I.O.S.

RESEARCH IN CONNEXION WITH THE POSSIBLE DISPOSAL OF HIGH LEVEL RADIOACTIVE WASTE ON OR BENEATH THE OCEAN FLOOR

Status Report — March 1982

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

REPORT NO. 153
1983

NATURAL ENVIRONMENT RESEARCH COUNCIL
INSTITUTE OF OCEANOGRAPHIC SCIENCES

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INSTITUTE OF OCEANOGRAPHIC SCIENCES

WORMLEY

Research in connexion with the possible disposal of high level radioactive waste on or beneath the ocean floor

Status Report - March 1982

Ocean disposal of high level radioactive waste

A research report prepared for the Department of the Environment

I.O.S. Report No.153

1983

This research has been carried out under contract to the Department of the Environment (United Kingdom), 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.

Additional funding was provided for part of the work (Chapter 2 sectors A, C and E from 1.1.1981) under Contract 257-81-7 WAS UK of the Commission of the European Community.

DEPARTMENT OF THE ENVIRONMENT

RADIOACTIVE WASTE MANAGEMENT

RESEARCH PROGRAMME 1979/82

DOE Report No: DOE/RW/82.089

Contract Title: Selection and evaluation of areas and sites for the disposal of high level radioactive waste

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Department of the Environment - Research in connexion with the possible disposal of high level radioactive waste on or beneath the ocean floor

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IOS work is done under five contracts

1. Selection and evaluation of areas and sites for the disposal of high level radioactive waste (DGR 481/179)

2. The properties of ocean sediments in relation to the disposal of radioactive waste (DGR 481/177)

3. Biological transfer of materials between seabed and surface (DGR 481/178)

4. Studies of the benthic boundary layer in relation to the disposal of radioactive waste (DGR 481/176)

5. Dispersion in the Northeast Atlantic (PECD 7/9/023)

Two principal options for oceanic disposal have been selected by the government for investigation.

On-the-Seabed disposal in which high level waste would be placed on the seabed in more or less long lasting containers would rely on the assumption that any release of radionuclides would be dispersed or otherwise disposed of in a way that presented no danger to man.

Assessment of this option requires knowledge of the diffusion to be expected in ocean waters, especially in the benthic boundary layer, and of any large scale advection that might transport released material rapidly in relatively concentrated form. It also requires knowledge of potential concentrating mechanisms in ocean sedimentation and in biological activity and of any biological pathways to man. An evaluation is also required of the possible effects of canister heat and of the likelihood that sediments will cover canisters or scrub any released material from the water column.

Below-the-Seabed disposal assumes canister burial probably beneath tens of metres of fine grained sediments. It requires the identification of suitable areas, including assessment of their geological stability, and evaluation of the physical and chemical properties of fine grained sediments as a guide to their effectiveness as a host to canisters and as a barrier to radionuclide release.

It also requires the knowledge needed for on-the-Seabed disposal since any unexpected release either from emplaced material or accidentally during emplacement will be similar to an on the bed disposal. For this reason it is convenient to consider the one as forming part of the other and to describe the whole programme in terms of sub-seabed disposal.

A report is given below on the status of IOS research under each of the five contracts.

1. Selection and evaluation of areas and sites

OBJECTIVE

To assess the availability of areas accessible to the United Kingdom which may be suitable for the disposal of radioactive waste beneath the sea bed.

