Flow through Discovery Gap

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ABSTRACT

A narrow gap (Discovery Gap) in the East Azores Fracture Zone at 37°N in the eastern Atlantic provides a channel for the exchange of bottom water between the Madeira and Iberian abyssal basins. A detailed survey defines its length (150 km), width (10–50 km), depth of sills (near 4800 m) and sediment thickness (0–500 m). Year-long measurements of deep flow are made from six moorings and ten current meters. Mean flows are about 5 cm s^{-1}. These data are supplemented by 10 days of float tracking near 4700 m and numerous density profiles within and around the gap.

A persistent southwest–northeast flow of dense water is found in Discovery Gap, and the flux of water colder than a potential temperature of 2.05°C is measured to be $(0.21 \pm .04) \times 10^6$ m^3 s^{-1}. This discharge spreads over an area of about 10^{11} m^2 beyond the Gap exit, where it is warmed both by geothermal heating and by mixing with overlying water. An estimate of 1.5 to 4 cm^2 s^{-1} is derived for the diapycnal diffusivity, similar to values determined from much larger channels in the western Atlantic, but the relative importance of boundary versus interior mixing cannot be established.

The cold water arrives from the south along the deep eastern margin; its hydrographic signal is the "piling up" of isotherms against the lower continental rise. Near 32°N, about 500 km south of Discovery Gap, the signal is small, and it is proposed that just south of this latitude the eastern boundary current ends.

1. Introduction

Measurements of abyssal temperatures in the eastern Atlantic show a marked variation with latitude. At a depth of 5000 m near 10°N the potential temperature is 1.8°C (McCartney et al., 1987); at the same depth near 50°N it is 2.1°C (Maillard, 1986). Much farther south, in the Antarctic, the abyssal temperatures are as low as −1.1°C, where they originate from deep wintertime convection at the edge of and under the polar ice (Warren, 1981). The northward warming of the bottom water throughout the entire Atlantic, including that within the Eastern Basin, results from its northward movement and mixing with the overlying warmer water (Warren). In most regions of the Atlantic even the direction of this slow and erratic creeping movement cannot be directly observed (Dickson et al., 1985), but where the deep basins interconnect through channels the flow inevitably becomes intensified. The flux of cold water may then be measured in such channels, and hence the rate of mixing of abyssal water in the basins may be estimated (Hogg et al., 1982; Whitehead and Worthington, 1982). This was the purpose of the observational program carried out in Discovery Gap and described in this paper.

2. Discovery Gap

Both the Madeira Abyssal Plain, lying west of Madeira and south of the Azores, and the Iberian Abyssal Plain, lying west of Spain and Portugal, have depths exceeding 5300 m. Between them, near 37°N, is an east–west ridge associated with the East Azores Fracture Zone, whose crest lies at depths of between 4000 and 4500 m (see Fig. 1). Low points on this ridge occur at 19°30′ and 16°W, with the latter feature, which we have named Discovery Gap,[1] both wider and deeper.

Bathymetric surveys carried out on *Discovery* cruises 117, 122, 130 and 138 provide a quite new picture of Discovery Gap, and a contoured map is presented in Fig. 2. The valley axis strikes approximately 240°–060° and is about 150 km in length. Based on observations of currents (section 3), the southwest end is referred to as the entrance and the northeast end as the exit. One sill lies at a location near the entrance, on the section AA′ shown in Fig. 2, and two lie near two exits to the valley at positions marked 326 and 327 on the map. Their depths and locations are described in Table 1.

The entrance sill lies about 600 m above the abyssal plains both north and south of Discovery Gap. The valley walls on each side rise approximately 500 m above the entrance sill, and in two locations the valley floor lies 500 m deeper than at the sill. Beyond the entrance the valley is about 50 km broad, but nearer the exits it contracts to a breadth of only 10 km. The section marked as BB′ on Fig. 2 has been termed Dis-

[1] "Discovery Gap" is not yet accepted by a Board of Geographical Names.

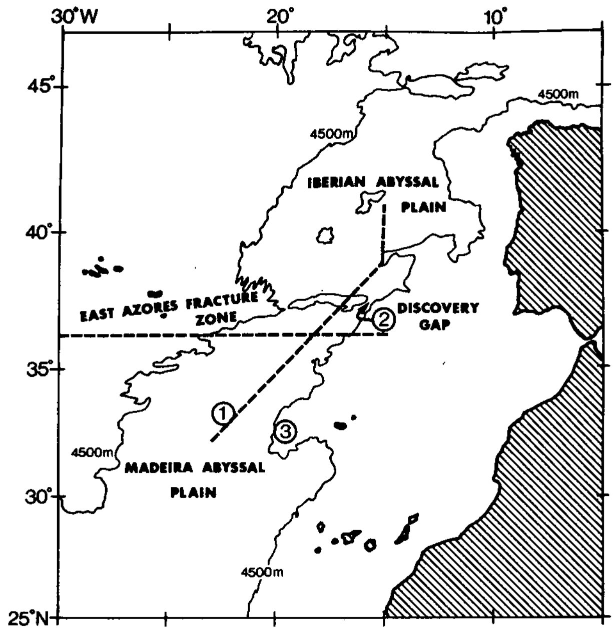


FIG. 1. Map of the northeast Atlantic showing the location of Discovery Gap and of long CTD sections shown in Figs. 3 and 4.

covery Gap Narrows. Two exits exist, one along the axis of the valley at a depth of 4780 m, and a second shallower one at 4620 m north of the Narrows. The scale of the topography is such that sounding lines at 5 km or closer spacing are essential. North of 37°15′N this coverage has been achieved; south of this point a sparser dataset exists and minor revisions can be anticipated.

Information about sediment thickness in the region can be obtained from seismic reflection profiling data (SRP). On *Discovery* cruise 43 (1971) a north–south section was made along longitude 16°30′W, just east of AA′ in Fig. 2. On *Discovery* cruise 54 (1973) a west–east section was made on latitude 37°10′N. On *Vema* cruise 27 (leg 07, 1969) a northwest–southeast section was made crossing the Narrows 10 km south of BB′ in Fig. 2. From this limited data in Discovery Gap and a survey of other unpublished data from surrounding areas the following tentative conclusions have been drawn.

The sediment thickness on the valley floor is about 300 m near the entrance (AA′) and decreases to 100 m approaching the Narrows section. Within the Narrows, sediment drape is rare and the bottom is rough. Ponds of sediment lie beyond the two exit sills: beyond the eastern exit the sea bed has a depth between 4900 and 4970 m and beyond the northern exit between 5000 and 5075 m. The along-valley distribution bears the mark of the action of currents.

