I.O.S.

BENTHIC BOUNDARY LAYER
IOS OBSERVATIONAL PROGRAMME
DISCOVERY GAP MEASUREMENTS, MARCH 1984

BY

P.M. SAUNDERS

REPORT NO. 180
1984

OCEAN DISPOSAL OF HIGH LEVEL RADIOACTIVE WASTE
A RESEARCH REPORT PREPARED FOR THE DEPARTMENT
OF THE ENVIRONMENT

NATURAL ENVIRONMENT RESEARCH COUNCIL
INSTITUTE OF
OCEANOGRAPHIC
SCIENCES

INSTITUTE OF OCEANOGRAPHIC SCIENCES

Wormley, Godalming,
Surrey, GU8 5UB.
(0428 - 79 - 4141)

(Director: Dr. A.S. Laughton FRS)

Bidston Observatory,
Birkenhead,
Merseyside, L43 7RA.
(051 - 653 - 8633)

(Assistant Director: Dr D.E. Cartwright FRS)

Crossway,
Taunton,
Somerset, TA1 2DW.
(0823 - 86211)

(Assistant Director: M.J. Tucker)

When citing this document in a bibliography the reference should be given as follows:-

SAUNDERS, P.M. 1984 Benthic boundary layer - IOS Observational Programme: Discovery Gap measurements, March 1984. *Institute of Oceanographic Sciences, Report,* No. 180, 44pp.

INSTITUTE OF OCEANOGRAPHIC SCIENCES

WORMLEY

Benthic boundary layer
IOS Observational Programme
Discovery Gap measurements, March 1984

by

P.M. Saunders

I.O.S. Report No. 180

1984

DEPARTMENT OF THE ENVIRONMENT RADIOACTIVE WASTE MANAGEMENT RESEARCH PROGRAMME 1983/84

DoE Report No. DoE/RW/84.052

Contract Title: Studies of the Benthic Boundary Layer in relation to the disposal of Radioactive Waste.

DoE Reference: DGR 481/176

Report Title: Benthic Boundary Layer - IOS Observational Programme: Discovery Gap measurements, March 1984.

Author/Affiliations etc. SAUNDERS, P.M.

Date of submission to DoE 17.4.1984
Period covered by report

Abstract (100-200 words as desired)

A narrow gap in the East Azores Fracture Zone provides a channel for the exchange of the bottom water between the Madeira and Iberian abyssal basins. It is named Discovery Gap and a detailed survey defines its length, morphology and sills. Year-long measurements of flow are made from six moorings and ten current meters. This data is supplemented by numerous measurements of temperature made from ship-lowered instruments.

A persistent S-N flow is found in Discovery Gap and an estimate of the flux of water colder than 2.05°C (potential temperature) is made. This discharge spreads over a region beyond the Gap exit where it is warmed both by the geothermal heating from the seabed and also by mixing with the overlying warm water. An estimate of approximately 2 $cm^2 s^{-1}$ for the through density surface diffusion is derived, quite similar to two values determined from much larger channels in the Western Atlantic. It is not known whether most of the mixing takes place near the sea-bed or not. The values are in quite striking contrast to those derived for diffusion along a density surface: in Discovery gap values are estimated to be about $5x10^6 cm^2 s^{-1}$.

Keywords:
299 93, 94, 126, 155

Contents

Page

Preface 7

Introduction 8

Discovery Gap 9

Table 1: Sills in Discovery Gap 10

The distribution of Potential Temperature 11

Table 2: Conversion between depth and pressure for Discovery Gap 12

Current measurements in Discovery Gap -

(a) float observations 14

(b) current meter observations 15

Table 3: Neutrally buoyant floats. Discovery Cruise 130 16

Table 4: Moorings and Current Meters 17

Table 5: Statistics of low frequency currents 19

Flux of mass through Discovery Gap 21

Table 6: Mass Flux 23

Diapycnic diffusion 24

Significance of results 26

References 29

Figure captions 31

PREFACE

The research described in this report is concerned with a small part of the scientific assessment of the feasibility of the disposal of heat generating radioactive waste (HGW) into the deep sea environment. A presentation is given of research aimed at understanding the initial mechanisms of dispersion of radionuclides introduced into the benthic boundary layer (BBL) of the deep ocean. This layer, adjacent to the seabed and varying from 10-100m in thickness is caused by friction between the moving ocean water and the stationary ocean bottom. Within the BBL turbulent mixing is sufficiently strong that the properties such as density (and by analogy a radionuclide source term), are rendered uniform in the vertical. Above it the density decreases with height and vertical exchange is suppressed.

The Natural Environment Research Council, through the Institute of Oceanographic Sciences, has a contract with the Department of the Environment (DOE, DGR481/176) to examine processes within the BBL both by direct measurement within the deep ocean and also by numerical modelling (DoE Report No. 83-070). The emphasis of the investigations has been placed on studying the processes relevant to radionuclide dispersal within the BBL in order that realistic predictive models can be developed.

INTRODUCTION

Measurements of abyssal temperatures in the E. Atlantic show a marked variation with latitude. At a depth of 5000m near 10°N the in-situ temperature is 2.3°C, at the same depth near 50°N it is 2.6°C. Much further south, in the Antarctic the abyssal temperatures are as low as -0.6°C, where they originate from deep wintertime convection at the edge of and under the polar ice[1]. The northward warming of the bottom water throughout the entire Atlantic, including that within the Eastern Basin, can only result from its northward movement and mixing with the overlying warmer water. In most regions of the Atlantic this slow and erratic creeping movement cannot be estimated, but since the deepest parts of the ocean basins are separated by ridges[2], where valleys intersect such ridges the bottom flow becomes intensified. The flux of cold water may then be measured in such regions and hence the rate of mixing of abyssal water in the basins may be estimated. This was the purpose of the observational programme carried out in Discovery Gap and described in this report.

DISCOVERY GAP

Both the Maderia 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 5300m. 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 4500m (see figure 1). Low points on this ridge occur at 18°30'W and 16°W, with the latter feature which we have named Discovery Gap both wider and deeper.

Bathymetric surveys carried out on Discovery cruises 117, 122, 130 and 138 have provided a quite new picture of Discovery Gap and a contoured map is presented in figure 2. The valley axis lies along the direction 240-060 approximately, and is about 150km in length. For reasons which will become evident when observations of currents and temperatures are discussed, the SW end is referred to as the entrance and the NE end as the exit. One sill lies at a location near the entrance, on the section AA' shown in figure 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 the accompanying table 1.

TABLE 1

Sills in Discovery Gap

	depth, m	location
Entrance sill - SW	4675	36 54N, 16 40W
Exit sill - NE	4780	37 30N, 15 24W
Exit sill - NW	4620	37 29N, 15 37W

Thus the entrance sill with a depth of 4675m lies about 600m above the abyssal plains both north and south of Discovery Gap. The valley walls on each side rise approximately 500m above the entrance sill, and in two locations the valley floor is 500m deeper than at the sill. Beyond the entrance the valley is about 50km broad but nearer the exits it contracts to a breadth of only 10km. The section marked as BB' on figure 2 has been termed Discovery Gap Narrows. Two exits exist, one along the axis of the valley at a depth of 4780m, and a second shallower one at 4620m to the North of the Narrows. The scale of the topography is such that sounding lines at 5km spacing are essential. North of 37° 15'N this coverage has been achieved: south a sparser data set exists and minor revisions can be anticipated.

THE DISTRIBUTION OF POTENTIAL TEMPERATURE

Sea water is slightly compressible and a change of depth results in a change in its (in-situ) temperature at a rate of about 0.1°C per km[3]. Potential temperature takes account of this effect and if there was no mixing and no heat flux through the sea-floor the potential temperature of a particle of sea water would be conserved even in vertical displacement. Sea water also contains a variable salt content. At depths in excess of 3000m measurements by the author[4] reveal a precise relation between potential temperature and salinity in the region under consideration. Thus potential temperature may also be interpreted as potential density.

Observations made with a lowered instrument between 32 and 41°N in the summer of 1982[4] are shown in figure 3. The section lies along the broken SW-NE line shown in figure 1 passing location (1) and intersects the East Azores Fracture Zone west of Discovery Gap. The S-N gradient in abyssal potential temperature referred to in the introduction is clearly seen on this figure. In this and subsequent figures the ordinate is pressure, db which can be converted to depth m via table 2. There is an abrupt change in potential temperature in crossing the ridge from about 2.01°C on the south side to somewhat less than 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 and on the northern edge of the Madeira Abyssal Plain: these observations are shown as a broken line on figure 1 just below location (2).[+] The isotherms are generally horizontal except at the east end of the section, where they indicate a piling up of the cold dense water against the lower continental rise at all depths below 3500m. From the high pressure there (associated with high density) a poleward flow strongest near the bottom is deduced. It is tempting to suppose this current continues

TABLE 2

Conversion between depth and pressure for Discovery Gap

depth, m	3000	3500	4000	4200	4400	4600	4800	5000	5200
presure,db	3040	3551	4064	4269	4474	4680	4885	5091	5298
diff	40	51	64	69	74	80	85	91	98

Taken from:

Saunders, P.M. 1981 Practical Conversion of Presure to Depth, J. Phys. Oceanog., 11, pp.573-74.

