I.O.S.

BENTHIC BOUNDARY LAYER
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BY
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OCEAN DISPOSAL OF HIGH LEVEL RADIOACTIVE WASTE
A RESEARCH REPORT PREPARED FOR THE DEPARTMENT
OF THE ENVIRONMENT

NATURAL ENVIRONMENT RESEARCH COUNCIL
INSTITUTE OF
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WORMLEY

Benthic boundary layer - IOS Observational Programme

Interim Report, January 1983

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P.M. Saunders

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DEPARTMENT OF THE ENVIRONMENT RADIOACTIVE WASTE MANAGEMENT

RESEARCH PROGRAMME 1983/84

DoE Report No. DoE/RW/ 83.067

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

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Report Title: Benthic Boundary Layer - IOS Observational Programme Interim Report January 1983

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Abstract (100-200 words as desired)

Measurements have been made over a period of seven months of currents and mixing near the seabed. The location of the study was in the N. Atlantic approximately midway between the islands of the Azores and Madeira. Currents were measured near the seabed in a water depth exceeding 5000m with moored internally-recording instruments. Maps of near bottom flow have been constructed and the dispersion of particles of water and therefore mixing of a tracer, such as radionuclide has been inferred. It is deduced that in a cloud of tracer of diameter between 1 and 20km, mixing causes the average concentration to halve approximately every fifteen days. Observations of the behaviour of clusters of free-drifting floats support this value. For cloud diameters of about 100km the time to halve the concentration is longer, about 60 days. These estimates take account of mixing along density surfaces and ignore the much slower mixing through them. A second experiment to determine this latter quantity began in mid 1982 but results are not yet available.

Other measurements of the benthic boundary layer have been hampered by the difficulty of distinguishing between the uniform density within it and the very weak gradients of density in the water above. But the analysis of sensitive temperature records has revealed the existence of benthic fronts, comparable with fronts in the atmosphere, where weak density changes are concentrated. Benthic fronts may pass any given locality at intervals of one to two months: on their passage the boundary layer can separate from the bottom and any tracer present in it can escape into the interior region.

A third experiment is proposed at slightly shallower depth where density gradients are stronger and where the properties of the benthic boundary layer may more easily be discerned.

Keywords:
299 93, 94, 126, 155.

This work has been commissioned by the Department of the Environment as part of its radioactive waste management research programme. The results will be used in the formulation of Government policy, but at this stage they do not necessarily represent Government policy.

Contents

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

Between November 1980 and July 1981 near bottom measurements were made of currents and temperatures near the sea floor on the Madeira abyssal plain in the eastern North Atlantic. The study was centred near 33°N, 22°W in a water depth of 5300m and both current and temperature measurements were made from moored internally-recording instruments for the whole period (see figure 1). In addition, for a period of about 20 days in January 1981, deep currents were observed by acoustic tracking of free-drifting floats. At the same time measurements of temperature and salinity were made from instruments lowered from the RRS Discovery. Further details of the work are described in a Discovery cruise report number 111, 1981[1]. In the following sections the principal results obtained to date are summarised. The aims of a second experimental study of near bottom currents and temperatures are described. No results are yet available from this experiment which is expected to end in July 1983.

The current meter deployments were a component part of experiments carried out by IOS in connection with other programmes. Measurements with lowered instruments and near bottom floats were added to complete the observations necessary to meet the Department of the Environment's objectives, as was the specialised interpretation of all data sets.

BENTHIC BOUNDARY LAYER

The benthic boundary layer on the Madeira abyssal plain has proved elusive. Currents measured with conventional rotor and vane sensors, at heights 10m and 100m above the sea floor, show neither the small veering in direction nor the reduction in speed on approach to the bottom, described and discussed by Weatherly and Martin[2]. Measured current differences or shear are dominated rather by instrumental noise, resulting from the low speed of the current and the erratic behaviour of both rotor and vane near their stalling speeds. Temperature measurements were expected to reveal a homogenous layer above the sea floor[3] but they too provide little information. The stratification above the bottom mixed layer is so weak that the boundary between the stratified and mixed regions can rarely be discerned. Some of the factors which control the thickness of the benthic boundary layer have been suggested by numerical modelling studies carried out at IOS under the same contract. Without measurements of thickness it is not possible to test these ideas. A limited number of very sensitive temperature records (with a resolution of .0001°C) have, however revealed the presence of sudden changes in temperature, preceded and succeeded by relatively uniform periods[4,5]. These sudden changes or 'fronts' have many of the characteristics of their atmospheric counterparts.

BENTHIC FRONTS

The analysis of temperature measurements made at heights between 10 and 70m above the sea-floor has revealed the presence of benthic fronts which separate water differing in temperature by only .002 to .004° C. Vertical cross-sections (Figure 2) reveal that the frontal surfaces are about 300m in width, tilt at a mean angle of 10 degrees to the horizontal, and meander over horizontal distances of 1 to 5 km. One front was observed to extend at least 30km in the horizontal and 600m in the vertical direction. Estimating the frequency of frontal passage is made difficult by repeated crossings of the same front, but several per year seems probable. Fronts are believed to sweep up water in contact with the bottom on one side and eject it at a height of 50 to 200m above bottom on the other side. Although not yet observed in the deep ocean, such behaviour has been seen and described at fronts in the upper ocean[6]. Benthic fronts are important because concentrations of tracer within the benthic boundary layer depend in part on the frequency and efficiency of this ejection process.

NEAR BOTTOM CURRENTS

Currents are considered in three categories: (a) tides, (b) inertial oscillations and (c) low frequency currents[7]. As numerical modelling studies show[8] all these components are important in influencing the thickness of the benthic boundary layer and therefore also in the dispersion of contaminants.

(a) Tidal currents

The analysis of the data from sixteen current meters in the array has revealed that the principal tidal component, the lunar semi-diurnal tide with period 12.42 hours, is predominantly associated with changes in sea level. The measured characteristics of the tidal ellipse - major and minor axis amplitudes, orientation and phase - are in good agreement with the tabulations of the global tidal model of Schwiderski[9]. Accordingly the predictable tidal component has been calculated for a number of sites in the eastern Atlantic of interest to radioactive waste disposal studies and the results are shown in the accompanying table. The Madeira abyssal plain and Great Meteor East areas have similar tides, the Kings Trough Flank area tide is 25% weaker and the cape Verde 2 area tide is 40% more energetic. It should be possible to test these estimates against existing current records.

(b) Inertial currents

In contrast inertial currents, clockwise rotary currents with a period near 22 hours on the Madeira abyssal plain, cannot be predicted. They are observed to have an amplitude of 1-2 cm s^{-1} and decay with increasing height above the bottom. Inertia waves are found to have long wavelengths in the deep water, approximately 100 km north-south and 3 km vertically, and propagate energy upwards from the bottom. If their energy flux decreases with height they represent a source of energy for mixing from one density surface to a neighbour.

