36. DEEP CIRCULATION IN THE SOUTHERN ROCKALL TROUGH—THE OCEANOGRAPHIC SETTING OF SITE 610[1]

Robert R. Dickson, Ministry of Agriculture, Fisheries and Food, Fisheries Laboratory, Lowestoft
and
Robert B. Kidd, Institute of Oceanographic Sciences, Wormley[2]

ABSTRACT

A review of recently acquired data from the Rockall Trough and from areas of eastern Atlantic immediately to the south shows that two southern sources of bottom water have a major present-day influence over the southern Feni Ridge. One source results from detachment and southward recirculation of water from a slope current, flowing northward along the west European continental margin. A second is the northward drift which occupies the deep layer of the Porcupine Abyssal Plain. Transport estimates on the overflow of Norwegian Sea Deep Water (NSDW) into the Rockall Trough suggest that NSDW probably had a lesser influence on the shaping of the Feni Ridge sediment drift, *if* its modern pattern and behavior pertained through the late Neogene and Quaternary. Analysis of the variability in current strength and direction over the flanks of Feni Drift show that the fine-grained, cohesive sediments which make up the sediment waves at DSDP Site 610 could locally be eroded and transported over much of the year.

INTRODUCTION

The pioneering work of Heezen et al. (1966) in the eastern Atlantic caused marine geologists to look more widely for the effects of deep bottom-current activity in sediment cores and profiling data. Seismic reflection profiles from the North Atlantic generally are replete with examples of large-scale sediment redeposition. These may be accumulations against and around preexisting topography or continental margins (sediment drifts and wave fields), or moats and channels resulting from erosion at sills or around upstanding features (Bryan, 1970; Jones et al., 1970; Johnson et al., 1971; Ruddiman, 1972). Deep-sea drilling has allowed the identification of hiatuses and condensed or expanded sequences, thus providing a time scale for the perceived effects of bottom-water circulation (Davies and Laughton, 1972) and allowing the development of one aspect of the discipline of paleoceanography (Berggren and Hollister, 1977).

During two decades of activity, the types of study just described have relied heavily upon early syntheses of oceanographic data to provide their concept of "present-day" circulation (Worthington and Volkmann, 1965; Worthington, 1976). Indeed, the geological studies have themselves gone on to refine considerably the pathways perceived for bottom-water circulation, using largely the location of identifiable sediment redeposition features (Davies and Laughton, 1972; Shor and Poore, 1979; Stow, 1982; Kidd et al., this volume). Recent syntheses of *in situ* bottom-current measurements (Dickson et al., 1985), however, provide a much improved basis for estimates of present circulation patterns in the eastern basins of the North Atlantic.

Deep Sea Drilling Project Site 610 on Feni Ridge (Fig. 1) was drilled both to examine the geological history of sedimentation on a major oceanic sediment drift and to investigate the field of large-scale sediment waves that decorate its bottom-water interface. Studies of the sediment wave field in particular require good information on the present-day bottom-water regime so that models of the formation and development of these waves may be considered. In this chapter we draw upon the recent long-term bottom-current measurements of Dickson et al. (1985) to establish the oceanographic setting of Site 610. Our purpose is twofold: (1) to demonstrate the importance of southern sources of bottom water in the southern Rockall Trough: these southerly flows combine with Norwegian Sea overflow to bring about a complex bottom-water regime over the southern Feni Ridge; and (2) to consider the variability of current speed and direction in the flow over the ridge: these data provide important insights on the processes of sediment redeposition likely to be active at the drill site now.

All long-term direct current measurements described in the following discussion were collected using Aanderaa RCM4 self-recording instruments set on moorings with subsurface buoyancy, and are therefore uncontaminated by wave action. The Aanderaa RCM4 instrument has a threshold current speed of ~ 1.5 cm s^{-1}. Sampling rate is normally hourly, except in some records from Porcupine Bank, where shorter deployments permitted 30-min. sampling. All data have been low-passed to remove frequencies higher than ~ 2 days, and are either presented as residual current vectors (12-hourly, daily, or record means) or are resolved into zonal and meridional current components (U and V, respectively, with eastward and northward denoted by positive values).

---

[1] Ruddiman, W. F., Kidd, R. B., Thomas, E., et al., *Init. Repts. DSDP*, 94: Washington (U.S. Govt. Printing Office).

[2] Addresses: (Dickson) Ministry of Agriculture, Fisheries and Food, Fisheries Laboratory, Lowestoft, Suffolk NR33 OHT, United Kingdom; (Kidd, present address, to November, 1986) Ocean Drilling Program, Texas A&M University, College Station, TX 77843-3469.

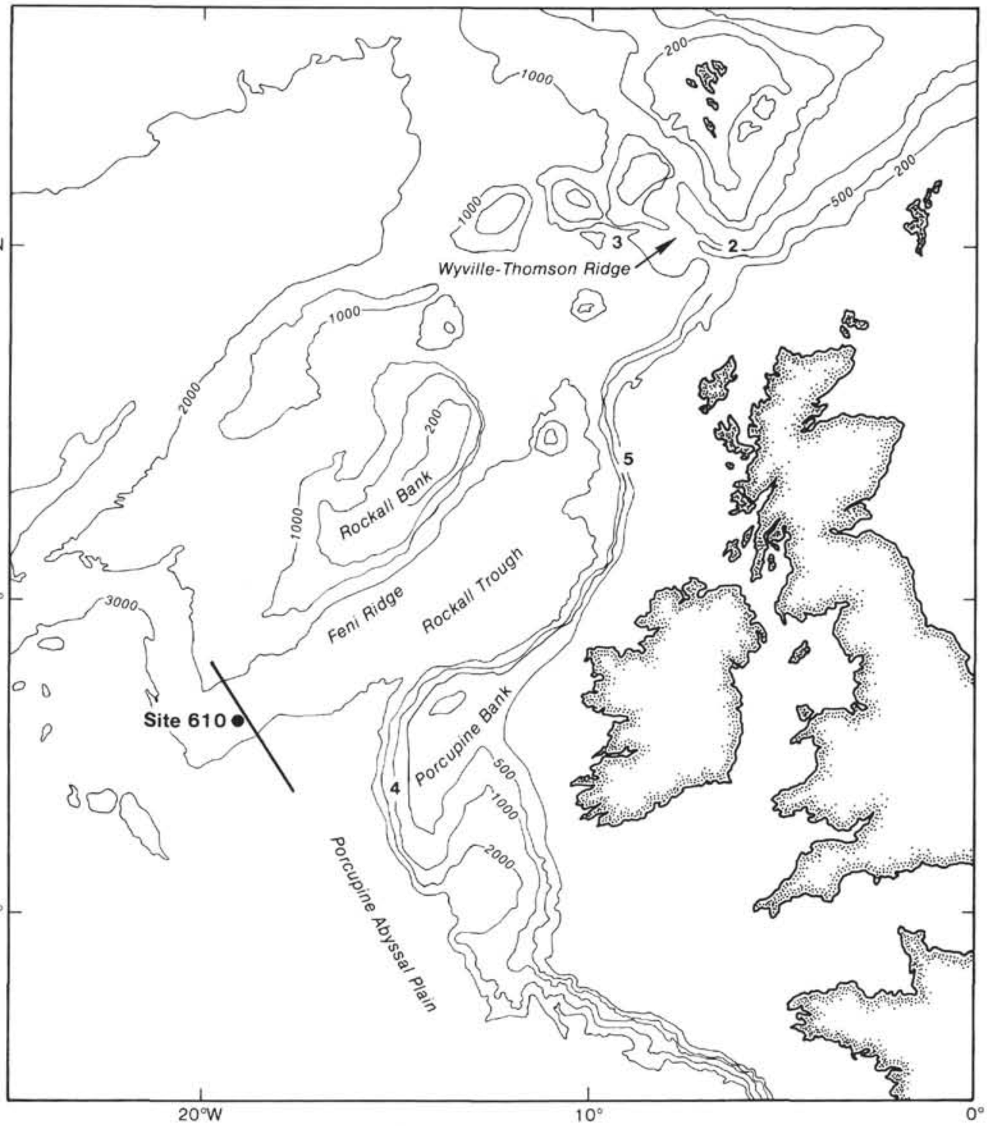

Figure 1. Location of Site 610 in the Rockall Trough, Numbers 2–5 are keyed to figures in this chapter, and represent locations of bottom-current data referred to here. Contours in meters.

THE DEEP MEAN CIRCULATION OF THE ROCKALL TROUGH

We recognize the three principal circulation components of potential importance to the sedimentation/erosion history of Site 610:

1. Overflows of Norwegian Sea Deep Water (NSDW) across the Wyville–Thomson Ridge.
2. Detachment and southward recirculation of water from the northward-flowing current along the European continental slope.
3. The northward drift which occupies the deep layer of the Porcupine Abyssal Plain and which turns to the west and southwest as the basin shoals in the north.

At present none of these circulation components is adequately described by the available direct current measurements. Nevertheless, drawing on recent data, it is possible to make some deductions about the circulation and its variability in space and time.