[+] Footnote: Data kindly provided by C. Wunsch, MIT.

northward through Discovery Gap. Further evidence for a northward flow along the eastern margin of the Madeira abyssal plain is found in two short sections made in July 1983[5] just west of the island of Madeira, near location 3 on figure 1, see figure 5. These sections show a similar piling-up of the dense-cold water against the lower continental rise and a similar north going bottom-intensified current is deduced.

Observations of potential temperature from a lowered instrument on section AA' of figure 2 just inside the entrance to Discovery Gap are shown in figure 6. The piling up of cold water on each side of the entrance indicates both inflow and outflow, the former on the SE side the latter on the NW. A similar effect can be seen on the Narrows section, BB' on figure 2, in figure 7 with current flowing with the slope (of the bottom) on the right-hand side. Here an asymmetry is more clearly visible, more cold dense water piled up to the SSE (right in the figure) than to the NNW (left) suggesting a stronger flow to the east than the return to the west. In figure 8, sections CC' and DD' of figure 2, the discharge from Discovery Gap into the Iberian basin is shown.

The distribution of Potential temperature shown in figures 3-8 reveals a swift near-bottom flow which extends along the eastern margin of the Madeira abyssal plain for about 500km and feeds Discovery Gap thence discharging cold water into the Iberian Basin. Some of the water entering Discovery Gap re-emerges and runs along the south side of the East Azores fracture zone, see figure 3. It is probable that this flow enters the northern basin through the 18° 30'W gap, see figure 1, because it is not seen at the west end of the section shown in figure 4. The data has been gathered over a two and one-half year period suggesting the circulation is persistent rather than transient.

CURRENT MEASUREMENTS IN DISCOVERY GAP

(a) Float observations

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

During Discovery Cruise 130 when many of the lowered temperature measurements were made 13 neutrally buoyant floats were launched and tracked for 2-10 days. Details of 10 of the float tracks are listed in table 3, the remaining 3 settling on the bottom and giving no useful data. Eight of the floats were ballasted for 4700m and occupied the depth range 4600 to 4800m approximately: two were ballasted for 4000m. All showed a displacement in a north-east direction, the tracks lying between 030 and 080°. The average speed of the deeper floats was approximately 4cm/s, that of the shallower pair 2 cm/s showing the flow to be strongest at the bottom as was deduced from the temperature measurements.

The floats were deployed about half way down the valley axis and moved through the Narrows section, see figure 9, where they reached maximum speeds of about 10 cm/s. East of this location they turned north and passed over the NW sill at a depth of 4620m. Many of the floats had equilibrium depths below the sill level and consequently were very slightly retarded by dragging along the bottom. (However the downward force is only about 10gm for a displacement of 100m and the float mass is 70kg). A number of the floats however did ground against bluff obstructions and these are mentioned in table 3. It will be noted 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, and six were laid in July 1982 and recovered in June 1983. The location of these moorings is shown on figure 2 and details of their positions and the instruments they carried are given in table 4. Four of the six moorings array were deployed in the Narrows section with 3 current meters at a depth of approximately 4400m, 3 at 4700m and 2 at 5000m. 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

TABLE 3

Neutrally buoyant floats. Discovery Cruise 130

(All dates July 1982: 1st ≡ day 182)

Float Number	Mk	Observed Depth,m	Time/date	Lat. N	Long.W	Time/date	Lat. N	Long.W	Avg. Speed	Direc.	When grounded
5	II	4603	1724/19	37 47.7	16 06.5	1604/31	37 40.1	15 31.2	4.3cm/s(a)	075°	<1306/30
1	II	4703	0318/21	37 18.6	15 58.6	0900/31	37 29.3	15 36.2	3.2cm/s	058°	
7	II	4687	0318/21	37 19.6	15 58.6	0615/31	37 31.3	15 34.9	3.5cm/s	058°	
10	II	4687	0318/21	37 20.6	15 58.5	1328/31	37 35.5	15 38.8	3.6cm/s	059°	<1214/30
8	II	4662	0236/22	37 17.7	15 57.9	0900/23	37 18.8	15 50.6	7.4cm/s(b)	080°	
17	II	4781	0236/22	37 17.9	15 58.2	0936/30	37 34.4	15 39.4	4.3cm/s	042°	<0936/30
11a	II	4009	0236/22	37 20.0	15 58.7	1050/24	37 20.7	15 54.4	2.4cm/s(c)	078°	
11b	III	4896	2240/23	37 24.9	15 45.6	1330/29	37 25.9	15 40.2	1.7cm/s	077°	<2154/28
8	II	4640	2330/24	37 23.6	15 42.6	1604/31	37 40.1	15 31.3	4.5cm/s	030°	<1604/31
2	I	4097	2330/24	37 22.0	15 40.6	0615/31	37 24.2	15 31.5	2.0cm/s(c)	073°	

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

TABLE 4

Moorings and Current Meters

Mooring Number	Latitude (deg,min,N)	Longitude (deg,min,W)	Water depth (m)	Record Duration (days)	Instrument depth (m)
310[1]	37 21.1	15 45.7	5046	344	4823
321[2]	37 20.7	15 41.4	4686	333	4673,4357
322[2]	37 21.6	15 43.3	4947	333	4934,4612,4295
323[2]	37 23.9	15 47.2	5009	333	4996,4673
324[2]	37 25.1	15 50.8	4429	333	4416
326[3]	37 30.8	15 40.3	4613	326	4601
327[3]	37 27.5	15 25.3	4820	326	4808

Notes: 1 Data period 18-7-1981 to 28-6-1982

2 Data period 23-7-1982 to 19-6-1983

3 Data period 29-7-1982 to 19-6-1983

4 All current meters Aanderaa RCM4 except those underlined (VACM).

overflow from each. The earlier mooring deployment also with a single current meter was made just west of the Narrows section. Instrument performance was extremely satisfactory and all the data was recovered. Pre- and post-cruise calibrations of temperature showed stability at the .002°C level as reported earlier[6]. Further details concerning the moorings will be found in the cruise report[7].

The character of the flow measurements can be summarised as follows: currents have (a) means of 2-6 cm/s, show (b) low frequency variability with a period 2-60 days and r.m.s. magnitude 2-3 cm/s, (c) tidal components with amplitude 3-5 cm/s and (d) weak inertial components of magnitude 0.5 cm/s. Characteristics (a) and (b) are elaborated in the following paragraph.

Table 5 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 per km. The direction of the mean current is (approximately) along the valley axis towards 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 NE. The observed mean flow is very similar to that derived from the distribution of potential

TABLE 5

Statistics of low frequency currents

Mooring/inst	depth (m)	direction deg.T	mean cm/s	mean potential temp,°C	root mean square variatic		
					down cm/s	cross cm/s	temperatur 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

temperature shown in figure 7. In figure 10 is combined float observations, made as they passed through the current meter moorings in the Narrows section, with 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 and the weak reversed flow on the north side. After passing through the section the floats turned North, see figure 9, and this led us to deploy mooring 326 on the NW 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. The downstream rms variation on the NE sill is only 2 cm/s and thus smaller than the mean, but on the NW sill it is 5 cm/s and thus comparable with 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. To oversimplify, there is a continuous discharge of cold water across the NE sill and a pulsating one across the NW sill: the characteristic time-scale of this pulsation is about 5 days. Similar behaviour is seen on the Narrows section itself: steady flows occur at moorings 310, 321, 322 but unsteady flows at moorings 323, 324.

Fluctuations in the flow affect the reliability with which its mean can be determined[8]. The required measures are the integral time scale, derived by integrating the lagged auto-correlation function, see figure 11, 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

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

where σ is the root mean square variability of the record and T is the record length. A value of $\varepsilon = \frac{\sigma}{8}$ is found, and hence has a magnitude between 0.3 and 0.7 cm/s. Thus the mean flows are relatively well determined.

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 figure 12 and the flux determinations shown in the last row of table 6. The values are uncertain by virtue of both the extrapolation and interpolation required: nevertheless the fluxes are well determined, $\pm.03 \times 10^6 m^3 s^{-1}$ for water colder than 2.05°C but poorly defined in the interval 2.05-2.10 because there is no certain way of calculating the leakage of such water across the ridge.

The geostrophic calculations[9] can be performed in two ways. The first method employs the data on the Narrows section, figure 7. The current shear can be estimated there and the values, 2-3cm/s/km, compare favourably with the current meter estimates. For reasons to be discussed shortly a (uniform) level of zero motion is selected at 3500db: the resulting transports are estimated in the last but one row of table 5. It will be noted that the geostrophic fluxes are approximately twice those found by direct measurement.

Yet another determination of flux can be made by combining the intersecting sections shown in figures 4 and 3, the former between 18°W and the continental margin and the latter between 36°N and the East Azores Ridge. Fluxes across these sections differ because of the component that passes through Discovery Gap. Again the question arises of the level of zero motion: it has been determined by combining these two sections outside the gap 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 ref. level. No exact fit exists but 3500db for zero velocity gave the smallest imbalances. These are displayed in rows 1, 2 and 4. The difference between the two fluxes outside the gap gives the third estimate, row 3: it is larger than the Discovery Gap Narrows flux from both previous estimates.

