

Bottom currents
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A near-bottom traverse of Rockall Trough: hydrographic and geologic inferences

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ABSTRACT

Two profiles with a deeply-towed instrument package provide a broken traverse of geologic and hydrographic data across the southern Rockall Trough. These near-bottom observations are supplemented with airgun profiles, a CTD cast, and current meter data. Symmetric sand ripples at bathyal depths on both margins, which are superimposed on a field of sand waves on the slope of Rockall Bank, are attributed to bed load transport by tidal currents. Abyssal thermohaline currents are inferred from ripples, scour crescents and other indicators on more than 2 000 stereo pairs of bottom photographs. In addition to the expected southerly currents on the western side of the trough, which is a passage for Norwegian Sea Overflow, there is evidence for fast, narrow and erosive currents of Labrador Sea Water and Northeast Atlantic Deep Water (Neadw) at the eastern boundary. The northeasterly Neadw current at the foot of the Irish Continental slope appears to be part of a cyclonic loop which brings silica-rich water into the trough, has built and is now eroding a narrow continental rise, and has transferred much terrigenous debris to the western side of the trough, for deposition along Feni Ridge. Maximum Late Pleistocene deposition on Feni Ridge has been on its northwest flank, beneath a weak reverse (northeasterly) current. On the southeastern flank of Feni Ridge local alternation of slow and fast sediment deposition (probably caused by topographically induced local variations in current speed of the benthic boundary layer) has created 2 km-wavelength mud waves that migrate up the regional slope at less than 1 m/1 000 years.

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RÉSUMÉ

Une traverse profonde du bassin de Rockall : conclusions hydrographiques et géologiques

Deux profils réalisés au sud du bassin de Rockall au moyen d'un ensemble d'instruments traînés sur le fond, apportent une série d'enregistrements géologiques et hydrologiques. A ces observations près du fond s'ajoutent des profils sismiques (canon à air), un enregistrement CTD et des mesures de courants. Des rides de sables symétriques observées sur les deux flancs du bassin en domaine bathyal, surimposées à un champ de dunes de sable sur la pente du banc de Rockall, sont attribuées à un charriage dû aux courants de marées. Ces rides, des traces d'érosions et d'autres indications observées sur 2 000 stéréophotographies du fond mettent en évidence la présence de courants de fond d'origine thermohaline. Un courant nord-sud, correspondant au passage de l'eau profonde de

la Mer de Norvège, existe sur le côté ouest du bassin. Dans la zone orientale apparaissent des courants rapides, très localisés et érosifs, provoqués par l'eau de la mer du Labrador et de l'eau profonde de l'Atlantique Nord-Est. La masse d'eau profonde de l'Atlantique Nord-Est qui semble être une portion de la loupe cyclonique située au pied de la pente irlandaise, enrichit le bassin en silice. Elle transporte un volume important de sédiments terrigènes sur le côté ouest du bassin et a ainsi édifié la ride Feni, qu'elle érode actuellement. Le dépôt le plus tardif sur la ride Feni au cours du Pléistocène terminal, a eu lieu sur son flanc nord-ouest sous un faible courant inverse dirigé vers le nord-est. Sur le flanc sud-est de la ride Feni, la vitesse des courants de fond a subi des variations locales probablement induites par la topographie. Ces variations ont entraîné localement une alternance de dépôts lents et de phases rapides; cette alternance est à l'origine de la mise en place d'une série de dunes de vases d'une période de 2 km, migrant vers le haut de la pente à moins de 1 m/1 000 ans.

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INTRODUCTION

Rockall Trough is a 250 km-wide oceanic basin whose formation, by Mesozoic sea-floor spreading, detached the microcontinent of Rockall from the continental margin of western Europe. The depression is bounded by step-faulted continental crust, and, to the north, by the Wyville-Thomson Ridge. It has provided a settling basin for several kilometers of pelagic and terrigenous sediments, and a passage for bottom-water currents that include a branch of Norwegian Sea overflow. Several studies have examined the interaction between currents and sediments in Rockall Trough, concentrating on the source of Norwegian Sea inflow (Ellett, Roberts, 1973), the formation of moats around its seamounts (Roberts *et al.*, 1973), and the growth of the Feni Ridge, a sinuous drift of current-deposited sediment (Johnson, Schneider, 1969; Jones *et al.*, 1970). Two recent comprehensive papers have described the source and circulation of water masses in the trough, as deduced from their physical and chemical properties (Ellett, Martin, 1973), and its structure and sedimentation, inferred mainly from low-frequency seismic reflection profiles (Roberts, 1975).

During the summer of 1975, on Expedition Natow, we made detailed surveys at several sites in the northeast Atlantic, examining the role of bottom currents in controlling abyssal sedimentation by studying small

areas of sea floor with a deeply-towed geophysical instrument package, arrays of near-bottom current meters, CTD-plus-nephelometer casts, and cores. Part way through these operations, a failure of the main propulsion unit (aft cycloid) of the vessel (R/V « Knorr ») made it impossible to maneuver while towing and we were then limited to making two long, straight tows (A and B of Fig. 1) which together form a broken traverse of Rockall Trough. A nephelometer and CTD station (Knorr Station 698) was occupied at the southeast end of segment A. During a brief spell of unusually calm weather a "normal" transponder-navigated deep tow + current meter + CTD + coring station was occupied further north on Feni Ridge (Site C of Fig. 1; Flood *et al.*, 1979). This paper describes the deep-tow traverse and the current meter results from site C.

The near-bottom geophysical instrument package used was the deep-tow "fish" of the Marine Physical Laboratory (Spiess, Mudie, 1970; Spiess, Tyce, 1973). Of its array of sensors, the most valuable on this traverse were the photographic system (a stereo-pair of vertically directed still-cameras, plus a snapshot television), the high-resolution 4-kHz profiler, and the pair of side-looking sonars (110 kHz). Bottom photographs were taken in 36 sets of 30 to 200 frames (a "photo run") distributed throughout the transect, to yield a total of 2 050 pairs of photographs (with an additional 1 000 pairs at station C). The orientation of each frame

is calculated from the track of the towing ship, as determined by satellite navigation and Loran C: the deep-tow fish has negligible yawing motion during a straight tow, and orientations are probably good to within 10°.

The bottom photographs provide new information on the distribution, direction and approximate speed of bottom currents in the trough. Side-looking sonar records and photographs allow the mapping of bedforms, rock outcrops, and loose rock fragments along the traverse. Our near-bottom reflection profiles have very limited penetration (< 100 m), but usefully complement low-frequency airgun profiles by providing high resolution of the superficial sediment layers, which should be most directly related to observable patterns of bottom circulation and sediment dispersal. Both parts A and B

of the traverse were along the tracks of Lamont-Doherty airgun profiles (Conrad 0913 and Vema 2305 respectively, both published in Ewing *et al.*, 1974).

BOTTOM WATER CIRCULATION

Photographic evidence of bottom currents

The art of interpreting bottom-current regimes from sets of oriented photographs has been codified by Heezen and Hollister (1964; 1971, pp. 335-421). The most useful indicators are regular bedforms (principally sand and silt ripples) and obstacle marks (e. g., scour crescents and sediment shadows); the texture of the sea floor may also be resolved and provide some clues.

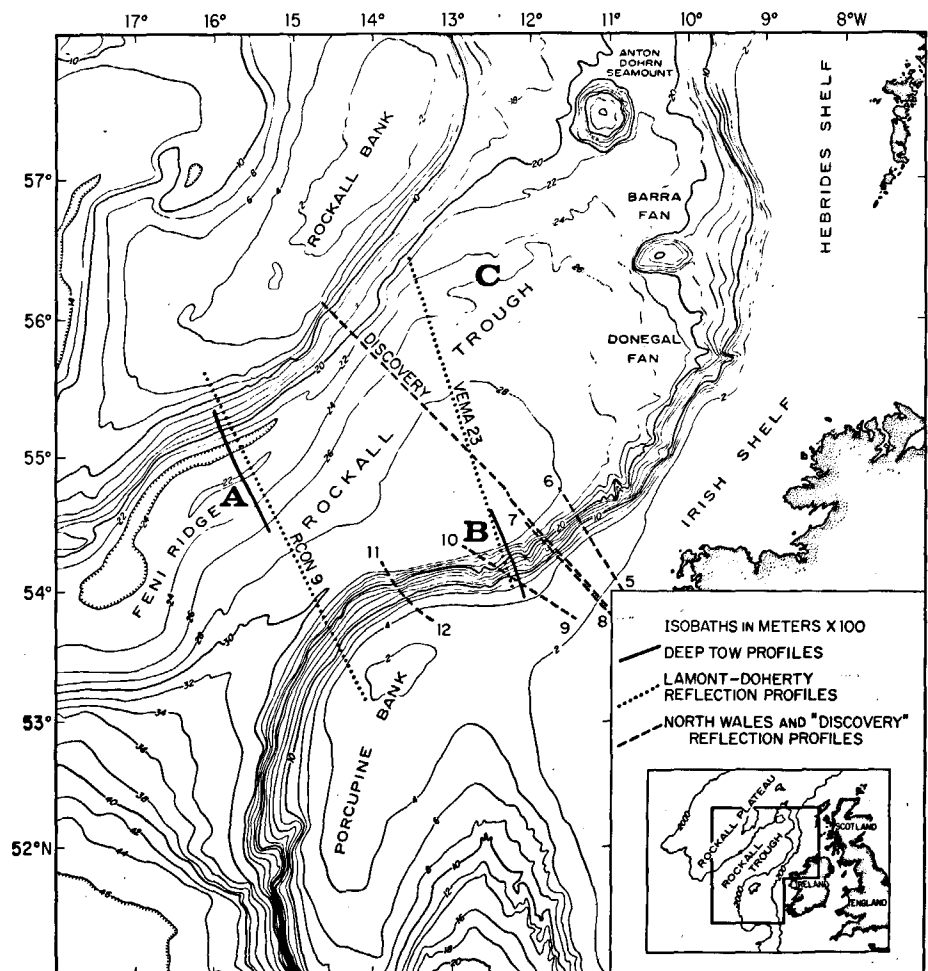


Figure 1
Bathymetry of Rockall Trough and vicinity, after Roberts (1975) and Johnson et al. (1971). Isobaths every 200 m; throughout this paper depths are in meters corrected for sound velocity by using Matthews Tables. "A", "B" and "C" are deep-tow sites. Location of other profiles from Ewing et al., 1974; Bailey et al., 1974 and Roberts, 1975. Inset shows regional location, and position of near-bottom current meter Natow 12CM, whose results are mentioned in the text.