Steep valley walls with slopes exceeding 1 in 5 are commonly free of sediment, although there are note-

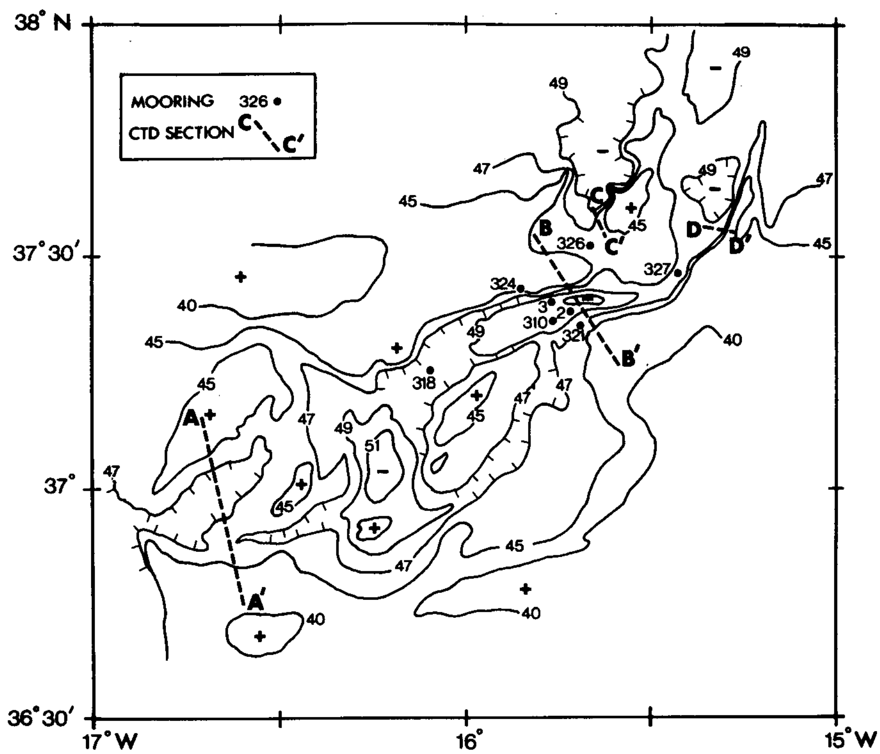


FIG. 2. Bathymetric map of Discovery Gap, with depths in 100 m. Mooring locations and CTD sections are indicated.

TABLE 1. Sills in Discovery Gap.

Sill	Depth (m)	Location
Entrance sill—SW	4675	36°54′N, 16°40′W
Exit sill—E	4780	37°30′N, 15°24′W
Exit sill—N	4620	37°29′N, 15°37′W

able deposits on the eastern and southern boundaries. The latter are part of the Madeira–Tore rise, which extends from 32° to 39°N. Between 34° and 38°N, at depths below 1500 m, this rise is covered with a pelagic drape whose thickness has a mean value of about 300 m and whose surface is covered with "mud" waves (spacing about 2 km). Bedforms of this type are commonly associated with relatively steady bottom currents (Heezen et al., 1966). At 37°10′N these waves extend to a depth of 4500 m. Just inside the valley entrance on the southern wall the basement is overtopped by about 500 m of sediment apparently free of waves, but, remarkably, near 36°30′N, 17°03°W just outside the valley entrance a minor basement outcrop supports a heap of sediment over 1 km thick. Depositional control by bottom currents is suspected. As described in the following sections there is a net flow through Discovery Gap from southwest to northeast, with maximum currents near the sea bed. The flow originates from the south and in order to enter the valley must undergo a sharp right turn. Deposits appear to accumulate on the turn as with a meandering river. Thus, deep channels afford sites for both erosion and deposition, a conclusion reached by Shor et al. (1979) in their study of the Charlie–Gibbs fracture zone.

3. The distribution of potential temperature

At depths below 3000 m in the area of the northeast Atlantic under consideration, there is a precise correlation between potential temperature and salinity (Saunders, 1986). In the following sections potential temperature may thus be interpreted as potential density.

Observations made with a CTD between 32° and 41°N in the summer of 1982 (Saunders, 1983a) are shown in Fig. 3. The southwest–northeast section intersects the East Azores Fracture Zone west of Discovery Gap. The meridional gradient in abyssal potential temperature is clearly seen on this figure, but there is an abrupt increase in potential temperature across the ridge from about 2.01°C on the south side to about 2.05°C on the north side. A poleward flow of abyssal water, warming as it goes, is suggested by this section.

Figure 4 shows an east–west section made in the winter of 1981 just south of Discovery Gap on the northern edge of the Madeira Abyssal Plain. The isotherms are generally horizontal, except at the east end of this section, where they indicate a piling up of the cold dense water against the lower continental rise at all depths below 3500 m. From the high pressure there (associated with high density) one infers a poleward flow that is strongest near the bottom. Of course, only the geostrophic shear can be deduced from this figure and not the flow direction, but direct current measurements in the area (section 4) show that the flow *is* bottom intensified and hence poleward. Evidence for a northward flow farther to the south along the eastern margin of the Madeira Abyssal Plain is found in two short sections made in July 1983 just west of the island of Madeira (Fig. 5). These sections show a similar pil-

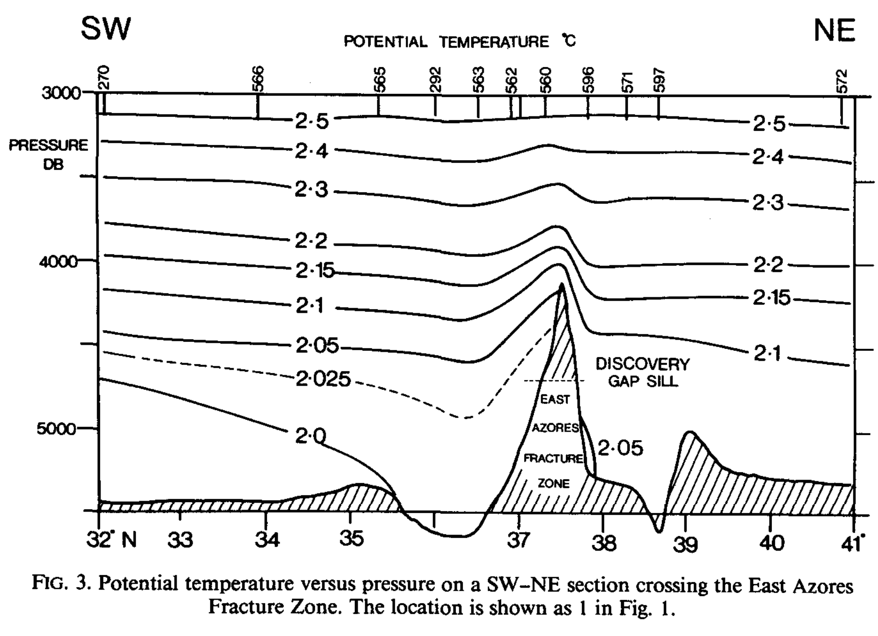


FIG. 3. Potential temperature versus pressure on a SW–NE section crossing the East Azores Fracture Zone. The location is shown as 1 in Fig. 1.

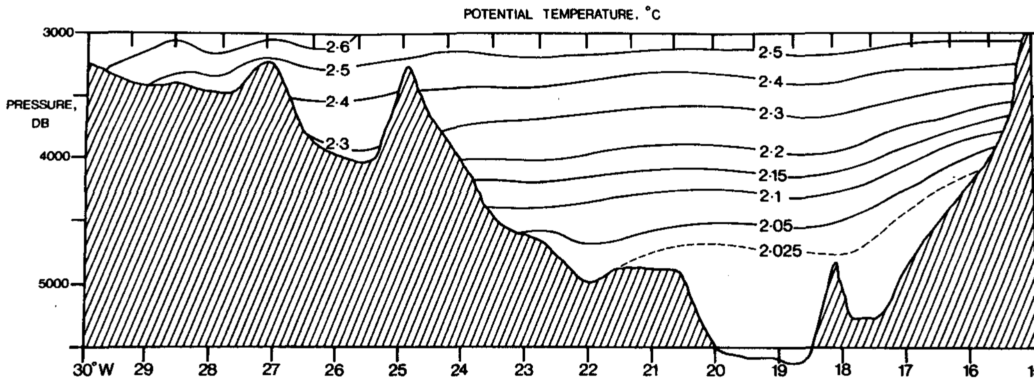


FIG. 4. Potential temperature versus pressure on a W–E section at 36°N. The location is shown below 2 in Fig. 1. (Courtesy of C. Wunsch.)

ing-up of the dense cold water against the lower continental rise, and a similar poleward bottom-intensified current is deduced. At this location both observations with neutrally buoyant floats and moored current meters (Figs. 3 and 16, Saunders and Richards, 1985) confirm the direction of the flow.