A. PRELIMINARY STUDIES

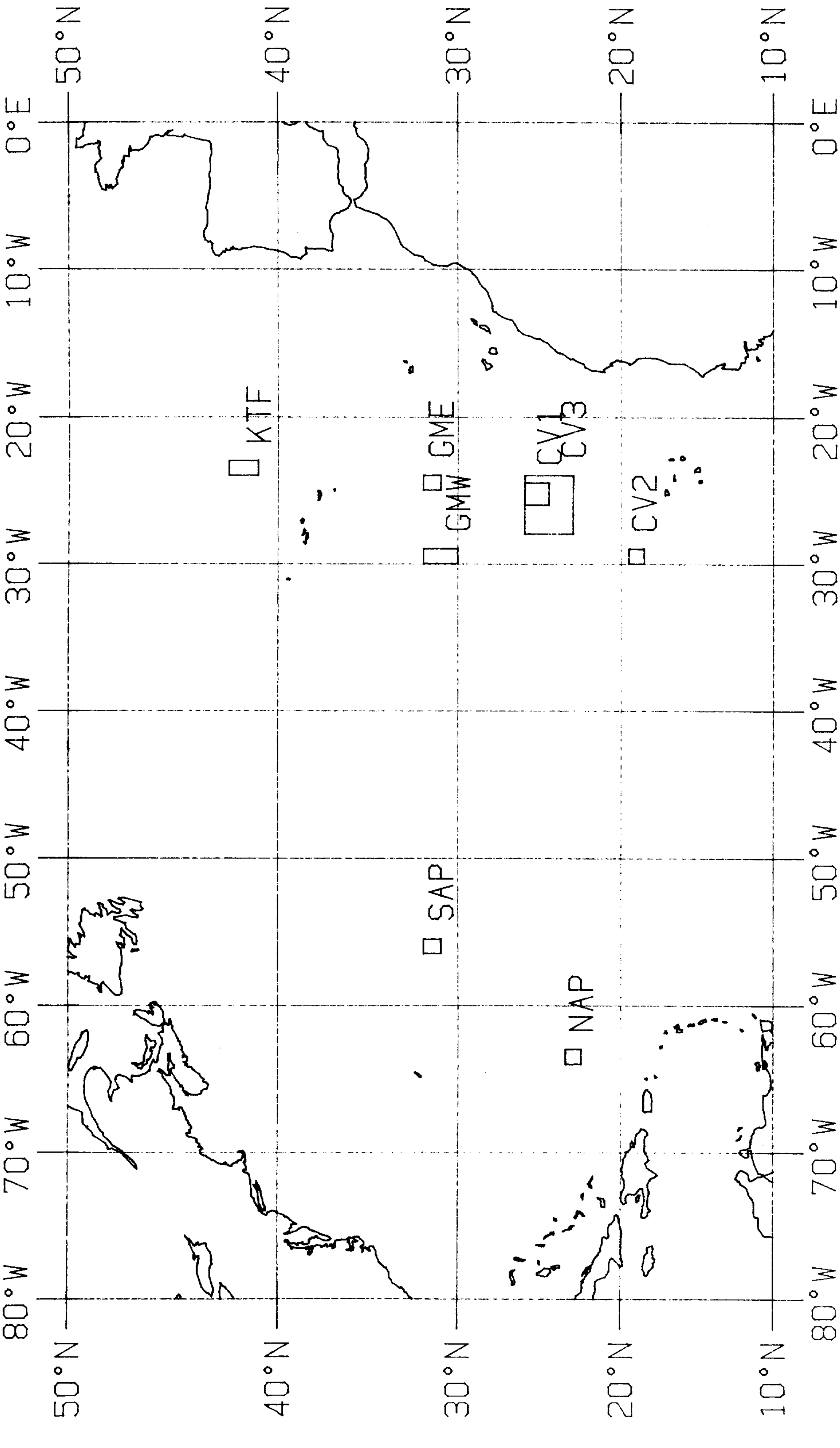
In 1979, following the production of IOS report 77 (3), a set of site selection guidelines was drawn up and used to carry out a preliminary assessment of areas in the North Atlantic that might prove suitable for HLRW disposal (23). In developing these guidelines, both on and sub-seabed disposal were considered, but it was concluded that, in the case of on-the-seabed disposal, site dependent factors that might influence the safety of disposal cannot be confidently identified at present. The guidelines were broadly classified as relating to the stability of the disposal site, the suitability of the sub-seabed disposal medium, oceanographic, biological, operational and general factors.

B. SITE SELECTION

Study areas

IOS work to date has been confined to the North Atlantic ocean, although the progress of US and Japanese studies of the North Pacific has been followed closely through the OECD Nuclear Energy Agency's Seabed Working Group (SWG). Indeed, throughout the IOS work there has been close co-operation with other nations through the SWG, with IOS providing the UK representatives of the SWG's Site Selection and Sediment and Rock Task Groups.