TABLE 1

Lunar semi-diurnal tidal currents at selected sites in the NE Atlantic according to model of Schwiderski (1979)[9]

Site	Location	cm/s			
		major	minor[1]	orientation, °T[2]	phase, deg[3]
MAP	33N, 22W	2.7	+0.2	37	13
		(3.4)	(-0.6)	(44)	(-2)[4]
GME	31.5N, 24.5W	2.7	-0.1	42	-6
KTF	41.5N, 23.5W	2.0	+0.6	42	43
CV2	19.5N, 30W	3.8	-1.3	12	-49

Note
1 The current vector traces an elliptical path, clockwise if negative
2 orientation of major axis of ellipse
3 phase of current w.r.t. max. equilib. tide at Greenwich
4 observations from Saunders (1983)[8].

(c) Low frequency currents

If the inertial and tidal components are filtered out of the current records the 'low frequency' currents remain. An example of such a record is shown in figure 3. The average of these low frequency currents can not be distinguished from zero (0.2 cm s^{-1}) but the energy in the time-varying parts can readily be measured. The kinetic energy is 3.6 cm^2s^{-2} at a height 10m above the bottom, decreasing to 1.6 cm^2s^{-2} at a height 600m above bottom. These values are quite similar to other determinations made on the central parts of both the Madeira and Iberian abyssal plain[10]. The dominant periods present in the low frequency currents are 50 to 100 days, emphasising the need to gather very long records in order to obtain statistically significant results.

The horizontal dimensions of the low frequency abyssal currents or eddies has been determined for the first time from this data. Current measurements made on moorings 35 km apart are uncorrelated in the study area. Freeland and Gould[11] found the corresponding figure at 1500m depth to be 50km. Thus slightly smaller eddies are observed at abyssal depth than at thermocline depth. Armed with this eddy size and utilising methods described by the same authors, the flow near the top of the benthic boundary layer has been mapped at two day intervals. A selection of such maps is shown in figure 4: a weak westward drift of eddies at about 1 cm s^{-1} is deduced.

Mapping the flow allows comparisons to be made between current meter measurements and free-drifting float observations. The trajectories of particles of water calculated from the maps for both 6 and 12 day periods, agree within estimated error with the drift of two groups of floats at depths 400-600m above the bottom, (see figure 5). The agreement, despite low frequency currents with a strength only marginally above the stalling speed of the current meter rotor, gives confidence for the calculations of dispersion which follow.

ABYSSAL DISPERSION - MIXING ALONG DENSITY SURFACES

The current meter measurements and float observations permit estimates to be made of the horizontal dispersion or dilution of a tracer released into the near bottom layer at a number of different scales. A comprehensive dispersion calculation for all scales up to basin size has been attempted by Kupferman and Moore[12].

(a) Small scales

The tidal and inertial currents carry fluid away from an instantaneous source and produce a fluid trajectory which exhibits sinuous meanderings, sometimes intersecting itself (figure 6). Such currents spread a plume from a maintained source over a domain about 500 to 1000m wide on the Madeira abyssal plain and are likely to have a similar effect at all the areas indicated in table 1. The measurements made in the course of this study do not allow us to estimate dispersion or dilution rates for these small scales.

(b) Pair dispersion, 1-20 km

From the flow maps, based on the 10m moored current measurements, the trajectories of pairs of particles of a given initial separation have been computed. From many such numerical experiments this novel technique allows the dispersion or mean increase in squared separation to be estimated for periods up to 10 days (figure 7). The calculations show that, on average, the squared separation doubles in about 15 days and is approximately independent of initial separations in the range 1 to 20 km. If through density-surface mixing is neglected, 15 days also represents the interval within which the average concentration of a cloud of tracer will halve.

Direct estimates of dispersion and dilution can be obtained from the behaviour of the cluster of free-drifting floats. The rate of increase of cluster size, shown in figure 8, is comparable to the indirect estimates described above, though the small sample of float data makes precise comparison impossible. The trajectory calculations show that on average particle pair separation grows approximately exponentially with time, $R^2=R_o{}^2 \exp \alpha t$, with α^{-1} approximately equal to 20 days. Given an initial separation of 500m, dispersion to 20 km occurs in about one half a year; the average concentration of a tracer falls by a factor of $(20/0.5)^2$ or 1600 in this time. The calculation refers strictly to the growth of a cloud of tracer but also approximates the lateral growth of a plume of similar material. These observations and inferences about potential dilution rates of tracer are quite new.

(c) Dispersion at larger than eddy scales (100km).

Tracer mixing rate at scales larger than eddy size have been shown equal to the product of a time scale with the energy of the eddy flow. From the near bottom current meter data the appropriate time scale has been estimated at 7±2 days. Within the bottom 100m of the ocean diffusivities are then found between 1 and 2×10^6 cm^2s^{-1}, decreasing to one half these values at heights 600m above the bottom. Given a diffusivity of 10^6 cm^2s^{-1} and a cloud of tracer with an initial diameter of 100 km the average concentration is computed to halve in about 60 days. For cloud diameters between 20 km and 100 km there is therefore a weak decrease in growth rate, the measurement of which requires techniques different from those employed here.

ABYSSAL DISPERSION - MIXING THROUGH DENSITY SURFACES

Mixing from one density surface to a neighbour in the water column is difficult to estimate*, and apart from the deliberate introduction of tracer material, or the accidental and natural occurrence of the same, indirect

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*In calculations of dilution in the previous paragraphs its rate has been assumed zero: dilution rates are therefore conservative.

methods must be used. One indirect method is to examine the abyssal heat and salt balance as has been done in the western Atlantic by Hogg et al[13]. In brief, the method is to measure the flux of heat and salt into a deep basin through a single narrow channel. If conditions in the basin are not changing with time the channel flux equals the exchange or mixing through density surfaces within the basin.

Such conditions appear to exist in the NE Atlantic (figure 9). The Iberian and Madeira abyssal basins are separated by a ridge, the East Azores Fracture Zone, through which a narrow channel runs (figure 10). An array of moorings was placed in this channel, which has been named 'Discovery Gap' in July 1982. The instruments should be recovered in July 1983. Details of the deployment, free drifting float tracks and lowered measurements of temperature and salinity are given in RRS Discovery cruise report 136, 1982.

CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER WORK

Considerable progress has been made in estimating the rate of dilution of a tracer released into the benthic boundary layer. Nevertheless, it is not known how rapidly a tracer dilutes when present either as a small cloud, less than 1km diameter, or as a cloud of diameter 20 to 100km. Observations at these sizes require new techniques. In future work we plan to study small scale processes employing a string of ultra-sensitive thermometers, and larger scale dispersion utilising groups of deep free-drifting floats tracked in the SOFAR channel for as long as two years. The measurements reported here have been derived for a smooth-bottomed region of the Atlantic dotted with small hills and is likely to underestimate mixing in rough areas or near continental margins. In order to determine the importance of bottom roughness we plan to make further measurements in such areas.

The recognition of benthic fronts and their potential role in the separation of the boundary layer from the bottom has been a notable advance. Efforts to measure and understand other characteristics of the bottom boundary layer, namely thickness and mixing within it, have met with less success. It has proved difficult to recognise the region of uniform density near the bottom because the ocean waters above are themselves so nearly uniform. Numerical modelling studies, carried out at IOS in parallel with the experimental program, indicate that improved conditions for observing the benthic boundary layer are stronger density gradients and stronger flows; the area for a new experiment in 1983 has been selected with this in mind.

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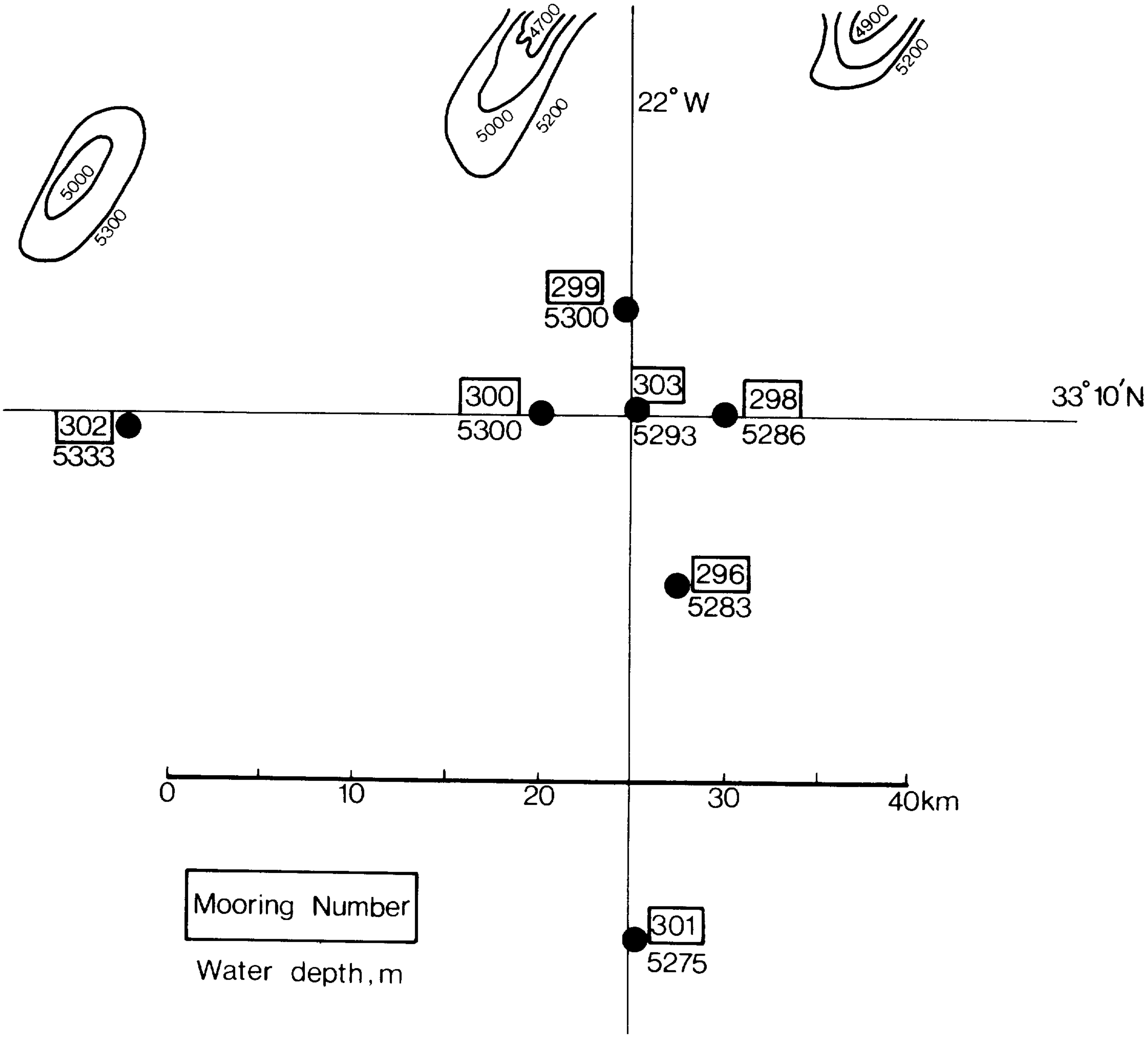
FIGURE CAPTIONS

Fig. 1	Location of moorings and water depth on Madeira abyssal plain.
Fig. 2	Near bottom isotherms showing the repeated crossing of a front in a 6 day period.
Fig. 3	Low frequency currents at 600m (upper) and 10m (lower) above the seabed on mooring 296. Tides and inertial currents have been filtered out.
Fig. 4	Streamfunction maps of the near bottom flow at 10 days intervals.
Fig. 5	Comparison between observed track of two groups of four floats (solid) and trajectories calculated from Eulerian current measurements. (Circles are a measure of the dispersion of the floats).
Fig. 6	Trajectory of a puff of tracer: point of release the solid spot. Two realisations (top 8 days, bottom 16 days duration) are superimposed.
Fig. 7	Computed behaviour of pairs of particles: initial separation R_o.

Fig. 8 Spread of float clusters: σ is rms separation from centre of mass.

Fig. 9 5000 m isobath in E. Atlantic.

Fig. 10 Discovery Gap: isobaths in 100s of m - provisional bathymetry.