Observations of potential temperature from section AA′ just inside the entrance to Discovery Gap are shown in Fig. 6. The piling-up of cold water on each side of the entrance indicates both inflow and outflow, the former on the south side the latter on the north. A similar effect can be seen on the Narrows section BB′ in Fig. 7, with the current flowing with the slope (of the bottom) on its right-hand side. Here, because of the large number of observations, an asymmetry is clearly visible, more cold dense water piled up to the south-southeast than to the north-northwest, suggesting a stronger flow toward the east than the return to the west. In Fig. 8 the discharge from Discovery Gap into the Iberian basin is shown.

The distribution of potential temperature shown in Figs. 3–8 reveals a continuous near-bottom flow that extends along the eastern margin of the Madeira Abyssal Plain for about 500 km and feeds Discovery Gap, thence discharging cold water into the Iberian Basin. Some of the water entering Discovery Gap reemerges to flow along the south side of the East Azores Fracture Zone (Fig. 3). It is probable that this flow enters the northern basin through the 19°30′W gap (see Fig. 1) and returns eastward along the north side of the ridge (recent unpublished CTD data by the author). Note that it is not seen at the west end of the section shown in Fig. 4. These data have been gathered over a two and one-half year period and, together with the geo-

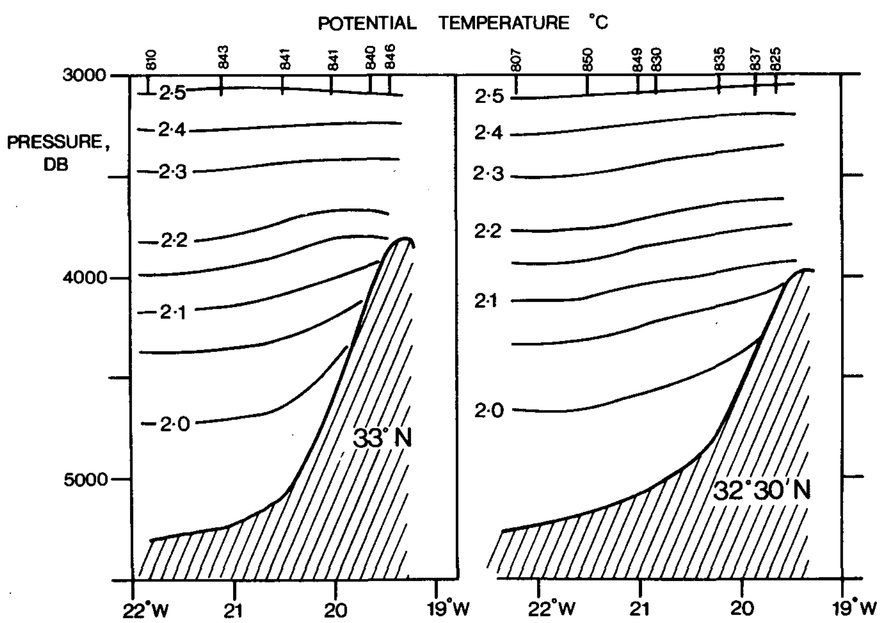


FIG. 5. As in Fig. 4. Two short west–east sections west of Madeira. The location is near 3 in Fig. 1.

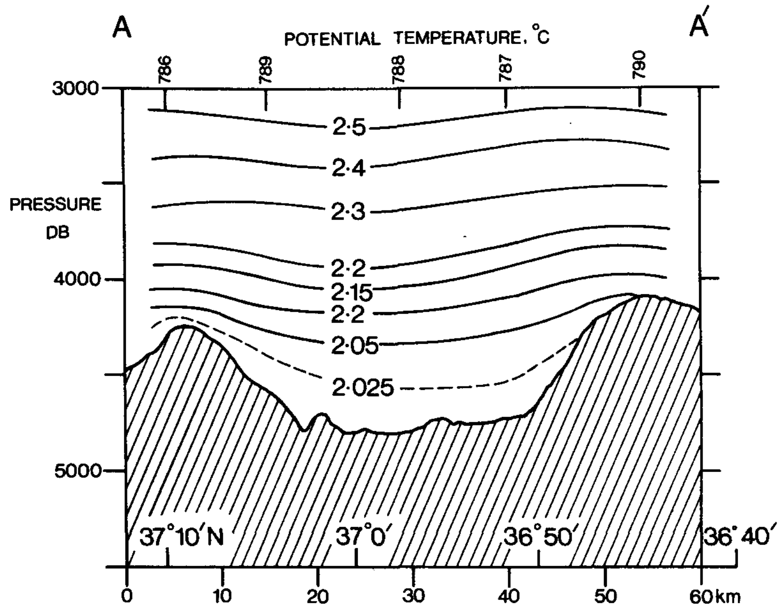


FIG. 6. As in Fig. 5. The entrance section AA' to Discovery Gap. (See Fig. 2.)

logical data, suggest that the circulation is persistent rather than transient.

4. Current measurements in Discovery Gap

a. Float observations

Direct observations of the flow have been made employing both moored current meters and drifting, acoustically tracked floats. The latter measurements are described first.

During *Discovery* cruise 130, when many of the CTD measurements were made (Saunders, 1983a), 13 neutrally buoyant floats were launched and tracked for 2–10 days. Details of ten of the float tracks are listed in Table 2. The remaining three settled on the bottom and gave no useful data. Eight of the floats were ballasted for 4700 m and occupied the depth range 4600

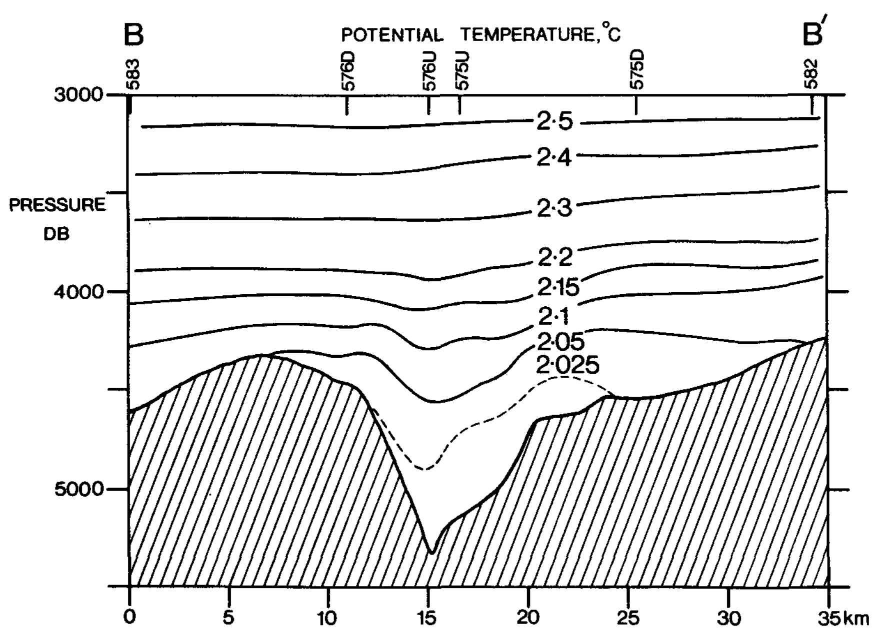


FIG. 7. As in Fig. 5. The Narrows section BB' in Discovery Gap. (27 lowerings were made.)