Norwegian Sea Overflows across the Wyville–Thomson Ridge

Johnson and Schneider (1969) and Jones et al. (1970) were the first to attribute the location and growth of the sedimentary Feni Ridge to the influence on sedimentation of southward-flowing bottom water of Norwegian Sea origin, constrained against the western margin of the Rockall Trough. Ellett and Roberts (1973) later traced the Feni Ridge along the entire length of the western Rockall Trough to the foot of the Wyville–Thomson Ridge and mapped the narrow gulley on the southwestern flank of the Ridge through which the overflow might occur. They showed the influence of the overflow water on the crest line in July 1972 in a 25-m thick near-bottom layer, and they recorded that water produced by mixing between the overflow and Atlantic water was present in June 1971 and July 1972 in the gulley below the Ridge crest. They described a picture of intermittent overflow in which the densest water drained rapidly down the gulley into the northern Rockall Trough, entraining behind it water from intermediate depths. Ellett and Edwards (1978) estimated the overflow transport at 0.3 Sverdrups (or 1.25 Sv with Atlantic water entrainment) and suggested that the mean for August 1973 reached 70% of these values (1 Sv = 10^6 m^3 s^{-1}).

Dooley and Meincke (1981) also provide a transport estimate for the overflow. They suggested that only a small fraction (0.1 Sv) of the 1.1 Sv of Norwegian Sea water (which flows southward and westward through the Faroe–Shetland and Faroe Bank Channels to the open Atlantic) overflows to the Rockall Trough, since it remained their assumption that the overflow was channeled principally through the single narrow gulley on the southwestern flank of the Ridge.

More recently, our understanding of the overflow process has improved dramatically with the recovery of the first long-term current-meter records from the Wyville–Thomson Ridge crest and flanks by H. D. Dooley (then at the Dept. of Agriculture and Fisheries for Scotland, Marine Laboratory, Aberdeen; personal communication, 1984) and from the northern Rockall Trough, close to the foot of the Ridge, by W. J. Gould (Institute of Oceanographic Sciences, Wormley; personal communication, 1984), as part of the Continental Slope Experiment (CONSLEX). Together with his mooring 198 (situated at the western end of the Ridge in 1980), Dooley's successive six-month records from mooring 224 (in the main gulley at 60°09.9′N, 7°44.5′W) and from mooring 233 (on the southeastern crest of the Ridge at 59°52.1′N, 6°24.1′W [Fig. 2]) suggest for the first time that Norwegian Sea water can overflow the Ridge crest throughout its length. They also suggest that the overflow signal is strongly periodic, with a marked ~30-day periodicity, and that overflow tends to vary inversely with westerly wind strength, although it *can* occur at any time of year (H. D. Dooley, personal communication, 1984). Overflow is therefore maximal in summer and tends to shut off during the west-wind maximum of winter, when warm water extends to the bottom along the Ridge crest. The latter point is confirmed in records from Gould's multi-year I-2 mooring at the foot of the Ridge to the east of the gulley exit (e.g., Fig. 3), although at that site the dominant periodicity was 15 days (similar to the periodicity observed on an earlier mooring by J. Crease in 1973—J. Crease, personal communication, 1984).

These recent and unpublished results do not greatly increase our estimate of the overflow transport. For example, a "best guess" of overflow based on the foregoing results (i.e., assuming that overflow takes place in the bottom 50 m [<3°C] over the western 50-mile [80-km] part of the Ridge crest, varying in residual current speed between 0 and 20 cm s^{-1} with a 30-day periodicity in summer and dwindling to zero overflow during the winter west-wind maximum) amounts to a transport of ~0.3 Sv averaged over the year. Thus, even allowing for a considerable error in this estimate, present-day transports are unlikely to be of great significance in shaping the Feni Drift.

During major overflow events, however, the peak near-bottom current speeds attained may nevertheless be of significance in eroding and contributing suspended sediment to the Feni Ridge downstream. Table 1 illustrates the development of one such extreme episode over a 5-day period in February 1983, recorded 4 m above the seabed near the saddle of the Wyville-Thomson Ridge in a water depth of 637 m (Department of Agriculture and Fisheries of Scotland [DAFS] record 224-3; data kindly provided by H. D. Dooley, personal communication, 1984).

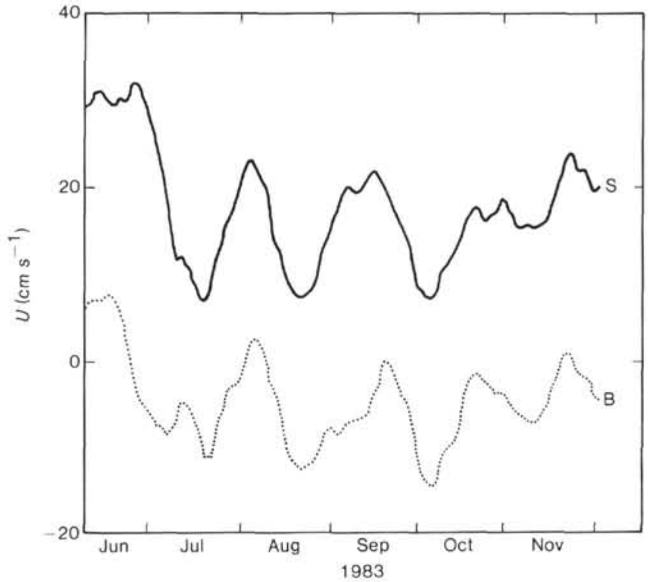

Figure 2. Fifteen-day running mean of low-passed data (*U*-component) for the two instruments of DAFS mooring 233 (CONSLEX D2, southeastern crest of Wyville–Thomson Ridge) in June–November 1983 (see Fig. 1). S and B refer to the near-surface (z = 100 m) and near-bottom (z = 477 m) instruments, respectively; water depth is 501 m. At times of extreme westerly-directed near-bottom flow, temperatures (not shown) fall to <4°C, confirming that these are overflow events. (Unpublished data, kindly provided by H. D. Dooley, ICES, Copenhagen; personal communication, 1984.)

Though these are daily means, the speeds are sufficiently steady to be reasonably representative of the maximum hourly speeds observed. In this case the absolute maximum hourly velocity observed on 7 February was 72.7 cm s^{-1}, 188°. This example was the extreme overflow event observed in a six-month period from November 1982 to May 1983, but peak overflow speeds of around 40 cm s^{-1} were relatively common at this site and depth. In the gulley below the basin which collects much of the overflow from the northwestern sector of the Ridge, the daily mean current, 12 m above the bottom in a water depth of 1140 m during 11 August to 4 September 1973, was 101 cm s^{-1} (J. Crease, personal communication, 1984), varying between 115 and 74 cm $^{-1}$. Current speeds of this order could clearly transport prodigious amounts of sediment in the bottom waters in the region of the overflow.

The Slope Current

Since the existence of a north-going residual Slope Current along the European continental margin was first postulated (Dooley and Martin, 1969; Swallow et al., 1977; Ellett et al., 1979), its presence has been confirmed