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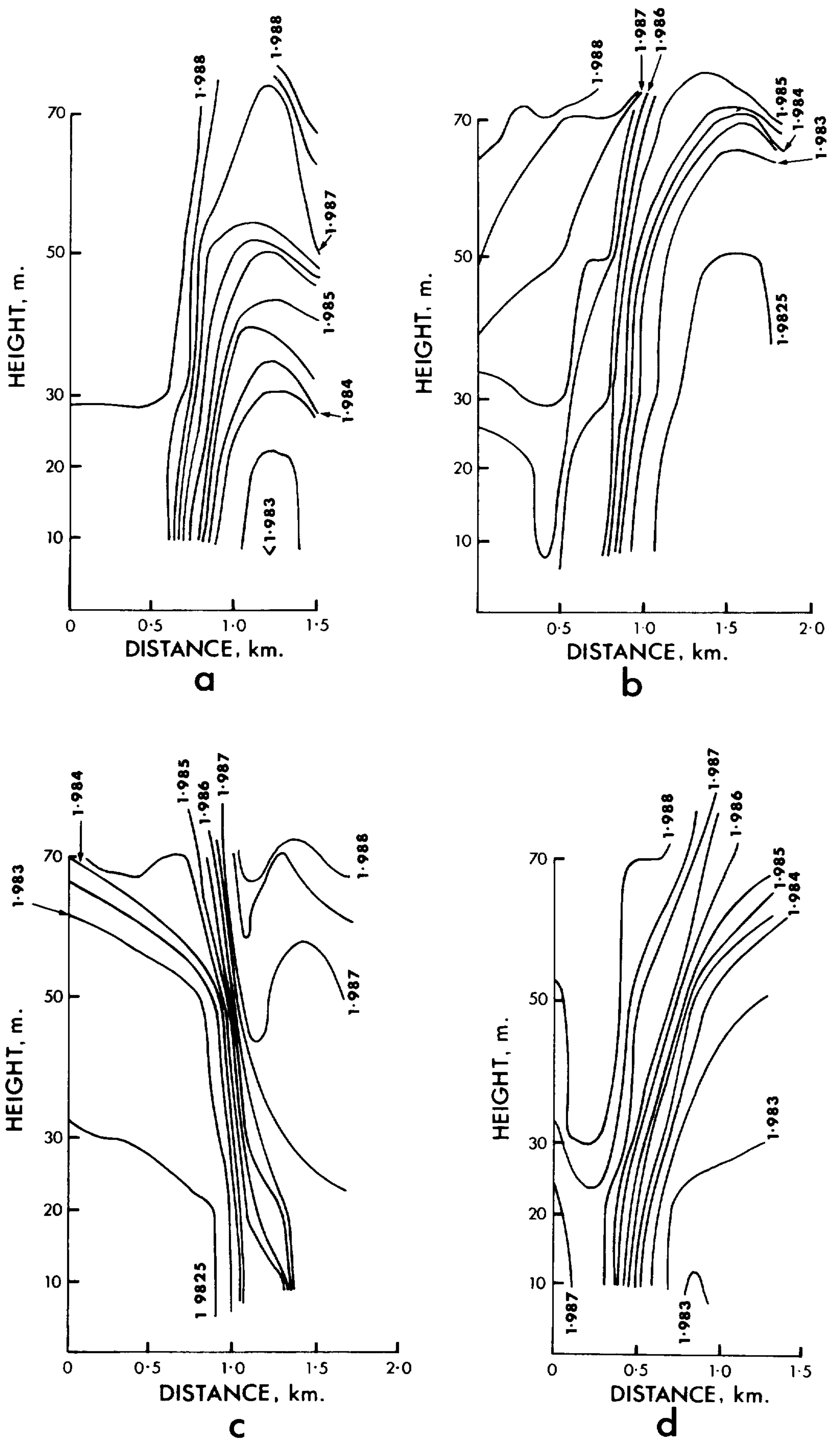
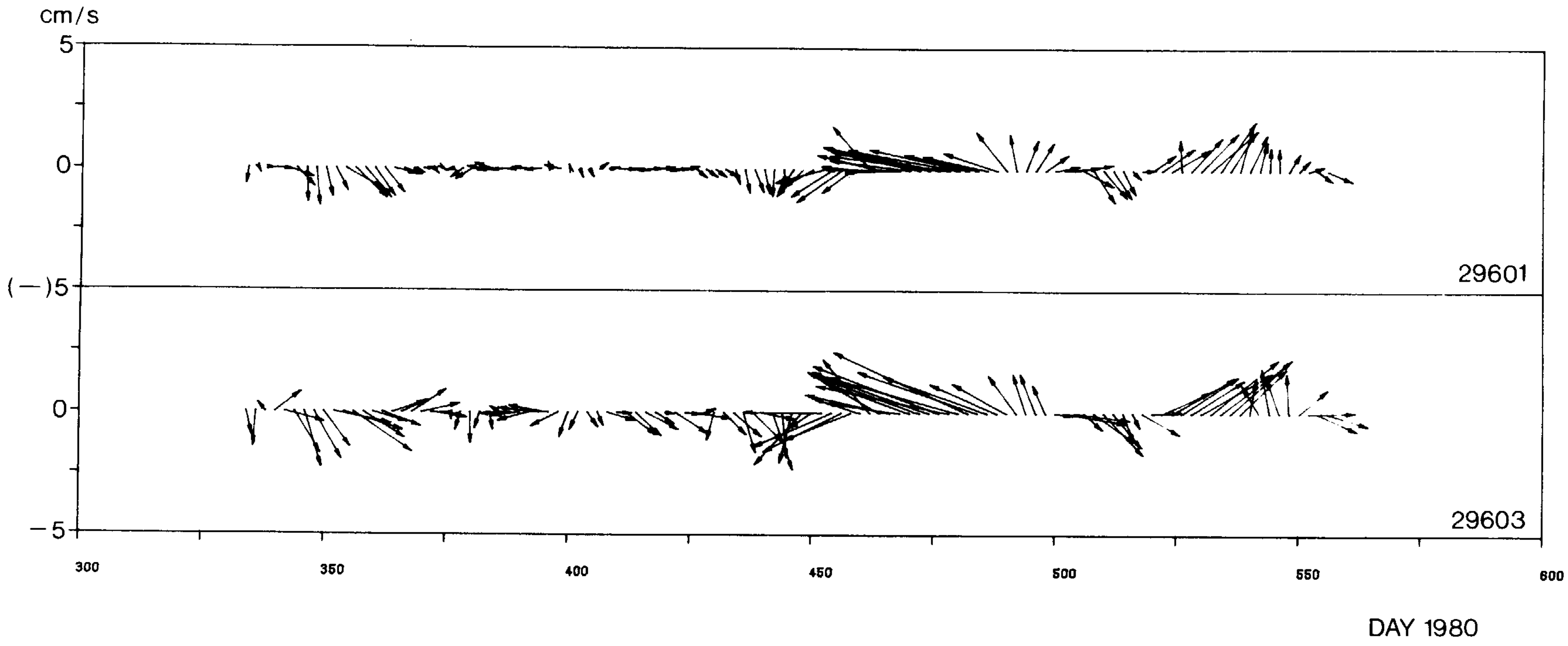


Fig. 2 Near bottom isotherms showing the repeated crossing of a front in a 6 day period.



