Preliminary observations of Neogene–Quaternary depositional processes in the Faeroe–Shetland Channel revealed by high-resolution seismic facies analysis

J. E. DAMUTH and H. C. OLSON

Mobil Exploration and Producing Technical Center, PO Box 650232, Dallas, Texas 75265 USA

Abstract: The Neogene and Quaternary sediments of the Faeroe–Shetland Channel and West Shetland slope have been deposited and modified through the interaction of a variety of downslope and parallel-to-slope depositional processes. The upper slope is dominated by mass-transport deposits (debris flows) which progressively diminish downslope. These were apparently deposited during glacial cycles when ice sheets reached the shelf edge and supplied large amounts of terrigenous sediment to the slope. Thin, prograding clinoforms separate packages of debris flows and may represent glacial marine sedimentation during periods of ice retreat from the shelf edge (e.g. interstadials). A few submarine canyons occur on the slope and probably provide conduits to the basin for turbidite currents and related mass flows. The middle to lower slope appears to be dominated by glacial marine, hemipelagic and possibly turbidity-current deposits, which have been subjected to reworking by contour currents at many locations. A thick deposit that has the appearance of a deep-sea fan occurs on the middle slope in the northeast part of the area. Although many individual seismic packages within this feature have the appearance of aggradational channel–levee systems, these packages may actually represent contourite deposits. Large migrating sediment waves occur just downslope from this feature and suggest that strong contour currents have interacted with the downslope processes to redistribute sediments on the lower slope. The basin floor has thin conformable sediments that appear to be predominantly glacial marine and hemipelagic with occasional turbidites and debris flows. Thick, extensive debris-flow deposits also occur beneath the basin floor in the northeastern part of the area. The Neogene–Quaternary sediments are separated from the Paleogene section by a major regional unconformity of latest Oligocene or early to middle Miocene age, which forms a major sequence boundary throughout the region.

Fig. 1. Bathymetric map of the Faeroe–Shetland Channel and West Shetland continental shelf and slope showing locations of seismic lines (dashed) interpreted. Solid portions of lines show profiles illustrated in Figs 2–7. Bathymetry is redrawn from Roberts et al. (1977). Contour interval is 200 m. Inset shows location of area.

Preliminary seismic-sequence and seismic-facies analyses of a grid of high-resolution (50–250 Hz airgun) seismic profiles from the southeastern side of the Faeroe-Shetland Channel (Fig. 1) were undertaken to understand better the Neogene and Quaternary depositional processes in this region. This study was conducted in conjunction with a detailed seismic-stratigraphic analysis using conventional multi-fold seismic of the underlying Paleogene strata of the Faeroe Basin (Mitchell et al. 1993). The Neogene-Quaternary section was studied using high-resolution seismic data because the higher frequencies recorded in these data can potentially provide extremely well imaged examples of the seismic facies, depositional features and stratal geometries and relationships. Thus, depositional features and processes can often be more easily and confidently identified than is possible with standard multi-fold seismic data. These Neogene features and processes can therefore provide important ‘modern’ analogues that may assist in the interpretation and identification of descriptive features in the more deeply buried Paleogene section, which are less well imaged on conventional multi-fold seismic data.

**Regional setting and previous work**

The Faeroe–Shetland Channel is an elongate basin that trends NE–SW between the West Shetland Shelf and the Faeroe Shelf (Fig. 1). The channel is up to 200 km wide between respective shelf breaks (200 m contour) and deepens to the northeast along its axis from about 1000 m at the southwestern end near the Wyville-Thompson Ridge to more than 1700 m where it enters the Norwegian Sea. The Faeroe–Shetland Basin beneath the channel is a major depocentre where sediments have been accumulating since the Paleozoic (Dundam and van Hoorn 1987; Haszeldine et al. 1987; Hunter and Ritchie 1987; Ziegler 1988; Stoker 1990a; Mitchell et al. 1993). A prominent mid-Tertiary unconformity (Fig. 2, latest Oligocene unconformity) forms a major erosional surface throughout the basin and is overlain by a clastic wedge of Miocene (?) to Holocene sediments, which ranges in thickness from less than 60 m beneath the channel floor to more than 400 m beneath the upper continental slope (Mudge and Rashid 1987; Stoker 1990a,b,c; Stoker et al. 1991; Mitchell et al. 1993).