In the writer's judgement the direct current estimates yield the best determination of the flux. The geostrophic calculations suffer because the data is poorly sampled: probably the density field needs to be observed several times during the course of the current meter deployment

TABLE 6

Mass Flux

Geostrophic estimates reference level 3500db, $10^6 m^3 s^{-1}$

Section	Potential temperature, range °C		
	2.025	2.025-2.05	2.05-2.10
E-W section on 36° N figure 4	.50	.20	.20
SW-NE section figure 3	.20	.10	.05
(Difference)	(.30)	(.10)	(.15)
D-Gap Narrows figure 7	.21	.14	.10

Direct current measurements, 8 instruments, $10^6 m^3 s^{-1}$

D-Gap Narrows figure 12	.09	.12	.08

in order to produce a compatible average. The principal conclusion reached is that based on a year's measurement, the flux of water colder than 2.05° C flowing through Discovery Gap is $(0.21\pm.04)\times10^{6}\mathrm{m}^{3}\mathrm{s}^{-1}$. The geostrophic estimates are between 0.35 and $0.4\times10^{-6}\mathrm{m}^{3}\mathrm{s}^{-1}$ but are not as reliable. The geostrophic estimates, however, do indicate the possibility of a further interbasin flux of cold water at 18° 30'W on the East Azores Fracture Zone - with a magnitude of perhaps one half that passing through Discovery Gap.

DIAPYCNIC DIFFUSION

If (fresh) cold water flows continuously into the bottom of the Iberian basin, but if the temperature (and salinity) remains steady then there must be a flux of heat (and salt) into the bottom waters. This flux is normal to density surfaces, of a turbulent character and is termed diapycnic diffusion. In order to determine it 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 diapycnic diffusion. A is the area within which the transformation takes place and K is the diapycnic diffusion coefficient.

Inserting values known including, $G=1.5\mu cal/cm^2/s$[10], we obtain

$$4.2x10^{3}-1.5x10^{-8}A = A.\ K\frac{\partial\theta}{\partial z} \qquad -(\text{units } {}^{\circ}Cm^{3}s^{-1})$$

where $\frac{\partial\theta}{\partial z}$ is evaluated on the surface $\theta=\theta_F(2.05^{\circ}C)$. The area A is not well defined by the data but is approximately equal to 12 one-degree squares or $1.2x10^{11}m^2$. The potential temperature gradient is determined by examining temperature profiles within the basin at 2.05°[4,11] whence $\overline{\frac{\partial\theta}{\partial z}} \approx 1.0x10^{-4}\ {}^{\circ}cm^{-1}$ and $K = 2x10^{-4}m^{2}s^{-1}$ or $2\ cm^{2}s^{-1}$.

Very similar values have been obtained in the Western Atlantic following the investigation of northgoing currents in the Vema channel[12] and on the Ceara Rise[13]. The scale of these phenomena was an order of magnitude larger than studied here.

The bounds on Discovery Gap value are determined mainly by uncertainties about the area A which might be 30% larger but could be a factor of 2 smaller. Thus K lays somewhere between 1.5 and 4 $cm^{2}s^{-1}$. Wherever the surface of the 2.05° C isotherm, which has area A, intersects the sea floor $\frac{\partial\theta}{\partial z}$ becomes very small $\sim 10^{-5}$°Cm^{-1}. From measurements it is known that diapycnic diffusivity becomes high in benthic boundary layer[14]. If $K=10^{-2}m^2s^{-1}$ or 100 cm^2s^{-1} and if as much as 10% of the area was occupied by active bottom diffusion this would account for the entire region's heat flux. The balance of terms is such that stirring near the boundaries must be a significant contributor to the required heat flux but one cannot say the same about stirring well away from the boundaries. The 'interior' values may or may not be an important contribution to diapycnic fluxes.

SIGNIFICANCE OF RESULTS

The presence of persistent and relatively swift currents on the lower continental rise at depths between 4000 and 5000m was quite unexpected. Their presence on the eastern side of the basin doubly so. Instead of viewing the deep NE Atlantic purely in a state of random stirring motion we must also take account of 'margin' currents which can carry water and hence tracer for considerable distances. Thus relatively high concentrations can be expected far from the tracer source. How far is unknown - but is the subject of continuing investigation.

Away from persistent mean currents dispersion of tracer is brought about by mixing along density surfaces; the rate can be determined from the product of a time scale, and the energy of the flow[8]. (Strictly speaking the (integral) time scale should be determined from observations of clusters of floats rather than from current meters but the difference is probably not more than a factor of 2 and only the current meters provide us with sufficient data). The downstream current has both mean and fluctuating energy which varies across the Narrows section between $8 cm^2 s^{-2}$ and $40 cm^2 s^{-2}$. Taking an average of $20 cm^2 s^{-2}$ 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[8].

This value for diffusion along a density surface is in striking contrast to the value of $2 cm^2 s^{-1}$ found for diffusion though a density surface. As discussed in an earlier report[15], the concentration of tracer is expected to dilute by a factor of ~1600 in half a year as a cloud of diameter ½km expands to a diameter of about 20 km. If the tracer was originally only 50m thick (such as would be produced by stirring within the benthic boundary layer and the subsequent separation of the layer) the tracer cloud would thicken only from about 50m to 150m, diluting by a further factor of 3. The anisotropy of spreading is clearly demonstrated by these figures.

As stated in the previous section it is not known whether diffusion through density surfaces occurs everywhere (on average) or whether it occurs predominantly where the density surfaces intersect the sea floor, subsequently reaching the interior locations by mixing along the density surfaces. An experiment was conducted in the lower continental rise west of Madeira in the summer of 1983, employing floats, current meters and lowered temperature profilers and it is hoped that an analysis of this data will shed light on the problem.

REFERENCES

1. B.A. Warren, 1981: Deep Circulation of the World Ocean. In Evolution of Physical Oceanography Ed. B.A. Warren and C. Wunsch. M.I.T. Press. p6-41.
2. General Bathymetric Chart of the Oceans 1982 (5th edition). Canadian Hydrog. Service, Ottawa.
3. Ninth Report of the joint panel on oceanographic tables and standard. Unesco technical papers in Marine Science, 30. Unesco, Paris, 1979. 32 pages.
4. Saunders, P.M., 1983: CTD data from the N.E. Atlantic 31°N-46°N, July 1982. Discovery Cruise 30. Report 165, Inst. of Oceanog. Sci., NERC.
5. Elliott, A.J., 1984: RRS Discovery cruise 139, 12 July - 2 August 1983. Inst. of Oceanog. Sci. Cruise Report No. 153, NERC.
6. Saunders, P.M., and J.W. Cherriman, 1983: Abyssal temperature measurements with Aanderaa current meters. Deep Sea Res., 30, 663-667.
7. Gould, W.J. and P.M. Saunders, 1982: RRS Discovery Cruise 130, 25 June - 5 Aug., 1982. Inst. of Oceanog. Sci. Cruise Report No. 136, NERC.
8. Saunders, P.M., 1983: Benthic observations on the Madeira abyssal plain: currents and dispersion. J. Phys. Oceanog., 13, 1416-1429.

9. Gill, A.E., 1982: Atmosphere-Ocean Dynamics, Academic Press p. 208 et seq.

10. Bullard, E.C., 1966: The flow of heat through the floor of the ocean. In The Sea, Vol.3. Interscience Pub., John Wiley, 218-233.

11. Saunders, P.M., 1981: CTD data from the N. Madeira Basin. Discovery Cruise 117. Inst. of Oceanog. Sci. Data Report 26, NERC.

12. Hogg, N., P. Biscaye, W. Gardner, and W.J. Schmitz, Jr, 1982: On the transport and modification of Antarctic bottom water in the Vema Channel. J. Mar. Res., suppl. vol 40, 231-263.

13. Whitehead, J.A. and L.V. Worthington, 1982: The flux and mixing rates of Antarctic Bottom Water within the N. Atlantic. J. Geophys. Res., 87, C10, 7903-7924.

14. Sarmiento, J.L., H.W. Feely, W.S. Moore, A.E. Bainbridge and W.S. Broecker, 1976: The relationship between vertical eddy diffusion and buoyancy gradient in the deep sea. Earth and Planet. Sci. Lett., 39, 235-240.

15. Saunders, P.M., 1983: Benthic Boundary Layer, IOS observational programme, Interim Report January 1983. Inst. of Oceanog. Sci. Report No. 163, NERC.

FIGURE CAPTIONS

Fig. 1	NE Atlantic map showing location of sections and sites of three experiments.
Fig. 2	Bathymetric map of Discovery Gap, depths in 100m. Mooring locations and sections shown.
Fig. 3	Potential temperature versus pressure on SW-NE section crossing East Azores fracture zone.
Fig. 4	Potential temperature versus pressure on W-E section on 36°N. Courtesy C. Wunsch.
Fig. 5	As previous; two short W-E sections west of Madeira.
Fig. 6	As previous; the entrance section AA' to Discovery Gap. (See fig. 2).
Fig. 7	As previous; the Narrows section BB' in Discovery Gap. (27 lowerings were made).
Fig. 8	As previous; the exit sections CC' and DD'. (8 and 6 lowerings were made, respec.)

Fig. 9 Selected float tracks in Discovery Gap. The fixes are near midnight against each date.