Our attention was initially concentrated on areas of pelagic, calcareous sediment (calcium carbonate). This was because extensive areas of pelagic clay (a favoured disposal medium in the Pacific) are rare in the Atlantic, and because it was feared that abyssal plains and continental rises (the only other areas of extensive sediment cover)


50°N
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30°W
40°W
50°W
60°W
70°W
80°W
KTF
GME
GMW
CV1
CV3
CV2
SAP
NAP

might prove too unstable. Only three reasonably large areas of uninterrupted pelagic carbonate remote from active lithospheric plate boundaries and major topographic features, and with a low probability of being affected by erosion, could be identified in the North Atlantic on the basis of existing information at the end of 1979. These were the southern flank of King's Trough (designated KTF), an area west of Great Meteor Seamount (GMW), and part of the Cape Verde Rise (CV2).

At the 1980 SWG meeting, it was decided to broaden the area of studies to include distal abyssal plains. Two further study areas, one east of Great Meteor Seamount (GME) and one just north of the Cape Verde Rise (CV1) were therefore adopted for international study; they had previously been independently selected by the Dutch and the French. At the 1981 SWG meeting, in view of disappointing results from CV1, it was agreed to search for a new distal abyssal plain study area (CV3) to the west of CV1.

Towards the end of 1981, US workers completed a review of existing data in the Nares Abyssal Plain (NAP), and recommended several study areas there.

Data compilations

An important part of the site selection process is compilation of relevant existing data. Three such compilations have been carried out at IOS. First, available seismic reflection data were compiled to produce a map of average widths of sediment basins throughout the North Atlantic (23). Secondly, a compilation of seismic reflection and core data was made for the distal abyssal plains between 30°N and 45°N (14), to complement a similar French compilation to the south.

It was used to infer sediment thickness, seabed sediment type and morphology in potential study areas. Finally, a compilation and analysis of all existing geophysical data in the KTF area is underway and should be completed by mid-1982.

Instrument development

It was clear at the outset of the IOS work that several new pieces of equipment would be needed for the site selection work (3). These included high resolution seismic profilers (both surface deployed and near-bottom versions) and a high capacity survey camera system. Development of suitable equipment was therefore included in the institute's general support program.

A 2 kHz hull-mounted profiler was developed for RRS Discovery and was tested on Cruise 106 in December 1979 (9). Although of limited value in rough weather, it gives excellent results in moderate to good sea conditions, with vertical resolution of 2-5m and penetration of up to 70m. It has been used on all subsequent Discovery RWD cruises including Cruise 108 over Nares Abyssal Plain (25). A near-bottom profiler, giving a penetration of over 30 m and resolution of 20 cm was built and successfully tested on Discovery Cruise 118 February-March 1981 (5). Extensive use of this instrument is planned for Cruise 126 in March 1982. Finally, a survey camera system was built, and successfully operated at three stations during Cruise 118. It has the capacity of taking up to 1600 frames, each covering 25 to 100 m^2, on each lowering.

Work at sea

Two cruises (Discovery 118 (5) and Farnella Cruise 3 (24)) have contained a large component of site selection work. In addition, eight cores were obtained from KTF during Shackleton Cruise 8/79 in autumn 1978 (6), and a small amount of 2 kHz profiling was carried out over NAP during Discovery Cruise 108.

Work is also planned for two cruises in March, 1982. Farnella cruises 8 and 9 will carry out Gloria surveys over NAP and KTF, and Discovery 126 will work in the Madeira-Cape Verde abyssal plain.

Discovery 118 was our first major cruise. Three long seismic reflection profiles (airgun and 2 kHz) were run in KTF to fill in and extend the earlier coverage. Planned dredge, camera and near-bottom profiler stations there had to be abandoned due to bad weather and a ship malfunction. 2 kHz profiles were also obtained in GME for inter-comparison with the Dutch 3.5 kHz profiles, and over the distal Cape Verde abyssal plain west of CV1, as part of the reconnaissance for CV3 (15).

Long runs with the survey camera were obtained in GME and over a small pelagic clay basin near 26°N, 31°W (the latter was used to study various apsects of the pelagic clay environment, although the basin is probably too small to be a potential disposal site). A report of the findings is in preparation.