The present watermass circulation in the Faeroe-Shetland Channel consists primarily of the warm (>9°C) Atlantic Surface Water, which flows northeastward into the Norwegian Sea, and the cold (<0.5°C) southwestward flowing Norwegian Sea Deep Water (NSDW), which returns cold water to the Atlantic (Crease 1965; Harvey 1965; Worthington 1970; Ellet and Roberts 1973; Meinecke 1983; Ellet et al. 1986; Saunders 1990). Current-meter data show that the NSDW extends from about 500 m water depth to the channel floor (Dooley and Meinecke 1981) and maintains a very strong SW to WSW current flow with mean velocities of 0.1 to 0.4 m/s and maximum velocities of 0.5 to 0.75 m/s (Akhurst 1991). Miller and Tucholke (1983) inferred that this vigorous southwest bottom-water flow from the Arctic through the channel into the North Atlantic was apparently initiated in the late Eocene to early Oligocene as a result of the separation of Greenland and Svalbard, and that bottom-water circulation stabilized to its present pattern in the middle Miocene. However, Eldholm (1990) concluded on the basis of more recent plate-tectonic and palaeoceanographic studies, that Norwegian-Greenland Sea deep waters were isolated throughout the Paleogene. Furthermore, vigorous deep-water exchange from the Arctic Ocean and the Norwegian-Greenland Sea to the North Atlantic basins was not initiated until the Neogene, probably during the middle or even late Miocene. A prominent mid-Tertiary erosional unconformity (Latest Oligocene Unconformity in Fig. 2) appears to separate the older Paleocene–Eocene succession from the overlying clastic wedge of late Tertiary age. This is thought to mark the onset of the strong abyssal circulation through the channel (Stoker 1990a,b; Stoker et al. 1991).

Recent studies using various high-resolution seismic records and shallow vibrocores (<10 m penetration) demonstrate that a variety of deep-water depositional processes have interacted to deposit the Pliocene and Quaternary sediments that form the late Tertiary clastic wedge in the Faeroe-Shetland Channel, and in the adjacent portion of the Rockall Trough to the south (Stoker et al. 1989, 1991; Holmes 1990; Stoker 1990a,b,c; Stevenson 1990a,b; 1991a,b; Akhurst 1991). In particular, studies by Akhurst (1991) and Stoker et al. (1991) were conducted at the southwestern end of the Faeroe-Shetland Channel in areas adjacent to, and slightly overlapping, the area.

---

**Fig. 2.** Multi-fold seismic dip line from Faeroe Basin showing Paleogene seismic sequences interpreted by Mitchell et al. (1993). Location shown in Fig. 1 (X-Z). The latest Oligocene unconformity is marked by the yellow/orange horizon near the top of the section. High-resolution seismic lines in Figs 3–7 image the relatively thin Neogene/Quaternary section above this unconformity (dashed lines labelled LOU). Note the presence of thick Oligocene section beneath the unconformity.
Fig. 3. High-resolution airgun dip seismic lines which extend from the West Shetland shelf to the Faeroe-Shetland Channel floor and illustrate the regional morphology, seismic facies and depositional features described in the text. Profile A–F (top) is from the northeastern part of the study area and Profile G–L (bottom) is from the southwestern end of the study area. The dashed line (LOU) marks the latest Oligocene unconformity and M marks the first water-bottom multiple on these profiles as well as profiles shown in Figs 4–7. Locations of all lines in Figs 3–7 (A–W) are shown in Fig. 1.
of the present study. Stoker et al. (1991) showed that mass-transport processes have formed pervasive deposits consisting mainly of debris-flow diamictons composed of redeposited glaciogenic deposits. Packages of acoustically transparent debris-flow deposits are separated by acoustically well-stratified sediments that consist primarily of glaciomarine hemipelagites and contourites. These debris flows were generated mainly during glacial cycles when ice-marginal sedimentation was pervasive on the outermost shelf and upper slope. Bottom-current activity (contour currents) was apparently relatively weak during glacial cycles, but became much more vigorous during the transition from glacial to interglacial cycles.

Based on detailed core studies, Akhurst (1991) documented the importance of contour-current activity in the channel during the latest Quaternary, and concluded that contour-current activity has led to decreased rates of sediment accumulation (generally  10 cm/10^7 yr) by entrainment and transport of the finer components of ice-rafted sediments as they were deposited. The strength of these bottom currents apparently fluctuated in cyclical patterns throughout stadial, interstadial, and interglacial conditions with the most intense fluctuations in velocity during both the Holocene and the Last (Eemian) Interglacial. In addition to deposition by ice-rafting and contour-current processes, Akhurst (1991) also documented evidence for mass-transport processes and weak ('low concentration') turbidity-current deposition.