Fig. 10 A comparison between float tracks and moored current measurements: the latter are centred thus ●.

Fig. 11 The lagged autocorrelation of the down- and cross-stream components of the flow in the Narrows sections of Discovery Gap.

Fig. 12 The computation of mass flux through the Narrows section. Based on 1 year records.

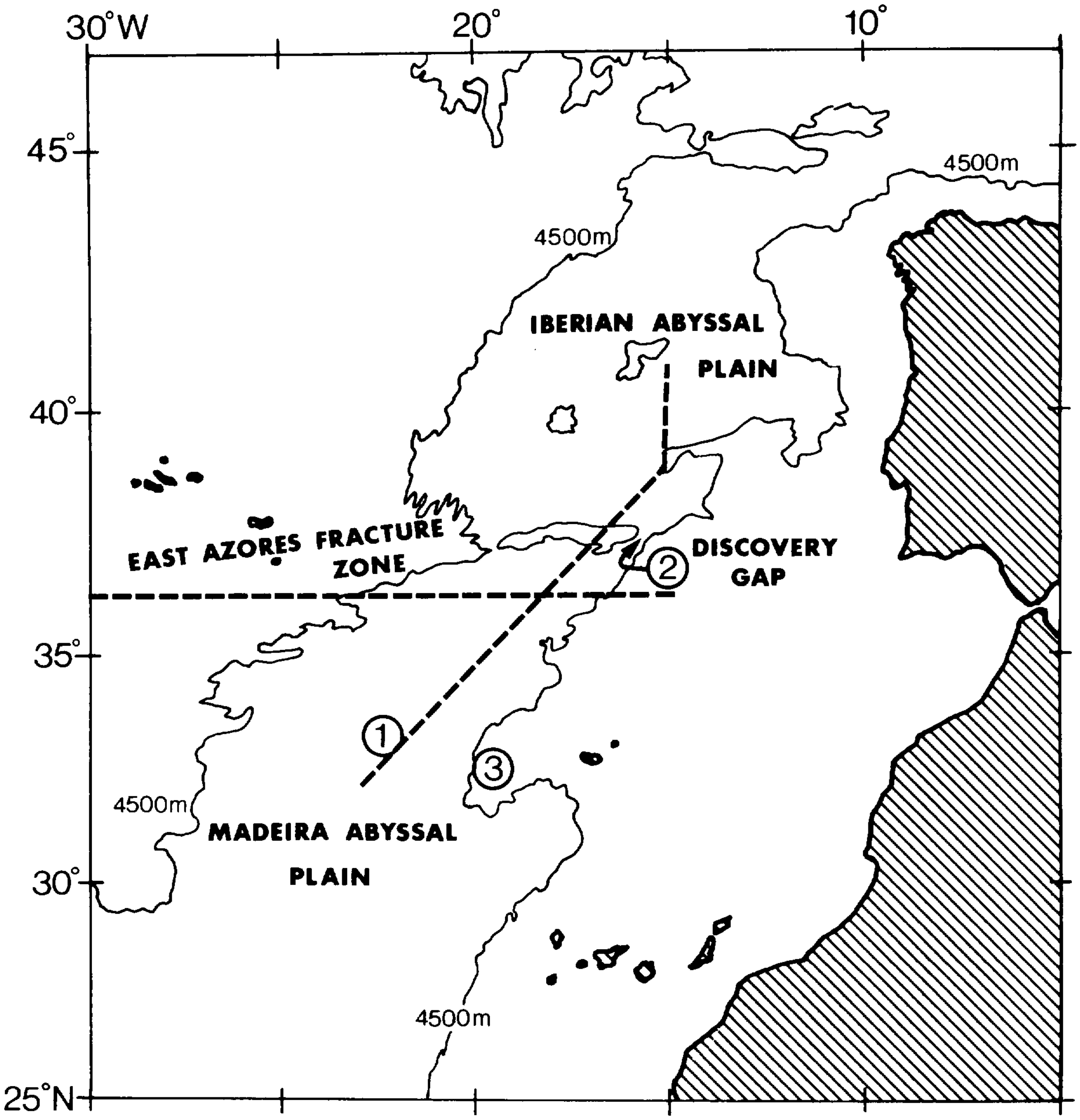

Fig. 1 NE Atlantic map showing location of sections and sites of three experiments.

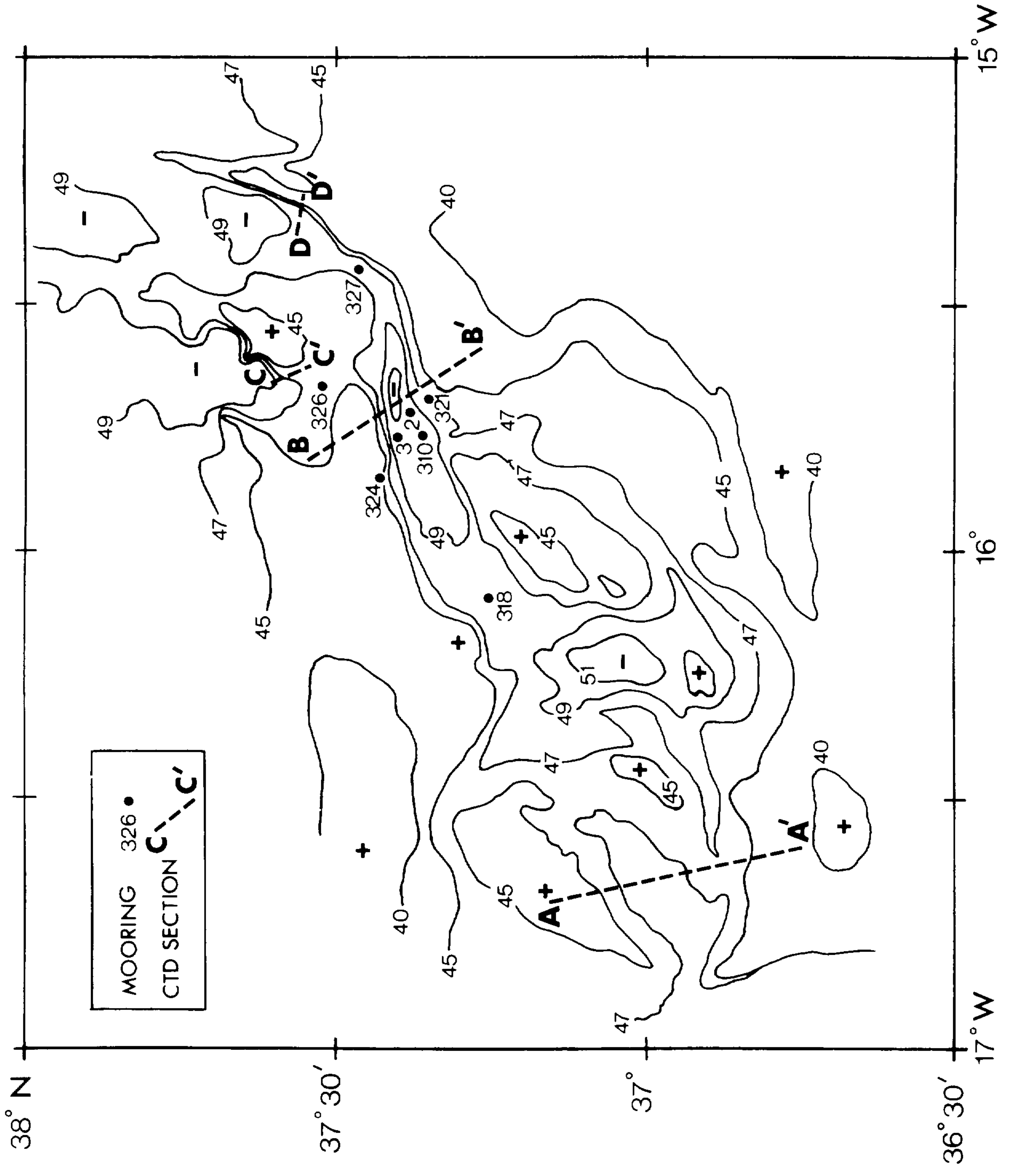

Fig. 2 Bathymetric map of Discovery Gap, depths in 100m. Mooring locations and sections shown.

