate downwards from the hemipelagite top ('E' division of Bouma, 1962)	Fine-scale bioturbation keeps pace with the slow rate of sediment accumulation. Later burrow structures transfer sediments upwards and downwards

result from erosion during periods of high current velocity.

Both partial and complete contourite sequences are present in the northeast Rockall Trough and in the Faeroe–Shetland Channel (Fig. 7). Those in which winnowing and erosion has downcut and removed the lower divisions of silty and muddy contourites, but has preserved the middle sandy and upper fine-grained divisions, are termed *top-only contourites* by Akhurst (1991) and Howe (1995). Other examples exist where the erosive/winnowing episode has not only left a sandy contourite sitting directly on hemipelagic–glacigenic sediment, but has been followed by current switch-off rather than a fining-upward contourite sequence. These isolated sandy contourites can also be termed *mid-only contourites*.

The implications of mid- and top-only contourites, in particular, are significant with regard to recognition of contourites in ancient successions. Sandy contourites, by their coarse-grained texture and formation under strongest bottom-current flows, are the most likely to be preserved in certain ancient sequences. This is not the case, however, for extensive mud and silt contourite drift deposits where current velocities were never strong enough to deposit sand or cause erosion. Top-only contourites with sharp, erosive bases, and moderately well-sorted sands that grade up into silts and muds may superficially resemble turbidites, particularly thin-bedded sandy turbidites. Considered in detail, however, there are significant differences (Table 2). Top-only contourites are typically bioturbated throughout, grading is not uniform, the standard sequences of turbidite structures (Bouma, 1962; Stow, 1977) do not occur, and their composition is commonly a mixture of local, pelagic and exotic material.

On parts of the Hebrides Slope, a 5–50 cm thick sandy contourite layer is quite extensive. Sea-bed photographs from the area of the Geikie Escarpment show areas of fine, rippled contouritic sand and local patches of hemipelagite or contourite muds (Howe and Humphrey, 1995). Unpublished side-scan sonar data show a mobile sand layer being actively transported along the sea bed parallel to the contours by a strong northerly flowing slope current (C.C. Graham, pers commun., 1994; J. Armishaw, pers. commun., 1995). In the hunt for areas of contourite sand accumulation, the Hebrides Slope provides an important relatively modern analogue (see Viana et al., 1998).

4.3. Glacigenic contourites

It is now well known that, wherever contourites occur, they tend to reflect the regional sedimentation pattern. In the open ocean, for example, biogenic contourites of typically pelagic aspect are common (Kidd and Hill, 1986), and adjacent to volcanic edifices, volcaniclastic contourites are the norm (Stow and Holbrook, 1984). This is because a large part of the contourite sediment is derived locally via pelagic, hemipelagic and turbiditic input, and a much lesser part is far travelled in the bottom current itself. In high-latitude areas, therefore, an ice-rafted component is typically present, as reported from the Barents Sea (Yoon and Chough, 1993) and Antarctic margin (Gilbert et al., 1998). Where significantly moulded by bottom currents, these can be referred to as *glacigenic contourites*.

Glacigenic contourites are present in both the northeast Rockall Trough and Faeroe–Shetland Channel, although particularly abundant in the latter. The sediments display many features of glaciomarine deposits, including dropstones, extremely poor sorting and a composition of both coarse and fine fractions that is clearly supplied by ice rafting. The bottom-current overprint is evident in terms of coarsening-upward to fining-upward couplets, winnowing, sharp erosional contacts, and rare indistinct lamination. However, some of the particularly coarse-grained, poorly sorted, pebbly muds do not show clear evidence of current transport and may well be interpreted as glacigenic hemipelagites with abundant oversize dropstones. Their intercalation in the succession must reflect, in part, a pulsed supply of coarse ice-rafted detritus to the margin, rather than simple lag concentration by bottom current winnowing. In some cases they have been interpreted as debrites, the occurrence of which is well documented from seismic profiles along the Hebrides–West Shetland margin (Stoker et al., 1991; Stoker, 1995).

The occurrence of true gravel-lag glacigenic contourites, however, is evident on some parts of the margin from sea-bed photographs (J. Armishaw, pers. commun., 1995). Their recognition in cores must be based on the presence of contouritic features coupled with a glacigenic composition. The introduction of such material to the slope by debris flows will produce distinct beds with clear, sharp boundaries. By contrast, most of the coarse glacigenic contourites observed have very gradational contacts and form part of coarsening-upward to fining-upward sequences.

4.4. Implications for the rock record

The style of contourite deposition described from the northwest margin of Britain has some bearing on the search for fossil contourites. Contourite drifts, whether of a sheeted or mounded form, are not normally visible at outcrop due to their large scale, typically being tens of kilometres long and up to several hundreds of metres in thickness. However, the 'top-only' and 'mid-only' contourites recognised in cores may have implications for the rock record. Sandy contourites, by their very coarse-grained nature and formation under the strongest current flow, may represent the best chances for preservation. The sandy 'mid-only' contourites with erosive bases and moderate sorting trends could easily be confused with thin-bedded sandy turbidites, although the pervasive bioturbation and lack of a progressive sequence of features (Table 2) may be of use in their discrimination.

5. Conclusions

(1) A variety of sediment-drift styles are preserved in the northeast Rockall Trough and Faeroe–Shetland Channel. These include distinctly mounded drift forms (single- and multi-crested elongate drifts), gently domed and flat-lying, broad sheeted drifts and patch drifts (including moat-related drifts), together with the localised development of sediment-wave fields. The contrasting styles of the drifts reflects the variable bottom-current regime under which they formed; this was influenced, to some extent, by the complex bathymetry of the continental margin bounding the two basins. Whilst the northeast Rockall Trough has largely been a region of net accumulation with the development of the bulk of the mounded/gently domed drifts, the Faeroe–Shetland Channel has been more an area of sediment export resulting in a much thinner sequence of flat-lying sheet-form drifts. Patch drifts (including moat-related drifts) occur in both basins. In the northeast Rockall Trough, the along-strike progression from single- to multi-crested elongate drifts is perhaps a further response to bottom-current changes influenced by developing drift topography.

(2) Sediment cores recovered from the uppermost part of the drift sequences confirm the variable bot-

tom-current regime prevailing in the northeast Rockall Trough and the Faeroe–Shetland Channel, in that both partial and complete contourite sequences are preserved. Muddy, silty-muddy and sandy contourites have been identified; their texture and composition reflect the regional sedimentation pattern prevailing on the margin at the time of their deposition. In this mid- to high-latitude setting, the supply of detritus to these uppermost sediments was largely controlled by the Late Pleistocene ice sheets (Stoker et al., 1993). The recovered sediments described in this paper can, therefore, be referred to, collectively, as glacigenic contourites.

(3) Sandy contourites are an important component of the drift sequences recovered in the sediment cores. Their coarse-grained nature, and formation under strongest bottom-current flows, suggest that they are the most likely to be preserved in certain ancient sequences. However, the scale of the sediment drifts preserved on the continental margin off northwest Britain should also be borne in mind with regard to the recognition of contourites in the rock record.

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