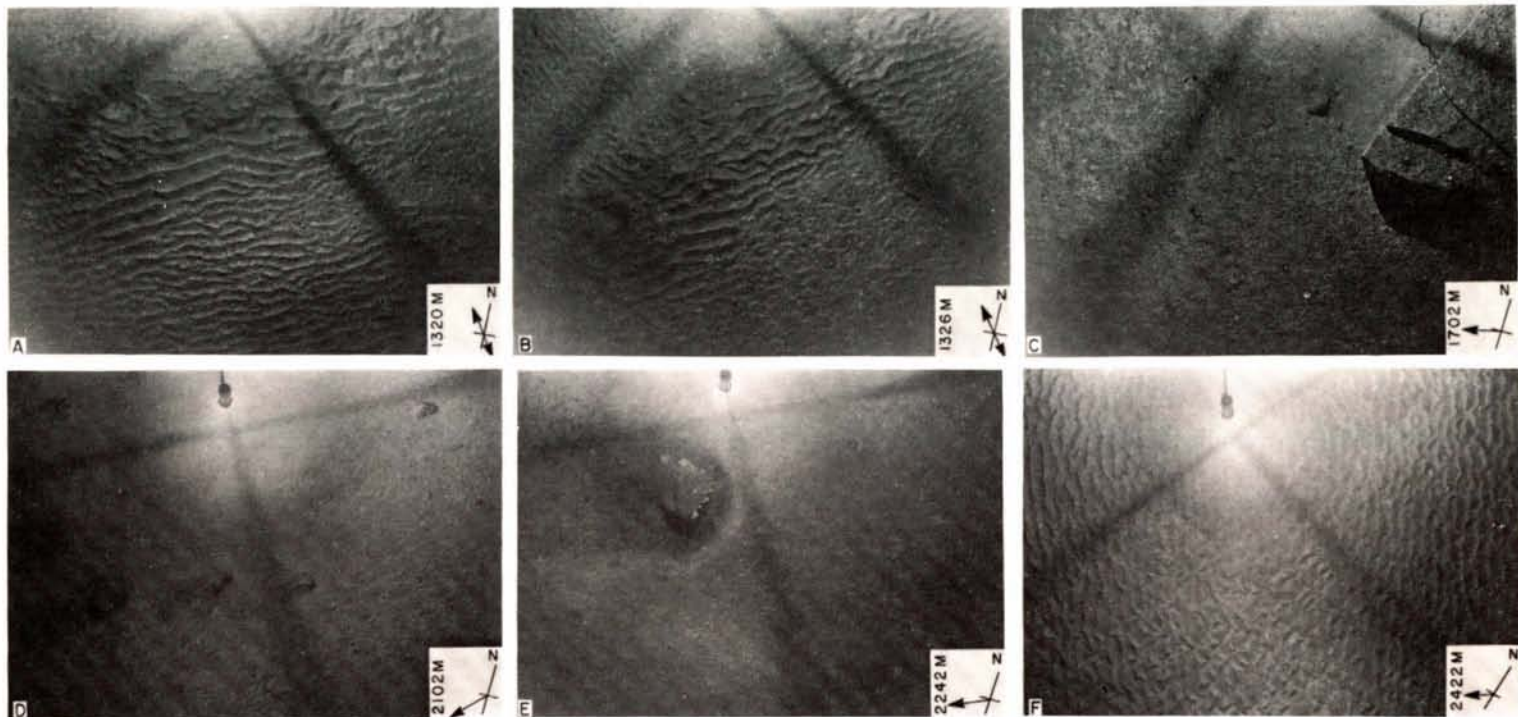
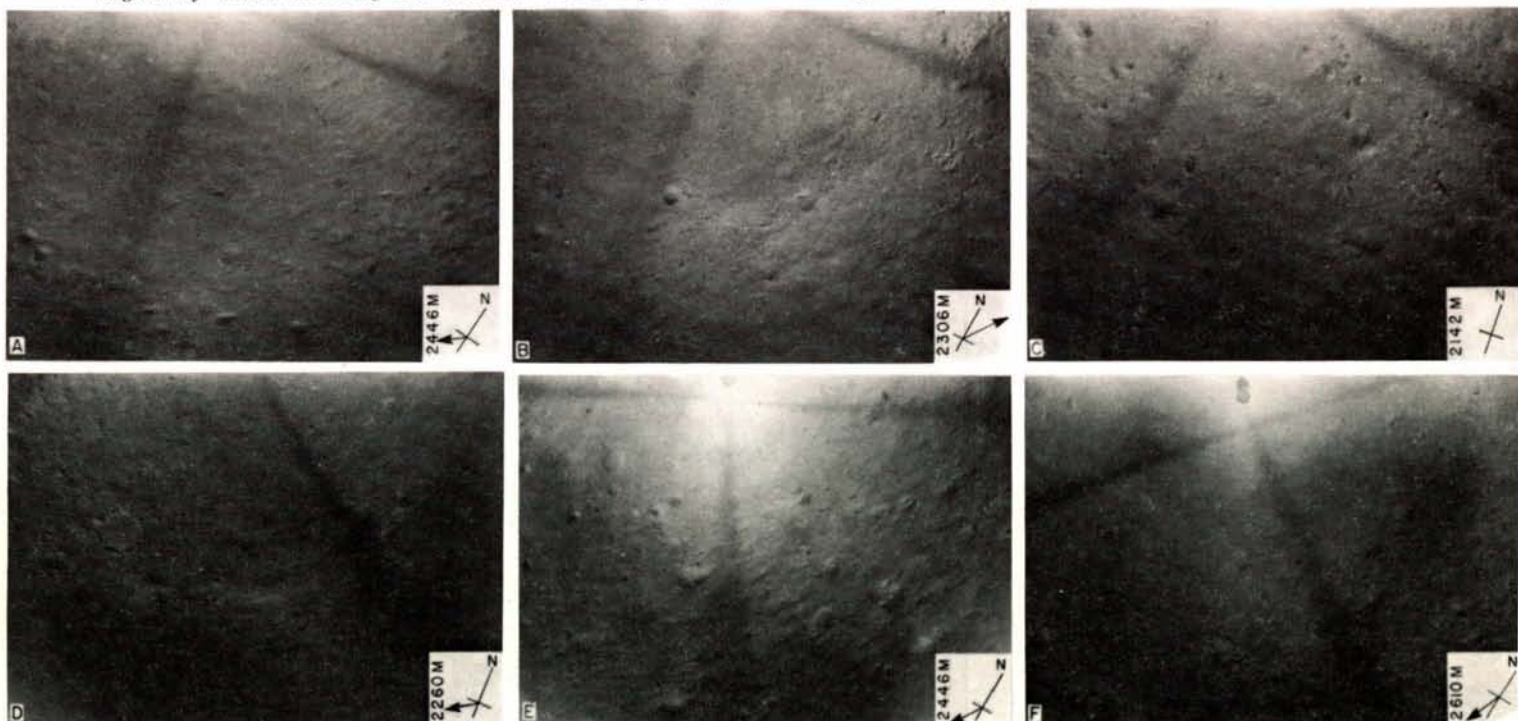


Figure 2
 Representative examples of bottom photographs from the slope of Rockall Bank, deep-tow profiles A (fig. 1). The data square on each frame covers 1 m²; it shows orientation of the photos, and the inferred current direction (arrows). All photos are illuminated from the top; on some the strobe is visible. Photo runs are located on Figures 6 and 9.
 a) Run A-1. Patterns of mostly symmetric sand ripples, with 12-25 cm wavelengths and gravel in their troughs.
 b) Run A-1. Abrupt alternations of ripple patterns. The large symmetric ripples in the center are on a steep ramp that slopes down to the northwest (upslope) and is the modified slip-face of a sand wave. Near the crest of this face (lower right) are asymmetric ripples migrating northwest; in the trough of a wave at the foot of

the slip-face (upper left) are asymmetric ripples migrating northeast.
 c) Run A-2. Outcrop of an angular block of sedimentary rock, or the edge of a very large glacial dropstone. The sea floor is current-smoothed, with gravel on part of the surface, moats around small sessil sponges, and a drift of fine sediment in the lee of the rock.
 d) Run A-3. Muddy sea floor with current lineations, and scattered rocks with scour crescents and leeside "negative drifts".
 e) Run A-4. Sandy or silty current-smoothed sea floor, with a deep moat around a rock, and a gravel-covered leeside "negative shadow" bordered by short-crested asymmetric ripples. Note obscuration of strobe by sediment suspended in the bottom water.
 f) Run A-5. A field of long-crested and lunate sand or silt ripples at the foot of the slope.

Figure 3
 Representative examples of bottom photographs from Feni Ridge, profile A (fig. 1). All show muddy bioturbated sea floor, with varying degrees of current-smoothing and lineation. Where a prevailing

direction of current activity can be interpreted, its direction is shown by the arrow within the 1 m² box. Photos are from runs A-6, in the marginal channel (frame a); A-7 on the northwest flank (b); A-8 on the ridge summit (c); and A-9, 11 and 13 on the southwest flank (d, e, f). See Figures 6 and 9 for photo run location.