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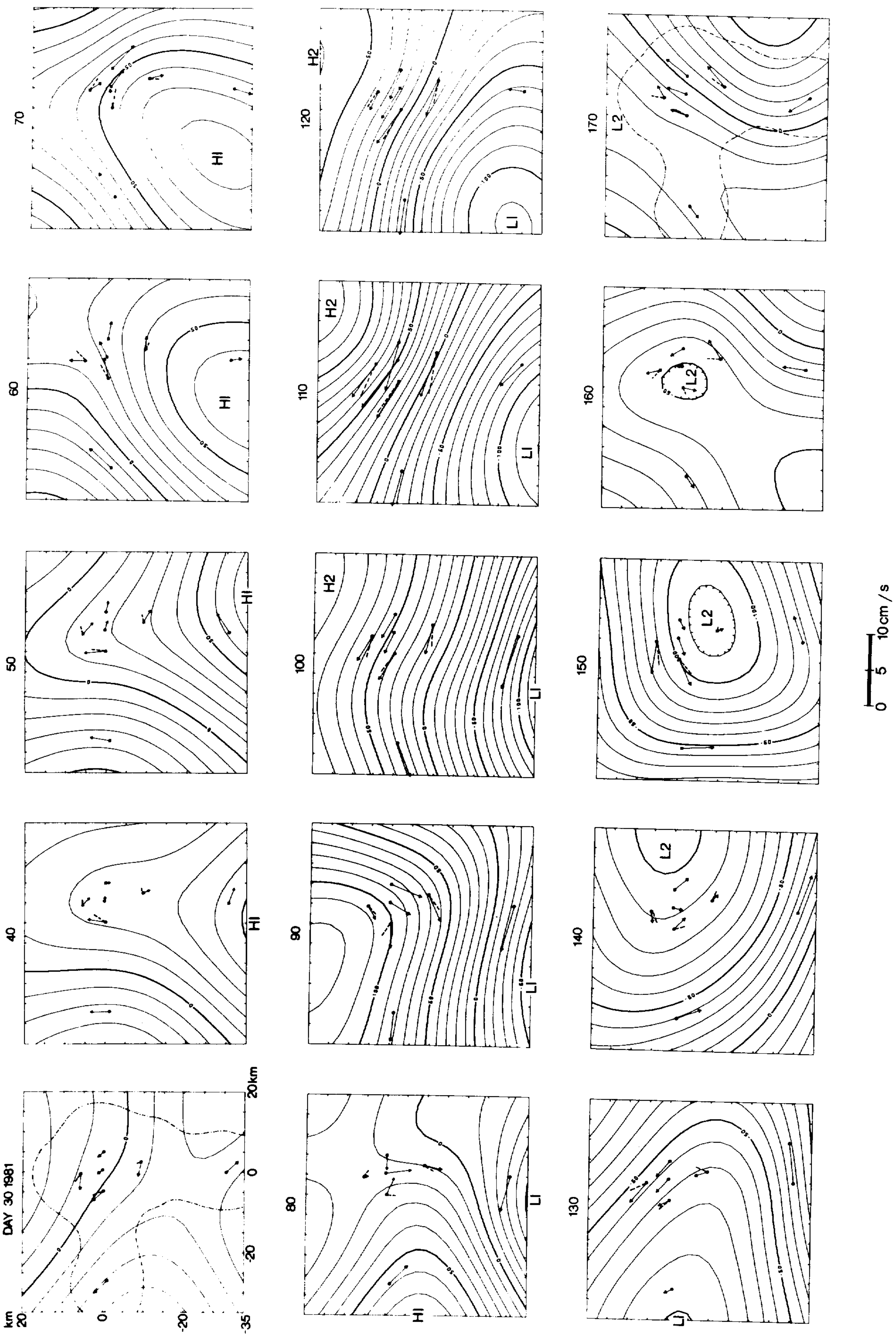
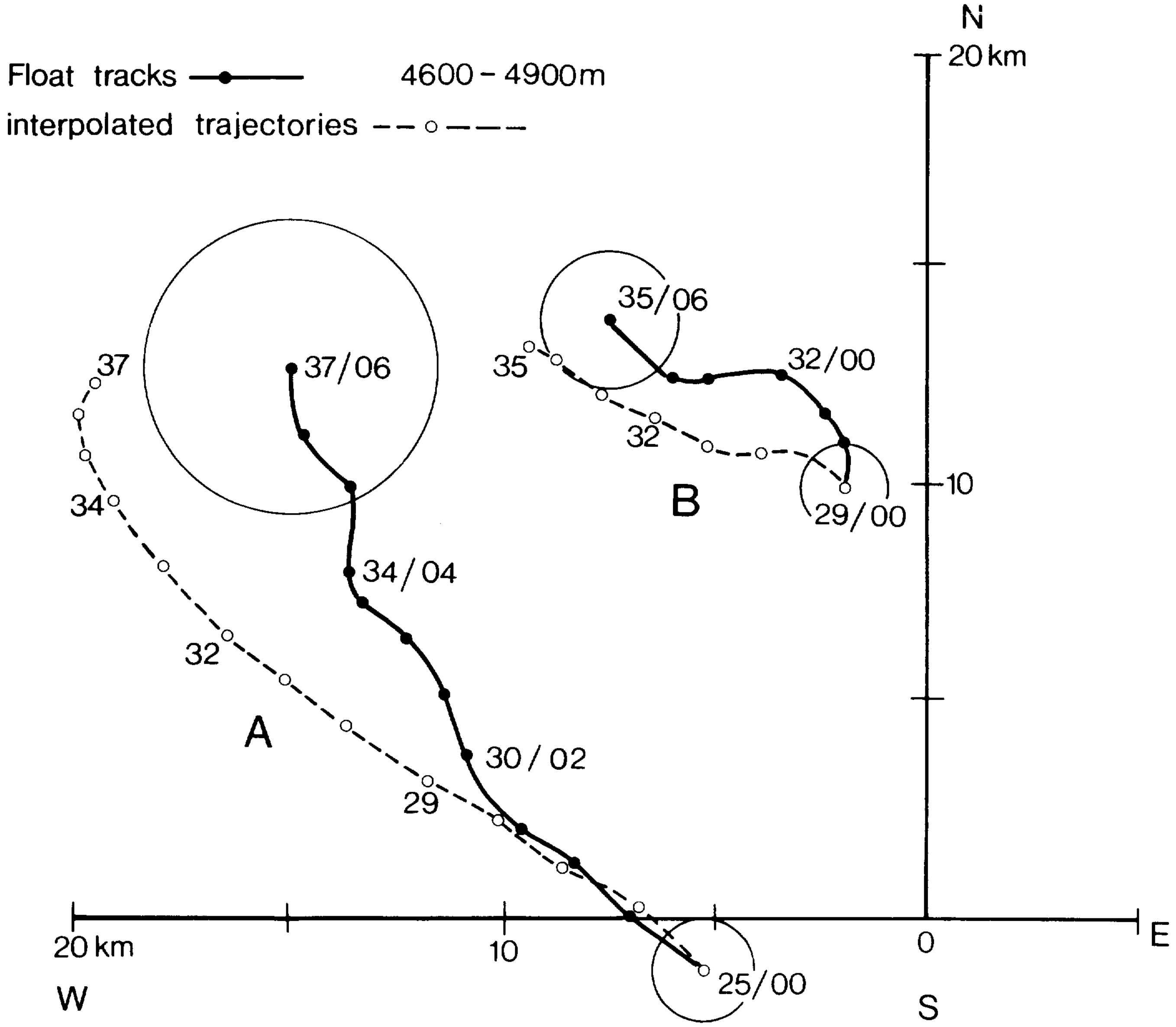