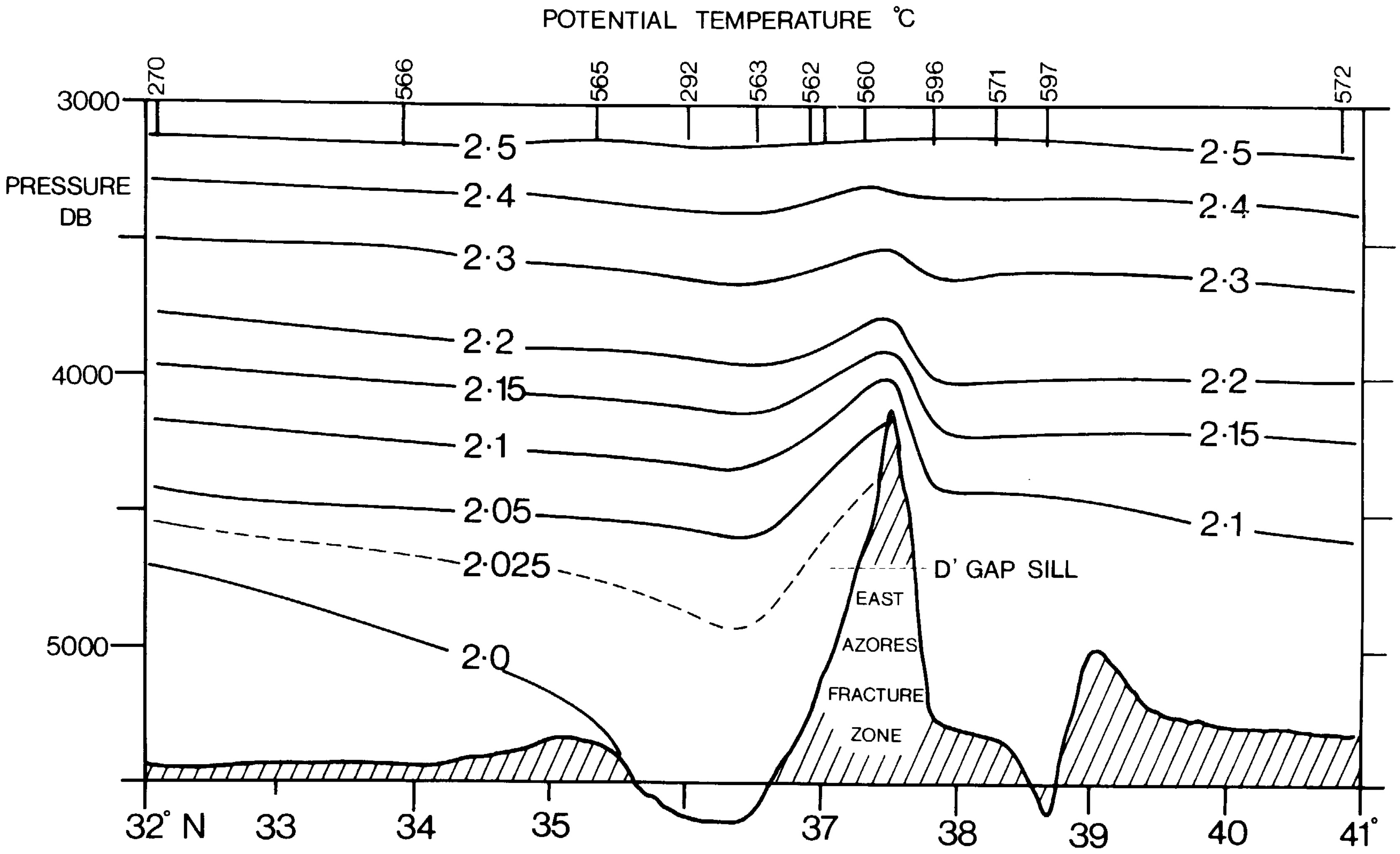

Fig. 3 Potential temperature versus pressure on SW-NE section crossing East Azores fracture zone.

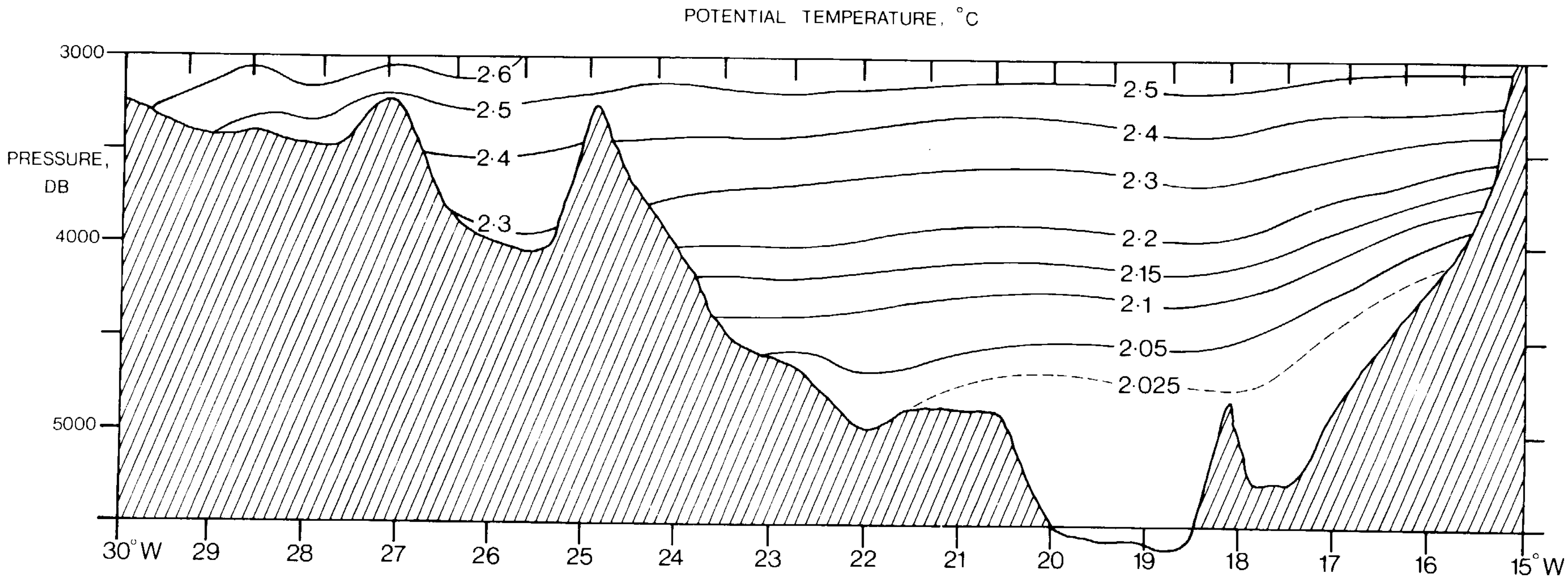

Fig. 4 Potential temperature versus pressure on W-E section on 36° N. Courtesy C. Wunsch.

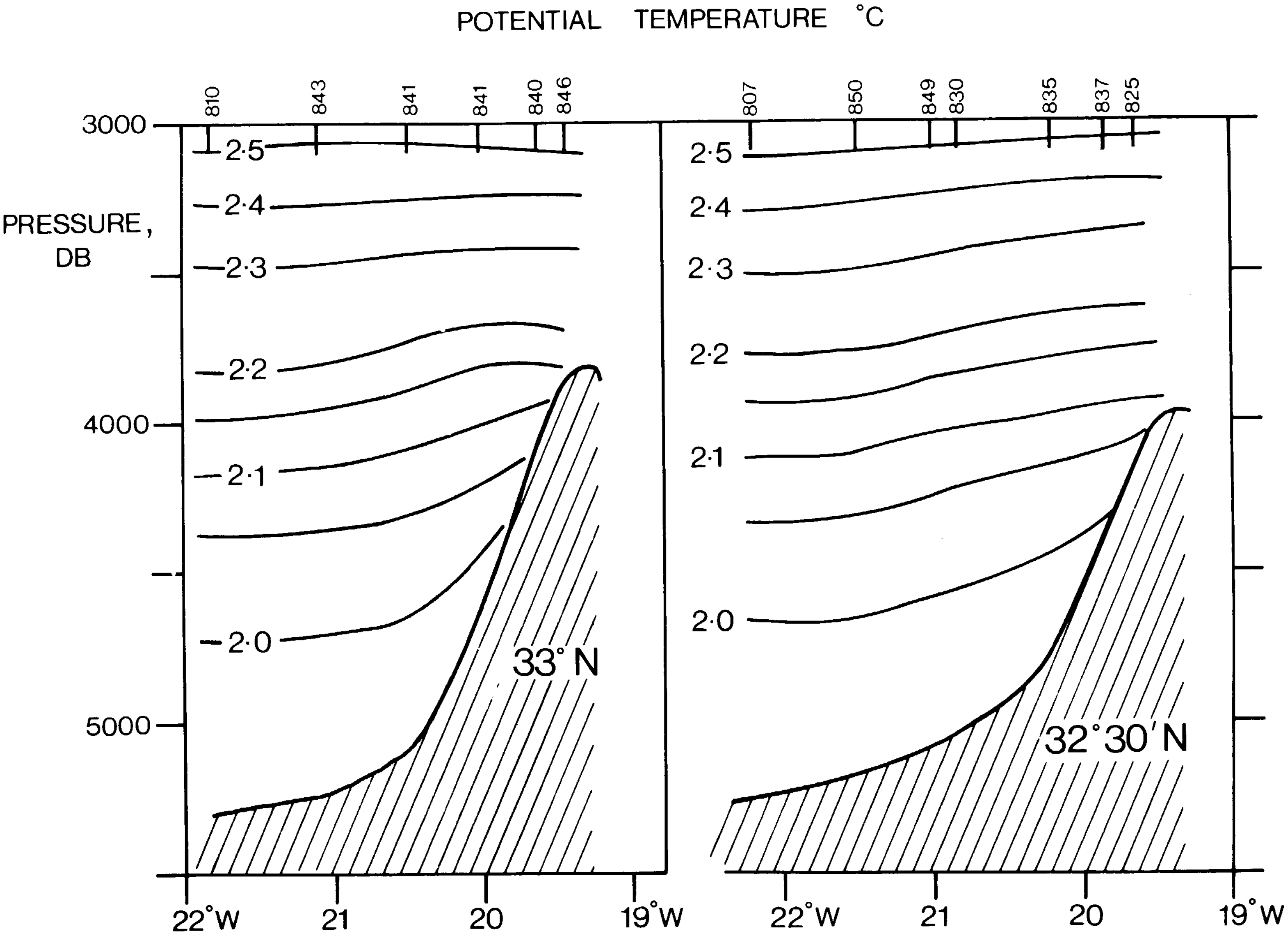

Fig. 5 As previous; two short W-E sections west of Madeira.