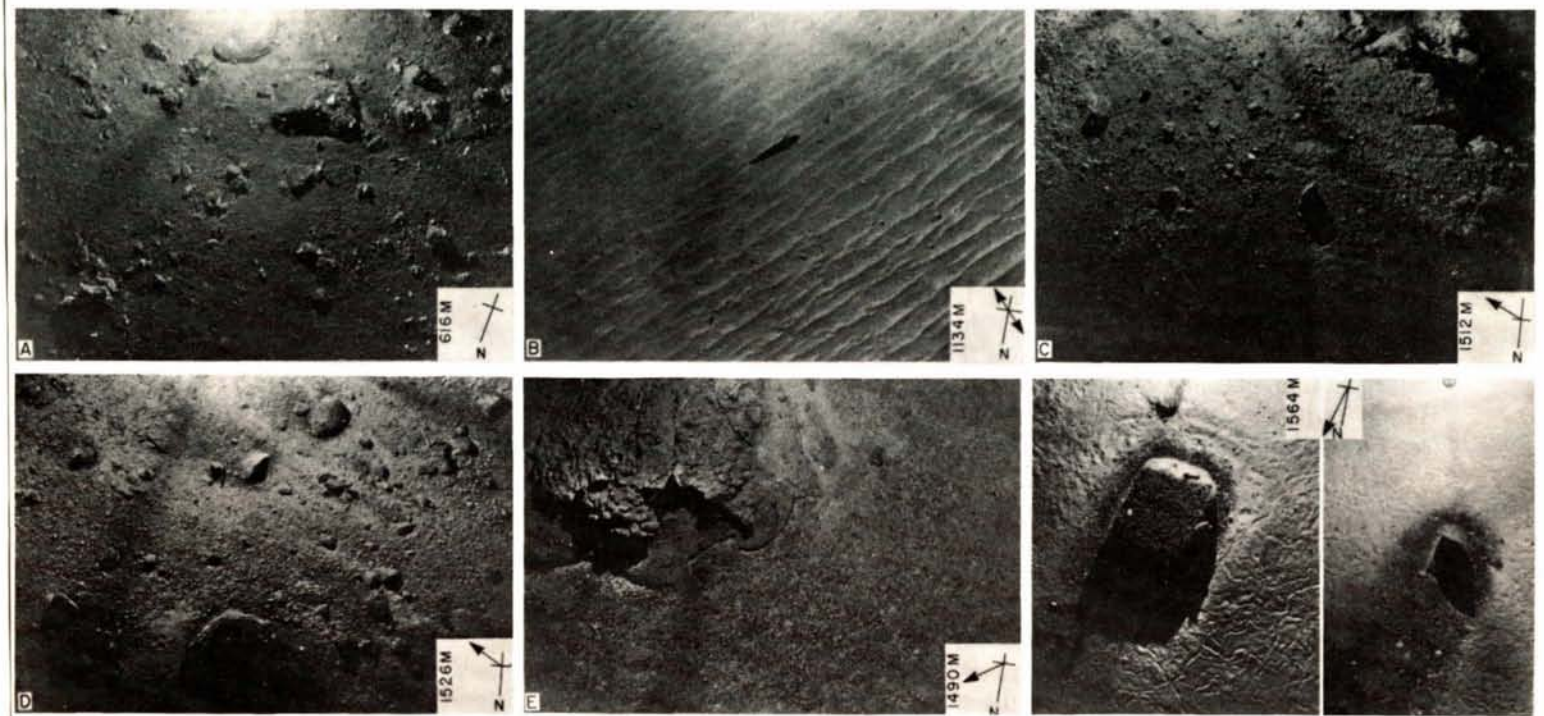


Figure 4

Representative examples of bottom photographs from the upper Irish slope, profile B (fig. 1). The data square on each frame covers 1 m²: it shows orientation of the photo and the inferred current direction (arrow). Photo runs are located on Figures 6 and 9.

- a) Run B-4, on the steep scarp at the top of the slope. Rounded boulders, probably dropped from young icebergs, that are now veneered with mud.
- b) Run B-6. A field of straight, sharp-crested symmetric ripples oriented along the slope. Wavelengths range from 10 to 40 cm, and there are concentrations of gravel in the ripple troughs.

Figure 5

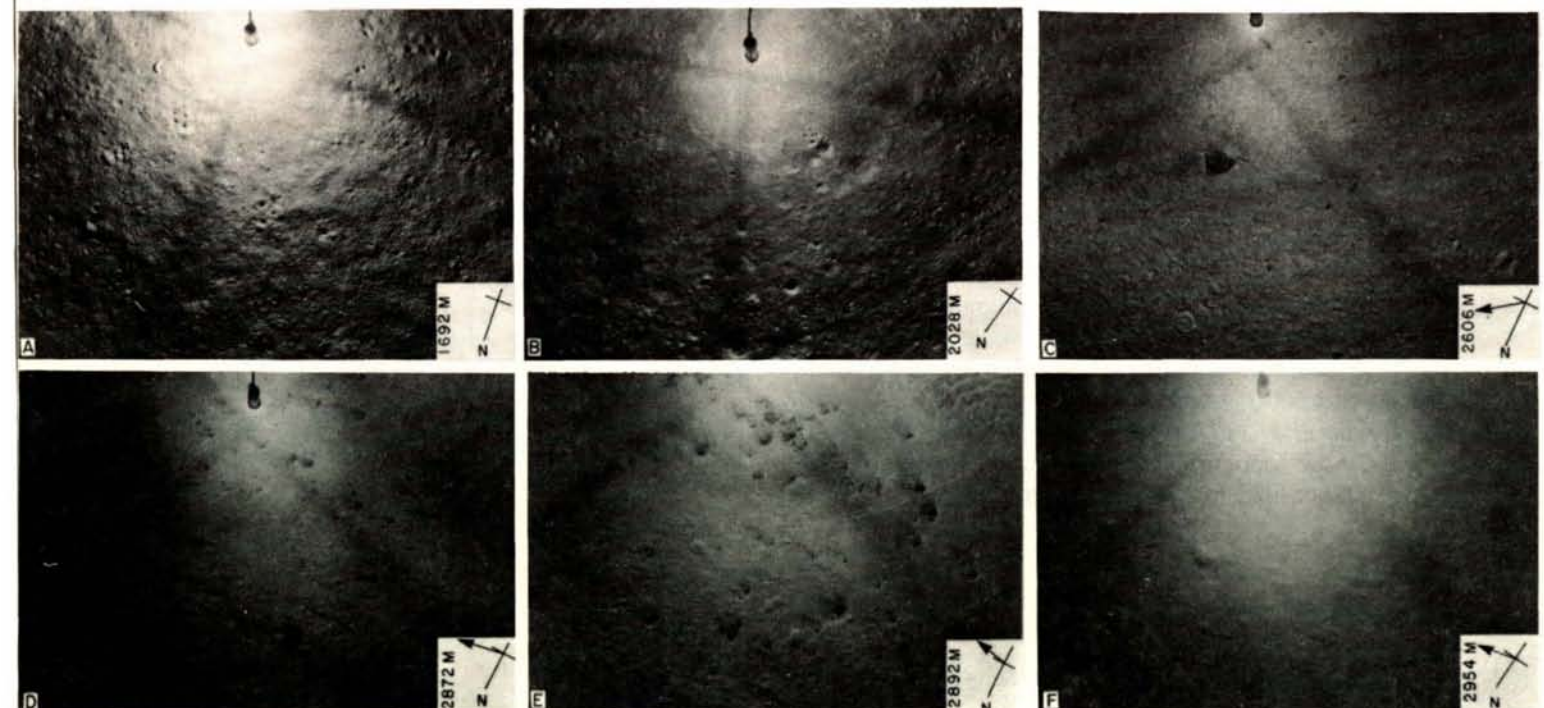
Representative examples of bottom photographs from deeper parts of deep-tow profile B (fig. 1). See Figures 6, 9 and 10 for photo run locations.

- a) and b) Runs B-10 and B-12. A stiff, muddy seabed, smoother by current activity but only slightly (if at all) lineated. Abundant rimless biogenic craters are characteristic of this part of the lower slope.
- c) Run B-15. Smooth, muddy sea floor on the continental rise, with little indication of a prevailing current direction except near the scattered rocks, which have small lee-side drifts and gravel-covered

- c) Run B-7. A current-swept outcrop of jointed rock, veneered with pebbles and small sand patches.
- d) Run B-7. Pebbles and boulders overlying a rock floor, with small patches of sand in the lees of some of the obstacles.
- e) Run B-8. A massive gnarled rock outcrop, surrounded by gravel.
- f) Run B-9. Two adjacent boulders, probably glacial dropstones, each with a gravel-filled moat. Surrounding sediment is heavily tracked. Note the divergence in inferred current direction during the nearby runs B-7 to B-9 is explained by local divergence of the slope contours: in all cases the inferred current is parallel to the local contours (fig. 6).

"negative shadows" formed by winnowing.

- d) and e) Run B-16, near the foot of the continental rise. Current-lineated sea floor densely strewn with rock fragments, which are surrounded with scour crescents and leeside drifts. There are occasional fields of asymmetric long-crested ripples (frame and, top right). The observed clustering of many of the pebbles into "rock nests" probably results from delivery to the sea floor of a group of stones frozen together with interstitial ice, which melted at depth.
- f) Run B-18, a streamlined muddy sea floor on the eastern margin of the sediment drift on the floor of Rockall Trough. Note obscuration of strobe, indicative of high bottom-water turbidity.