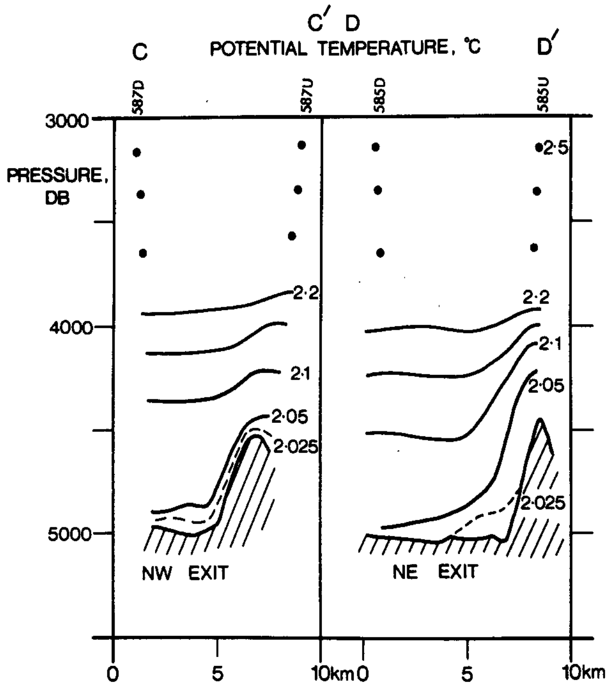


FIG. 8. As in Fig. 5. The exit sections CC′ and DD′. (Eight and six lowerings were made, respectively.)

to 4800 m approximately; two were ballasted for 4000 m. All showed a displacement in a northeast direction, the tracks lying between 030° and 080°. The average speed of the deeper floats was approximately 4 cm s^{-1}, with that of the shallower pair only 2 cm s^{-1}, showing the flow to be strongest at the bottom (as suggested by the temperature measurements).

The floats were deployed about halfway along the valley and moved through the Narrows section (Fig. 9), where they reached maximum speeds of about 10 cm s^{-1}. East of this location they turned north and passed over the northern sill (depth 4620 m). Many of the floats had equilibrium depths below the sill level and consequently were slightly retarded by dragging along the bottom. (The downward force is about 10 g for a displacement of 100 m, and the float mass is 70 kg). A number of the floats, however, did ground against bluff obstructions and these are noted in Table 2. It will be seen that the floats and, by implication, the water crossed the bathymetric contours.

b. *Current meter observations*

An exploratory mooring was laid in July 1981 and recovered in June 1982. Six additional moorings were laid in July 1982 and recovered in June 1983. The location of these moorings is shown in Fig. 2, and details of their positions and the instruments they carried are given in Table 3. Four of the six moorings were deployed in the Narrows section with three current meters at a depth of approximately 4400 m, three at 4700 m and two at 5000 m. This group of measurements was designed to determine the flux of cold water through Discovery Gap. In addition, moorings with single instruments were placed on each exit sill in order to monitor the overflows. The earlier mooring deployment, also with a single current meter, was made just west of the Narrows section. Instrument performance was extremely satisfactory and data were recovered from all meters. Pre- and postcruise calibrations of temperature showed stability at the 0.002°C level (Saunders and Cherriman, 1983).

The character of the flow measurements can be summarized as follows: currents have means of 2–6 cm s^{-1}, show low-frequency variability with a period of 2–80 days and rms magnitudes of 2–3 cm s^{-1}, tidal components with amplitudes of 3–5 cm s^{-1}, and weak inertial components of magnitude 0.5 cm s^{-1}.

Table 4 presents the statistical properties of the currents filtered to remove the tides and inertial motions. The direction of the mean flow is shown in column 3 and its magnitude in column 4. It will be noted that records on the same mooring have very similar characteristics, (i.e., currents are vertically coherent) and increase with increasing depth at a rate of between 1 and 2 cm s^{-1} km^{-1}. The direction of the mean current is approximately along the valley axis, toward 060° on the southern moorings (310, 321, 322) but weakly in the reverse direction on mooring 323. At mooring 324 the mean current has a component along the axis to the northeast. The observed mean flow is very similar to that anticipated from the distribution of potential temperature shown in Fig. 7. In Fig. 10 are combined float observations, made as they passed through the current meter moorings in the Narrows section, with moored current measurements. Very satisfactory agreement is seen throughout the section, showing the persistent flow on the south side of the channel with speeds of 5–10 cm s^{-1} and the weak reversed flow on the north side. After passing through the section the floats turned north (see Fig. 9), and this observation led us to deploy mooring 326 on the northern sill.

The currents crossing the two exit sills show a quite different character from one another, though they have similar means of about 5 cm s^{-1}. The downstream rms variation on the eastern sill is only 2 cm s^{-1} and thus smaller than the mean, but on the northern sill it is 5 cm s^{-1} and thus comparable to the mean. A steady, almost unidirectional, current is implied in the former case, as compared with an unsteady current in the latter, with many periods of flow reversal (Fig. 11). To oversimplify, there is a continuous discharge of cold water across the eastern sill and a pulsating one across the northern sill; the characteristic time scale of this pulsation is about 5 days. Similar behavior is seen on the Narrows section itself: steady flows occur at moorings 310, 321 and 322, but unsteady flows at moorings 323 and 324.

TABLE 2. Neutrally buoyant floats. Discovery cruise 130. (All dates July 1982: 1st ≡ day 182.)

Float number	Mk	Observed depth (m)	Launch Time/date	Launch Latitude (deg, min, N)	Launch Longitude (deg, min, W)	Recovery Time/date	Recovery Latitude (deg, min, N)	Recovery Longitude (deg, min, W)	Avg. speed (cm s^{-1})	Direction (deg)	When grounded (time/date)
5	II	4603	1724/19	37 17.7	16 06.5	1604/31	37 40.1	15 31.2	4.3[a]	075	1306/30
1	II	4703	0318/21	37 18.6	15 58.6	0900/31	37 29.3	15 36.2	3.2	058	
7	II	4687	0318/21	37 19.6	15 58.6	0615/31	37 31.3	15 34.9	3.5	058	
10	II	4687	0318/21	37 20.6	15 58.5	1328/31	37 35.5	15 38.8	3.6	059	1214/30
8	II	4662	0236/22	37 17.7	15 57.9	0900/23	37 18.8	15 50.6	7.4[b]	080	
17	II	4781	0236/22	37 17.9	15 58.2	0936/30	37 34.4	15 39.4	4.3	042	0936/30
11A	II	4009	0236/22	37 20.0	15 58.7	1050/24	37 20.7	15 54.4	2.4[c]	078	
11B	III	4896	2240/23	37 24.9	15 45.6	1330/29	37 25.9	15 40.2	1.7	077	2154/28
8	II	4640	2330/24	37 23.6	15 42.6	1604/31	37 40.1	15 31.3	4.5	030	1604/31
2	I	4097	2330/24	37 22.0	15 40.6	0615/31	37 24.2	15 31.5	2.0[c]	073	

[a] Longest float track = 53.6 km.
[b] 1.3 days duration only.
[c] Two floats ballasted for 4000 m, eight others 4700 m.
Note: Three other floats yielded no useful data.