**Database**

The present study utilized high-resolution seismic lines selected from grids acquired by the British Geological Survey (Fig. 1). Most of the lines are from the 44-line BGS 85/05 survey in the northeastern half of the study area; the remaining lines are from the BGS 79/14 and 83/04 surveys. Only the lines shown (Fig. 1) were available for the present study. Line spacing generally ranges between 10 to 25 km and averages about 15 km. Thirteen of the lines are NW-SE dip lines that extend from the West Shetland continental shelf (water depth <200 m) or upper slope north-westward to the axis of the Faeroe-Shetland Channel in water depths of up to 1700 m. In the northeastern half of the study area, only five strike lines intersect these dip lines and extend southwest–northeast along the basin-floor axis, the lower continental slope and the continental shelf northwest of the Shetland Islands (Fig. 1). Three other strike lines extend through the southwestern half of the study area and continue south-westward beyond the limits of Fig. 1 onto the Wyville-Thompson Ridge and into the Rockall Trough area. Five other lines in the southwestern portion of the study area, two oriented east–west and three north–south, were also utilized.

All seismic lines utilized are unprocessed analogue records shot with small (40 cubic inches) airguns and generally filtered between 50 and 250 Hz. Acoustic penetration is quite variable throughout the grid, as well as along individual lines, but generally ranges between 0.5 and 1.5 s below the sea floor (Fig. 3). Maximum penetration is generally achieved on the lower continental slope and the adjacent basin floor. Uplift, from water depths of about 500 m, and especially landward of the continental shelf (water depth <200 m), penetration is severely limited (0.2 s or less beneath the shelf) by two factors: (i) the nature of the shelf deposits, which have been subjected to intense scouring by icebergs during interglacial cycles and glaciogenic depositional processes beneath ice sheets during glacial cycles (Belderson et al. 1973; Stoker 1990a,b; Stoker et al. 1991); and (ii) the presence of strong water-bottom multiples that obscure the signal (Fig. 3).

**Latest Oligocene unconformity**

A very prominent regional unconformity (Fig. 2, latest Oligocene unconformity) is observed throughout the region and represents a major sequence boundary that can be consistently traced from beneath the West Shetland Shelf downslope to the axis of the Faeroe-Shetland Channel (dashed horizon labelled LOU in Figs 3–7). This unconformity represents a major erosional surface at most locations, especially in the southwestern end of the channel (Fig. 3, Line 83/04-32, G-L). The section above this unconformity generally shows highly reflective, parallel, acoustically well-stratified deposits that thin upslope from a maximum thickness of 0.4–0.5 s beneath the middle of the continental slope. On some lines (e.g. Fig. 3) this unconformity becomes obscured beneath the upper slope (water depth <400 m) by the water-bottom multiple. However, on other lines that extend well across the continental shelf, the unconformity is observed to shallow progressively landward to less than 0.02–0.03 s below the sea floor. Here it often becomes obscured by the bubble pulse. In contrast, the section below the unconformity is generally non-reflective to semi-transparent, and acoustic penetration is usually very limited. At many locations, groups of dipping reflectors with various orientations appear to represent steeply dipping sets of clinoformes; whereas at other locations the reflectors show evidence of extensive faulting and deformation (Fig. 3, Line 85/04-10, A–F). Because of poor acoustic penetration below this unconformity, older, regionally extensive sequence boundaries or other horizons could not be identified.

Stoker (1990a) and Stoker et al. (1991) suggest that this unconformity may have formed in response to the initiation of intense bottom-water flow from the Arctic to the North Atlantic, which was inferred by Miller and Tucholke (1983) to have occurred after the separation of Greenland and Svalbard during the late Eocene to early Oligocene. We cannot determine the precise age of this unconformity; however, the following lines of evidence suggest that it probably formed somewhat later during the latest Oligocene or early to middle Miocene. A sequence-stratigraphic analysis of the Paleocene section beneath the West Shetland Shelf and Faeroe-Shetland Channel by Mitchell et al. (1993) established the approximate top of the Eocene section throughout the present study area using a close-spaced grid of standard multi-fold seismic lines (Fig. 2). We cross-correlated many of our high-resolution seismic lines with this multi-fold data set and determined the depth (in two-way travel time) to the top of the Eocene section at 60 locations throughout the study area from the modern shelf edge downslope to the basin axis. This correlation revealed that the top of the Eocene section occurs well below the prominent unconformity at most of these locations (e.g. Fig. 2), and indicates that a thick Oligocene section is present throughout most of the region.

An exception is at the extreme southwestern end of the Faeroe-Shetland Channel where the Eocene and older deposits shallow progressively beneath the unconformity, as well as the sea floor, as they extend up the northeastern flank of the Wyville-Thompson Ridge. In this area the Oligocene has locally been completely eroded and the prominent unconformity cuts into the Eocene section. Eocene strata crop out locally in this region (Stoker 1990c); however, these Eocene strata rapidly plunge toward the northeast beneath the Faeroe-Shetland Channel floor, resulting in preservation of a thick Oligocene section throughout most of the basin (e.g. Fig. 2).