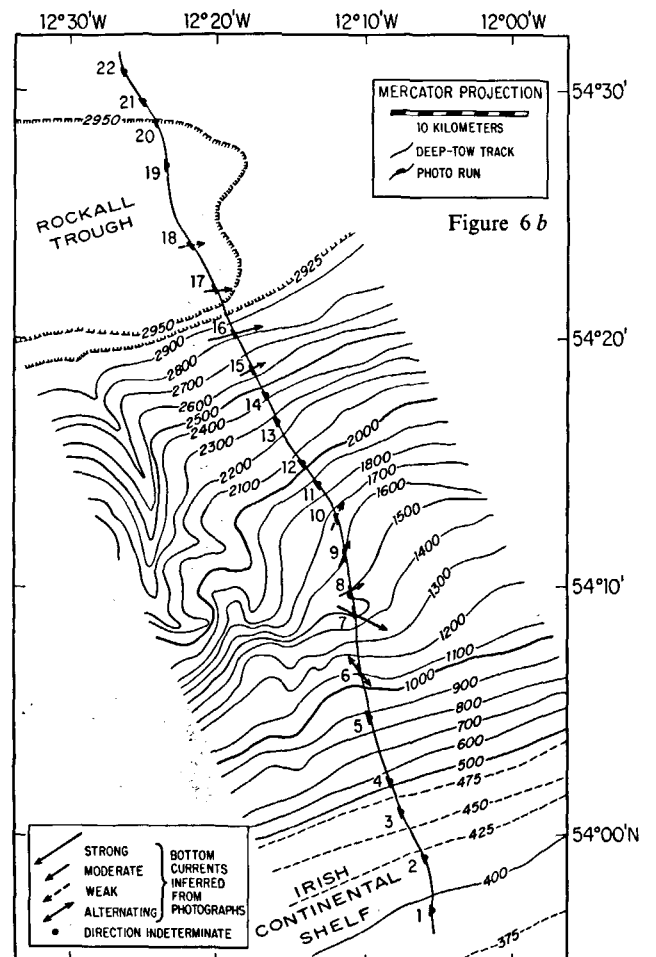
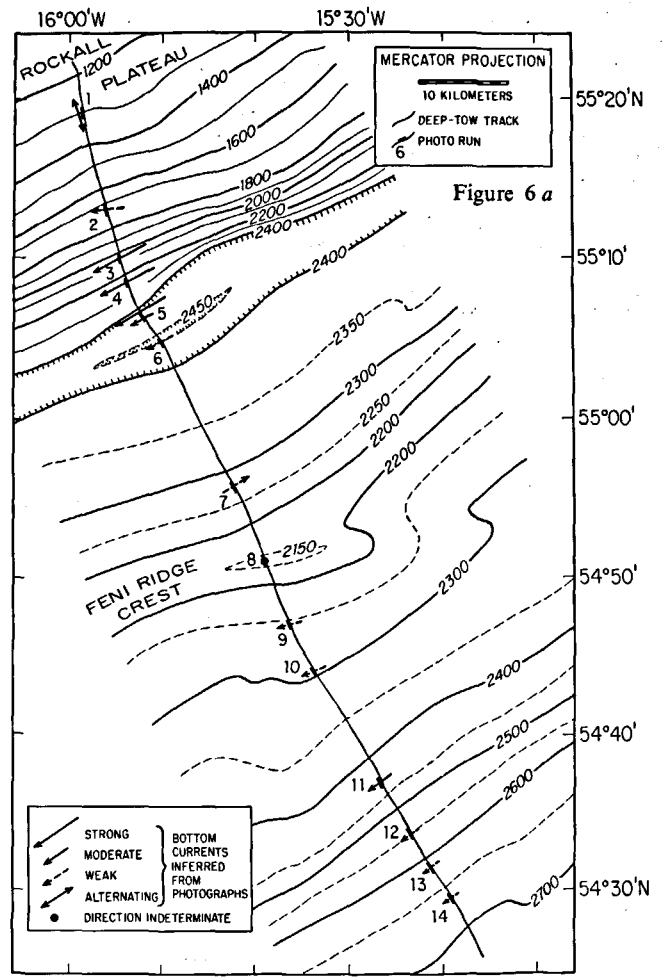


We infer "strong" bottom currents where most of the photographs in a photo run show asymmetric sand ripples (Fig. 2 f); deep scour crescents, often partially filled with coarse gravel, upstream of rocks (Fig. 2 d); and "negative shadows" downstream of obstacles, where increased turbulence creates an elongate patch of coarse lag gravel, rather than a lee drift (Fig. 2 e). Although we lack direct confirmation from Rockall Trough, we suggest that these characteristics indicate a persistent bottom current of at least 12-15 cm/sec., with maximum speeds probably greater than 20 cm/sec. For example, a current meter (Natow 12 CM) 20 m above photographically identical terrain at the foot of Hatton Drift on the western side of Rockall Plateau (see Fig. 1, inset) recorded a very steady flow with an average velocity of 13.8 cm/sec., an average speed of 14.9 cm/sec., and a maximum speed of 22 cm/sec., during its 1 week of operation.

Photographic evidence for "moderate" currents includes drifts of sediment in the lee of small obstacles (Fig. 5 c), with deep scour crescents and lee-side scour only around the largest rocks (Fig. 4 f). Where obstacles are absent, we do not find regular bedforms, but there are distinctly elongate drifts of sediment (Fig. 3 e).

Strong to moderate bottom currents are inferred at four places on the Rockall Trough traverse (Fig. 6 a and b), and in each case the currents are flowing parallel to local contours, in the following regions: at 2 000 to 2 400 m beside the foot of the Rockall Plateau continental slope, flowing southwest; at about 2 400 m on the southeast flank of Feni Ridge, also flowing southwest; at 2 600 to 2 960 m in the angle between the foot of the Irish continental slope and the adjacent abyssal plain, flowing east-northeast; and at 1 400 to 1 600 m beside the Irish continental slope, flowing south and north of east.

During photo run A-1, at 1 315-1 345 m on the slope of Rockall Plateau, the side-looking sonars mapped a field of transverse sand waves, with a wavelength of 7-8 m, and heights of less than 0.5 m. Crest-lines are oriented along the contours, and the pattern of echoes and acoustic shadows indicates that their steepest slopes face uphill, to the northwest. Bottom photographs at this site show a rippled sea floor of winnowed sand (Fig. 2 a and b). Many of the ripples, including those superimposed on steep slopes identified as sand waves' relict slip faces (Fig. 2 b), are symmetric. Some of the ripples are asymmetric, and the orientation of most of their slip faces indicates upslope migration, though there are locally divergent directions (Fig. 2 b). A similar bedform assemblage (symmetric and asymmetric ripples superimposed on asymmetric sand waves, with a net upslope bed load transport) has been described from depths of 1 600-1 700 m on the flanks of Horizon Guyot (Lonsdale *et al.*, 1972), where direct current measurements show topographically accelerated internal tides to be responsible for bedform migration. By analogy,



Figures 6 a and b
Deep tracks of profiles A and B, with locations of camera runs, and inferred directions and approximate magnitudes of bottom currents. Bathymetry after Johnson *et al.* (1971).

we attribute the bedforms of photo run A-1, and symmetric sand ripples aligned parallel to the regional contours of the upper Irish continental slope (Fig. 4 b), to bed-load transport by oscillatory tidal currents.

Inferred bottom currents are weak elsewhere on the traverse, even on the Irish continental shelf, which here is unusually deep and probably therefore unaffected by the surface storm waves that are effective agents on most of this exposed shelf (Draper, 1967). On some frames of some photo runs in the trough, careful scrutiny reveals a subtle lineation of the sea floor, with small sediment drifts in the lee of biogenic bumps and obstacles, and the current direction inferred in these instances has been plotted on Figure 8: the most interesting pattern revealed is of a reverse (i. e., northeasterly) flow on the north-west flank of Feni Ridge (photo run A-7; Fig. 3 b). In almost all photographs, even on photo runs from which no current direction can be extracted, the sea floor appears to have been smoothed by some form of current activity, and does not show the maze of trails and the litter of faecal mounds that are characteristic of the most tranquil abyssal environments. Smoothed, but non-lineated, sea floor is also characteristic of the photographs from site C, where 2 current meters moored 20 m above the sea floor for 4 1/2 days recorded a flow to the west-northwest with average velocities of only 3.7 and 3.3 cm/sec. However, superimposed on this slow thermohaline flow was a strong semidiurnal tidal oscillation, with the major axis of the tidal ellipse, at 210°, oriented at right angles to the net flow. The average current speeds at each meter were almost twice the average velocities, and the maximum speed, averaged over 15 minutes, was 13.5 cm/sec.

Significance of the observations

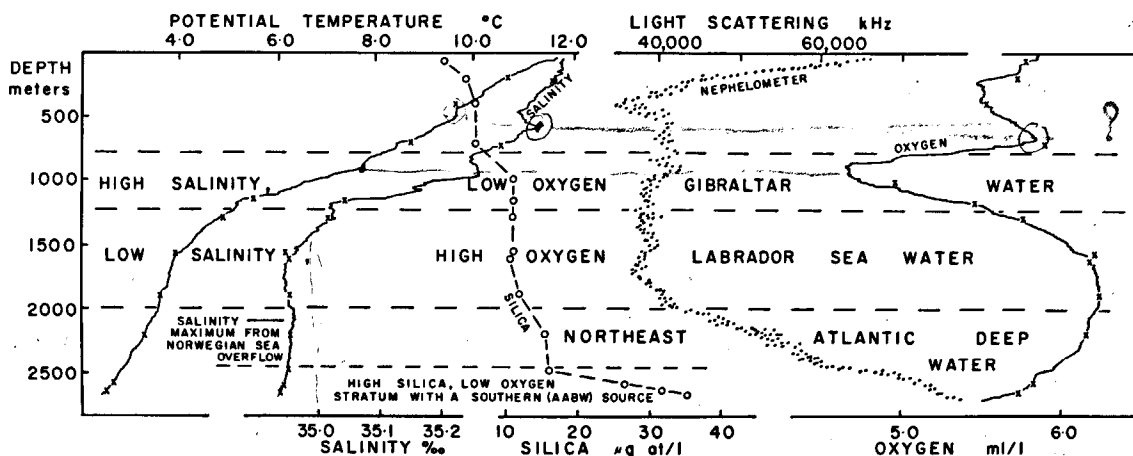
Beneath the surface waters, where the North Atlantic Current has a local anticyclonic gyre, the water masses

recognized in Rockall Trough by Ellett and Martin (1973) are: Gibraltar Water, at 800 to 1 200 m, characterized by high salinity and low oxygen; Labrador Sea Water, at 1 200 to about 2 000 m, with high oxygen (exceeding 6.0 ml/l); and the underlying Northeast Atlantic Deep Water (Neadw). Our new measurements at Station 698, in the center of our traverse, show a similar stratification (Fig. 7). The deep salinity maximum near the top of the Neadw indicates a northern, Norwegian Sea, source, and recent observations have confirmed that a branch of dense Norwegian Sea Overflow leaks at high velocity (> 80 cm/sec.) across Wyville-Thomson Ridge into the northern end of Rockall Trough (Ellett, Roberts, 1973; Roberts, 1975). However, the maximum potential density (σ_θ) measured in this leak, immediately downstream from this sill out of Faeroe Bank Channel (in which $\sigma_\theta > 28.0$), is only 27.85, because of dilution with overlying Atlantic Water near the sill on Wyville-Thomson Ridge (Ellett, Roberts, 1973). Below 2 500 m at station 698 potential density exceeds 27.9. Episodic spillover of undiluted overflow water from Faeroe Bank Channel might be a possible source of this deepest stratum in Rockall Trough. However, its high silica concentration strongly suggests a southern origin, with an immediate source in the West European Basin, which receives Antarctic Bottom Water (Aabw) that has crossed the Mid-Atlantic Ridge in equatorial regions and spread northward (Mann *et al.*, 1973), mixing en route with the densest Neadw (which has flowed out of Faeroe Bank Channel and passed west of Rockall Plateau).