Fig. 4 Streamfunction maps of the near bottom flow at 10 days intervals.



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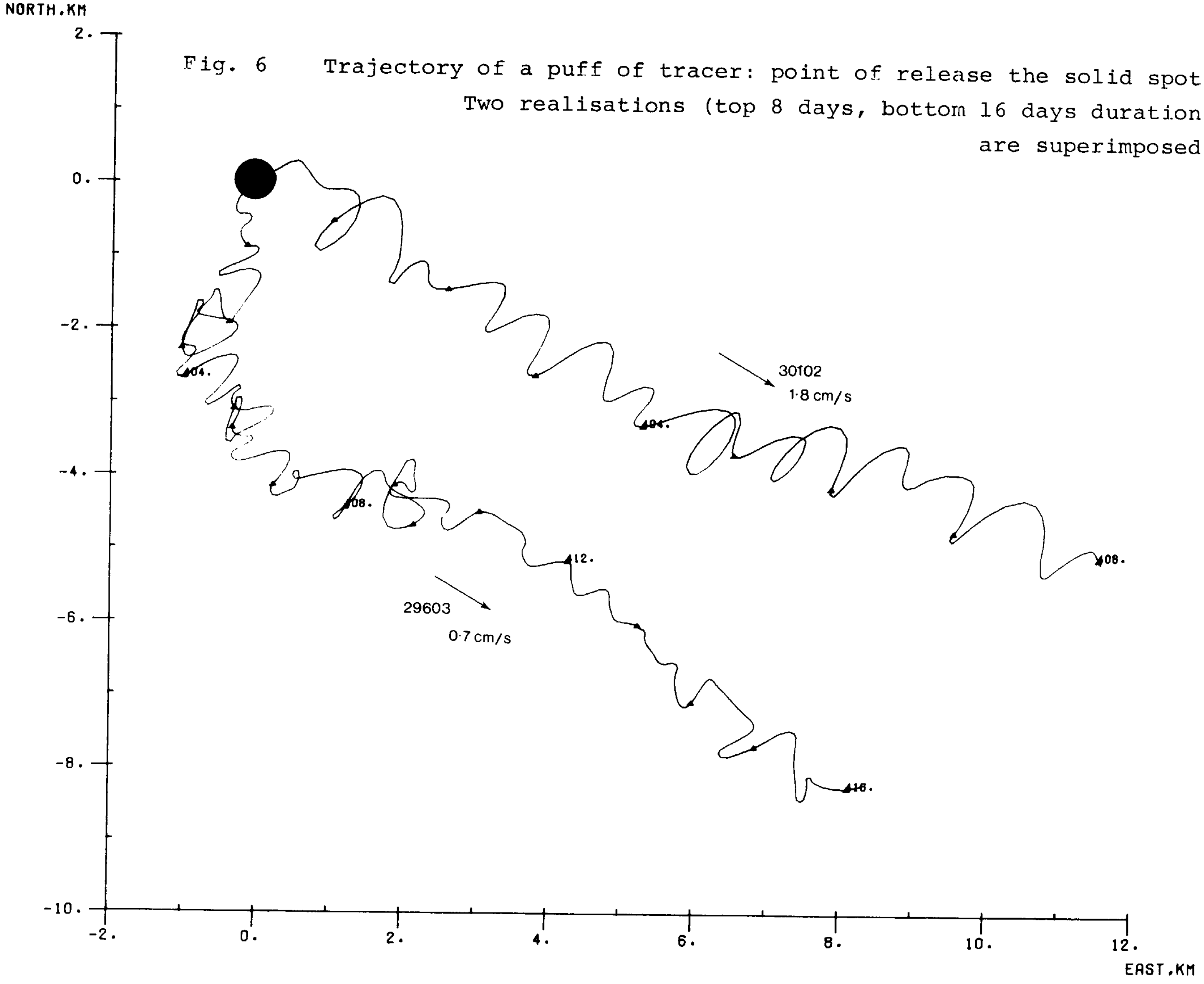