Another exception is beneath the outer West Shetland Shelf where this Oligocene section thins progressively landward until the Top of Eocene horizon is less than 0.1 s (<100 m) below the prominent unconformity. The multi-fold seismic lines (Mitchell et al. 1993) show that the thickness of sediment between the top of Eocene horizon and the prominent regional unconformity rapidly increases basinward from the shelf edge, with thicknesses ranging from 1.0 to 2.5 s beneath the base of the modern slope. The Oligocene section becomes even thicker
in the Faeroe Basin beneath the modern channel axis (Fig. 2). This pattern contrasts somewhat with the Neogene-Quaternary clastic wedge above the prominent regional unconformity, which is thickest beneath the present-day upper slope, but rapidly thins basinward beneath the lower slope and Faeroe-Shetland Channel axis (e.g. Stoker et al. 1991).

The presence of this thick Oligocene sequence throughout most of the basin suggests that the major unconformity was not formed during the late Eocene or early Oligocene (Stoker 1990a; Stoker et al. 1991), but is much younger. A younger age for this unconformity is also supported by more recent plate-tectonic and palaeoceanographic data from the Norwegian-Greenland Sea, which suggest that the exchange of deep and intermediate water from the Arctic to the North Atlantic was restricted throughout the Paleogene and that intense bottom-water flow was not initiated until at least the middle Miocene (Ekdholm 1990 and references therein). A Miocene age for the initiation of vigorous bottom-water flow through the Faeroe-Shetland Channel and the resultant sea-floor erosion is more consistent with the presence of the thick Oligocene section observed throughout the basin (e.g. Fig. 2).

In addition, subsidence history curves for the Faeroe Basin show a sharp increase in subsidence rate from c. 38–25 Ma during the Oligocene (J. M. Vizirda, pers. comm. 1992). The multi-fold (Mitchell et al. 1993) and high-resolution seismic lines show extensive faulting and tilting confined to the Oligocene strata; no faulting or deformation extends upward into the Neogene above the unconformity, nor is extensive faulting observed below the Oligocene. This observation also suggests increased basal subsidence during the Oligocene. Thus several lines of evidence suggest that the prominent regional unconformity formed near the end of the Oligocene or during the early to middle Miocene in response to increased rates of tectonic subsidence coupled with erosion by vigorous bottom-water flow. These are: (1) the presence of a very thick Oligocene section; (2) the apparent absence of intense bottom-water flow from the Norwegian-Greenland Sea into the North Atlantic until at least middle Miocene; (3) markedly increased subsidence rate during the Oligocene; and (4) intense faulting and tilting of just the Oligocene section during or shortly after deposition. Because of the uncertainty of the age of this unconformity, we refer to it throughout this paper as the latest Oligocene unconformity (LOU) and suggest that it may mark approximately the boundary between the Paleogene and Neogene sections in the study area.

Neogene-Quaternary seismic facies and depositional processes

Upper slope

The strata above the late Oligocene unconformity/sequence boundary are well imaged throughout the study area, especially seaward of the modern continental shelf edge (e.g. Figs 3 and 4). The northwest-southeast-trending dip lines all show the same seismic facies relationships and depositional patterns from the shelf edge, seaward down the continental slope, to the Faeroe-Shetland Channel floor. The sediments beneath the upper continental slope (shelf edge to 600–800 m water depths) are characterized by extensive zones of hummocky to chaotic (occasionally transparent) seismic facies (Figs 3 and 4). These facies occur in multiple, discrete packages with mound- or lens-shaped external forms. These packages are often separated by thin zones of continuous, parallel, often highly reflective facies (Fig. 4). At many locations these continuous, parallel strata have clearly been eroded or truncated and the hummocky facies lie directly on top of local unconformities. Some of these erosional surfaces appear to represent small submarine canyons or gullies filled with hummocky to chaotic facies (e.g. Fig. 3). Many of these local unconformities and other continuous reflective horizons observed within the upper slope between the hummocky deposits may represent candidate sequence or systems-tract boundaries. Unfortunately, the regional extent for these surfaces could not be determined because of the limited number of seismic lines available (Fig. 1).
Dip lines in the southwestern part of the region show several of these highly reflective, continuous horizons prograding seaward beneath the continental shelf to the modern shelf edge as a series of large clinoforms (Figs 3 and 4). Some of these clinoform surfaces extend down beneath the continental slope to depths of 800 m as thin, continuous parallel reflections, which separate the hummocky, mound packages described above (Fig. 4C). In addition, these individual clinoforms often downlap onto these hummocky mound packages. These relationships appear similar to stratigraphic relationships shown in the Exxon model for continental margin systems tracts (Posamentier and Vail 1988) where highstand, prograding slope-clinoform sets downlap onto lowstand basin-floor deposits. However, analysis of additional closely spaced lines in this region will be required to interpret the observed facies confidently in the context of the Exxon sequence-stratigraphic model.