The photographic traverse helps assess the supply routes and rates for some of the water masses in Rockall Trough. Our observation of the effects of an intense but thin (500 m) and narrow (10 km) current entering the trough along the foot of the Irish continental slope defines a section of the flow path of silica-rich bottom water from the West European Basin. We suggest that this current makes a cyclonic loop in Rockall Trough:

Figure 7
Data from CTD Cast 698 (see Fig. 1 for location), with approximate water mass boundaries delineated. Northeast Atlantic Deep Water (Ellett, Martin, 1973) is interpreted as a mixture of Norwegian Sea

Overflow Water that has leaked across Wyville-Thomson Ridge, and Eastern Basin Water that ultimately has an Antarctic Bottom Water source. The light scattering data from the Geosecs nephelometer is on an arbitrary scale.



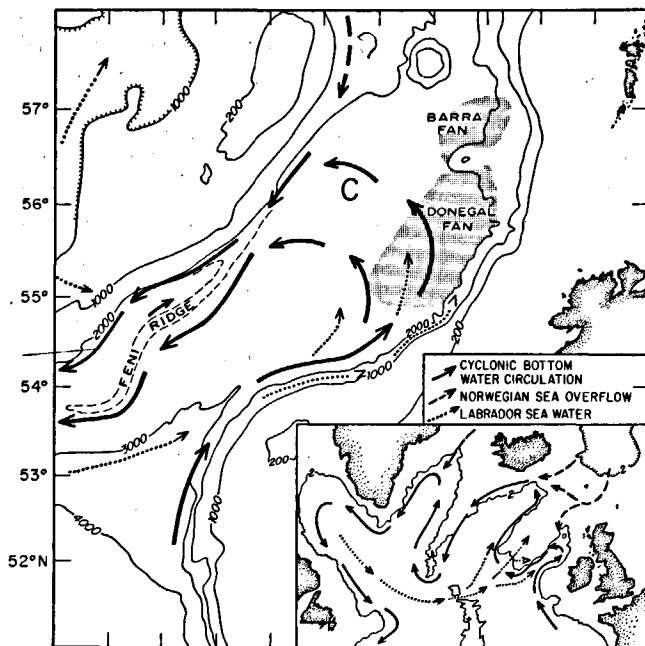


Figure 8

The deduced pattern of deep circulation in Rockall Trough. The current direction at site C is as recorded by our meters. Inset map (after Ivers, 1975; and Roberts, 1975) shows how the Rockall Trough circulation fits into the overall pattern of the deep North Atlantic. Gray pattern denotes turbidity-current-produced deep sea fans.

the inflow hugs the southeast margin of the trough, crosses to the northwest margin in a broader, slow flow (as measured at Site C) near 56°N, and exits along the flank of Feni Ridge (Fig. 8). The exiting (southwesterly) current is augmented by slightly less dense Norwegian Sea Overflow that has leaked out of Faeroe Bank Channel and flowed south between Rockall Bank and Anton Dohrn Seamount (Roberts *et al.*, 1973). Across our traverse, the combined outflow current is broad, and covers most of the width of Feni Ridge; however, it has a narrow high-velocity core which hugs the foot of the Rockall slope. Another axis of faster flow at about 2 400 m depth on the southeast flank of Feni Ridge (Fig. 6 a), probably diverged from the core of the current upstream, where the crest of Feni Ridge separates from the continental margin near 55°30'N. Between the axes of the southwesterly current is a weak reverse flow (to the northeast) on the northwest flank of Feni Ridge.

We identify the strong current at 1 500-1 650 m on the middle Irish slope with the core of the Labrador Sea Water. The high velocities indicated for this region suggest that much of this stratum may also be renewed by a narrow jet along the southeastern margin of the trough, though this contradicts the widely-held notion that Labrador Sea Water spreads so slowly that its core is a suitable "level of no motion" for use in geostrophic calculations (e. g., Worthington, 1976). We find no clear evidence of a current of Labrador Sea Water on the northwest margin of the trough, though the extensive reworking and moating of sediments at similar depths elsewhere on Rockall Plateau (Davies, Laughton, 1972) have also been attributed to motion in this water mass. There is significant sediment reworking and bed load transport at depths of 1 300-1 350 m (Fig. 2 a and b),

but the observed effects are attributable to strong oscillatory currents that effectively mask any signal from a net flow. Similarly, on the upper Irish slope there are symmetric ripples at the depth of Gibraltar Water, and effects of the current that supplies this water mass cannot be distinguished. Symmetric ripples have also been photographed near the top of the continental slope off Brittany (Heezen *et al.*, 1959, Plate 11).

Our interpretation of the bottom circulation should be compared with those based on geostrophic calculations. Ellett and Martin (1973, p. 616) constructed a geostrophic velocity section across the central Rockall Trough, but chose 1 800 m as the level of no motion, because they had "no evidence of a strong circulation which could impart movement to lower layers", and therefore derived negligible current velocities deeper than 1 500 m (the depth of the shallowest "strong current" inferred in Figure 6 b). Ivers (1975) selected a "level" of no motion which varied in depth across the section ("Discovery II", Stations 3 823-3 833), and obtained a cyclonic circulation below 1 500 m, with a northeasterly current flowing faster than 5 cm/sec. along the Irish continental slope, and a southwesterly flow, at approximately the same velocity, on the western side of the trough. Our data support Iver's analysis of the Neadw circulation pattern, which he interpreted as a local loop of a general North Atlantic cyclonic bottom circulation.

Inferring bottom currents from density distributions or from snapshots of the sea floor is a poor substitute for measuring them with current meters. Perhaps the most significant result of our photographic traverse was the discovery of the effects of fast boundary currents that seem amenable to study with even short-term current meter deployments, but which are so narrow (10-20 km, Fig. 6 a and b) that accurate geostrophic analysis would be difficult, even if closely-spaced casts were available. Some of these fast bottom currents occur in water masses and at eastern boundary situations where conventional wisdom suggests that thermohaline motions should be slow: the same is true for bottom currents at the eastern boundary of the Iceland Basin, where a steady flow with an average velocity of 14 cm/sec. has been measured (Hollister *et al.*, 1976).

GEOLOGY OF THE MARGINS

Rockall Slope

Deep-tow traverse "A" (Fig. 1) included a profile down the lower half of the southeast flank of Rockall Bank, from a depth of 1 200 m to the "marginal channel" (Roberts, 1975) as its foot. Although this part of the slope has a gentle gradient (average 2.5°) and lacks evidence of the slumping that has denuded the slope further north (Roberts, 1972), its cover of unconsolidated sediment is very sparse. Between depths of 1 300 and 1 400 m there are patches of sediment which show up as thin (< 10 m) lenses of acoustically transparent material on the near-bottom 4-kHz profile and have rippled, winnowed sand at the surface (e. g., Fig. 2 a

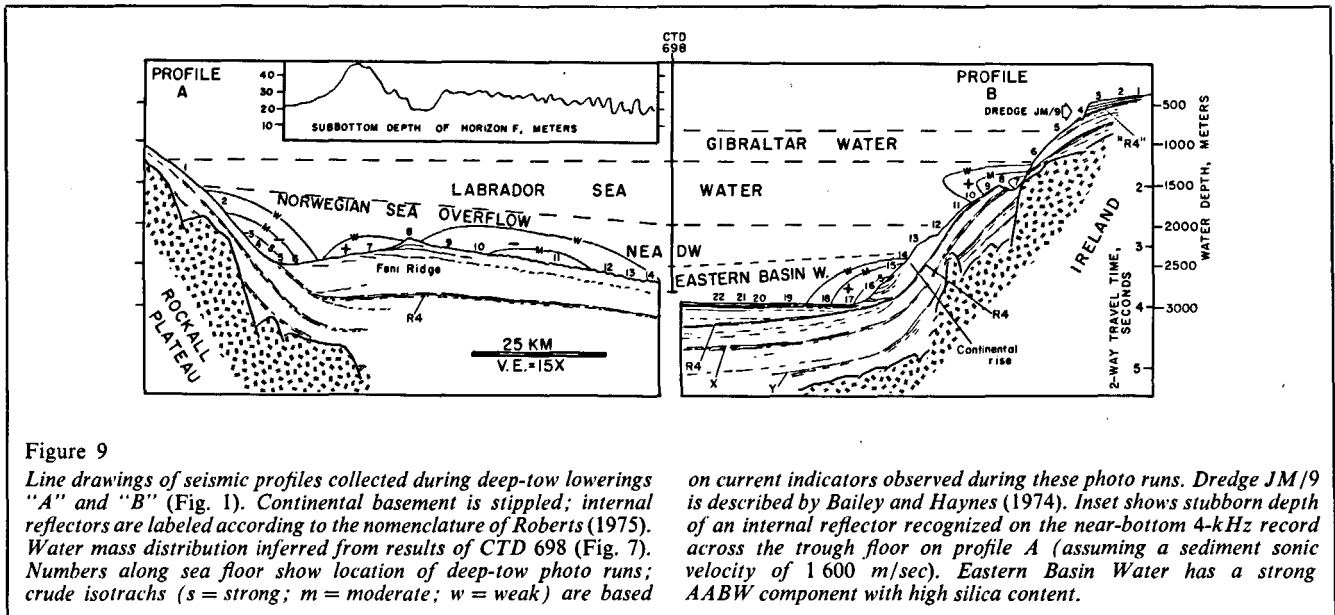


Figure 9
Line drawings of seismic profiles collected during deep-tow lowerings "A" and "B" (Fig. 1). Continental basement is stippled; internal reflectors are labeled according to the nomenclature of Roberts (1975). Water mass distribution inferred from results of CTD 698 (Fig. 7). Numbers along sea floor show location of deep-tow photo runs; crude isotrachs (s = strong; m = moderate; w = weak) are based

on current indicators observed during these photo runs. Dredge JM/9 is described by Bailey and Haynes (1974). Inset shows stubborn depth of an internal reflector recognized on the near-bottom 4-kHz record across the trough floor on profile A (assuming a sediment sonic velocity of 1600 m/sec). Eastern Basin Water has a strong AABW component with high silica content.