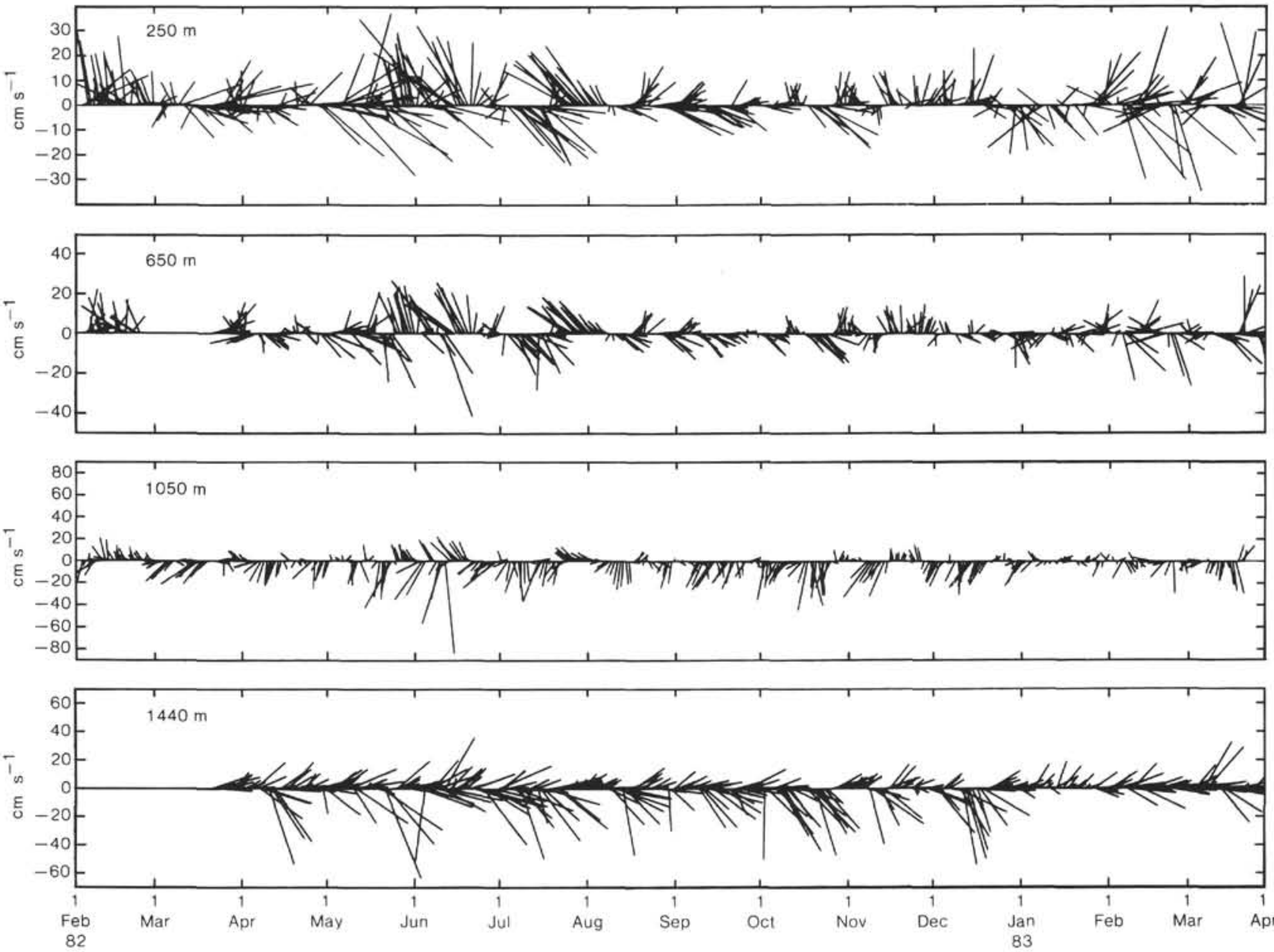

Figure 3. Stick-plots of daily mean current vectors for the four instruments of IOS mooring I-2 in 1982–1983. This mooring was laid in the northern Rockall Trough, close to the exit of the main overflow gulley in the Wyville-Thomson Ridge (see Fig. 1). The relative quiescence of the two near-bottom records during winter confirms that overflow reaches a minimum at that time of year. (Unpublished data, kindly provided by W. J. Gould, IOS, Wormley; personal communication, 1984.)

Table 1. Extreme overflow event recorded at DAFS mooring 224, Wyville-Thomson Ridge (U and V are zonal and meridional current components, respectively; overbar denotes daily average).

Date	$\overline{U}$ (cm s^{-1})	$\overline{V}$ (cm s^{-1})	$\overline{T}$ (°C)
5 Feb. 1983	−1.84	−9.55	4.21
6 Feb. 1983	−15.79	−41.96	0.29
7 Feb. 1983	−11.95	−61.82	−0.46
8 Feb. 1983	−11.00	−47.84	−0.66
9 Feb. 1983	−0.83	−18.13	−0.25

wherever direct current measurements have been made on the slope and over a large depth range. In their review of 131 long current-meter records from the deep layer of the eastern North Atlantic, Dickson et al. (1985) include four records from the area between the Celtic Sea slope and the slope west of Porcupine Bank, which show that a north-going flow of 1.4 to 3.4 cm s^{-1} extends to at least 2500 m depth in this region. Figure 4 shows that a steady northward flow blankets the west slope of Porcupine Bank over a depth range of 275 to 2354 m (current-meter records from the multi-year Ministry of Agriculture, Fisheries and Food/Scottish Marine Biological Association [MAFF/SMBA] array, October 1981–January 1984). Booth and Ellett (1983) describe remarkably steady northward flows from SMBA mooring P, farther north (57°06′N, 9°22′W), on the eastern slope of the Rockall Trough, in the summers of 1979 and 1982, for a combined record length of 250 days. They find that the persistent northward flow above 700 m depth (Figure 5) is associated with a core of warm, light water over the shallow side of the slope, and estimate the northward volume transport over the upper 500 m to be 0.5 Sv. The deepest instrument, at 892 m, did not show a persistent northward flow, but lay within the main thermocline. Sixty km west of P, a mooring by Ellett (personal communication, 1984) in 2250 m water depth showed highly variable current directions throughout the water column in 1978–1983, confirming that the slope current does not extend far off-slope. More recently, preliminary results from the 1982–1983 CONSLEX experiment are becoming available, but have not yet been published. Information kindly supplied by W. J. Gould (personal communication, 1984) suggests that south of the Wyville-Thomson Ridge, the Institute of Oceanograph-

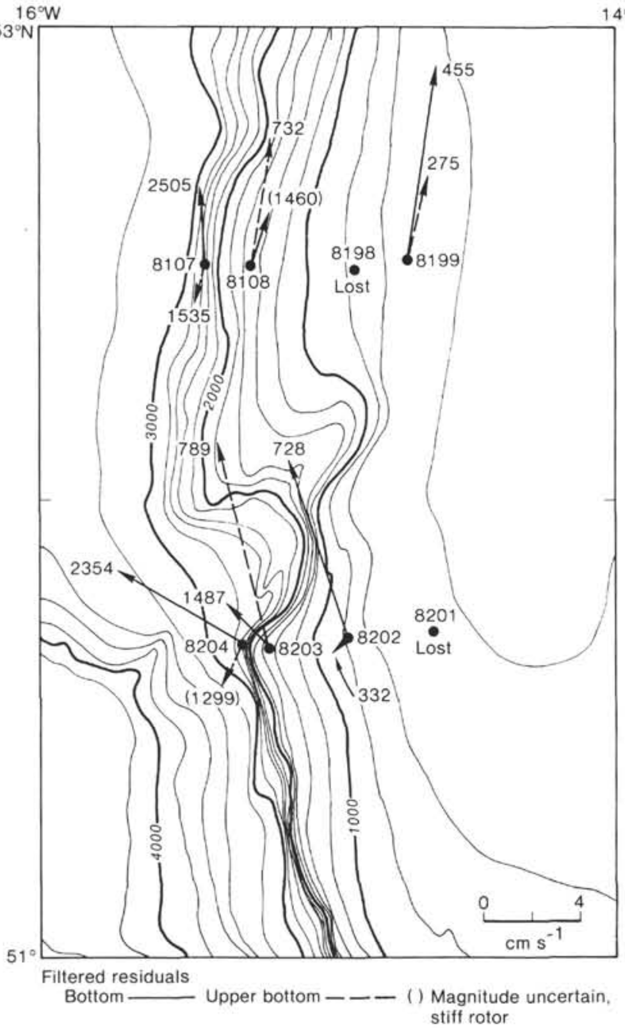

Figure 4. Residual current vectors from long-term current-meter moorings on the western slope of Porcupine Bank (MAFF/SMBA array) (see Fig. 1). Mooring identifiers are given by the 8000-series numbers, and the instruments depths (m) are shown at the head of each arrow. Contour interval is 200 m.

ic Sciences (IOS) slope moorings B-3 and C-2, in 500 m water depth and with instruments at three depths from 100 to 500 m, showed the strongest and most persistent northward flow.

The cause of the slope current is not yet clear. In the present context, the key point is not the cause of the slope current, but the fate of that part of the current sufficiently shallow to enter the Rockall Trough but too deep to cross the Wyville–Thomson Ridge. The most plausible suggestion is that this water must detach from the slope as the Rockall Trough shoals in the north (especially where the current encounters the Wyville–Thomson Ridge) to flow westward and then southward at depth along the western margin of the Trough. This suggestion is as yet unsupported by direct long-term current measurements, but Lonsdale and Hollister (1979) provide indirect and short-term current-meter evidence that such a "cross-over" flow takes place.

They point out that although episodic overflow of NSDW might be a possible source of the deepest water stratum in the Rockall Trough (>2500 m), the high silica concentration of the deepest waters in the Trough suggests a southern origin. Short-term (4.5-day) current measurements at their C site near 56°N (Fig. 6) recorded a flow to the west-northwest at mean speeds of 3 to 4 cm s^{-1} (maximum speed = 13.5 cm s^{-1}). Their data therefore support Ivers' (1975) contention that the circulation of the southern Rockall Trough takes the form of cyclonic loop of North Atlantic Deep Water (NADW), which enters along the foot of the Irish continental slope, crosses the Trough in a broad slow flow at around 56°N, and exits along the flank of Feni Ridge (Fig. 6).

Lonsdale and Hollister (1979) are more speculative about the cause of the Feni Ridge, concluding that temporal variations in the speed and turbidity of the cyclonic loop of NADW have probably been more important than changes in the NSDW overflow; specifically, they suggest (1979, p. 102) "that a large fraction of the sediment load of turbidity currents that reach this (eastern) part of the trough floor has been pirated by thermohaline currents and transferred by the cyclonic loop of the bottom water circulation to the western half of the trough where it built the Feni Ridge . . ." and (p. 104) "Norwegian Sea overflow currents have had a minor role in transporting sediment and shaping the ridge."