Heat flow measurements and coring for stratigraphic and physical properties were carried out in or near KTF, GME and elsewhere; dredging was completed at GME and in two other locations; and earthquake seismicity and controlled source seismic observations were made. These operations are described more fully elsewhere in this report.

Farnella 3/81 used the long-range sidescan sonar Gloria to survey several areas in the Madeira-Cape Verde abyssal plain. A detailed survey of GME was accomplished, a preliminary study of the area of sediment mass-movement just up-slope from GME was carried out, and an extensive reconnaissance of the CV1/CV3 area was undertaken. The last revealed extensive lineaments on the sea-floor, that suggest the presence of widespread sea-bed sediment transport in this region.

Farnella 8 and 9 are planned to provide detailed Gloria coverage of the NAP and KTF study areas. Discovery 126 (March 1982) is planned to undertake stratigraphic, physical properties, heat flow, seismic velocity, dredge and camera work in GME, and to identify the sediment type and microstructure associated with various Gloria targets in this vicinity.

Study area status

The following summarises the status of the Northeast Atlantic study areas as at February 1982.

KTF

An area about 70 x 150 km, between 41°10' and 42°40'N, 23°00' and 24°00'W, appears to be free of basement outcrops, although there are some low but steep sediment scarps. There is a record of continuous sedimentation during the past 250,000 years (25). The area therefore still appears promising as a generic pelagic carbonate area. Future work must include investigation of the stability of the sediment scarps, and extension of the heat-flow observations.

GMW

This area has been downgraded for shallow disposal following Dutch discoveries of pronounced sediment instabilities (debris flows).

GME

The area west of 24°W appears to be characterised by a continuous succession of distal turbidites and hemipelagic marls. An area from 31°15' to 31°45'N, 24°15' to 25°oo'W, is completely free of abyssal hills. This area is a candidate generic distal abyssal plain. Future work should extend the heat flow observations and investigate possible fluctuations through time of the proximal/distal abyssal plain boundary.

CV1

This area has been strongly downgraded for shallow disposal following French recovery of thick, shallow, coarse sands.

CV3

The status of this area is uncertain, pending confirmation of the nature of the sediment lineaments seen on the Gloria images.

CV2

No IOS work has been carried out at this site. The SWG SSTG still considers it suitable for continued study.

C. SEDIMENT STABILITY

Sediment stability studies are aimed at assessing the likelihood and consequences of changes in sedimentary regime at possible disposal sites. It has been necessary to employ a range of stratigraphical techniques to build a refined picture of sedimentation changes in study areas over the last quarter-million years. Such fine-scale stratigraphic resolution over relatively small areas of the abyssal plains and plateaux has required the introduction of some new techniques.

Eight gravity cores taken on RRS Shackleton Cruise 8/79 (6) and one core taken on Discovery Cruise 118 from the King's Trough Flank study (KTF) area have been correlated using planktonic foraminifera and coccoliths (25). Various techniques were tried with the aim of producing an accurate fine-scale stratigraphy. Oxygen isotopes and CLIMAP-type methods using cold and warm water species to identify glacial and interglacial intervals have proven unreliable in some cases and it has been decided to rely more heavily on a coccolith biostratigraphy. This has been developed and has been used to date the 14 cores taken on Discovery Cruise 118 (5).

Criteria for the selection of possible sub-seabed disposal areas weigh heavily on a need to demonstrate horizontal and vertical continuity of the proposed sediment barrier (23). Core to core correlation in the KTF study area shows that the upper few metres of sediment change little, with continuous deposition over the last 170,000 years, although one core from the east of the area shows considerable sediment disturbance before 170,000 years. The KTF area is a high-carbonate area, most of the sediment being almost pure carbonate ooze (85-90% $CaCO_3$); the calcium carbonate content falls during glacial cycles to about 60-70% due to less coccolith carbonate production and the sediments are marls. Sedimentation rates in the area reflect the calcium carbonate content with about 2.5 cm/1000 years during interglacials and about 1.8 cm/1000 years during glacials (25).