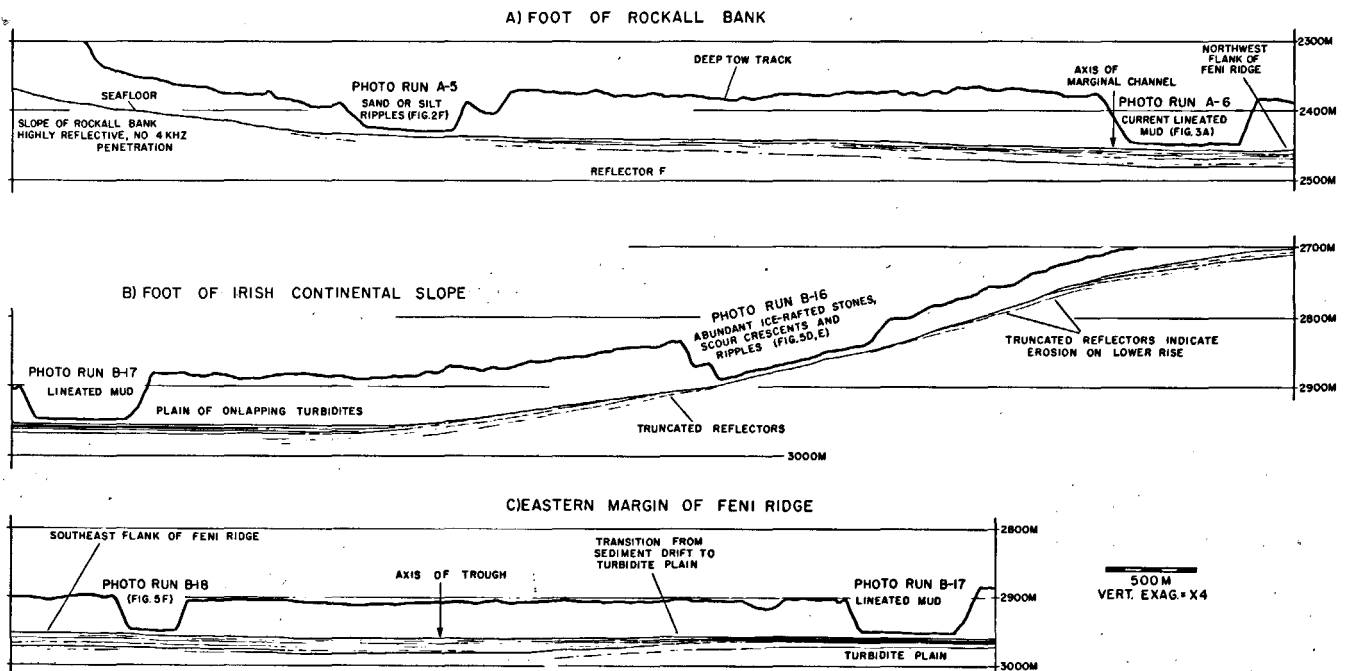
and b). Elsewhere, however, the near-bottom profiler recorded a strong reverberant echo from a rocky sea floor that allows no 4-kHz penetration, and the side-looking sonars mapped ledges of outcropping stratified rock and abundant detached boulders, which have either been shed from ledges or dropped from icebergs. On the lower slope there is an increasingly continuous veneer of fine-grained sediment between the moated rock fragments (Fig. 2 c and d). Here the bottom water appears more turbid with suspended sediment, as can be deduced from the less distinct strobe image. On low-resolution airgun profiles (Fig. 9) the entire slope appears to be

developed in a sequence of sedimentary rocks that extends beneath the floor of Rockall Trough and is believed to be mainly of Cretaceous age (Roberts, 1975). Near the foot of the slope the gradient abruptly decreases to less than 1°, and there is a 3 km-wide transition zone between the slope's rock-strewn surface and the northwest flank of Feni Ridge, which is completely covered with muddy sediment (Fig. 10 a). Rippled sand or silt patches occur in this transition zone (Fig. 2 f). At the axis of the marginal channel between Rockall Bank and Feni Ridge, the upper sedimentary sequence is almost 0.5 seconds (perhaps 450 m) thick. Photos from

Figure 10

Line drawings of sections of the near-bottom 4-kHz records collected on profiles A and B (Fig. 1). Location of photo runs allows cross reference to Figures 6 and 9.
a) The foot of Rockall Bank, showing the abrupt transition from a slope almost bare of unconsolidated sediment to a thick trough fill.

Samples of photos from some of the photo runs are shown in Figure 2 (frames d, e, f).
b) The foot of the Irish slope, showing the lower continental rise with erosionally truncated internal reflectors and an abrupt transition to a turbidite plain.
c) The transition from an acoustically layered (turbidite) sequence to a thicker sediment drift, deposited from thermohaline currents.



the axis (photo run A-6) indicate a smoothly streamlined sea floor being swept by a muddy southwesterly bottom current.

Irish continental margin

The deep-tow instrument was lowered to within 50 m of the sea floor on the outer continental shelf, and towed about 10 km to the deep (495 m) shelf break. The track down the continental margin (Fig. 6 b) lay between two large slope canyons across the narrow (10 km wide) continental rise, and onto the abyssal plain (Fig. 9).

This part of the outer shelf, remote from the main dispersal routes of terrigenous sediment (Kenyon, Stride, 1970), has but a thin cover of Neogene sediments unconformably overlying an older, mainly Mesozoic lens up to 500 m thick, and Paleozoic basement (Fig. 11; Bailey *et al.*, 1974). Sonar records and bottom photographs indicate a smooth sandy bottom, without the spectacular sand waves and ribbons characteristic of more current-swept parts of the West European Shelf (e. g., Kenyon, Strike, 1970). Near the shelf edge (photo run B-3), the seabed is strewn with ill-sorted, angular rock fragments and rounded cobbles up to 1 m diameters. These are probably proximal glacio-marine deposits (Vanney, Dangeard, 1975), left by the Pleistocene Irish ice sheet which extended across the entire shelf.

The continental slope has an average inclination of 4°, and its upper half has a very thin and patchy veneer of unconsolidated sediments. Immediately below the shelf break is a 200 m-high scarp whose 12° slope truncates

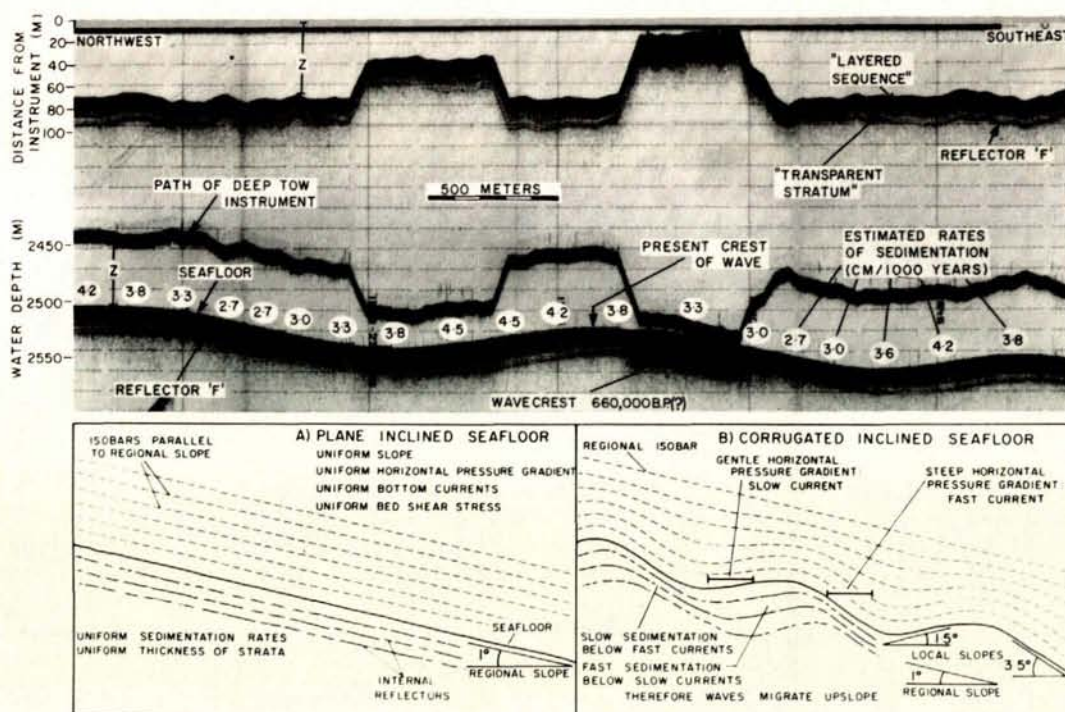
the entire section of flat-lying shelf strata, the underlying unconformity, and the upper part of the older, westward-dipping sedimentary prism. Ledges of consolidated rock crop out on this scarp, and most of the photographs (photo run B-4) show abundant boulders and cobbles (e. g., Fig. 4 a). Dredging of the scarp (Bailey, Haynes, 1974, Dredge JM/9) has yielded lithified calcarenite with reworked Upper Eocene microfossils (Dobson *et al.*, 1976), partly justifying the correlation, based on continuity of acoustic stratigraphy, between the shelf-edge unconformity ("R4" of Figure 9) and the deep-water basal Oligocene unconformity of Rockall Trough and Plateau (responsible for Reflector R 4; (Roberts, 1975).