The local circulation around the Feni Ridge, inferred by Lonsdale and Hollister (1979), will be considered in detail in the section on the local environment of Site 610.

Northward Deep Drift in the Porcupine Abyssal Plain

In the deep water west of the slope, residual current vectors for a range of years suggest a fairly systematic circulation which flows in a cyclonic sense, northward at a mean speed of 1 to 2 cm s^{-1} up the Porcupine Abyssal Plain to turn westward and southwestward as the basin shoals in the north and thence southward or westward along the eastern flanks of the Mid-Atlantic Ridge (Dickson et al., 1985). Maximum speeds observed in the bottom kilometer over the open abyssal plain are in the range of 13 to 22 cm s^{-1}. Since this deep drift appears to be at least 1000 m thick, it is likely to penetrate the Rockall Trough, but will turn to the south within the southern Rockall Trough to flow out along the southern and eastern margin of the Feni Drift at depths >2500 m (i.e., south of about 55°30′N).

No records more recent than those described by Dickson et al. (1985) have been recovered from the Porcupine Abyssal Plain. However, in July 1984, MAFF recovered a mooring (83-06) from a deep gap in the Azores–Biscay Rise immediately west of the Charcot Seamounts; records showed average velocities of 7.40 cm s^{-1} northeastward at 4574 m depth over a record length of 353 days, and this surprisingly strong mean flow (for this depth layer) may well be the origin (or partial origin) of steady northward drift over the Porcupine Abyssal Plain.

THE LOCAL ENVIRONMENT OF SITE 610 ON FENI RIDGE

Mean Flow

Figure 7 displays the mean flow vectors measured or inferred from the vicinity of Site 610. The more northerly line of vectors are those inferred from photo tra-

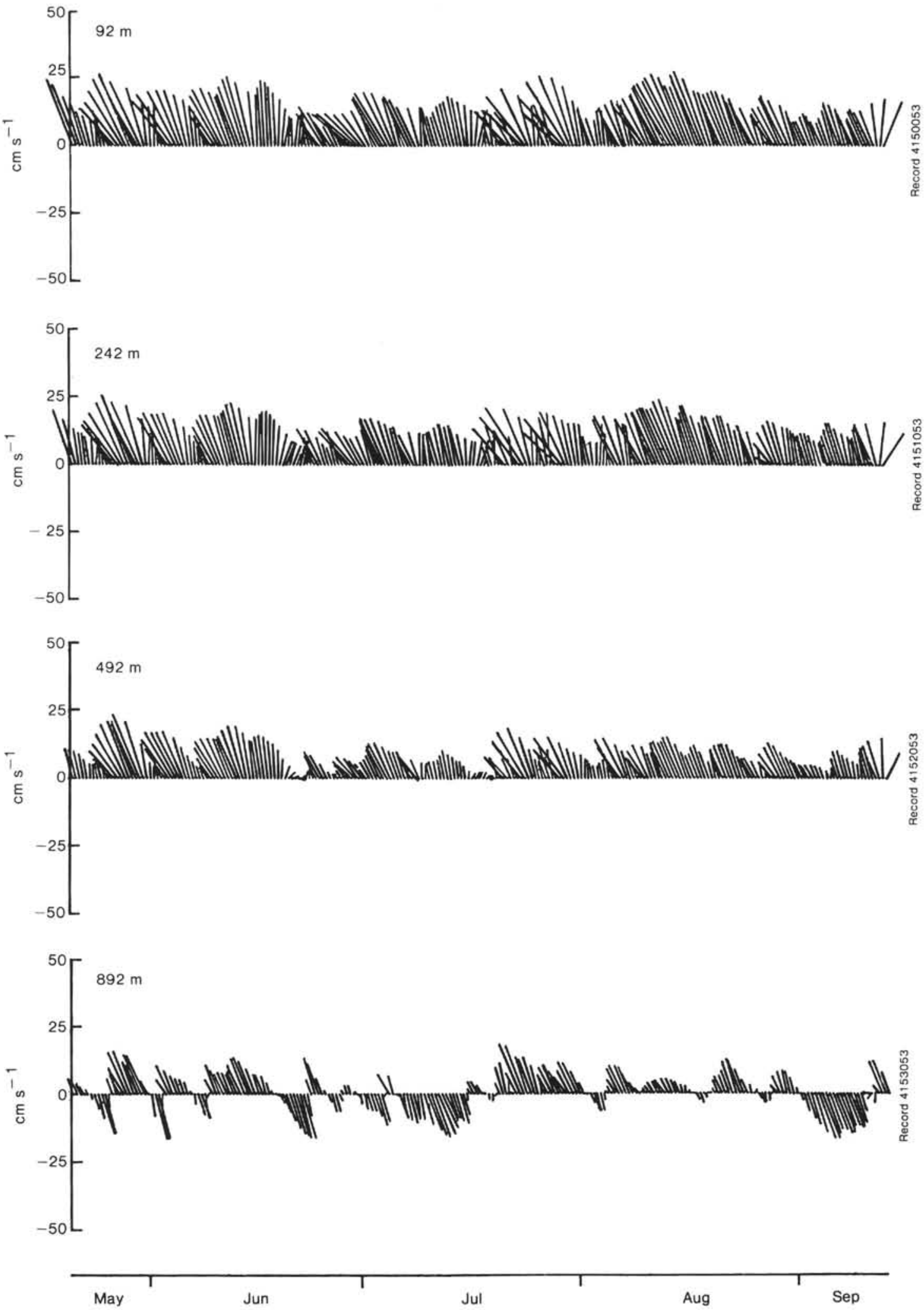

Figure 5. Twelve-hourly vectors (Doodson-filtered) for four instruments on SMBA mooring P (western Scottish continental slope, 57°06′N, 09°24′W), May-September 1979 (location shown in Fig. 1). (From Booth and Ellett, 1983.)

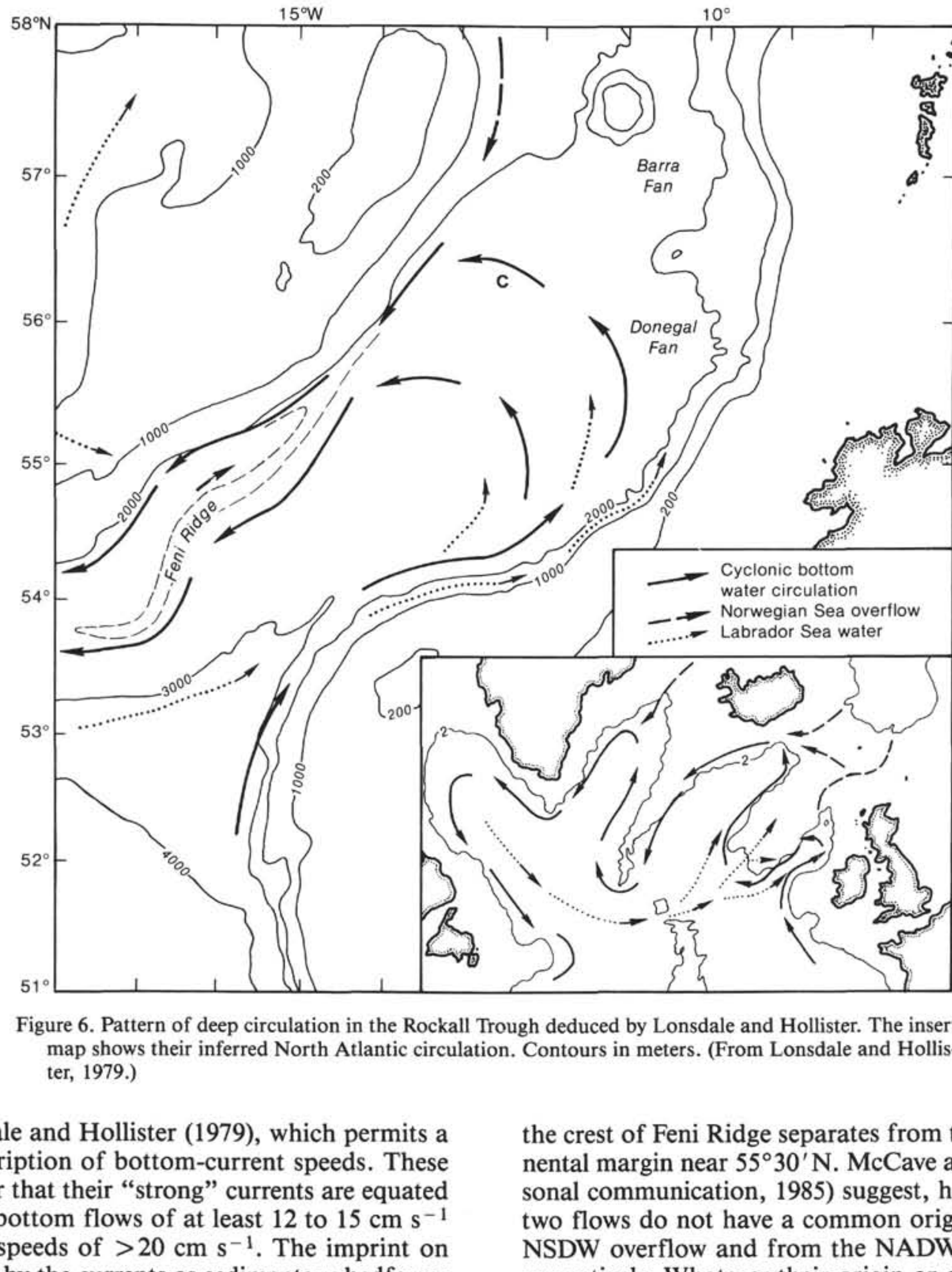

Figure 6. Pattern of deep circulation in the Rockall Trough deduced by Lonsdale and Hollister. The insert map shows their inferred North Atlantic circulation. Contours in meters. (From Lonsdale and Hollister, 1979.)