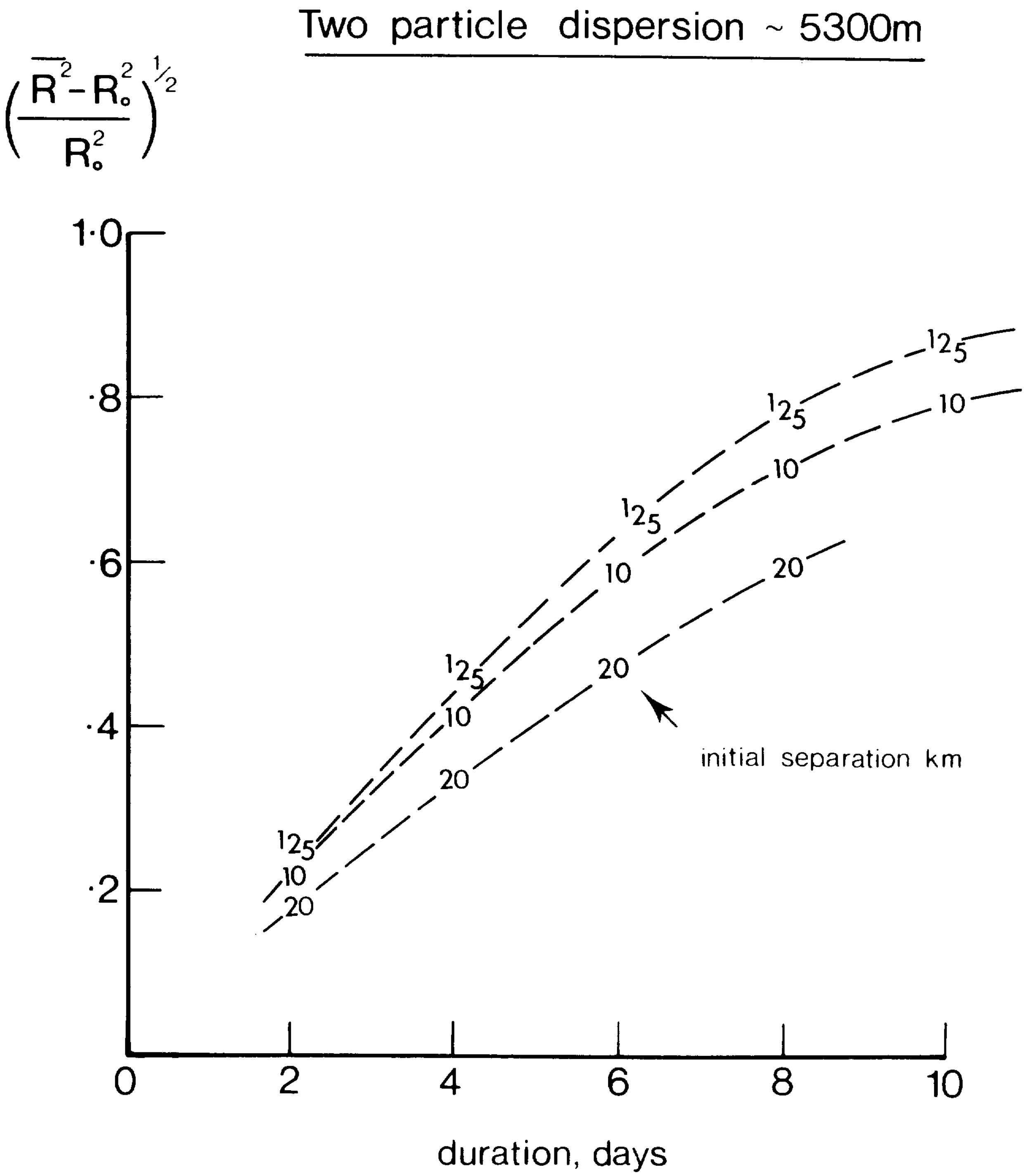

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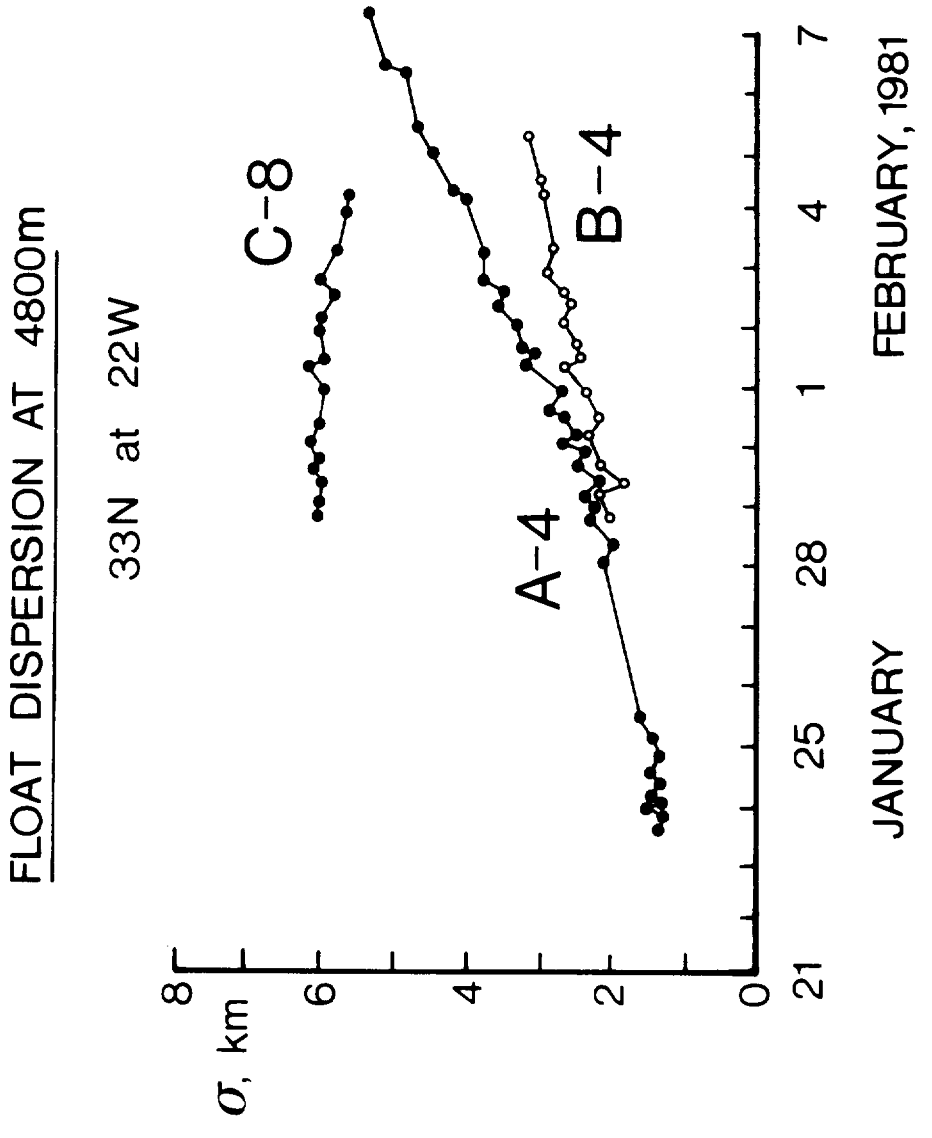