Truncation of strata on this rather gentle scarp seems to have been by current erosion, rather than by post-depositional faulting or slumping, for which we have no evidence on the near-bottom 4-kHz profile. We suspect that thermohaline currents associated with bottom water formation during glacial periods were responsible for the erosional trimming of the sedimentary prism, and that the fields of worn cobbles (Fig. 4 a) are glacio-marine lag deposits, like those photographed at similar depths near present Antarctic ice fronts (Dangeard, Vanney, 1975). A light dusting of fine-grained sediment on the cobbles at the top of the Irish slope indicates that this lag deposit is relict, and is not being maintained by the present current regime. In the Climap reconstruction of the North Atlantic circulation at the last glacial maximum, 18 000 BP, this part of the margin, where relatively saline surface waters at the margins of the

Figure 11

A section of near-bottom 4-kHz data from mud waves on the southeast flank of Feni Ridge, located between photo runs A-11 and A-12 of Figures 6 and 9. The top trace, which shows internal stratification most clearly, is a record of the sea floor and subbottom layer that is uncorrected for variable depth of the instrument package; Z is the altitude of the instrument above the sea floor. The middle trace shows the path of the deep-tow instrument; its vertical excursion, bringing it closer to the sea floor than usual, were made in a vain search for

small-scale bedforms. The lower trace shows that "true shape" of the sea floor and internal reflectors, with a vertical exaggeration of about 4X. Note variable thickness of the stratum overlying Reflector F; the numbers are estimates of post-F sedimentation rates, assuming a sediment sonic velocity of 1 600 m/sec, and a 660 000 BP date for the reflector. The sketches illustrate models of sediment deposition over (a) a flat sea floor sloping at right angles to the current direction and (b) a sea floor with regular mud waves corrugations superimposed on the regional transverse slope.



subtropical gyre came in contact with the ice shelves, is considered the likeliest glacial North Atlantic equivalent of the present Weddell Sea (McIntyre *et al.*, 1976, p. 71). Fast (> 25 cm/sec.) bottom currents at the Weddell Sea shelf-break have been measured by Foldvik and Kvinge (1974), and their geological effectiveness is attested by the scour and lag deposits there.

The deepest erosional incision, a notch through the entire sedimentary sequence to the Paleozoic (?) continental basement occurs between 1 300 and 1 500 m on the middle part of the slope (Fig. 9). The sides of the notch have been terraced by differential erosion, with resistant ledges occurring at the outcrop of the principal internal reflectors. Photographs of jointed and massive rock outcrops, and gravel and boulder pavements (photo runs B-7 and B-8; Fig. 4 *c*, *d* and *e*) show that current erosion, or at least nondeposition, is presently active, with a high-velocity jet of low-turbidity Labrador Sea Water as the agent. Surrounding bathymetry (Fig. 6 *b*) is good enough to confirm that the erosional notch in the slope is not a tributary of a submarine canyon, cut primarily by turbidity currents; besides, significant though less intense scour occurs beyond the notch (e. g., photo run B-9, Fig. 4 *f*).

Deeper than about 1 700 m on the slope the near-bottom 4-kHz profiler resolved a continuous layer of unconsolidated sediment overlying Reflector R4. Superficial rock fragments are absent from side-looking sonar records or on photographs from runs B-10 to B-14, implying that any glacial dropstones have been buried by postglacial sediment accumulation. The seabed is smooth and pockmarked with rimless biogenic craters (Fig. 5 *a* and *b*). The post-R 4 stratum thickens downslope, gradually at first, and then abruptly to about 400 m at a water depth of 2 100 m (Fig. 9), close to the level of transition from clear Labrador Sea Water to turbid Neadw at CTD 698. We consider this youngest sediment prism, extending from a depth of 2 100 to 2 950 m, as a miniature continental rise, though its regional gradient is about 4° , the same as on the rest of the continental slope. The surface of the rise, especially in its convex upper part, is hummocky, with broad along-slope corrugations, up to 30 m high and 2 km across, superimposed on the regional slope.

The deepest part of the continental rise, especially below 2 700 m, is a site of recent, and probably continuing, erosion. Internal reflectors of the rise are truncated by the sea floor (Fig. 10 *b*), which is littered by a relict deposit of ice-rafted gravel and cobbles similar to that presently accumulating on Antarctic continental rises (Heezen, Hollister, 1971; Dangeard, Vanney, 1975), and has patches of winnowed, rippled sand (Fig. 5 *d* and *e*). The image of the strobe is slightly blurred in photographs from photo run 16 (e. g., Fig. 5 *d*), indicating that the bottom water is somewhat more turbid than on shallower parts of the continental slope and rise. At the foot of the rise there is an abrupt stratigraphic transition to acoustically laminated, flat-lying strata (Fig. 10 *b*), and the lag deposit of superficial rock fragments, mapped by side-looking sonars, ends abruptly at the margin of this plain. The streamlined microtopography of the muddy abyssal plain (e. g., Fig. 5 *f*) demonstrates that

the fast bottom current extends onto the plain, but that there it is depositional rather than erosional. The indistinctness of the strobe image (Fig. 5 *f*) shows that bottom water turbidity is much greater than on the rise.

Discussion

Existing descriptions of sedimentation on the margins of Rockall Trough rely mainly on low-resolution seismic profiles (e. g., Bailey *et al.*, 1974; Roberts, 1975). The near-bottom acoustic and photographic records enhance these studies, not merely by allowing description of finer detail (e. g., of ripple and sand wave distribution), but by resolving the structure of the most recent sediments, those that are being deposited or eroded because of existing (and measurable) environmental conditions. It is often misleading to relate structures mapped by seismic profilers to patterns of bottom water currents and turbidity determined by oceanographic measurements, because the low-resolution profiler displays only the integrated results of millions of years of deposition and erosion (see discussion by Worthington and Wright, 1971). For example, seismic reflection profiles show the scarp eroded at the top of the Irish slope (Bailey *et al.*, 1974), and a narrow continental rise deposited along part of the margin of Porcupine Bank and Ireland (Roberts, 1975), but near-bottom data are needed to show that these features are not related to the present dynamic regime: the recent (probably postglacial) history is of deposition on the scarp (Fig. 4 *a*), and erosion on the rise (Fig. 10 *b*). In contrast, erosion of the middle Irish slope inferred from airgun records (Fig. 9) could have been attributed to turbidity current excavation of a now-extinct canyon, except that the near-bottom data shows that continuing erosion by a thermohaline current is a better explanation.

Further examples of sites where airgun records indicate sea-floor erosion but the higher-resolution deep-tow profiles show recent rapid deposition occur on the floor of the trough, and are discussed below. Of course, Rockall Trough is a particularly bad place for relating large-scale geologic structures to existing hydrography, because the latter has prevailed for only a short (postglacial) time. For most of the past million years the trough was bordered with ice-sheets, which delivered large volumes of terrigenous debris and certainly modified the deep circulation, if only by preventing Norwegian Sea overflow (Streeter, 1973; Alvinerie *et al.*, 1978). The narrow continental rise at the foot of the Irish slope may have been almost entirely built during the Pleistocene, by deposition from a boundary current which swept northeastward into the trough as it does today (Fig. 6 *b*), but was much more turbid because of the glut of terrigenous input during glacials. Recent erosion like that on the Irish continental rise is a common feature of continental rises and sediment drifts in the western North Atlantic that experienced very rapid deposition during most of the Pleistocene (e. g., Hollister *et al.*, 1974; Johnson, Lonsdale, 1976), and a postglacial decrease in bottom water turbidity (rather than an increase in current speed) may be a general explanation.

SEDIMENTATION ON THE FLOOR OF ROCKALL TROUGH

The turbidite plain

The eastern half of the central Rockall Trough is dominated by gently sloping turbidite fans and their distal plains. Their principal sediment sources have been the Irish and Hebridean continental margins (Roberts, 1975), though in the Pleistocene some sediment was transferred there by debris flows which moved down the southeast slope of Rockall Bank and across the northern Feni Ridge (Flood *et al.*, 1978). In the southern part of the trough, where direct terrigenous influx from the margin has been limited, turbidites are less extensive. Low-frequency seismic profiles at the site of our deep-tow profile "B" (Fig. 1) have been interpreted as showing a 100 km-wide turbidite plain, incised by "small channels" (Roberts, 1975). Our high-resolution deep-tow profile showed that the modern plain, with flat-lying acoustically laminated surface sediments, is much narrower, and our track crossed no turbidite channels. Only 2.6 km from the foot of the Irish continental rise (Fig. 10c) there is an abrupt transition from horizontal, layered sediments, interpreted as turbidites, to a thicker, acoustically more transparent section. The latter thickens upslope, to the northwest, and appears identical to the drifts of sediment deposited by southwesterly thermohaline currents in the western half of the trough.

Airgun profiles and the near-bottom 4-kHz profile together show that any turbidite strata in this region are thin, and that coeval sediment drifts are thicker. We deduce that a large fraction of the sediment load of turbidity currents that reached this part of the trough floor has been pirated by thermohaline currents and transferred by the cyclonic loop of the bottom water circulation (Fig. 8) to the western half of the trough, where it built Feni Ridge. Alternatively some of the quartz-rich material recovered in cores on the Feni Ridge may have come from the eastern portion of the Wyville-Thomson Ridge during interglacial periods (Latouche, Parra, 1976).

Feni Ridge

Deep-tow profile A (Fig. 1) included a complete traverse of Feni Ridge sediment drift, from the marginal channel at the foot of Rockall Plateau to the depression between Feni Ridge and the smaller, secondary ridge on its southeast flank (Jones *et al.*, 1970, Profile J). At this crossing the crest of Feni Ridge is 30 km from the foot of Rockall Plateau, having diverged from the margin about 100 km upstream. Maximum sediment thickness of this part of Feni Ridge, above the almost flat-lying Reflector R4, is 0.9 seconds, or about 800 m.