Grain-size studies show that most of the sand size component of the KTF sediments is planktonic foraminifera debris. Median grain-sizes are in the range 2 to 8 microns which suggests that significant radionuclide adsorption could occur, even though this is a high carbonate area. Small patches of ice-rafted gravel have been found in the cores, mostly associated with the glacial periods. Should this area be selected for advanced site specific studies, near-bottom surveys for glacial erratic distributions will be necessary.

A proposal has been prepared and submitted to the JOIDES/IPOD organisation for a 'Glomar Challenger' drillsite to be located on the edge of the KTF study area. This is proposed on palaeoenvironmental grounds, because of its locations close to the glacial Polar Front, and on tectonic grounds, to investigate the formation of King's Trough to the north. Nevertheless, should the site be drilled, it will extend our high-resolution stratigraphy to depths well beyond the range of conventional piston coring. Also, geochemical and geotechnical studies directly relevant to the HLRW disposal programme will be carried out.

The cores taken on Discovery Cruise 118 represent a series of deep-sea environments. Some were taken within the study areas and others between the study areas to provide stratigraphic links and to sample other sediment types such as pelagic clay. The most reliable age determinations on these cores have been given by coccoliths. These fossils can be used even in areas where dissolution has reduced the carbonate content of the seidments, such as in the Great Meteor East and Cape Verde One areas. Stratigraphic histories have been produced for all the cores taken on D.118 [27]. Turbidites have been identified in the eastern part of the GME area and also in a deep area east of the CV1 site. The latter discovery of (very) distal turbidite material within the ridge flank province, well beyond the edge of the Cape Verde Three (CV3) area, was our first indication that the southern Cape Verde Abyssal Plain was being completely traversed by recently active turbidity currents. Subsequently acquired GLORIA coverage has provided further evidence of these processes and the area may possibly now be downgraded as a candidate for any further studies.

Studies of sediment mass movement on slopes using GLORIA, which have been carried outon other IOS projects, have formed the basis of interpretation of long range sidescan coverage in and around HLRW disposal study areas. These have become more directly relevant with the discovery that sand beds were reaching the GME and CV1 areas, resulting from large-scale submarine slide activity on the continental margins to the east. Near-bottom surveys including sediment sampling and bottom photography are now planned within the scope of this project to aid our interpretations of the GLORIA coverage over the northern slide areas.

D. GLACIAL ERRATICS

Pebble to boulder size rocks dropped by melting icebergs and now lying on the sea-bed or within the sediments, were identified as a possible hazard to emplacement of radioactive waste canisters into the sediments of the North Atlantic ocean (3). Studies of erratics were initiated with three main objectives in mind:

1) To determine the southernmost limit of ice-rafting in the North Atlantic.

2) To determine the grain-size characteristics of ice-rafted material.

3) To determine the size-distribution and concentration of ice-rafted material in selected areas of the N.E. Atlantic.

The project began with an examination of biological sampling residues held in the 'Discovery Collections' at the Institute. These had been collected from abyssal plains and contained glacial erratics, volcanic ejecta and clinker (dropped from coal-burning ships). This work revealed that rock material on the surface of abyssal plains appeared to be of small size (approx. 2 cm diameter) (10).

Rock material already collected and held in repositories in the UK, France and the USA was then examined. These collections covered 130 sampling stations in the N.E. Atlantic from 25-65°N and included material collected from both abyssal plains and submarine outcrops. Grain size data distributions were determined for these collections and a preliminary report produced (8). This demonstrates that ice rafted material occurs at least as far south as 30°N and gives statistical estimates of the likely occurrence of boulder-size material north of this.

Ocean bottom photographs have also been examined. These have provided information upon processes which may lead to the burial of ice-rafted material on the sea-floor and on the quantitative efficiency of bottom photography in detecting erratics in study areas. A paper has been published upon some of these results (11) and further work upon the subject is is progress.

Sampling using a modified IOS epibenthic sledge was carried out at two stations in the N.E. Atlantic on Discovery Cruise 118 (5). These stations were near the southern limit of glacial erratic transport indicated by the earlier work. The results from this sampling have supported our previous deductions.