Table 5 gives further information about the fluctuating currents in Discovery Gap Narrows. Two subinertial intervals have been selected having periods of 1–5 days and 5–85 days, respectively, and the kinetic energy in these bands has been determined. By rotary spectral analysis (Gonella, 1972) the clockwise and anticlockwise contributions have been extracted and their ratio determined. The rotary polarization of the currents is seen to have a simple geographical distribution. For the lower frequency band, currents on the southern side of the Narrows (321, 322) are seen to be clockwise polarized, those on the northern side (323, 324) anticlockwise. Such a distribution would arise were waves to travel with the mean current in the WSW–ENE direction while trapped in the NNW–SSE direction by the topography of the channel (Fig. 12). In contrast, for the higher frequency band, currents are polarized only on the south and center of the channel where we presume waves are trapped at the bottom of the southern slope. On the northern slope fluctuations have no rotary character, and in the weak mean current they are themselves less vigorous.

Fluctuations in the flow affect the reliability with which its mean can be determined (Flierl and McWilliams, 1977). The required measures are the integral time scale, derived by integrating the lagged autocorrelation function (Fig. 13), and the variance. The integral time scale τ_I, derived from the records in the Narrows section, is found to have a value of 2.7 ± 0.5 days for the downstream component of flow, so that the standard error of the estimate of the mean ϵ is given by

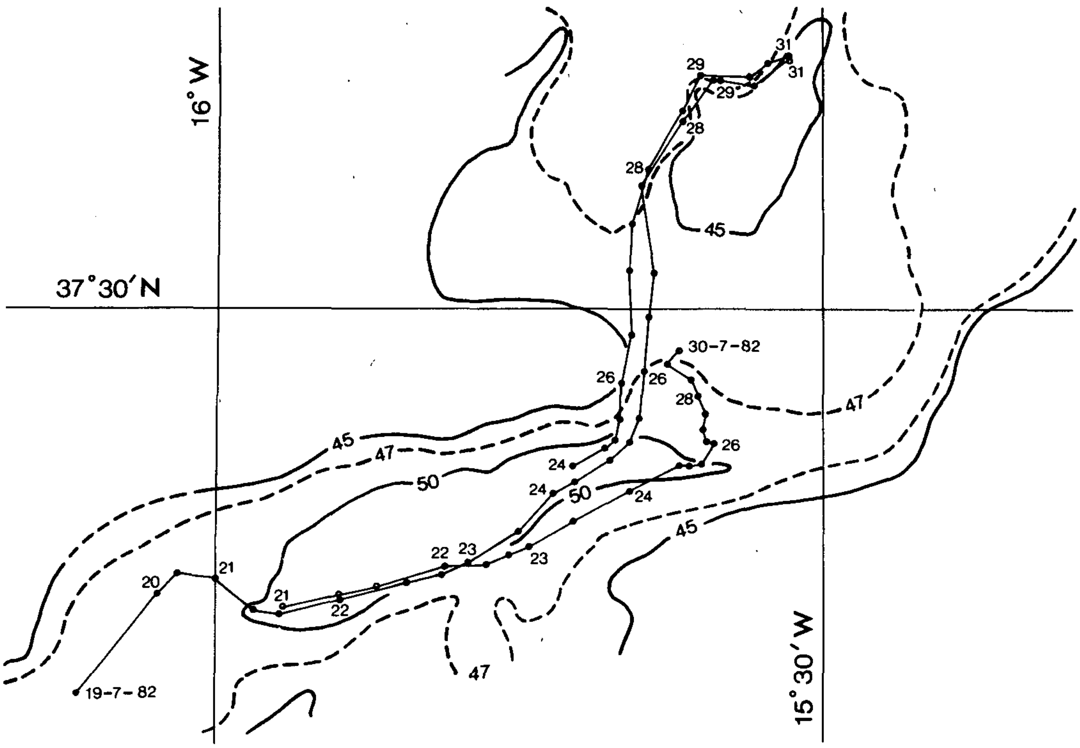
$$\epsilon^2 = \frac{2\tau_I \sigma^2}{T}$$

where σ is the rms variability of the record and T is the record length. A value of $\epsilon = \sigma/8$ is found and hence has a magnitude between 0.3 and 0.7 cm s^{-1}. Thus the mean flows are relatively well determined.

5. Flux of mass through Discovery Gap

The flux of cold water through Discovery Gap can be estimated directly from the current meter measurements. The details of the estimates are shown in Fig. 14 and the flux determinations in the first row of Table 6. The values are uncertain by virtue of both the extrapolation and interpolation required and the uncertainty of the means. Nevertheless, the fluxes are determined to within $\pm 0.03 \times 10^6$ m^3 s^{-1} for water colder than 2.05°C, but quite uncertainly determined in the interval 2.05°–2.10°C because of the possible leakage of such water across the ridge crest.

Geostrophic calculations can be performed in two ways. The first employs the data on the Narrows section (Fig. 7). The current shear there is estimated as 2–3 cm s^{-1} km^{-1} and compares favorably with, though somewhat exceeds, the current meter estimates. As is



SELECTED FLOAT TRACKS : FIXES 22-24Z ON DATE

FIG. 9. Selected float tracks in Discovery Gap. The fixes are near midnight for each date.

discussed in the next paragraph, a (uniform) level of zero motion is selected at 3500 db; the resulting transports are shown in the second row of Table 6. The geostrophic flux for the deepest layer is approximately twice that found by direct measurement, and it will be recalled that a similar discrepancy was found by Whitehead and Worthington (1982) on the Ceara Rise.

Yet another determination of flux can be made by combining the intersecting sections of Figs. 4 and 3, the former betweeen 18°W and the continental margin and the latter between 36°N and the East Azores Ridge (see also Fig. 1). Fluxes across these two sections differ because of what passes through Discovery Gap. In order to determine the level of zero motion, the data from these two sections outside the gap have been combined with that across the Narrows. Because of their proximity a common zero level is assumed for the three sections. The transports are then calculated for each section as a function of the chosen zero level. No exact fit exists for any level between 2500 and 5000 db, but near 3500 db the smallest imbalances are found. The fluxes are displayed in rows 2, 3 and 4. The difference

TABLE 3. Moorings and current meters. All current meters Aanderaa RCM4 except those in italics (VACM).

Mooring number	Latitude (deg, min, N)	Longitude (deg, min, W)	Water depth (m)	Record duration (days)	Instrument depth (m)
310†	37 21.1	15 45.7	5046	344	4823
321*	37 20.7	15 41.4	4686	333	*4673*, 4357
322*	37 21.6	15 43.3	4947	333	4934, *4612*, 4295
323*	37 23.9	15 47.2	5009	333	4996, *4673*
324*	37 25.1	15 50.8	4429	333	4416
326@	37 30.8	15 40.3	4613	326	*4601*
327@	37 27.5	15 25.3	4820	326	4808

† Data period 18 July 1981 to 28 June 1982.
* Data period 23 July 1982 to 19 June 1983.
@ Data period 29 July 1982 to 19 June 1983.