verse by Lonsdale and Hollister (1979), which permits a qualitative description of bottom-current speeds. These authors consider that their "strong" currents are equated with persistent bottom flows of at least 12 to 15 cm s^{-1} and maximum speeds of >20 cm s^{-1}. The imprint on the seafloor left by the currents as sedimentary bedforms probably represents, however, the *last* major pulse of strong bottom-water flow, so these values would equate best with maxima in the current-meter records, rather than with averages over the period of deployment.

Strong to moderate bottom currents are inferred at two locations on this traverse, in each case flowing parallel to local contours: at 2000 to 2400 m at the foot of the Rockall Plateau continental slope, flowing southwest, and at ~2500 m on the southeast flank of Feni Ridge, embedded in a broad but weaker southwestward flow. There is evidence of a weak reverse (i.e., northeasterly) flow, sandwiched between these southerly flows, along the northwestern flank of Feni Ridge.

Lonsdale and Hollister (1979) suggest that the two southwestward flows originate by splitting from a single southwestward flow some 100 km to the north, where the crest of Feni Ridge separates from the Rockall continental margin near 55°30′N. McCave and Tucholke (personal communication, 1985) suggest, however, that these two flows do not have a common origin but stem from NSDW overflow and from the NADW "loop current," respectively. Whatever their origin or origins, these currents also appear to have an important role in the overall dynamics of sedimentation on the Ridge. Recent sediment deposition is concentrated along the northwestern flank of the Ridge, where the deep southwesterly current is decelerated or reversed.

Thus, the present shape of Feni Ridge tends to control the pattern of NADW flow along it, although the NADW "loop" reinforced by "a leak" of NSDW overflow from the north, has also controlled the spatial pattern of sedimentation across the Ridge crest.

The more southerly line of vectors shown in Figure 7 derives from long-term current measurements by the MAFF Fisheries Laboratory, Lowestoft, between June 1982 and July 1983. This "Rockall Bank array" was designed for a purpose different from that of assessing the dynamics of sedimentation at the Feni Ridge, but since

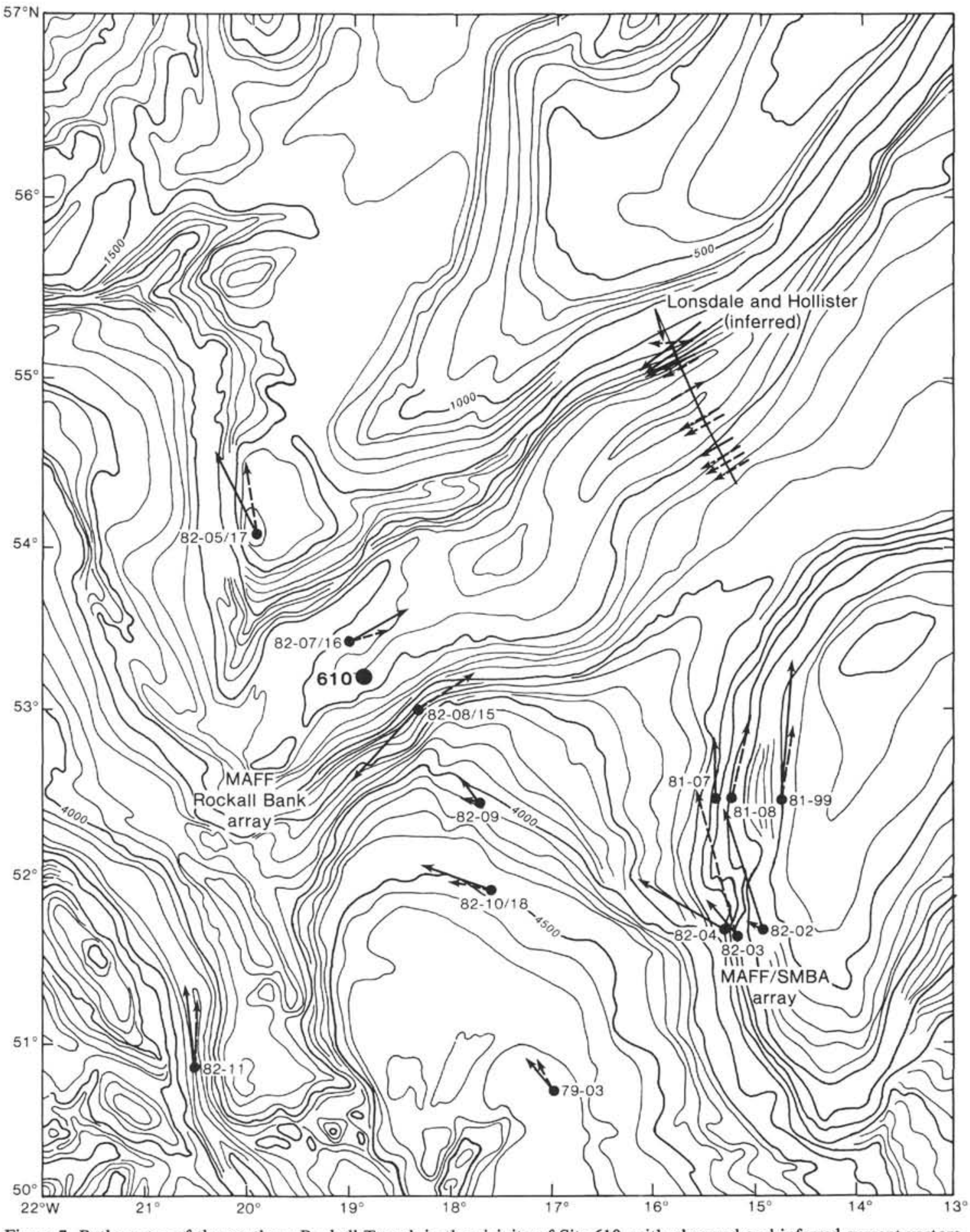

Figure 7. Bathymetry of the southern Rockall Trough in the vicinity of Site 610, with observed and inferred current vectors superimposed. Vectors from long-term direct measurements (identified by mooring numbers) are mainly from MAFF Rockall Bank array and the MAFF/SMBA array on the western slope of Porcupine Bank; solid lines represent the near-bottom vector (normally 50 m above seabed). The group of unlabeled vectors at 54°-56°N, 15°-17°W are those inferred from bedforms detected in a bottom photograph transect by Lonsdale and Hollister (1979).

the line of moorings passes through Site 610 it has provided some parameters relevant to this study (Table 2). Excepting the full-depth mooring 82-09, which was left in place for 366 days the moorings were deployed for successive periods of ~152 and 210 days, and the combined statistics from the two deployments are described here. Mooring 82-06, set on the steepest part of the Rockall continental slope at 53°45.8′N, 19°35.5′W, was damaged during launch, broke adrift after only 33 hours, and was not replaced.

Of the remaining records, the most relevant to the present study are those from moorings 82-07/82-16 and 82-08/82-15, which were set on the northwestern and southeastern flanks of the Feni Ridge, respectively, brack-

Table 2. Statistics from the MAFF Rockall Bank array, June 1982–July 1983 ($\overline{U}$, $\overline{V}$ as defined in Table 1 caption).

Mooring	Latitude, longitude	Sounding (m)	Instrument depth (m)	Record duration (days)	$\overline{U}$ (cm s^{-1})	$\overline{V}$ (cm s^{-1})	Stability factor (%)	Max hourly speed (cm s^{-1})
82-05/82-17	54°05.2′N, 19°55.2′W	1332	415	327	−0.73	4.00	34	51
			1290	210	−2.52	5.06	85	28
82-06	53°45.8′N, 19°35.5′W	1904	647	1.3	—	—	—	—
			1859	LOST	—	—	—	—
82-07/82-16	53°25.4′N, 19°01.8′W	2498	1266	368	1.89	0.76	27	37
			2453	368	3.57	1.03	48	31
82-08/82-15	52°58.9′N, 18°23.6′W	3162	1778	367	3.45	2.14	68	22
			3117	367	−3.92	−4.39	68	39
82-09	52°27.3′N, 17°42.9′W	4135	547	366	2.81	−0.64	19	56
			1559	366	0.18	0.09	4	23
			2346	366	0.05	−0.15	3	19
			3109	366	−0.51	0.47	12	21
			3910	366	−1.21	1.55	26	27
82-10/82-18	51°54.2′N, 17°38.7′W	4470	3556	368	−1.59	0.36	29	28
			4425	368	−4.19	1.31	55	30

Note: Dashes indicate inadequate data.

eting Site 610. Essentially these records support the findings of Lonsdale and Hollister (1979) from their photo transect; mooring 82-07/82-16 shows a reasonably steady northeastward mean drift of 3.7 and 2.0 cm s^{-1} at heights of 45 and 1232 m above the seabed, whereas 82-08/82-15 shows that the southeastern flanks of the Ridge are swept by a steady and vigorous southwestward mean flow of 5.9 cm s^{-1} at a height of 45 m above the seabed.