Subsequent to Discovery Cruise 118 some material collected with benthic sledges from low-level disposal areas by the Bundesforschungsanstaldt (Hamburg) has come to light. This material is being used to complete grain-size studies of ice-rafted material as outlined in IOS Internal Document No. 129 (8).

E. ESTIMATION OF SEISMIC RISK AT ATLANTIC OCEAN INTRA-PLATE SITES

Earthquakes recorded by the World Seismological Network have been used to assess the seismic hazard for sites within the Atlantic Ocean intra-plate region. For the period for which we have the most complete data (1964-1979) over 100 events can be identified as occurring within the intra-plate regions of the Atlantic (12). From these data it is possible to identify a region of greater than average activity to the East and North-East of the Caribbean, which may be the result of slight relative motion of the North and South American plates. Such a zone may not truly represent an oceanic intra-plate region and the data were excluded from seismic risk estimates. Seismicity appears relatively

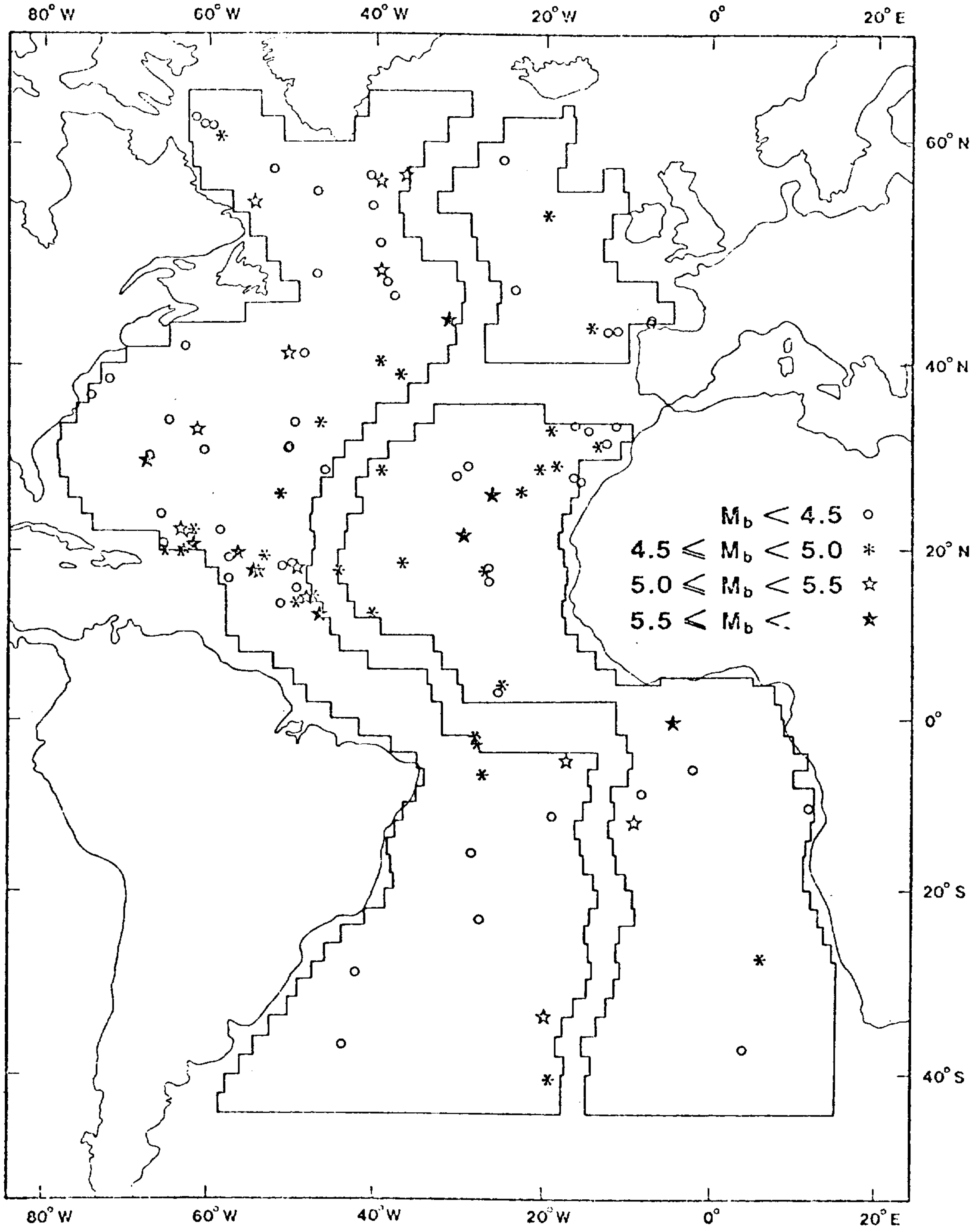


Figure 1. Teleseismically observed intraplate earthquakes in the Atlantic Ocean during the period 1964-1979 inclusive.

uniform over the remaining regions but overall activity in the South Atlantic is about half that in the north even after correction for network detection thresholds. Relocation and examination of events prior to 1964 gives a similar difference in activity although the zone of high activity near the Caribbean is less evident (13).

The largest earthquake for the period 1964-79 had a magnitude of 6.4 on the surface wave scale (M_s) whilst during the whole period for which we have data (1913-79) the largest magnitude recorded is 7.2. An extreme value analysis of the magnitude of all the oceanic intra-plate events gives a value of 7.3 for the upper limit and therefore 7.5 would be a conservative upper bound to assume in seismic risk estimation. Below this value the seismicity for North Atlantic intraplate events can be described by the magnitude frequency relation:

$$\mathrm{Log}_{10} N = -5.63 - 0.44\, M_s$$

where N is the number of earthquakes per annum per square km with magnitude greater than M_s.

The larger events are capable of causing considerable damage and liquefaction effects near their epicentre. The seismic risk at any given site however depends on the spatial distribution of the above seismicity with respect to the site. If the seismicity is everywhere uniform over long periods then assuming attenuation relations used for land sites the return period for 0.1g peak acceleration (a point at which slope instability and liquefaction may occur) is estimated to be circa 10,000 years. If, as suspected in published work on these earthquakes, the seismicity is concentrated along zones of weakness such as fracture zones then the return period in such zones may be as short as 2000 years.