TABLE 4. Statistics of low-frequency currents.

					Root-mean-square variation		
Mooring/instrument	Depth (m)	Direction (deg *T*)	Mean (cm s^{-1})	Mean (potential temp, °C)	Down⁺ (cm s^{-1})	Across⁺ (cm s^{-1})	Temperature (10^{-3} °C)
31001	4822	055	3.73	2.017	3.1	2.1	1.5
32101	4357	044	5.63	2.029	2.4	1.2	4.6
32102	4673	048	6.37	2.016	2.8	1.3	2.4
32201	4295	059	5.00	2.048	2.5	1.45	9.7
32202	4612	056	5.58	2.020	3.2	1.45	2.8
32203	4934	052	5.78	2.015	3.5	2.0	1.7
32301	4673	251	1.39	2.023	2.5	1.1	1.9
32302	4996	264	1.61	2.013	2.4	1.6	1.1
32401	4416	007	1.86	2.043	1.9	2.3	12.1
32601	4601	004	5.36	2.049	5.3	2.7	17.9
32701	4808	044	5.15	2.013	2.7	1.0	1.5

⁺ Down is in the direction of mean flow; across is normal to down.

between the two fluxes outside the gap gives the third estimate, row 5; the values exceed those for the Discovery Gap Narrows from both previous estimates.

Clearly, the direct current estimates yield the best determination of the flux. The geostrophic calculations suffer because the data is poorly sampled in time: the density field needs to be observed *several* times during the course of the current meter deployment in order to produce a compatible average. Thus, based on one year's measurement, it is concluded that the flux of water colder than 2.05°C flowing through Discovery Gap is $(0.21 \pm 0.04) \times 10^6$ m^3 s^{-1}. The geostrophic estimates are between $(0.35$ and $0.4) \times 10^{-6}$ m^3 s^{-1} but are not as reliable. The geostrophic estimates, however, do indicate the possibility of a further interbasin flux of cold water at 19°30′W on the East Azores Fracture Zone, with a magnitude of perhaps one half that passing through Discovery Gap.

6. Diapycnal diffusion

If relatively cold (fresh) water flows continuously into the bottom of the Iberian Basin, and if the temperature (and salinity) remains steady, then there must be a flux of heat (and salt) into the bottom water. This flux is normal to density surfaces, is of a turbulent character,

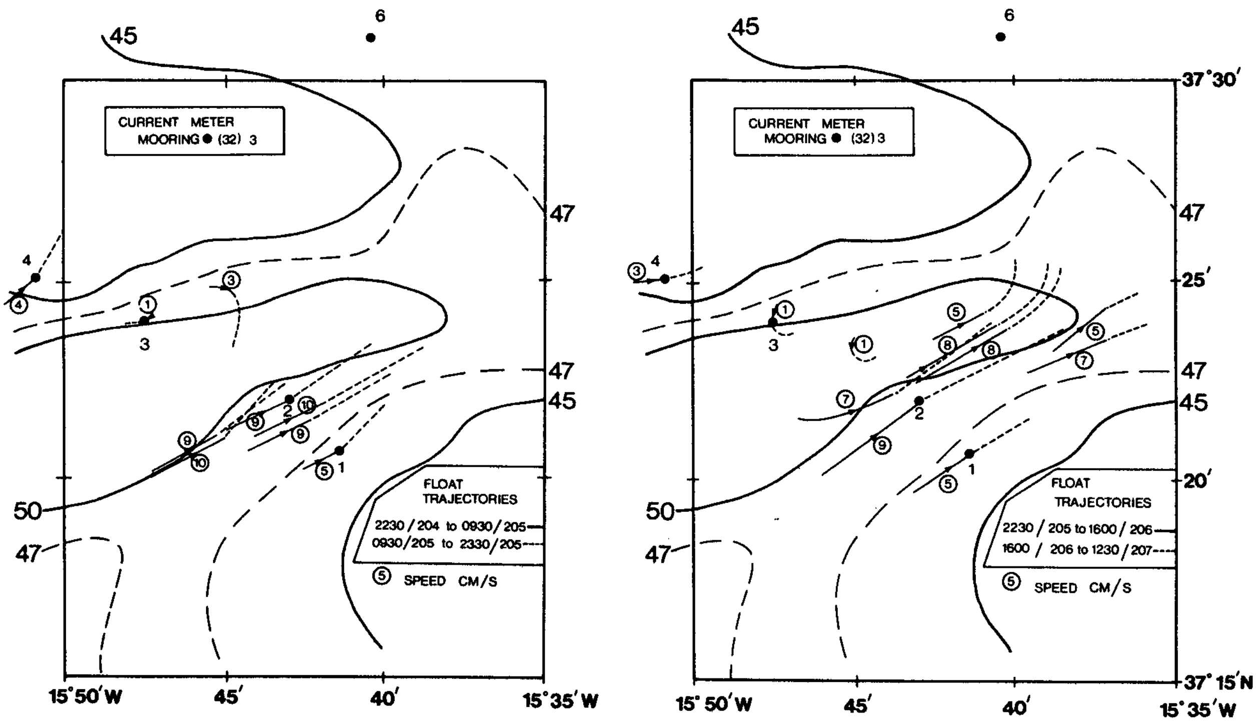


FIG. 10. Comparisons between float tracks and moored current measurements: data from two intervals are shown on each figure. Current meter vector end/start on a filled circle, a feature absent on float tracks.