These records do suggest, however (as Lonsdale and Hollister's data could not), that the northeasterly "reverse flow" is not merely confined to the northwestern flank of Feni Ridge. Since a steady northeastward flow of 4.1 cm s^{-1} is also present at mooring 82-08/82-15, at a height of 1384 m above the bottom (i.e., at a depth of 1778 m), this flow may form a stratum of some horizontal extent which merely intersects the rising seafloor topography along the northwestward face of Feni Ridge (and possibly the Ridge crest). These results place the division between northeastward-flowing and southwestward-flowing layers at around 2500 to 2600 m in the vicinity of the Ridge. Variation in the location of this division may be the cause of the complex interplay of sediment wave trends around Site 610 (Roberts and Kidd, 1979).

The four deep records (>2500 m) from moorings 82-09 and 82-10/82-18 provide evidence of a broad, deep, and rather variable northward and then westward drift flowing along the contours of the Continental Rise, at the mouth of the Rockall Trough. We interpret this flow as stemming from the deep northward flow along the Porcupine Abyssal Plain. Mean speeds recorded at heights of 225 and 45 m above bottom at these two moorings were 2.0 cm s^{-1}, 287°, and 4.98 cm s^{-1}, 356°, respectively, over record lengths of 366 and 368 days (Table 2). By our interpretation, this deep flow along the Rise will unite farther west with the more vigorous and more directional southwestward flow along the southeastern flanks of the Feni Ridge (already described), which is thought to have a southerly source (either the deep northward drift up the Porcupine Abyssal Plain or the recirculation of the northward current along the Irish continental slope).

Variability of Near-Bottom Currents in Space and Time

The maximum near-bottom current speeds, the degree of fluctuation about the mean flow at a given point, and the geographic variation of the latter on the Rockall Bank array are all important in assessing the dynamics of sedimentation over Feni Ridge.

Figure 8 augments Table 2 in illustrating the spatial variation of these parameters across the array, from the tail of Rockall Bank across the Feni Ridge (and the area of Site 610) to the head of the Porcupine Abyssal Plain. Maximum near-bottom current speeds over ~1 yr. are relatively unvarying across the array, lying in the range of 27 to 39 cm s^{-1} (Fig. 8A). These values are in general agreement with the regional trends of maximum near-bottom current speed recorded at a standard height of ~50 m above the bed throughout the eastern Atlantic (Fig. 9; from Rees, personal communication, 1985).

The "percentage exceedance" recorded on the array (i.e., the percentage of time that the current exceeded certain speeds) is tabulated in Table 3 for the near-bottom instruments only.

Though the maximum speeds and percentage exceedances of near-bottom flow do not vary greatly across the transect, the directional stability of the flow does vary. We can illustrate this in three ways. First, Figure 8B gives the "stability factors," which is the ratio of mean vector speed to mean scalar speed, expressed as a percentage. Apart from the deep record at the tail of Rockall Bank (mooring 82-05), we find, as expected, that maximum values (reflecting greater directional stability) are at mooring 82-08/15, where the flow direction is constrained by the southeastern flank of Feni Ridge.

A second measure, which compares the mean flow with the eddy motions superimposed on it, is the ratio of the eddy kinetic energy per unit mass (k_E) to the kinetic energy of the mean flow (k_M) (Fig. 8C). The ratio k_E/k_M is generally low in near-bottom records on this array, but reaches a minimum at 82-08/15 ($k_E/k_M = 2$) and 82.05 (where k_M actually exceeds k_E). A third illus-

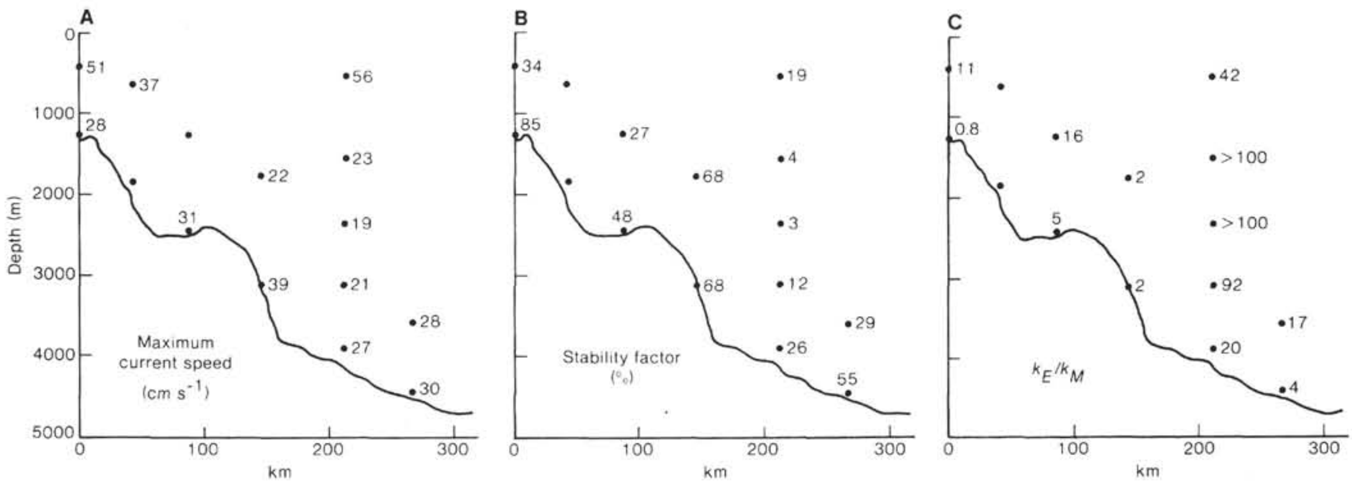

Figure 8. (A) Maximum current speed, (B) "stability factor," and (C) ratio of eddy kinetic energy per unit mass (k_E) to the kinetic energy of the mean flow (k_M) for all instruments of the MAFF Rockall Bank array, July 1982–July 1983. (The line of this array is indicated in Figs. 1 and 7.)

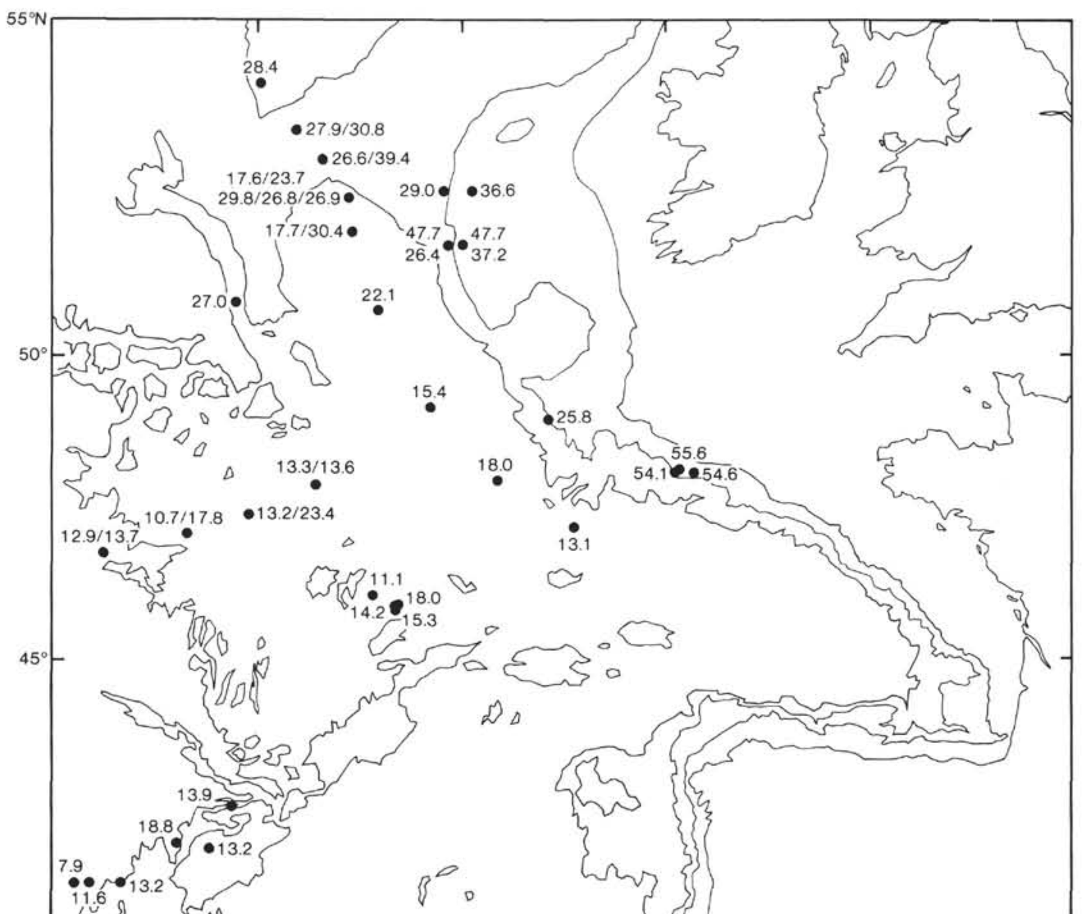

Figure 9. Maximum current speeds (cm s^{-1}) from northeast Atlantic long-term moorings recorded at a standard height of 50 m from the seabed (from J. M. Rees, personal communication, 1985). A range of values at the same location indicates the results of successive moorings at that site.