In addition to the above analysis of teleseismically recorded earthquakes, work is is progress to extract seismic risk information from the very much smaller data base of local events recorded on the sea-floor by ocean bottom seismographs. A small contribution to expanding this data base was made on Discovery Cruise 118, when OBS and PUBS were deployed to record local seismicity in the vicinity of the GME study area.

2. The Properties of Ocean Sediments

OBJECTIVE

To assess the properties of sediments at possible ocean disposal sites in relation to the emplacement of canisters of radioactive material and the retention of radionuclides eventually released from the canisters.

INTRODUCTION

The requirement to study the feasibility of disposing of high-level radioactive waste in deep-sea sediments revealed many gaps in our knowledge of such sediments. It is necessary to understand relevant natural physical and chemical processes in the sediments as well as the physical and chemical effects of canister emplacement and of post-emplacement heating. Work at IOS has so far concentrated on improving our understanding of natural processes.

Deep-sea sediments are deposited by a variety of processes, at mean rates of the order of 10 metres per million years, onto a slowly subsiding and cooling igneous basement. When the igneous basement is young heat is lost by conduction and by hydrothermally-driven convection of sea-water. Although hydrothermal vents are eventually buried by sediment, convection probably continues within the igneous rocks until pathways become blocked by mineral deposits. It appears possible that, at least until this stage is reached, pore-water flow driven by the underlying convective cells may persist within the sediments.

Existing knowledge and understanding of the chemistry of deep sea sediments requires supplementation by study of the detailed processes most relevant to waste disposal.

The sediments thought to be most likely to be suitable as hosts for waste canisters are the very fine grained material, with high clay mineral content, found at the greatest oceanic depths. More needs to be known of the chemical and mineral composition of fine sediments from otherwise suitable places, of the chemical fluxes between sediments and their pore waters, vital to an understanding of the sediments' potential to retain radionuclides released into them and of the nature and behaviour of sediment material in the ocean water column.