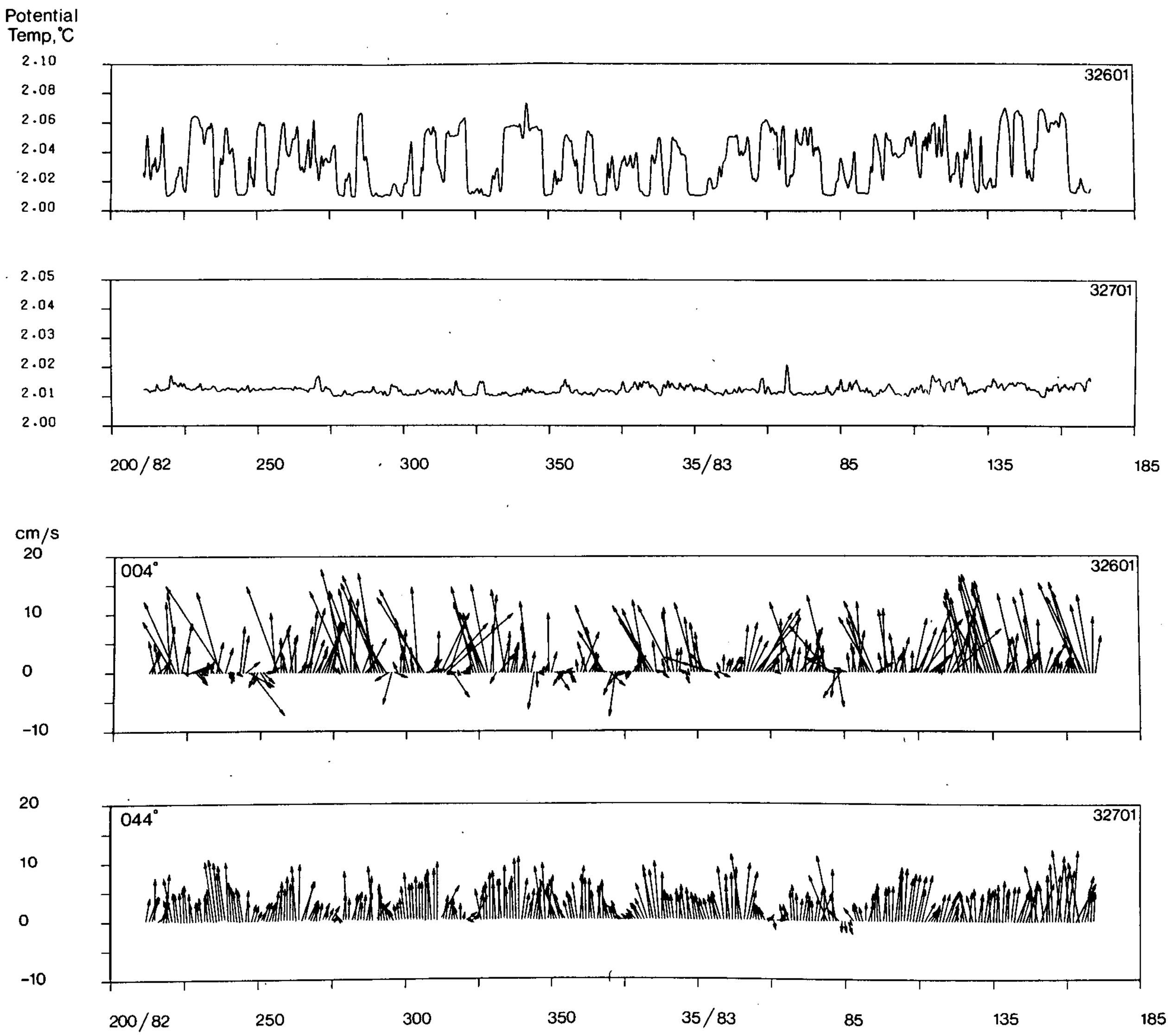


FIG. 11. Temperature and current vectors 10 m above the bottom on the two exit sills of Discovery Gap. Moorings 326 and 327 located as shown in Fig. 2.

and is termed diapycnal diffusion. In order to determine the flux, the heat balance equation is written

$$\int(\theta_F-\theta)dV=\left(\frac{G}{\rho C_p}+K\frac{\partial\theta}{\partial z}\right)A$$

which asserts that a flux of water δV entering the basin at temperature θ is heated to temperature θ_F (here taken as 2.05°C), and the heat to provide this is supplied by the geothermal heat flux ($G/\rho C_p$ in appropriate units) and by diapycnal diffusion. Here A is the area within which the transformation takes place and K is the diapycnal diffusion coefficient.

Inserting values known for this region, including $G = 1.5\ \mu\text{cal cm}^{-2}\ \text{s}^{-1}$ (Bullard, 1966), we obtain

$$4.2\times10^3-1.5\times10^{-8}A=A\cdot K\frac{\partial\theta}{\partial z}\quad[\text{units }^\circ\text{C m}^3\,\text{s}^{-1}]$$

where $\partial\theta/\partial z$ is evaluated on the surface $\theta=\theta_F$ (2.05°C). The area A is not well defined by the data but is approximately equal to 12 one-degree squares or $1.2\times10^{11}\ \text{m}^2$. The potential temperature gradient is determined by examining temperature profiles within the basin at 2.05° (Saunders, 1981, 1983a) whence

$$\overline{\frac{\partial\theta}{\partial z}}\approx1.0\times10^{-4}\,^\circ\text{C m}^{-1}\quad\text{and}$$

$$K=2\times10^{-4}\,\text{m}^2\,\text{s}^{-1}\quad\text{or}\quad2\ \text{cm}^2\,\text{s}^{-1}.$$

Very similar values have been obtained in the western Atlantic following the investigation of north-flow-

TABLE 5. Fluctuation kinetic energy. Italicized ratios are different from unity at the 90% significance level.

			Periods 5–85 days		Periods 1–5 days	
Period	Mooring	Instrument depth	KE ($cm^2 s^{-2}$)	Clockwise/ anticlockwise	KE ($cm^2 s^{-2}$)	Clockwise/ anticlockwise
1982–83	32101	4357	2.27	*1.53*	0.80	*3.75*
	32102	4673	2.92	*1.30*	1.80	*2.7*
1982–83	32201	4295	3.02	*1.59*	0.67	0.9
	32202	4612	4.15	1.26	1.1	0.9
	32203	4934	5.21	1.23	1.52	0.9
1981–82	31001	4822	4.80	1.00	1.62	*0.5*
1982–83	32301	4673	2.90	*0.62*	0.44	0.75
	32302	4996	3.21	*0.67*	0.54	1.1
1982–83	32401	4416	3.31	*0.6*	0.96	1.2

ing currents in the Vema channel (Hogg et al., 1982) and on the Ceara Rise (Whitehead and Worthington, 1982). The scale of these phenomena was an order of magnitude larger than studied here. Here the bounds on diapycnal diffusivity result mainly from uncertainties about the area A, which might be 30% larger but could be a factor of 2 smaller. Thus, K lies somewhere between 1.5 and 4 $cm^2 s^{-1}$.

Wherever the surface of the 2.05°C isotherm, which has area A, approaches the sea bed, it may enter the well-mixed bottom boundary layer (Armi and Millard, 1976). Here the cross-isopycnal diffusion occurs entirely within the boundary layer and becomes essentially horizontal. The contribution from this component is $K_H A' (\partial\theta/\partial s)$ where K_H is the horizontal diffusivity in the boundary layer, $\partial\theta/\partial s$ the horizontal temperature gradient also in the boundary layer, and A' its cross-sectional area. This latter quantity is the product of boundary-layer mean thickness and horizontal length, and a value of 50 m × 1000 km (=0.5 × 10^8 m) is estimated. Determination of K_H has been made within 10 m of the sea bed on the abyssal plain (Saunders, 1983b) and on the abyssal rise (Saunders and Richards, 1985), yielding values of 10^2 and 10^3 $m^2 s^{-1}$, respectively. Using the lower of these values with

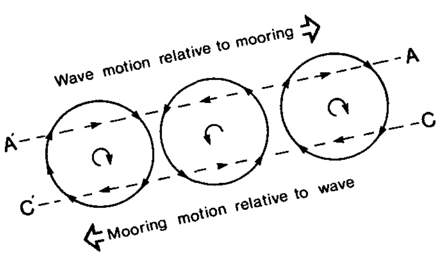


FIG. 12. Plan view of waves of subinertial frequency advected in a mean flow past moored current meters. On line AA′ (tracing the mooring passing through the waves) the observed current rotates anticlockwise; on line CC′ the current rotates clockwise.

a horizontal gradient of 2×10^{-7} °C m^{-1} [2] gives a product of 1×10^3 m^3 °C s^{-1}. This figure is between one-third and one-half of the oceanic heat flux term and if subsequently validated would somewhat reduce the true diapycnal diffusivity.