The packages of hummocky to chaotic seismic facies which predominate beneath the upper slope appear to represent a range of large-scale mass-transport deposits (mainly debris flows with some slumps and slides) emplaced by numerous, recurrent episodes of sediment failure. The acoustic characteristics of these deposits include (1) transparent to hummocky, structureless internal reflection character; (2) mounded to lens-shaped external form; (3) erosional surfaces at the base; and (4) external dimensions and thickness. These are all consistent with characteristics that have previously been well documented for debris flows and related mass-wasting deposits (Embrey 1976, 1980; Jacobi 1976; Embrey and Jacobi 1977; Damuth 1980; Damuth and Embrey 1981). Recently, Stoker (1990a) and Stoker et al. (1991) describe deposits with similar acoustic characteristics from the Hebrides Slope at the northeastern end of Rockall Trough and from the southwestern end of the Faeroe-Shetland Channel adjacent to the present study area. They attributed these deposits mainly to debris flows and described shallow vibracores from the youngest deposits, which support their seismic interpretation. These cores show that turbidity-current deposits are also present to a much lesser extent. Stoker (1990a) suggested that these debris-flow and turbidity-current deposits represent redeposited glacial marine sediments that were emplaced mainly during glacial cycles when an ice sheet extended to the shelf edge and could deliver large amounts of terrigenous detritus directly to the upper slope. Based on their acoustic characteristics and their direct analogy to the deposits described by Stoker, we suggest that the deposits of the upper West Shetland Slope are mainly debris flows. Interbedded glacial marine and hemipelagic deposits comprise a relatively minor portion of the total deposits at most locations.

The seismic-facies relationships described by Stoker (1990a) for the Hebrides Slope are quite similar to those we observe beneath the upper West Shetland Slope (Fig. 3). Stoker attributed the continuous, parallel high-amplitude reflections and clinoforms, which separate the hummocky debris-flow packages, to periods of slower glacial marine and hemipelagic sedimentation when the ice sheet retreated (at least temporarily) from the shelf edge. We speculate that ice-sheet retreat may have been coupled with glacio-eustatic sea-level rise during interstadial periods. Sea-level rise coupled with ice-sheet retreat could have temporarily prevented large quantities of terrigenous sediments from being transported across the outer shelf to the slope. If this were the case, then the continuous high-amplitude reflections and clinoforms may represent periods of slower hemipelagic sediment accumulation (i.e. condensed sections), and therefore may be analogous to transgressive and highstand systems-tract deposits in the Exxon sequence-stratigraphic model; whereas the hummocky debris-flow deposits may represent lowstand systems-tract deposits (Figs 3 and 4). However, precise dating and regional mapping of the clinoforms and other deposits would be required to confirm this interpretation.

Occasional erosional features that have the appearance of submarine canyons are observed in the study area. Submarine canyons form predominantly through mass-wasting and turbidity-current processes. Thus, when active, canyons can provide conduits for transport of sands to the lower slope and basin floor. A major canyon-like feature, now filled and buried, is observed in the northeastern part of the upper West Shetland slope (Figs 5B and C). This feature is up to 200 m deep, more than 3 km wide and filled with deposits that return transparent to chaotic seismic facies, which, based on the discussion, appear to represent mass-transport deposits (debris flows, etc.). This canyon feature apparently has an interesting, complex history of development. The southwestern wall of the canyon clearly represents a major erosional scarp that has truncated at least 200 m of older strata. These truncated strata appear to be interbedded mass-transport deposits and clinoform surfaces similar to those described above. In contrast, the northwestern wall of the canyon is a constructional feature returning continuous, parallel to subparallel or migrating reflections, and has the appearance of thick levee or overbank sediments deposited on an erosional unconformity that extends upslope to the scarp (Figs 5B and C).

Stevenson (1991b) interpreted this scarp and associated unconformity as a slide scar or zone of sediment removal associated with a large mass-transport deposit informally named the Miller Slide. He interprets the constructional wall of the canyon feature as contourite mounds. Certainly this constructional canyon wall has the appearance of contourite deposits. The occurrence of smaller migrating sediment waves within these deposits (Fig. 5B) suggests that these deposits have been affected by contour-current activity. However, based on the data at hand, we cannot rule out the possibility that this aggradational feature was also at least partially formed by overbanking of downslope flows such as turbidity currents and related mass flows. Further downslope this canyon appears to be an entirely constructional channel feature with both walls consisting of levee-like deposits (Fig. 5D). At this location, the canyon may actually be an aggradational channel/levee system (see below).