Table 3. "Percentage exceedances" of hourly mean speeds at near-bottom instruments of the Rockall Bank array.

Mooring	Duration (days)	≥10 cm s^{-1}	≥20 cm s^{-1}	≥30 cm s^{-1}
82-05/17	210	32	3	0
82-07/16	368	35	4	0
82-08/15	367	38	9	1
82-09	366	33	3	0
82-10/18	368	31	5	0

tration of the spatial variability of near-bottom currents across the array is provided in Figure 10, which superimposes stick plots of daily mean current vectors for each of the five near-bottom records available to us. Though still subject to variations in speed and direction, the greatest directional stability of the topographically constrained flows at 82-05/17 and 82-08/15 is clear.

The longer-term time scales of variation, affecting both the mean flow and the eddy field, have not yet been fully analyzed. Figure 11, however, shows that the mean *U* and *V* components at the near-bottom instruments at 82-08/15 and 82-09 do *not* indicate any sign of a systematic seasonal variation; this may lend support to the suggestion that the source of these flows is *not* Norwegian Sea overflow. At 82-08/15, in particular, covering the vigorous flow along the southeastern margin of the Feni Ridge, both *U* and *V* show (if anything) a tendency to increase to maximal values during the winter quarter, when overflow should be at a minimum.

DISCUSSION AND CONCLUSIONS

This review of modern bottom-water circulation in the Rockall Trough suggests that overflow of Norwegian Sea Deep Water is neither the sole nor is likely to be the dominant flow over DSDP Site 610. Transport estimates suggest that NSDW is unlikely to have had great influence on the shaping of the southern Feni Drift, *if* circulation patterns and behavior stayed similar to those of the present day throughout the history of its buildup. Drilling results at the site show that the drift was made up almost entirely of pelagic lithologies at least as far back in time as the early Miocene. The major perturbations of advancing ice and lowered sea levels during the glacial periods did not result in accumulation of lithologies markedly different from those at more open-ocean, non-drift locations such as Site 609. Without this information it would have been tempting to identify the slope current as a major source of both water and sediment for the drift. Dickson and McCave (1986) have collected along with their current measurements (Fig. 4), nephelometer data which suggest that plumes of fine sediment peel off the slope during periods of protracted along-slope (northerly) wind, and this sediment would be expected to mix westward across the Trough. The anomalous pelagic buildup of sediment since the Oligocene in the southwestern Rockall Trough has clearly been under the influence of both southern and NSDW sources of bottom water. Which has dominated at any given geological period is difficult to read from the lithological record (see Kidd and Hill, this volume).

The MAFF Rockall Bank current-meter array has confirmed previous suggestions (e.g., Lonsdale and Hollister, 1979) that the crest of Feni Ridge at its southern end lies between two bottom-water flows traveling in opposite directions. It is possible that the complexity in the trends of mudwaves axes, demonstrated previously from GLORIA coverage along the axis (Roberts and Kidd, 1979) and amply displayed in *Glomar Challenger's* near-site profiling surveys during Leg 94 (Kidd and Hill, this volume), reflects the interplay of these opposing water masses.

None of the current-meter stations reported here lay in the immediate vicinity of Site 610, so they permit little assessment of the local sedimentary processes on the sediment wave field. The speed exceedances reported here, on the other hand, show that the potential for local erosion and transport of the fine-grained cohesive sediments is much greater than has generally been thought. It is important to recognize both the variability and erosion potential of these currents if we are to construct models of the relationship of sediment wave fields to the currents that shape them.

ACKNOWLEDGMENTS

We wish to thank H. D. Dooley, D. J. Ellett, W. J., Gould, J. M., Rees, and J. Crease for permission to use some of their unpublished data in order to make this review possible. They also provided comments on an early partial draft of the manuscript.

REFERENCES

Berggren, W. A., and Hollister, C. D., 1977. Plate tectonics and paleocirculation—commotion in the ocean. *Tectonophysics*, 38:11-48.

Booth, D. A., and Ellett, D. J., 1983. The Scottish Continental Slope Current. *Cont. Shelf Res.*, 2:127-146.

Bryan, G. M., 1970. Hydrodynamic model of the Blake Outer Ridge. *J. Geophys. Res.*, 75:4530-4537.

Davies, T. A., and Laughton, A. S., 1972. Sedimentary processes in the North Atlantic. *In* Laughton, A. S., Berggren, W. A., et al., *Init. Repts. DSDP*, 12: Washington (U.S. Govt. Printing Office), 905-934.

Dickson, R. R., Gould, W. J., Muller, T. J., and Maillard, C., 1985. Estimates of the mean circulation in the deep (>2000 m) layer of the eastern North Atlantic. *Prog. Oceanogr.*, 14:103-127.

Dickson, R. R., and McCave, I. N., 1986. Nepheloid layers on the continental slope west of Porcupine Bank. *Deep-Sea Res.*, 33: 791-818.

Dooley, H. D., and Martin, J. H. A., 1969. Currents at the continental slope of the northern North Sea [mimeo]. ICES CM (Int. Council for the Exploration of the Sea, Council Meeting) 1969/C:4.

Dooley, H. D., and Meincke, J., 1981. Circulation and water masses in the Faroese Channels during Overflow 1973. *Dt. Hydrogr. Zeitschr.*, 34:41-54.

Ellett, D. J., Dooley, H. D., and Hill, H. W., 1979. Is there a northeast Atlantic slope current? [mimeo]. ICES CM 1979/C:35.

Ellett, D. J., and Edwards, A., 1978. A volume transport estimate for Norwegian Sea overflow across the Wyville-Thomson Ridge [mimeo]. ICES CM 1978/C:19.

Ellett, D. J., and Roberts, D. G., 1973. The overflow of Norwegian Sea Deep Water across the Wyville-Thomson Ridge. *Deep-Sea Res.*, 20:819-835.

Heezen, B. C., Hollister, C. D., and Ruddiman, W. F., 1966. Shaping of the continental rise by deep geostrophic contour currents. *Science*, 152:502-508.

Ivers, W., 1975. The deep circulation in the northern North Atlantic [Ph.D. thesis], Univ. of Calif., San Diego.

Johnson, G. L., and Schneider, E. D., 1969. Depositional ridges in the North Atlantic. *Earth Planet. Sci. Lett.*, 6:416–422.

Johnson, G. L., Voigt, P. R., and Schneider, E. D., 1971. Morphology of the northeastern Atlantic and Labrador Sea. *Dt. Hydrogr. Zeitschr.*, 24:49–73.

Jones, E. J. W., Ewing, M., Ewing, J. I., and Ettreim, S. L., 1970. Influences of Norwegian Sea Overflow Water on sedimentation in the northern North Atlantic and Labrador Sea. *J. Geophys. Res.*, 75:1655–1680.

Laughton, A. S., Roberts, D. G., and Hunter, P. M., 1984. Reykjanes Ridge and Rockall Plateau—bathymetry of the North Atlantic. *Inst. Oceanogr. Sci. Sheet*, No. C6566, Taunton (chart).

Lonsdale, P., and Hollister, C. D., 1979. A near-bottom traverse of Rockall Trough: Hydrographic and geologic inferences. *Oceanol. Acta*, 2:91–105.

Roberts, D. G., and Kidd, R. B., 1979. Abyssal sediment wave fields on Feni Ridge, Rockall Trough: Long-range sonar studies. *Mar. Geol.*, 33:175–191.

Ruddiman, W. F., 1972. Sediment distribution on the Reykjanes Ridge: Seismic evidence. *Geol. Soc. Am. Bull.*, 83:2039–2062.

Shor, A. N., and Poore, R. Z., 1979. Bottom currents and ice rafting in the North Atlantic: Interpretation of Neogene depositional environments of Leg 49 cores. *In* Luyendyk, B. P., Cann, J. R., et al., *Init. Repts. DSDP*, 49; Washington (U.S. Govt. Printing Office), 859–872.