7. Discussion

Gargett (1984) has argued for an isopycnal diffusivity that is a decreasing function of buoyancy frequency. The experimental evidence derives primarily from lakes and shallow fjords and is rationalized by appealing to an (internal) wave-breaking argument. According to this formulation, values of diapycnal diffusivity in the ocean range from 0.1 $cm^2 s^{-1}$ in the seasonal thermocline to about 4 $cm^2 s^{-1}$ at abyssal depths. The latter value is in accord with the value reported here. It should be emphasized that the diapycnal diffusivity is estimated for the region lying north of Discovery Gap. It is assumed that the flux determined within the Narrows passes unaltered across the exit sills, which are no more than 20 km distant. Beyond the sills the terrain is quite irregular and tracing the outflow in detail is a very time-consuming task. Within Discovery Gap itself the *isopycnal* diffusivity can be determined from the Lagrangian integral time scale and the kinetic energy of the flow (Taylor, 1921). The cluster of floats does not provide sufficient data to estimate the former, so the current meter data has been used instead. The difference is probably not more than a factor of 2 if experience of the atmosphere is a valid guide (Murgatroyd, 1969). The downstream current has both mean and fluctuating energy, which varies across the Narrows section between 8 and 40 $cm^2 s^{-2}$. Taking an average of 20

[2] Not a well defined quantity. Thorpe (1983) has shown that weak fronts exist in the bottom boundary layer with gradients of 10^{-5} °C m^{-1} across them.

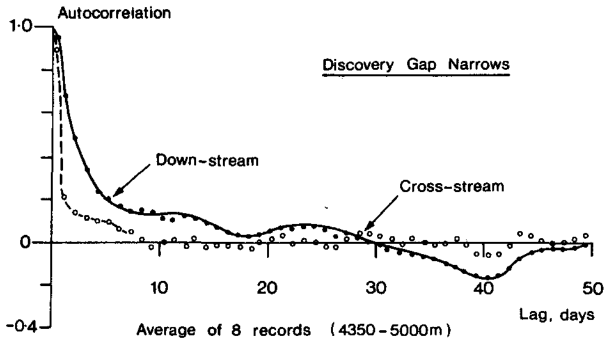


FIG. 13. The lagged autocorrelation of the down- and cross-stream components of the flow in the Narrows sections of Discovery Gap.

$cm^2\ s^{-2}$ and an integral time scale of 2.7 days gives a diffusivity of $5 \times 10^6\ cm^2\ s^{-1}$, a factor of 3 larger than values found on the Madeira Abyssal Plain (Saunders, 1983b).

The discovery of a persistent and relatively swift current on the lower continental rise south of Discovery Gap was unexpected but can be rationalized as follows. The mean potential temperature of the densest water crossing the sill at 4800 m near 37°30'N is very close to 2.01°C (see Table 4). Southwest of the entrance to Discovery Gap, in the nearly stagnant bottom waters of the Madeira Abyssal Plain (Dickson et al., 1985), such a temperature is found at depths of 5300 m. Could such fluid be lifted 500 m and accelerated to the speeds of 5–10 cm s^{-1} found in Discovery Gap? Bryden and Stommel (1984) examined a similar problem concerning the ascent and outflow of deep Mediterranean Water across a shallow sill. They used a layered model (appropriate to the Mediterranean Sea), but the extension of their theory to a continuously stratified fluid (appropriate here) appears intractable. *By observation* we suggest that for Discovery Gap an alternative strategy is adopted by the ocean; namely, dense fluid flows along the (eastern) boundary at a depth shallow enough to pass over the sill. In the boundary flow the 2.01°C isotherm is at 4800 m on 36°N but nearer to 4500 m at 33°N. In the ocean interior the isotherms rise to the south more steeply (see Fig. 3) so that eventually the height difference between the interior isotherms and those on the margin vanish. This probably occurs southwest of Madeira near 31°N, where the depth contours turn east and hence represent the "inlet" region for the boundary flow.

Based on this reasoning we propose that upstream boundary currents may be found wherever dense, cold bottom water flows through a channel and over a sill. In the Southern Hemisphere the currents will keep topography on the left; in the Northern Hemisphere topography will be on the right. This idea is based on the simple notion that the flow at the bottom is a maximum and decreases (to small or zero values) with increasing height above bottom in response to the thermal wind equation. Thus, in the Northern Hemisphere on a western boundary, a cold bottom-intensified current will flow southward (e.g., the recently discovered "cold filament" described by Weatherly and Kelly, 1985). If the flow were northward in those circumstances the current *could not* be a maximum on the bottom (unless the current were warm) so that if a bottom-intensified

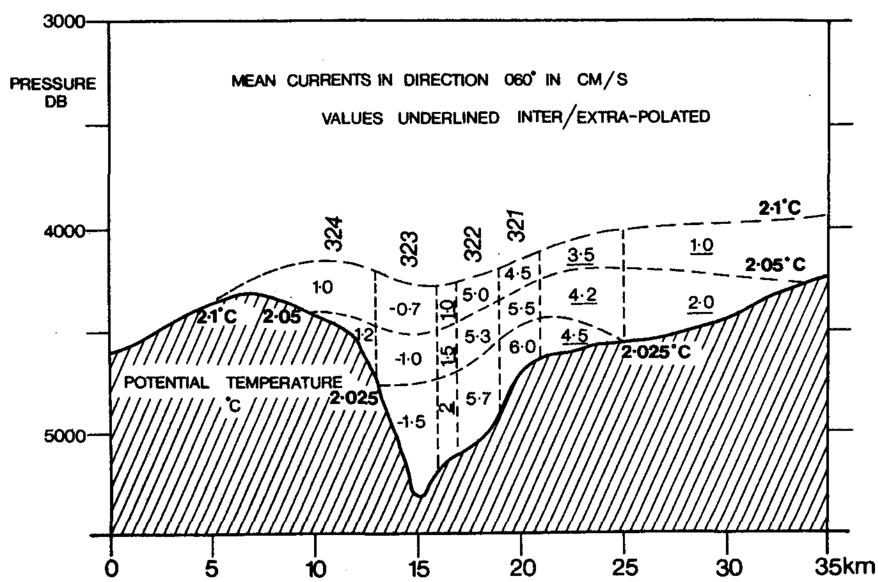


FIG. 14. The computation of mass flux through the Narrows section. Based on 1-year records.

TABLE 6. Mass flux.

Section	Potential temperature range (°C)		
	<2.025	2.025–2.05	2.05–2.10
Direct current measurements, 8 instruments, 10^6 m^3 s^{-1}			
Discovery Gap Narrows Fig. 14	0.09	0.12	0.08
Geostrophic estimates, reference level 3500 db, 10^6 m^3 s^{-1}			
Discovery Gap Narrows Fig. 7	0.21	0.14	0.10
E–W section on 36°N) Fig. 4)	0.50	0.20	0.20
SW–NE section) Fig. 3)	0.20	0.10	0.05
(Difference)	(0.30)	(0.10)	(0.15)

flow were to approach Discovery Gap from the Mid-Atlantic Ridge it would do so as a warm current.[3]

The observation of a deep eastern boundary current is at variance with the known preference of the ocean for flowing along western boundaries and may require revision of the dynamical arguments used to account for the preference. This will not be considered here. The ability of swift flows on the margins to carry water properties and tracers rapidly over considerable distances will also require revision of the view that the abyssal northeast Atlantic is merely weakly stirred.

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[3] There is hydrographic evidence for such a current, but only between 20° and 30°N.

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