Canyon-like features of various sizes are observed along Profile G-L (Fig. 3). Two small buried canyon features occur between H-J. At the end of this profile (beneath G) the southeastern half of an apparent large modern canyon, which is up to 250 m deep and several kilometres wide, is observed, and an older, now buried, canyon-like feature of similar size is present on that same profile just upslope from this modern canyon (Figs 3 and 5A, Profile G-H). The buried feature is filled with highly reflective parallel to subparallel beds. These features clearly have eroded down through large sections of Oligocene strata and their floors and walls form part of the late Oligocene unconformity (LOU). Because of the sparse data coverage, we were unable to map the trends of these and other canyon-like features observed in the study area; thus, their relationships to the continental margin and their true origins remain uncertain. For example, bathymetric contours (Stoker 1990b), as well as GLORIA side-scan sonar images (N. H. Kenyon, pers. comm.), in the area of the modern canyon-like feature at the end of Profile G-H (Figs 3 and 5A) suggest that this erosional feature is actually an oval-shaped depression of uncertain origin, not a linear canyon. Additional mapping of the trends of the other canyon-like features will be required to confirm whether they are submarine canyons.

Middle to lower slope

In contrast to the predominantly hummocky seismic facies of the upper slope, the deposits of the middle to lower slope
Fig. 5. Examples of submarine canyons and channels. (A) Large buried submarine canyon (?). Note eroded, outcropping strata in canyon wall. Erosional scarp near G is apparently not a canyon (see text). (B) and (C) Buried submarine canyon (?) beneath the upper slope. Hummocky to chaotic deposits filling canyon appear to be mass-transport deposits. Note erosional southeastern wall of canyon as opposed to the constructional, levee-like northwestern canyon wall (see text). (D) Deep-sea fan-like feature on the continental slope. Note possible modern channel and levees at apex and buried channel filled with chaotic and hummocky facies just beneath. Feature on the sea-floor at left end of profile may be another channel-levee system, or alternatively, migrating sediment waves (see text). A small triangle at the top of a profile indicates intersection with another illustrated profile.
(water depths of 600–1200 m) are generally characterized by highly reflective, continuous parallel to subparallel seismic facies (Fig. 3). Some of the zones of hummocky facies extend downslope to this region from the upper slope and form interbeds within these parallel facies; however, the number and thickness of hummocky packages progressively decrease downslope. This facies transition indicates that the mass-transport deposits so prevalent on the upper slope become progressively less frequent and widespread across the middle slope until they are only rarely present on the lower slope (Fig. 3). The highly reflective, parallel to subparallel facies of the middle to lower slope deposits appear to be interbedded hemipelagic and glacial marine deposits with occasional turbidity-current deposits.

The single strike line along the middle slope that was available for this study shows seismic facies and stratigraphic relationships which suggest that a deep-sea fan-like feature may be present on the northeasternmost part of the West Shetland slope (Fig. 5D). This feature is up to 0.5 s thick and is composed of a series of lens-shaped or mounded seismic packages that contain continuous parallel to subparallel, or occasionally migrating, sub-bottom reflections. These packages and their internal reflections show discordant, onlapping relationships to one another and are similar in appearance to seismic facies patterns associated with overlapping distributary channel-levee systems of modern deep-sea fans (e.g. Bouma et al. 1985 and references therein; Kolla and Coupes 1987; Damuth et al. 1988; Weimer 1990). Figure 5D shows a feature that has the appearance of a modern fan channel perched atop an associated natural levee system at the present apex of the fan. Channel relief at the sea floor is up to 75 m deep and more than 1 km wide. The associated levee/overbank deposits extend at least 10 km away from this channel in each direction. A broader (>4 km), now buried channel of even greater relief (>200 m) is visible beneath this modern channel and is partially filled with chaotic seismic facies which appear to be mass-transport deposits (Fig. 5D). This buried channel may be the downslope continuation of the large submarine-canyon feature observed just upslope in this region (discussed above; Figs 3B and C). Elsewhere, several features that have the appearance of smaller channels and associated levee systems occur both on the present fan surface (e.g. Fig. 5D, left end) of a field of migrating sediment waves that occur just down slope (see below). Unfortunately, the bulk of this fan-like feature appears to be located northeastward of the study area beyond the existing seismic coverage. In addition, only one strike line across this feature was available; thus we are unable to confirm whether these apparent channel-levee systems are, in fact, linear features that trend downslope. Therefore, we cannot confirm that this feature truly represents a deep-sea fan. A plausible alternative is that these deposits may represent a series of contourite drift deposits (see below).