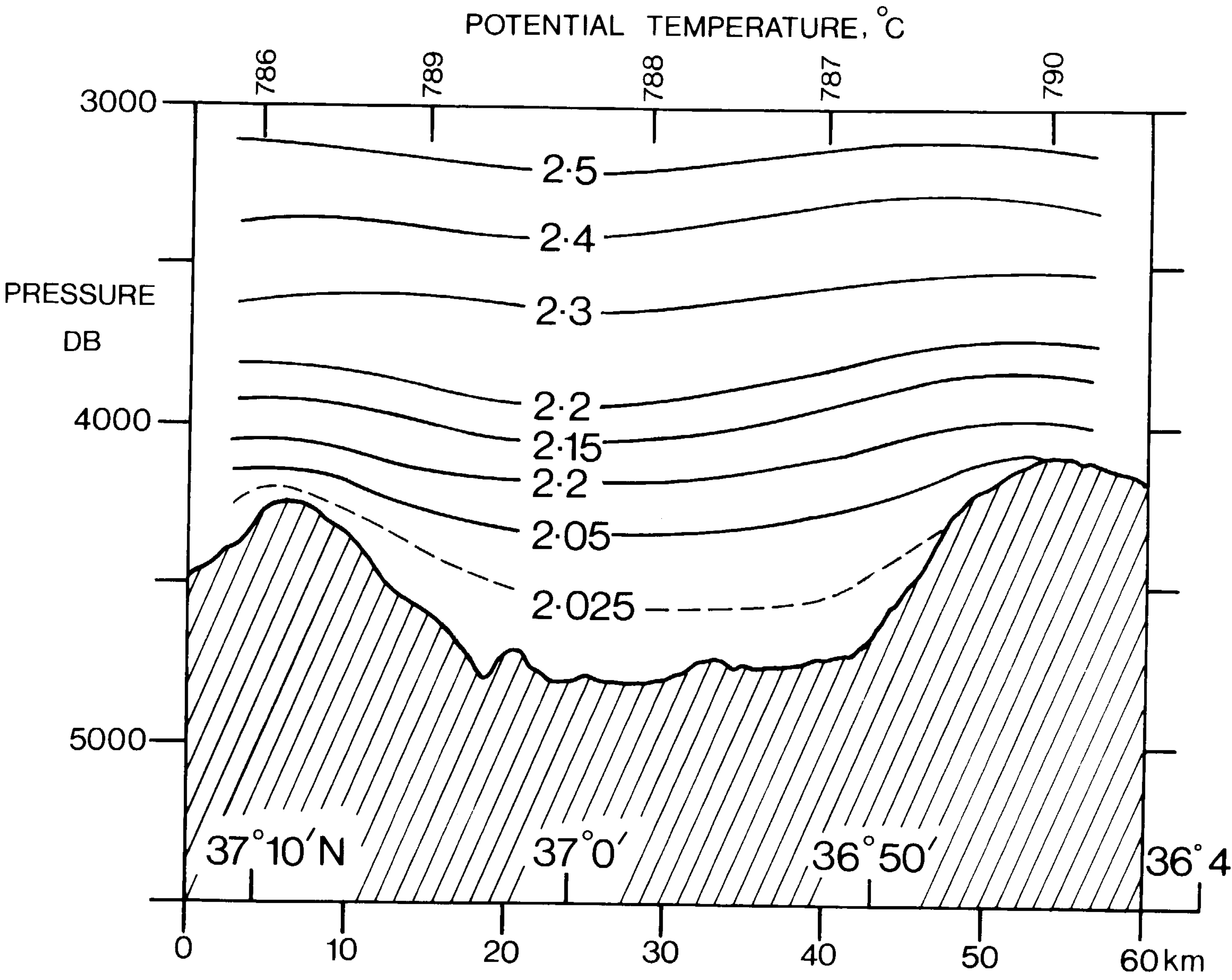

Fig. 6 As previous; the entrance section AA' to Discovery Gap. (See fig. 2).

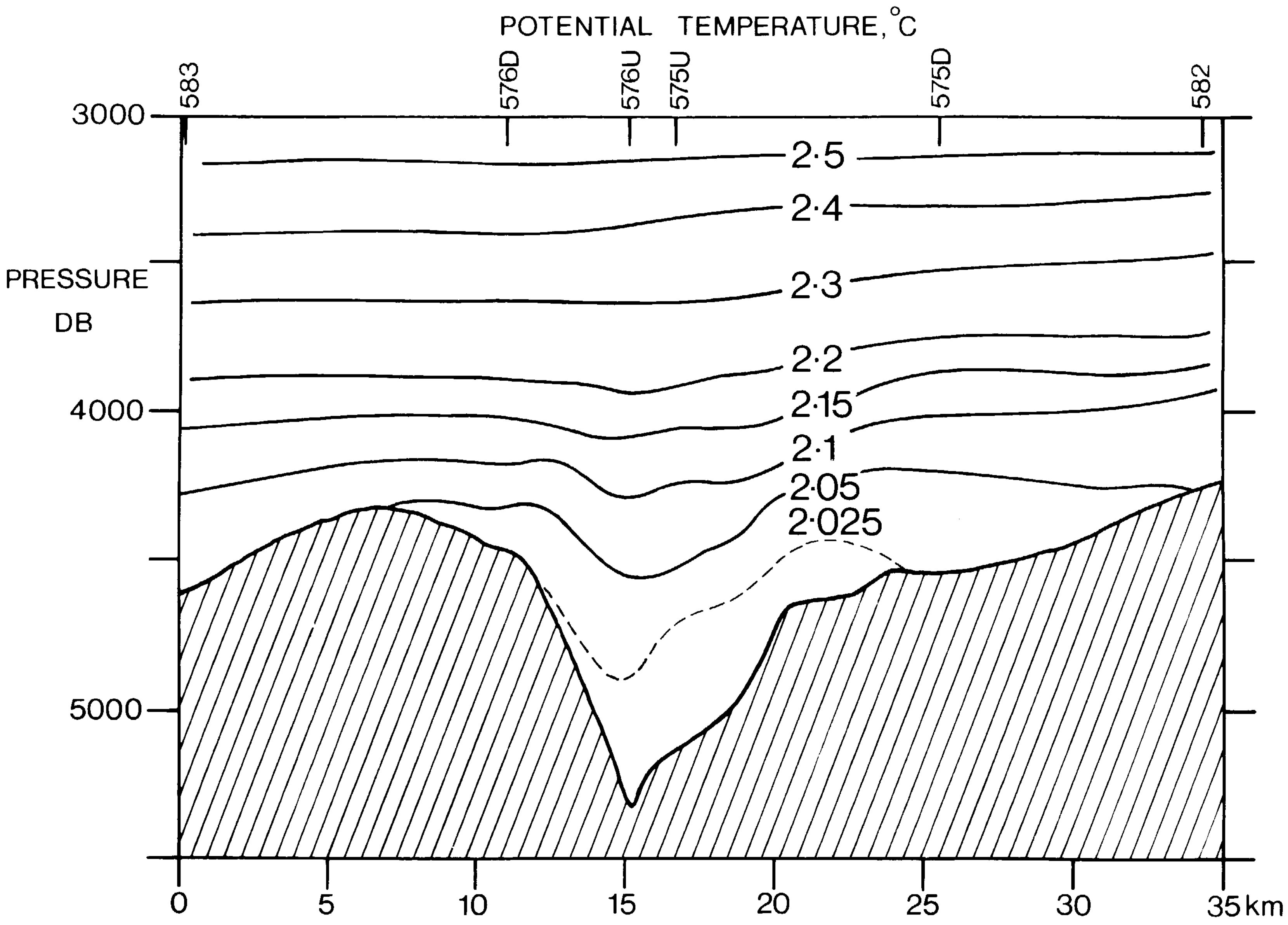

Fig. 7 As previous; the Narrows section BB' in Discovery Gap. (27 lowerings were made).