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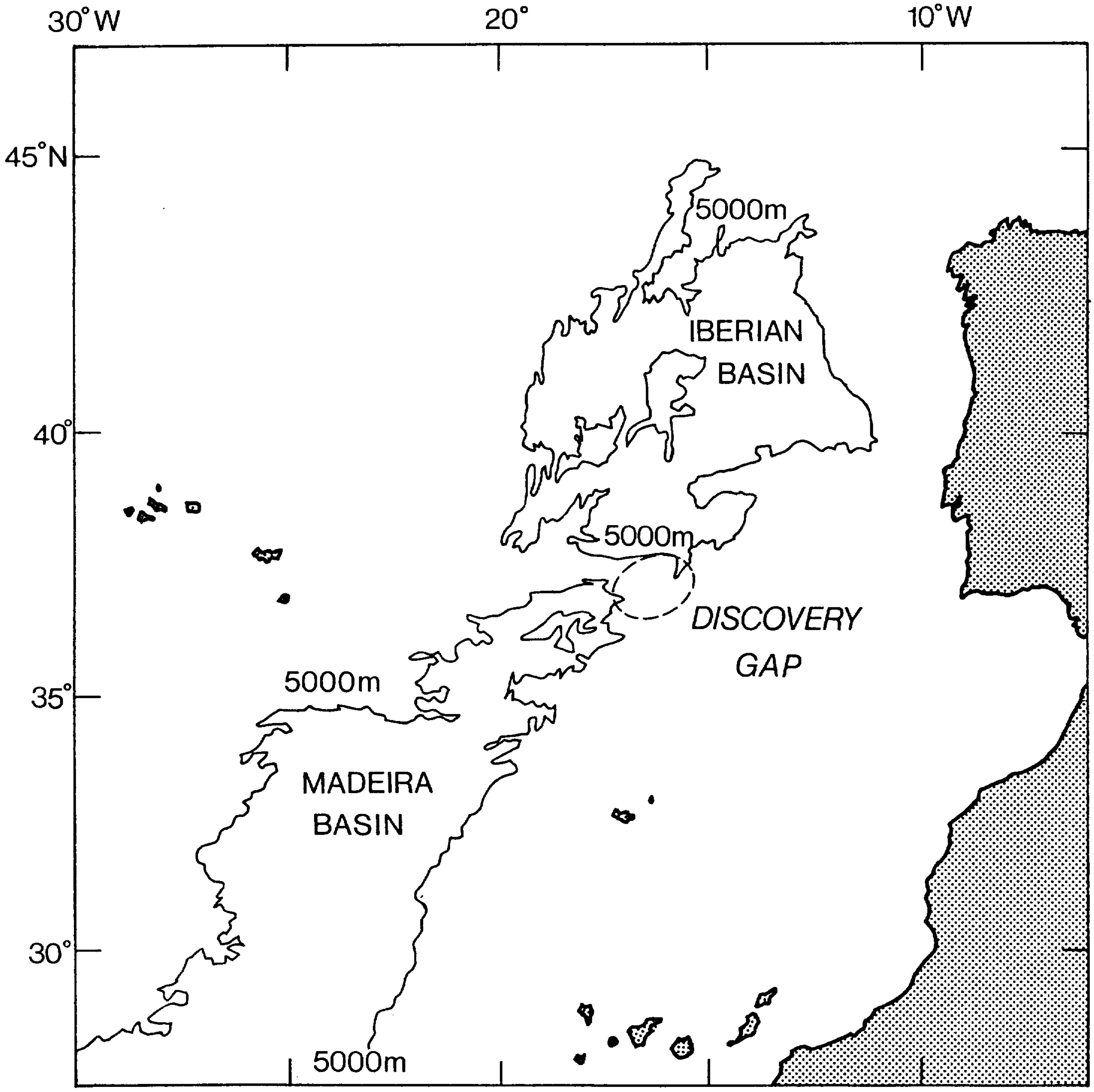

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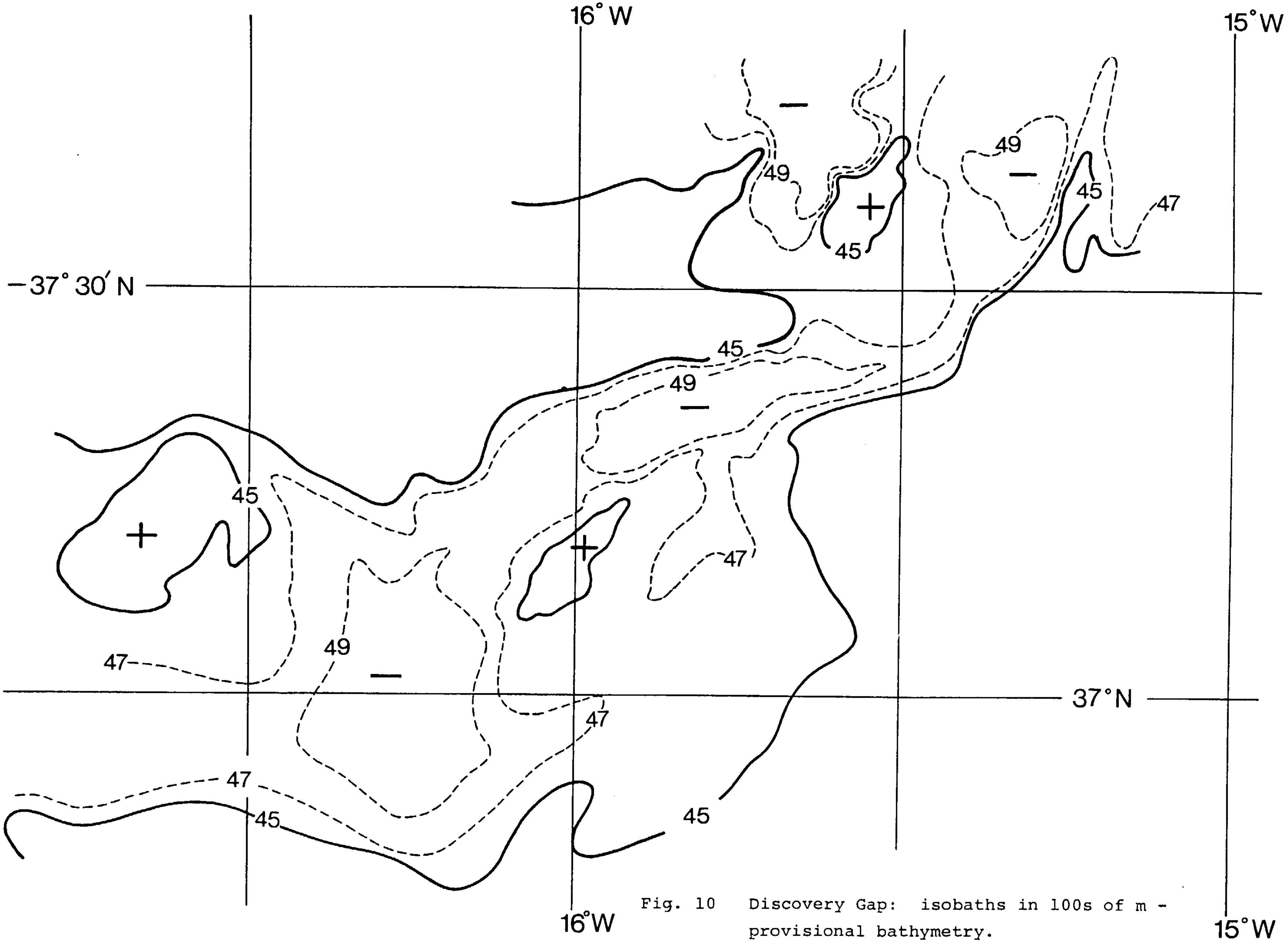

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