At some locations on the lower slope in the northeastern part of the study area (generally between 900–1200 m water depths), the continuous parallel to subparallel seismic facies that characterize the middle slope and the fan-like feature described above abruptly pass into a regular, migrating internal reflection configuration which apparently represents migrating wave- or dune-like bedforms (Fig. 3). These migrating waves are best developed along the dip lines where they show amplitudes of up to 50 m and wavelengths of up to 1 km or more (Fig. 6). These migrating waves extend downward from the present sea floor for 0.2–0.3 s (approximately 200–300 m). No strike lines extend through these deposits, and an inadequate number of dip lines were available to map the trends or orientations of the wave crests or troughs. However, Kenyon (1987) reported the presence of five 'slope ridges' on a GLORIA sonograph and seismic lines from this region. These have similar amplitudes and wavelengths to the migrating waves and extend parallel to the West Shetland slope for up to 20 km in about the same location as the waves reported here. Unfortunately, Kenyon's (1987) seismic data do not resolve the internal character of these ridges. He suggested that these features could either be slump folds formed by downslope mass-transport processes, or longitudinal sediment waves formed by contour-current processes.

Based on the regular, migrating sub-bottoms that we observe in these bedforms (Fig. 6), we believe that they represent migrating sediment waves or dunes deposited by (1) contour-current activity, (2) turbidity-current overbanking of canyon or channel walls and levees or (3) a combination of both processes. The presence of a strong southerly flow of North Atlantic Deep Water (NADW) through the Faeroe-Shetland Channel floor, the documentation of reworking of sediments by contour-currents based on current measurements, cores and seismic data (Akhurst 1991; Stoker et al. 1991) and the apparent orientation and extent of the waves (Kenyon 1987) all argue for a contour-current origin for these waves. In addition, a large field of modern-to-buried migrating waves of similar amplitudes, wavelengths and internal configuration occurs at the north-

Fig. 6. Examples of migrating sediment waves or drift deposits from the lower continental slope.
eastern end of the adjacent Rockall Trough and has been attributed to contour-current activity related to the overflow of the NSDW from the Faeroe-Shetland Channel (Richards et al. 1987; Stoker 1990a). Elsewhere in Rockall Trough, the Feni Drift is also a contourite deposit that has comparable sediment waves (Floed et al. 1979; Roberts and Kidd 1979). Similar sediment waves have been documented as contourite deposits at other locations around the world (e.g. Damuth 1980; Flood 1988).

However, migrating sediment waves can also be created by overbank flow of turbidity-currents on the backs of submarine-fan channel levees and on submarine canyon walls (Damuth 1979; Normark et al. 1980; Carter et al. 1990). Recently, Savoye et al. (in press) showed examples of large migrating sediment waves developed on a levee of the main channel of the Var Deep-Sea Fan off Nice, France. These sediment waves are similar in size (wavelengths of 1-7 km, amplitudes of 10-50 m) and appearance to the waves on the West Shetland slope but were created by overbank flow of thick turbidity currents moving down the fan channel. Thus, we cannot rule out the possibility that the sediment waves observed on the West Shetland slope (Fig. 6) may have been, at least in part, formed by overbanking of turbidity currents flowing down the submarine canyon and fan channel (Fig. 5D) just upslope of the wave field. If so, the regular migrating wave-like bedforms observed between 1000 and 1300 m water depths (Fig. 6) just downslope of this fan channel could be a function of the oblique orientation of the dip lines across channel-levee/overbank deposits of the fan, rather than migrating sediment waves of contour-current deposits. In addition, the constructional levee-like northwest wall of the submarine canyon on the upper slope (Fig. 5B) shows zones of smaller, regular migrating waves within the overall levee deposits, which also could have been created by the interaction of overbank flow and contour-current flow.

In summary, although migrating sediment waves can be created by overbanking turbidity flows, given the well documented contour-current flow of the NSDW through this region during the Quaternary, many of the sediment-wave deposits observed in the study area, especially the larger wave fields (e.g. Fig. 6), were probably created primarily by the action of contour-currents. Sediments moving downslope in gravity-controlled flows, as well as glacial marine sediments falling through the water column, were probably entrained within the contour-currents and redeposited along the slope as sediment drift deposits. However, more closely spaced seismic lines are needed to determine the true orientation and extent of individual waves and wave sets, and thereby confirm the true origin of these features.

Basin floor

The basin floor of the Faeroe-Shetland Channel (water depths >1300 m) is characterized by highly reflective, continuous parallel facies. Some individual reflections were traced continuously for more than 100 km along the basin axis. These deposits apparently represent predominantly hemipelagic and glacial marine deposits with rare interbedded turbidity-current, and related gravity-controlled flow deposits which have spread out and ponded in the basin axis (Akhurst 1991; Stoker et al. 1991). In addition, occasional, thin hummocky to transparent zones of seismic facies are observed between these parallel beds and appear to be minor debris flows or other mass-transport deposits that sometimes flow out onto the channel floor. In contrast to these widely spaced minor debris-flow deposits, three or more very large mass-transport deposits (up to 0.15 s thick) occur beneath the lower slope and channel floor (Fig. 7) just downslope from the deep-sea fan feature and the migrating sediment waves (Fig. 3). Stevenson (1991b) interpreted these deposits as composite mass-flow lobes of the Miller Slide complex.