Stow, D. A. V., 1982. Bottom currents and contourites in the North Atlantic. *Bull. Inst. Geol. Bassin Aquitaine*, 31:151–166.

Swallow, J. C., Gould, W. J., and Saunders, P. M., 1977. Evidence for a poleward eastern boundary current in the North Atlantic Ocean [mimeo]. ICES CM 1977/C:32.

Worthington, L. V., 1976. *On the North Atlantic Circulation*. Johns Hopkins Oceanographic Studies No. 6: Baltimore (John Hopkins University Press).

Worthington, L. V., and Volkmann, G. H., 1965. The volume transport of the Norwegian Sea overflow water in the North Atlantic. *Deep-Sea Res.*, 12:667–676.

Date of Initial Receipt: 12 November 1985
Date of Acceptance: 21 November 1985

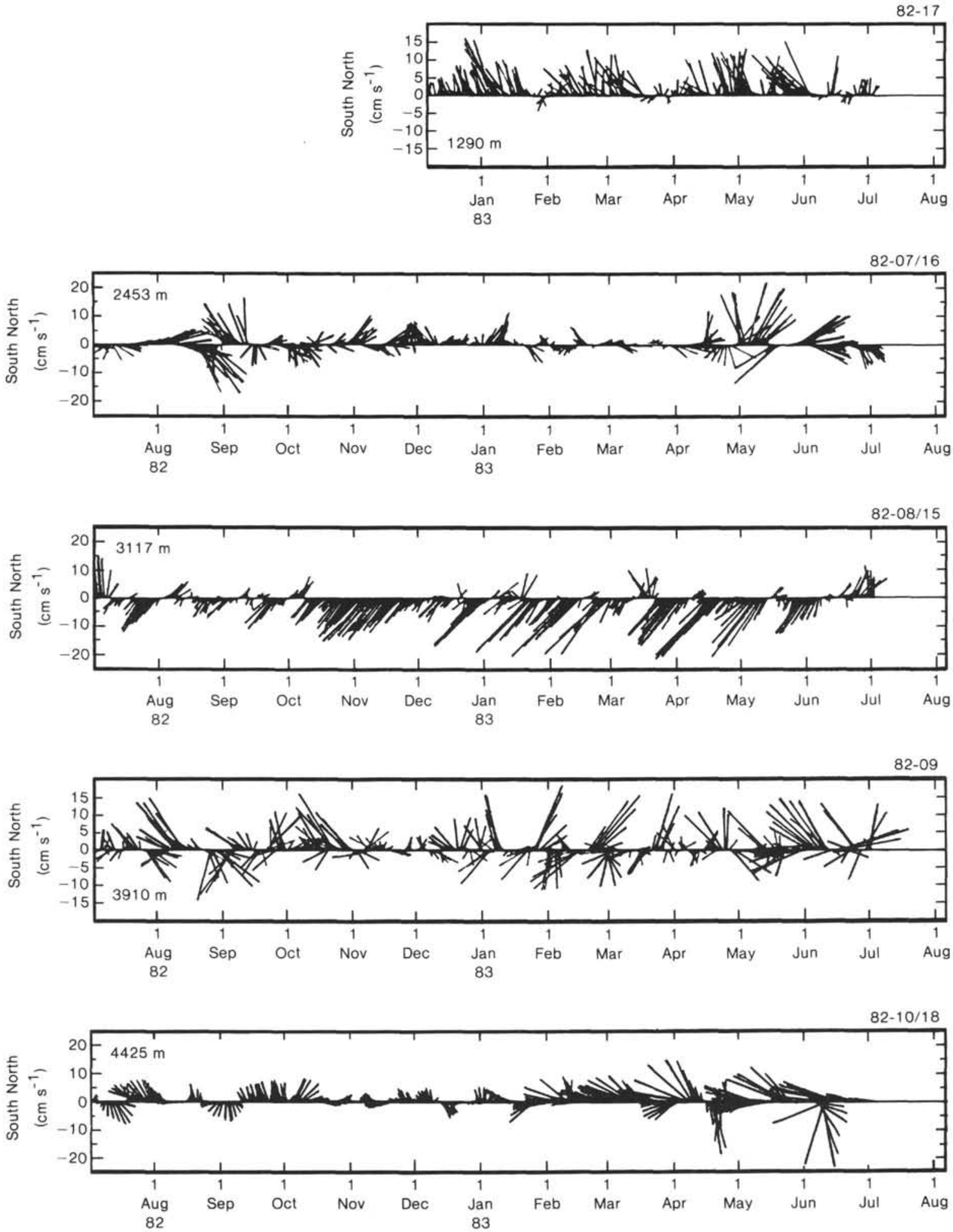

Figure 10. Stick plots of daily mean current vectors for the five near-bottom records on the MAFF Rockall Bank array, July 1982–July 1983.

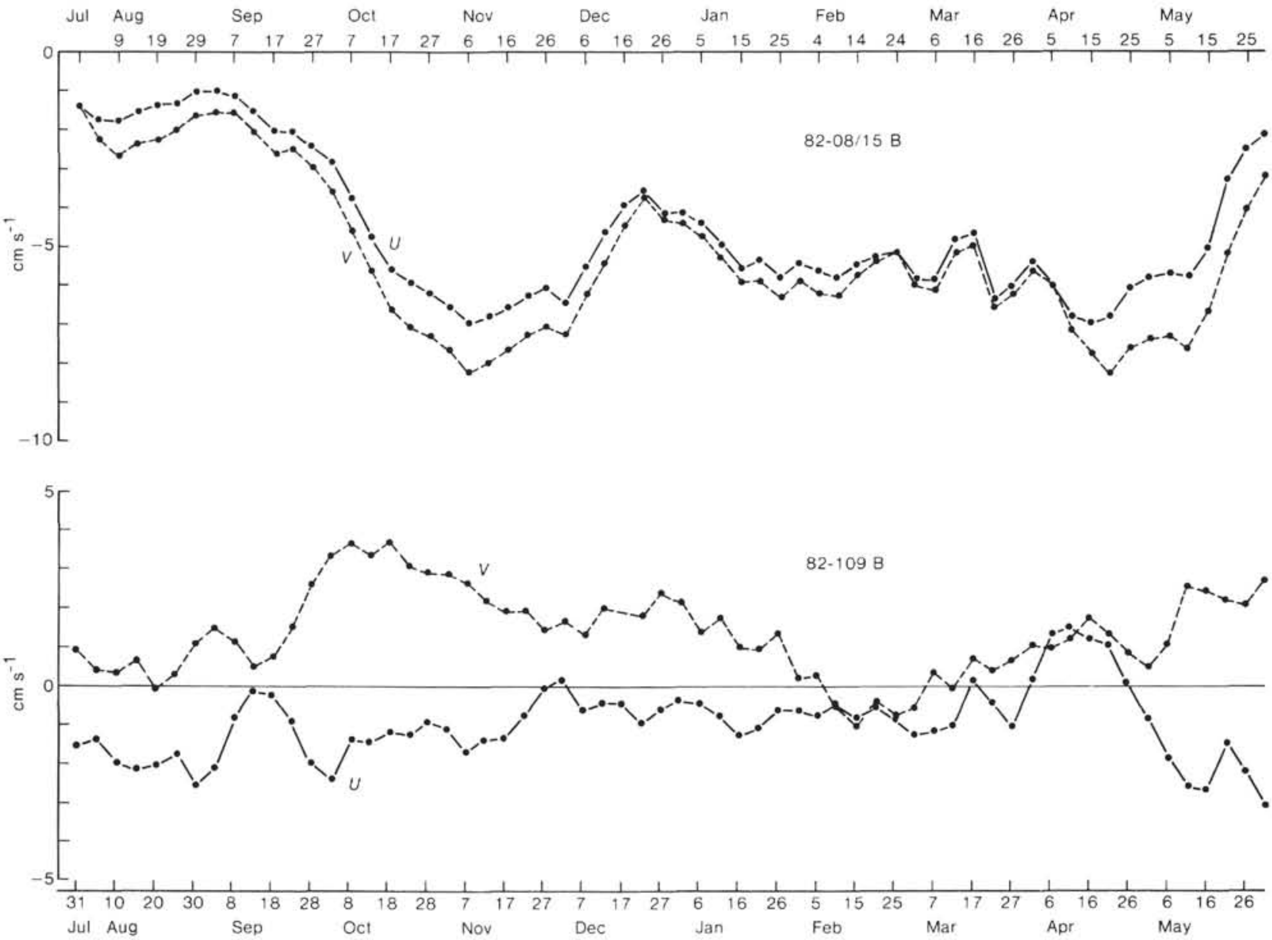

Figure 11. Mean U and V components for the near-bottom instruments of moorings 82-08/15 and 82-09, MAFF Rockall Bank array. Estimates are for 60-day pieces of record, stepping by 5-day intervals.