The near-bottom 4-kHz profiler recorded a distinctive acoustic stratigraphy across the entire ridge, with 4-5 continuous and closely-spaced reflectors in the upper 10-20 m, a fairly transparent stratum, and a strong reflector (designated "F") at a subbottom depth of 20-50 m. Some of these reflections are probably caused

by zones rich in coarse-grained volcanic ash: core RC9-225, taken on the profile at the position of photo run A-7 (Fig. 9), has two such ash zones in its upper 10 m (Ruddiman, McIntyre, 1976). Reflector F is at a depth of 48 m at the site of this core, which had an average accumulation rate of 7.3 cm/1 000 years for the past 127 000 years (Ruddiman, McIntyre, 1976): by extrapolation, the age of Reflector F is about 660 000 BP, and, if it is a synchronous horizon, the variation in its subbottom depth across the ridge (Fig. 9 inset) records spatial variations in sediment accumulation since that time. As expected, the post-F stratum thins towards the margins of the ridge, but there is also a local minimum within 5 km of its crest. The maximum post-F accumulation is on the northwest flank of the ridge, where truncation of reflectors in the upper part of the post-R4 sequence records an earlier episode of erosion. High Pleistocene sedimentation rates at the sites of Core RC9-225 and the nearby V 23-81, which are near the post-F depocenter, were caused by rapid deposition during the glacials of fine-grained terrigenous debris, that was delivered not by icebergs but by bottom currents (Ruddiman, McIntyre, 1976). The spatial variation in Late Pleistocene accumulation rates on the Feni Ridge transect is therefore mainly attributable to differential deposition from muddy glacial bottom currents, with preferential deposition on the northwest flank because the currents were decelerated there. Further north where no marginal channel separates the summit of Feni Ridge from the foot of Rockall Bank, the pattern of Pleistocene deposition from thermohaline currents has been disrupted over a wide area of the ridge (e. g., at Site C of Figure 1; Flood *et al.*, 1979) by erosive debris flows spawned from slumps on the slopes of the bank (Roberts, 1972).

On the lower southwest flank of the ridge there is a spatial periodicity in the thickness of the post-F stratum, associated with the presence of large-scale bedforms. These are regular symmetric mud waves, subparallel to the regional contours and to the current, which have an average wavelength of 2 km, and amplitudes of up to 30 m. The marked local variation in accumulation rates is not between ridges and troughs of the waves (which would cause a change in amplitude), but between slopes of different aspect, which causes the waves to migrate. Accumulation rates on northwest-facing slopes, inferred from the thickness of the post-F stratum, are as much as 70% greater than on slopes that face southeast (Fig. 11), and as a result the waves have migrated slowly northwest, up the regional slope of Feni Ridge and across the prevailing current, at an average rate of 0.25 m/1 000 years. Fields of similar mud waves are characteristic of many sediment drifts at the margins of North Atlantic basins, where shaping of rapidly deposited terrigenous sediment by thermohaline boundary currents is known or suspected (e. g., Fox *et al.*, 1968; Rona, 1969; Johnson, Schneider, 1969; Jones *et al.*, 1970; Markl *et al.*, 1970; Ruddiman, 1972; Jacobi *et al.*, 1975; Embley, Langseth, 1977), and upslope migration of the waves is typical. Undulation of subbottom reflectors on airgun records indicates that mud waves have been present throughout the deposition of the upper 0.5 seconds of sediment, and

were probably initiated in the Late Miocene (Roberts, 1975).

Speculations on the dynamics of sedimentation from thermohaline currents

The striking local and regular variations in sediment accumulation rates on the mud waves of Feni Ridge, with parallel bands less than 1 km apart whose accumulation rates differ by 70%, could be explained by regular cross-stream variations in either the turbidity or the current speed of the benthic boundary layer. Cross-stream alternation of fast and slow currents, which is required in the explanation of other types of longitudinal abyssal bedforms (Lonsdale, Spiess, 1977) is the more plausible. Density or pressure surfaces in deep currents flowing over inclined plane beds tend to parallel the regional slope of the sea floor (Amos *et al.*, 1971; Stommel, Aarons, 1972). However, where the bottom is regularly corrugated, with large-scale waves whose long crests are parallel to the flow, isopycnals near the bottom tend to conform to the actual topography (Stommel, Aarons, 1972, p. 715). As a result, horizontal pressure gradients in the near-bottom water are locally intensified over parts of the wave that face southeast, down the regional slope (Fig. 11): this causes faster currents there, greater shear stress on the bed, and impeded deposition. In contrast, immediately above the upslope faces of the waves, where the 2.5° local slope is opposed to the 1° regional gradient, horizontal pressure gradients are reduced, and there is relatively slack water which favors deposition. According to this theory a stable configuration is attained, with regular corrugations in the bed being maintained by regular threads of fast and slow flow (presumably connected by a secondary circulation which feeds turbid water from fast to slow bands) that are caused by the regular bedforms. To test it we need new observational data, in the form of measurements by current meters precisely positioned onto the different slopes of an active mud wave.

The dynamics of current flow and sediment deposition on Feni Ridge, in the section where the crest is detached from Rockall Slope, mimic on a giant scale those deduced for individual mud waves on its surface. The southeast side of the ridge is swept by a moderately fast southwesterly current that delivers fine-grained terrigenous sediment in suspension, but which impedes deposition. Deposition is concentrated on the northwest side where, because the slope of the topography is opposite to that of isobars in a deep southwesterly current, the current is decelerated, and even reversed (at photo run A-7, Fig. 6 a), just as on Blake-Bahama Outer Ridge (Heezen *et al.*, 1966; Amos *et al.*, 1971). The mere presence of slack water over the northeast slope is not enough to account for the preferential deposition there: what is important, just as in differential deposition on the mud waves, is that a band of slack water is sandwiched between fast currents that can provide a continuous supply by turbid water by cross-flow secondary circulation. The northwest slopes of Feni Ridge, and of its

mud waves, are zones of bottom water deceleration, and experiments with dilute suspensions of fine cohesive sediments in turbulent flows (e. g., Partheniades *et al.*, 1968) have shown that rapid deposition is an immediate consequence of deceleration. Differential deposition on Feni Ridge has not resulted in simple northwest migration of its crest during the Late Pleistocene, as it has on individual mud waves, because of limited deposition near the summit (Fig. 9, inset). Less deposition may occur on the shallowest parts of the ridge because they are above the most turbid bottom water (Fig. 7), though the nepheloid layer tends to maintain a constant thickness rather than a constant upper limit (Jones *et al.*, 1970).

The present shape of Feni Ridge tends to control the pattern of Neadw flow over it. Its shape, particularly the separation of its crest from the slope of Rockall Bank, has probably been controlled by the interaction of Neadw with the overlying Labrador Sea Water. The divergence of the crest from the slope occurs close to the intersection of the muddy southwesterly Neadw current with a clear easterly Labrador Sea Water current that has been channeled between Rockall Bank and Lorient Bank (where its geological effects have been described by Roberts, 1975). Bryan (1970) explains the origin of the Blake-Bahama Outer Ridge with a simple hydrodynamic model of deposition at the convergence of a muddy Western Boundary Undercurrent with the shallower, clearer Florida Current, and his model seems directly applicable to Feni Ridge. However, the explanation is not complete, since the Neogene histories of both the Blake-Bahama Outer Ridge and Feni Ridge have been complex, and they have also been shaped by erosion (on the northwest flank of Feni Ridge; on both flanks of the Blake-Bahama Outer Ridge, Ewing, Hollister, 1972). Sedimentation on Feni Ridge has doubtless been affected by changes in the bottom water circulation that resulted from changing geography and climate. Temporal variations in speed and turbidity of the cyclonic loop that brings Neadw from potential sources of suspended sediment along the West European Margin have probably been more important than changes in the intensity of Norwegian Sea Overflow. The latter current may have been initiated only at the end of the Miocene, following subsidence of the Iceland-Faeroe Ridge (Schrader *et al.*, 1976), and was not active during most of the Late Pleistocene, when the Norwegian Sea was ice-covered (Streeter, 1973; Kellogg, 1976): despite this, Late Pleistocene sediment accumulation rates on the ridge of up to 12 cm/1 000 years (at Core V 23-81; Ruddiman, McIntyre, 1976) were much greater than the post-R 4 average rate (Roberts, 1975).

SUMMARY OF CONCLUSIONS

The most important bottom current in Rockall Trough, both hydrographically and as a geological agent, is a cyclonic loop of Northeast Atlantic Deep Water (including a basal silica-rich stratum that ultimately has an Antarctic source) that enters along the northwest margin of Porcupine Bank and exits as a southwesterly current

along Feni Ridge and the lower slopes of Rockall Bank. The southwesterly flow is reinforced by a leak of overflow water from the Norwegian Sea. Although the Northeast Atlantic Deep Water is commonly regarded as a fairly stagnant water mass in this part of the ocean, on both western and eastern margins of the trough it is fast enough to cause erosion and bed load transport of sand, though on the eastern boundary these effects are restricted to a very narrow band at the foot of the slope. Labrador Sea Water, generally assumed to spread throughout the North Atlantic as a slow drift, also forms a fast erosive current on the Irish slope. At slightly shallower depths oscillatory tidal currents shape sand into small ripples and larger waves.

The Irish continental slope near 54°N and the southeast slope of Rockall Bank near 55°N both have only a thin and discontinuous cover of unconsolidated Tertiary sediment, not because it has slumped off them, but because of limited supply of terrigenous debris and current scour. Erosional truncation of a shallow-water lens of Tertiary sediment at the top of the Irish slope probably occurred at periods during the Pleistocene when bottom water was produced near a local ice front. Typically stony proximal glacio-marine deposits here are now being slowly buried with fine-grained sediment. Superficial glacial dropstones are common in Rockall Trough wherever postglacial deposition has been restricted by current activity. They are exposed as a lag deposit on the lower slopes of a narrow Irish continental rise, which was probably constructed by the inflow current of the Neadw loop during the Pleistocene, when it had a high suspended load of terrigenous glacial flour.

Most of the post-Eocene sediment in Rockall Trough, including a large fraction of that originally delivered by turbidity currents, has been entrained by cyclonic bottom circulation and deposited on the western side of the trough in sediment drifts, of which the largest is Feni Ridge. Norwegian Sea Overflow currents have had a minor role in transporting sediment and shaping the ridge. During the Late Pleistocene, sedimentation rates on Feni Ridge were high (> 3 cm/yr), especially on the northwest slope (> 7 cm/yr), where there is now a slow reverse (northeasterly) current. On the southeast flank of the ridge sediment accumulation was also highest on local slopes inclined to the northwest, namely the upslope faces of large-scale longitudinal mud waves. As a result the mudwaves migrated upslope, across the current, at about .25 m/1 000 years. The 70% difference in accumulation rates on the different faces of a single mud wave are thought to be caused by topographically induced alternations of fast and slow currents in the benthic boundary layer, and this process may account for the maintenance and migration of similar abyssal mud waves on current-swept sediment drifts at the margins of other ocean basins.

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