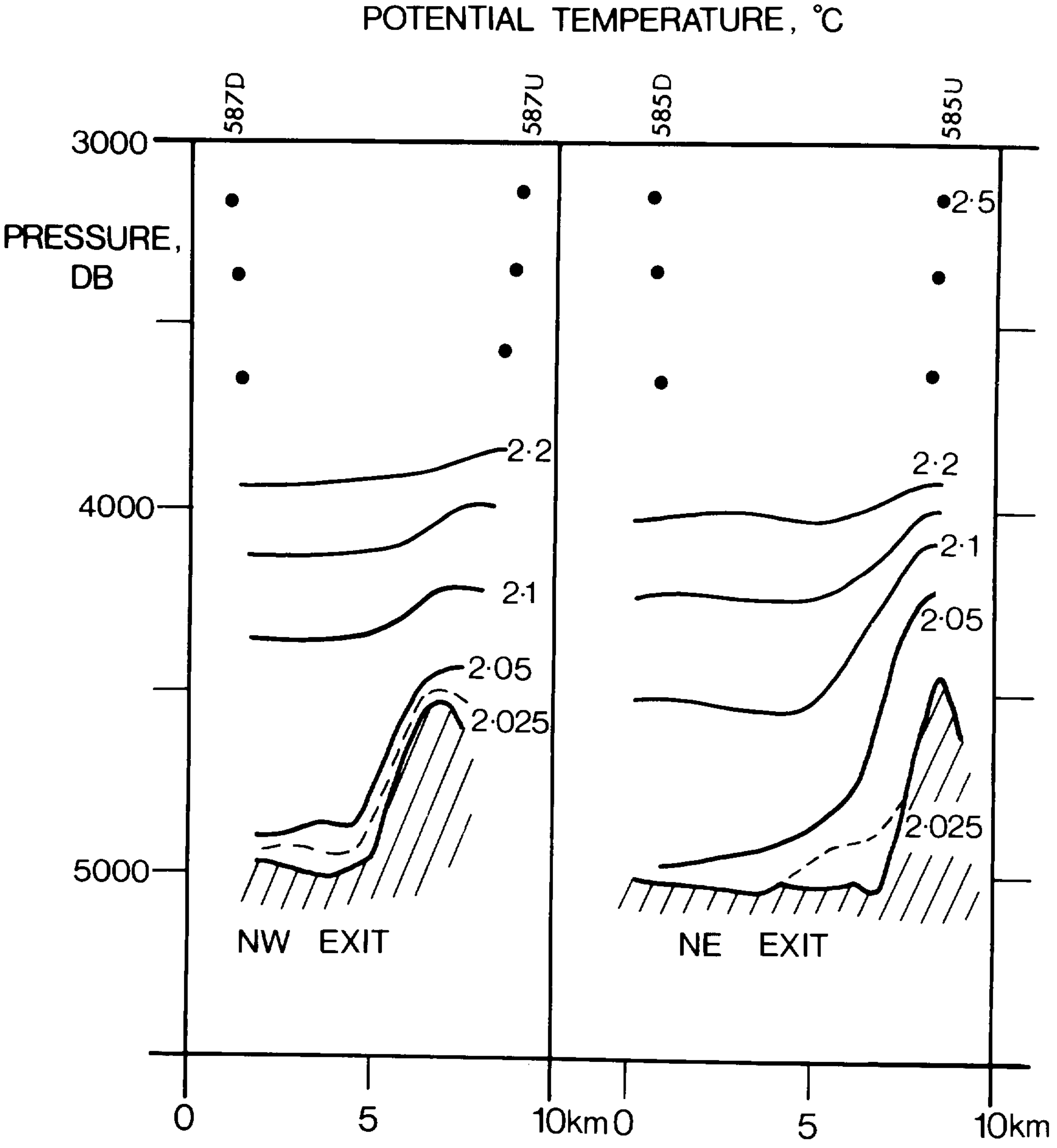

Fig. 8 As previous; the exit sections CC' and DD'. (8 and 6 lowerings were made, respec.)

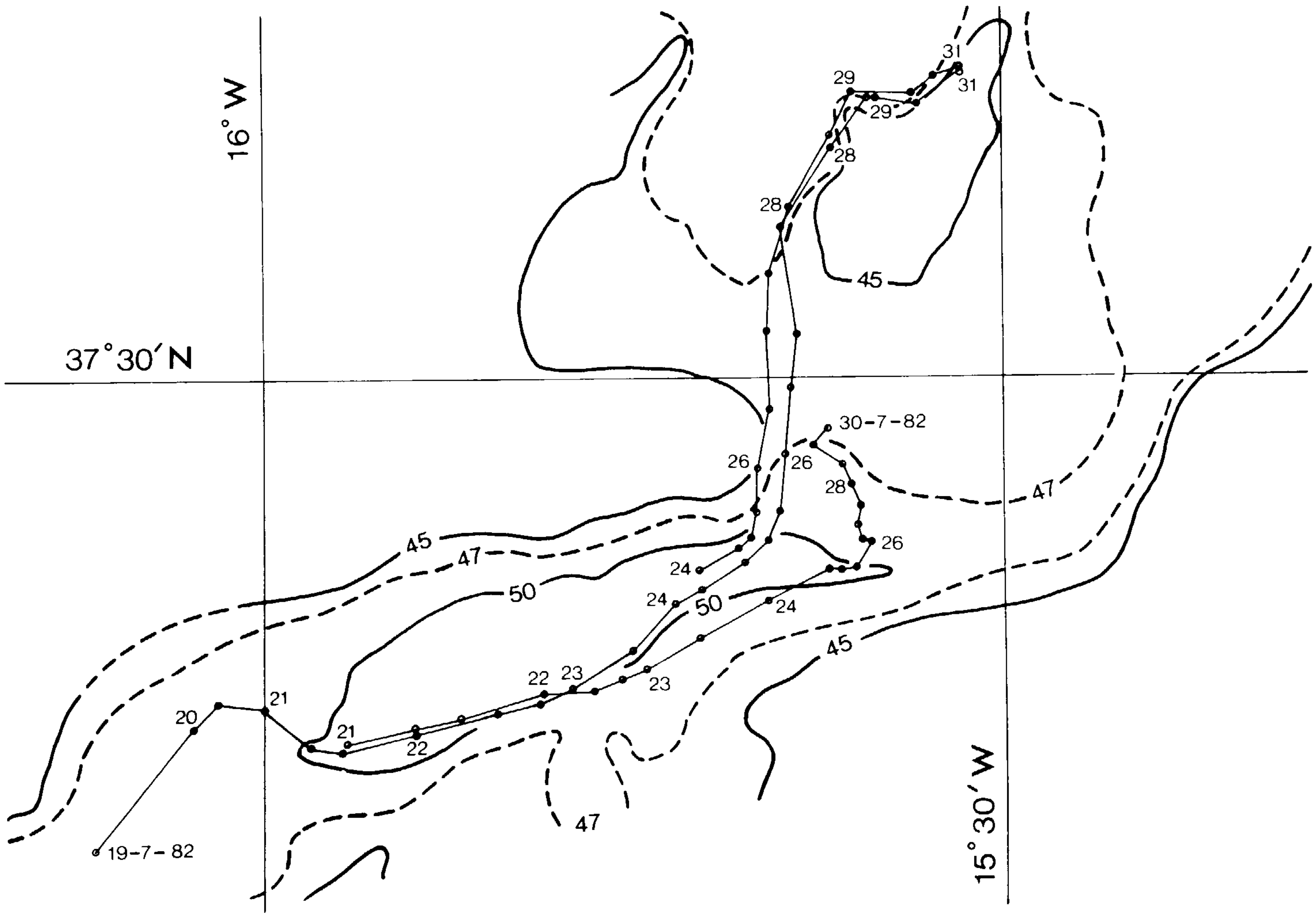

Fig. 9 Selected float tracks in Discovery Gap. The fixes are near midnight against each date.