Large mass-transport deposits such as these are often common on the lower continental rise around the world and have been shown to have moved downslope slopes of <1° for up to hundreds of kilometres to form deposits extending throughout thousands of square kilometres (Embley 1976, 1980; Jacobi 1976; Embley and Jacobi 1977; Damuth 1980). In addition, these large mass-transport deposits commonly occur in association with large deep-sea fans and often contribute to their construction (e.g. Damuth and Embley 1981).

Conclusions

A prominent regional unconformity, herein referred to as the Latest Oligocene Unconformity (LOU), forms a major sequence boundary that approximately separates the Neogene and Quaternary clastic sediments from the older Paleogene deposits beneath the West Shetland slope and Faeroe-Shetland Channel. Although this unconformity is a major erosional surface, which locally cuts into Eocene strata at the southwestern end of the channel, a thick section of Oligocene sediments is present beneath the unconformity throughout most of the region and indicates that this unconformity did not form until at least the latest Oligocene or the early to middle Miocene. This unconformity apparently formed in response to increased basin subsidence coupled with vigorous erosion of the sea floor related to the initiation of intense bottom-water flow through the channel from the Arctic to the North Atlantic.

The post-Oligocene sediments above this regional unconformity show a variety of seismic facies and morphologic features on high-resolution seismic lines that indicate these sediments have been deposited and modified by a variety of deep-water depositional processes, which include both downslope and parallel-to-slope processes. The upper portion of the West Shetland slope (~200-800 m) is dominated by mass-transport deposits, predominantly debris flows with some slumps and slides, that were apparently deposited during glacial cycles when sea level was low and an ice sheet extended to the shelf edge and supplied large quantities of terrigenous sediment to the upper slope (Stoker 1990a). Thin, highly reflective packages of prograding clinoforms often replace mass-flow deposits and may represent glacial marine (ice-rafted) sedimentation during times of ice-sheet retreat from the shelf edge (Stoker 1990a), possibly in response to sea-level rise associated with interstadials. Submarine canyons and gullies of various sizes are occasionally present, are often filled with mass-transport deposits and may have provided conduits for turbidity currents and related mass flows to reach the basin floor.

In contrast to the upper slope, the middle to lower slope (~800-1200 m) appears to be dominated by glacial marine and hemipelagic sediments along with possible significant deposition by turbidity currents and related gravity-controlled flows. At many locations, especially on the lower slope, these deposits apparently incurred major reworking by contour-current activity. At the northeastern end of the study area, a possible deep-sea fan-like feature is present on the middle slope, which appears to be composed of several overlapping, aggradational channel-levee systems including a 25 km wide modern channel-levee system whose channel is 75 m deep. However, just downslope from this feature, large migrating sediment waves or dunes are observed which appear to represent major contourite deposits. The available data are too sparse to allow delineation and mapping of the shapes and trends of these various features; consequently, we cannot yet confidently determine whether the sediment waves and the levee-like features represent contourites, overbank turbidites, or a combination of both. However, given the strong south-
westerly thermohaline flow of the Norwegian Sea Deep Water through the channel and sedimentary evidence of contourites (Akhurst 1991), we believe that much of the lower slope has at least been shaped by contour-current activity.

The relatively thin sediments of the channel axis are highly reflective and individual beds can sometimes be traced for more than 100 km. These sediments appear to be dominantly glacial marine with some input by turbidity currents and mass-transport deposits. An exception exists at the northeastern end of the study area just downslope from the deep-sea fan feature and the sediment waves where several major mass-transport deposits occur. The data presented in this paper demonstrate the ambiguity or uncertainty of interpreting complex interactions between downslope and parallel-to-slope depositional processes based on inadequate seismic coverage. Analysis of additional infill seismic and core data is currently underway to substantiate the preliminary observations and interpretations put forward here.

We thank Mobil North Sea Ltd., Mobil Research and Development Corp., Lasmo (TNS) Ltd. and the British Geological Survey for permission to publish this paper. We thank M. S. Stoker, O. Eldholm, A. M. Spencer, R. B. Bloch, S. M. Mitchell, G. A. Hird, L. K. Vopni and W. P. Alves for reviewing the manuscript critically and offering constructive comments. We also thank N. H. Kenyon, M. C. Akhurst, D. Long, R. Holmes and A. Dobinson for helpful discussions.

References


—. 1990b. Judd (Sheet 60°N-06°W) Quaternary Geology. (1:250,000 Offshore Map Series.) British Geological Survey.

—. 1990c. Judd (Sheet 60°N-06°W) Solid Geology. (1:250,000 Offshore Map Series.) British Geological Survey.