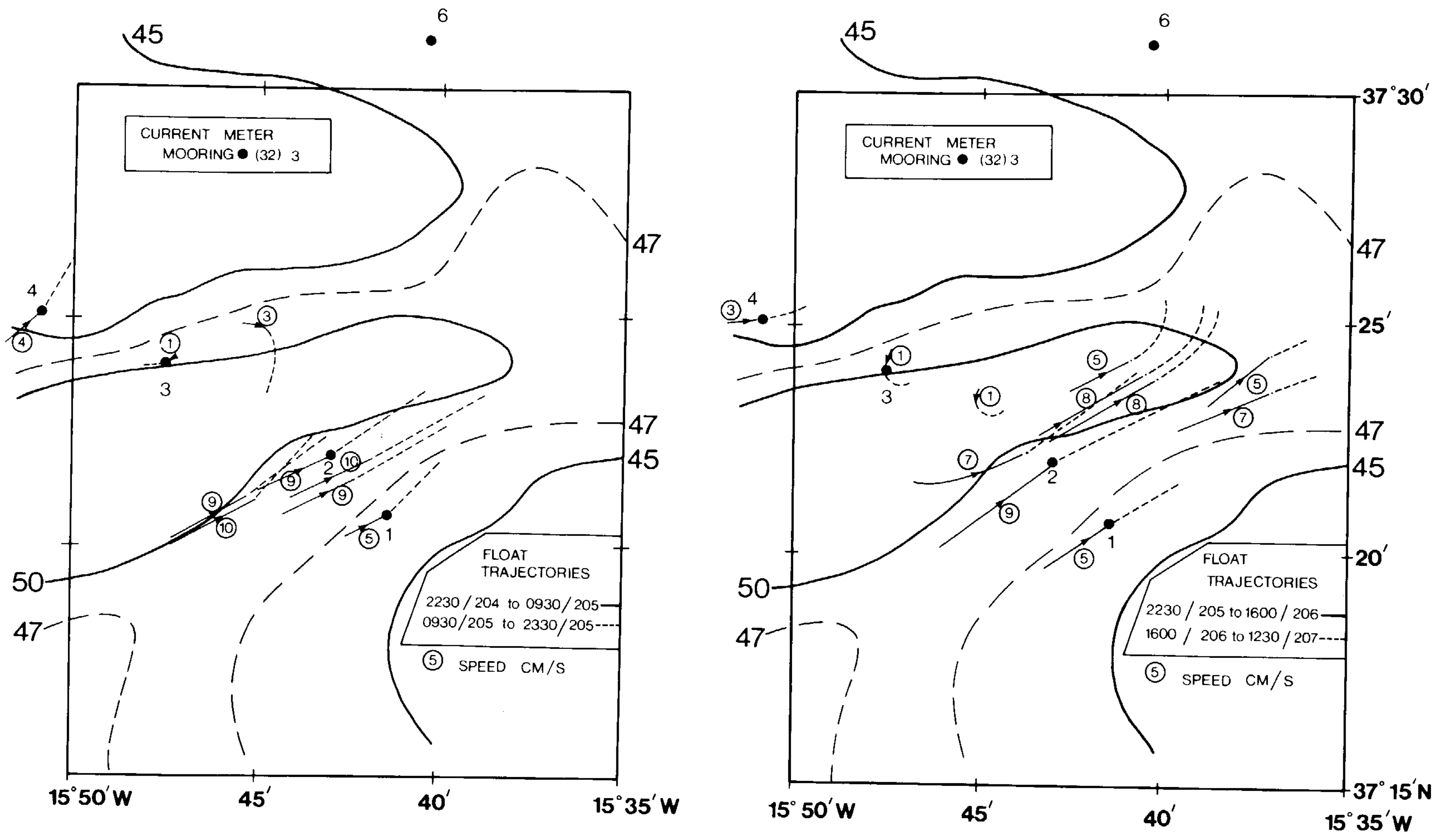

Fig. 10 A comparison between float tracks and moored current measurements: the latter are centred thus ●.

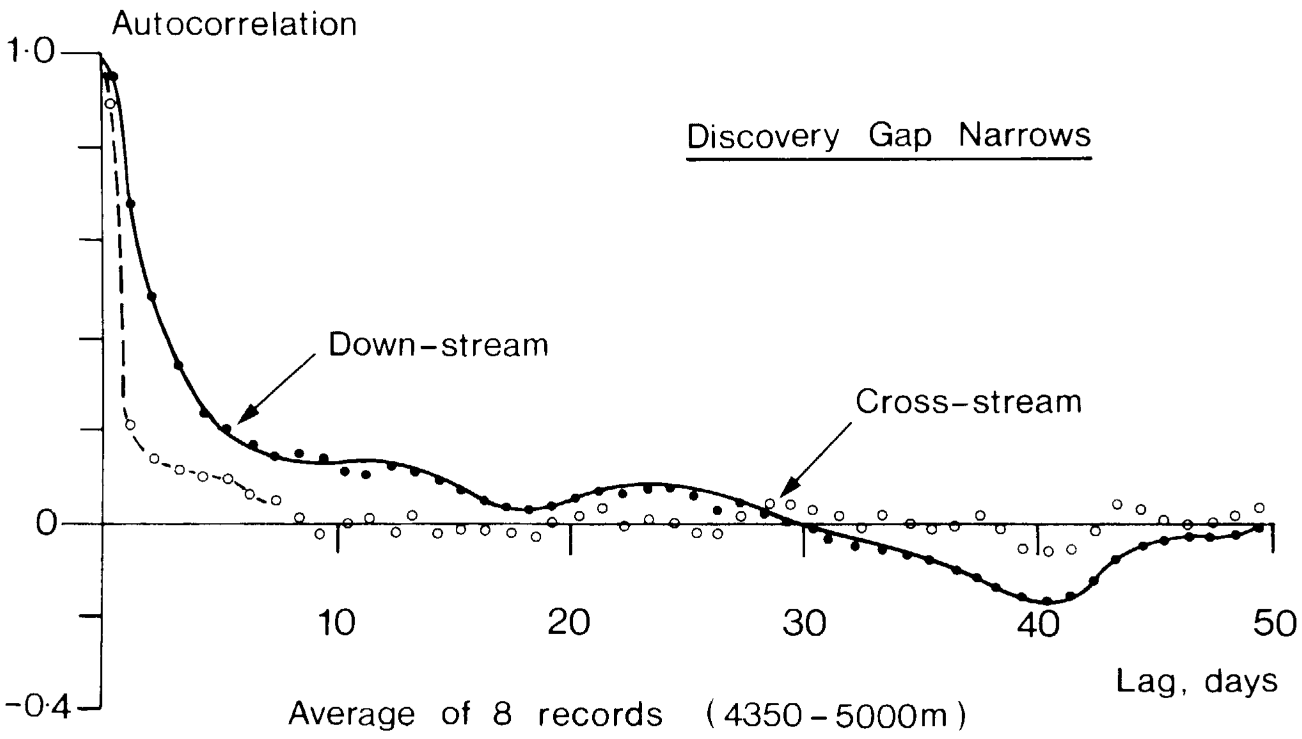

Fig. 11 The lagged autocorrelation of the down- and cross-stream components of the flow in the Narrows sections of Discovery Gap.

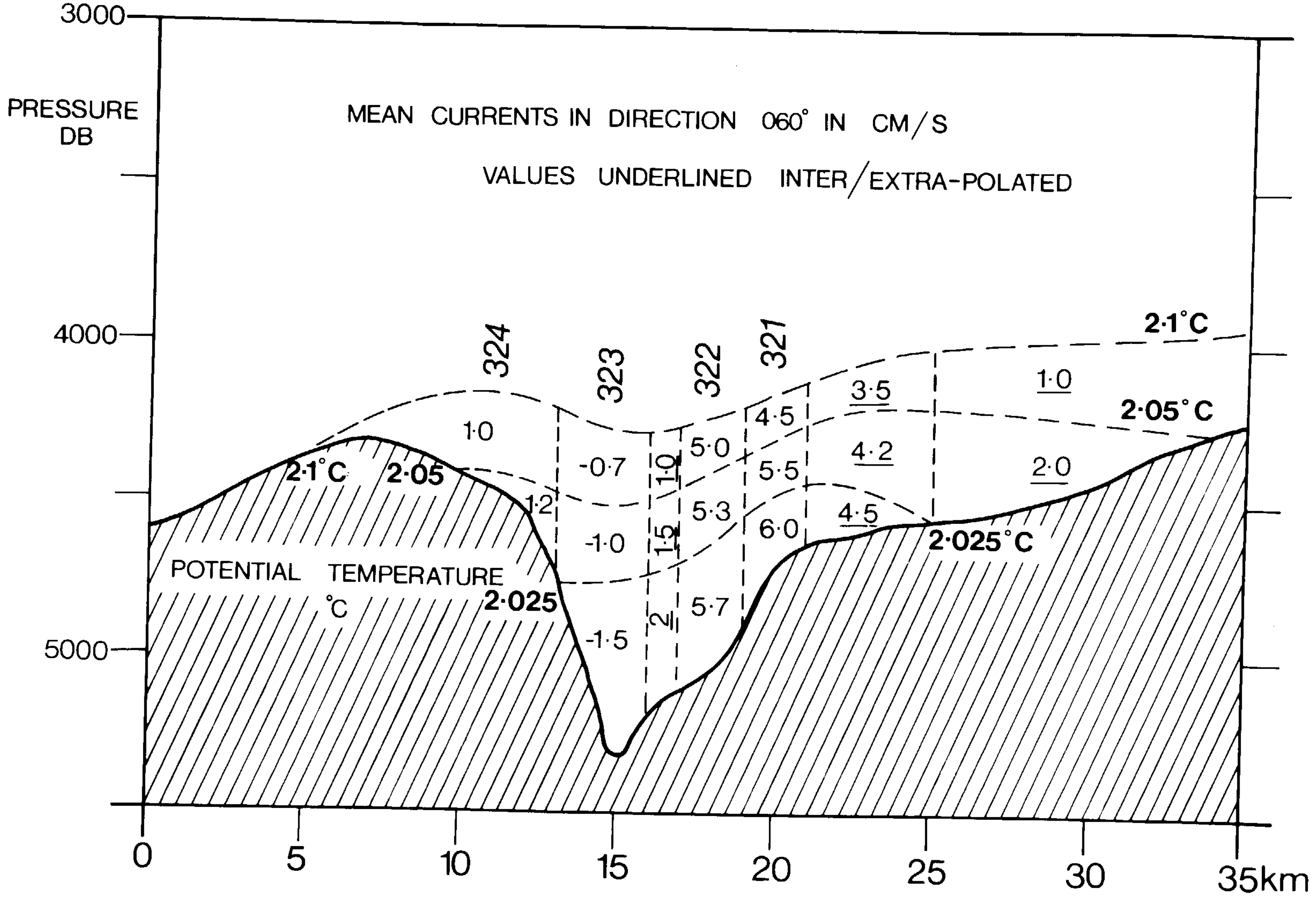

Fig. 12 The computation of mass flux through the Narrows section. Based on 1 year records.