A. PHYSICAL PROPERTIES OF SEDIMENTS

Conflicting evidence was obtained from studies of temperature and pore-water chemistry profiles from three sites in the equatorial Pacific Ocean, where thermal evidence of hydrothermal circulation exists. Theoretical curves fitted to profiles of pore-water sulphate versus depth and which allowed for diffusion, advection and reaction processes yielded pore-water flows at least 150 times less than those calculated from geothermal observations!

The fact that results of different approaches to pore water movement could not be resolved strongly influenced the initial direction of the physical properties work at IOS. While it seemed prudent to enter the heat flow field ourselves, particularly since North Atlantic heat flow measurements are rather sparse, it was also clearly desirable to tackle the problem from a different direction. Therefore a programme of work was devised to directly measure sediment permeability in the laboratory and, subsequently, to measure pore-water pressures *in situ*, since non-hydrostatic vertical pressure gradients must accompany any vertical advection.

The remainder of this section outlines the work already completed in the last two years which falls within the framework outlined above. A starting point was provided by a literature review of the state-of-the-art of deep-sea geotechnical sampling and measurement techniques.[22] This report identifies those geotechnical parameters most sensitive to sampling disturbance and which therefore should be measured *in situ* if meaningful values representative of natural conditions are required.

Properties controlling pore water movement in sediments

The movement of water in a saturated porous medium at the rates usually encountered in nature is governed by Darcy's law:

$$Q = kAi$$

where Q = rate of flow

k = coefficient of permeability

A = cross-sectional area

i = the hydraulic gradient

The seepage velocity (v_s) of water flowing through a sediment layer of permeability k and porosity n under a hydraulic gradient i is given by:

$$v_s = ki/n$$

Therefore three parameters (k, i and n) need to be measured to calculate, for instance, the delay time provided by a sedimentary barrier before mobile waste reaches the sea-bed. However, the rate at which such waste might reach the sea-bed is independent of porosity.

Two of the required parameters, porosity and permeability, can conveniently be measured on sediment samples obtained by coring techniques whereas the third parameter, the hydraulic gradient, can only be measured *in situ*. Consequently the research programme is divided at this stage into two distinct parts:

1) Sampling of "undisturbed" sediment for measurement of permeability and porosity in the laboratory.

2) Development of an instrument to measure the *in situ* hydraulic gradient.

Because suitable equipment to measure permeability and hydraulic gradient is not commercially available much of the last two years has been spent in designing and developing suitable equipment as well as in obtaining samples at sea.

Deep sea sediment cores brought to the sea surface will usually suffer some degree of disturbance due to the change in temperature and pressure. However, the total amount of disturbance experienced by the samples taken from the core will depend on the corer used, the core handling and the sub-sampling techniques as well as on the method of transport and storage of the core and samples. All these factors have been considered and special equipment has been designed and built for sub-sampling, transport and storage. An electro-osmotic cutting technique is used which minimises the disturbance caused when trimming the samples to size.

Porosity is easily measured by standard volumetric and weight measurements on the samples. Permeability, however, is not so easily measured and a special laboratory apparatus had to be developed. The apparatus contains an oedometer cell, which was designed at the Institute and which enables consolidation tests to be performed on samples under a hydraulic back-pressure as well as permitting permeability measurements by the direct method. These measurements are conducted at varying hydraulic gradients produced by a system of compressed air and water. Volume flow measurements are made by observing the movement of a coloured paraffin/water interface through high precision glass capillary tubes. Volume resolution is as low as 5×10^{-8} litres thereby enabling very low flow rates to be measured accurately and rapidly. The whole apparatus is housed in a constant temperature walk-in unit to minimise the volume changes caused by temperature fluctuations.

To measure the hydraulic gradient, i, it has been necessary to design an instrument capable of measuring differential pore-water pressures in-situ. The instrument, which has been called a Pop Up Pore Pressure Instrument (PUPPI), has the following design features. It consists of two parts, a long thin probe (4-5m) which penetrates the sediments and contains a pore-pressure port at its tip, and a head section which houses the differential pressure transducer, two release mechanisms, a solid state data logger, acoustic telemetry equipment, a penetration and tilt indicator, four buoyant glass spheres and lead weights. The probe is designed to be lowered on a warp and driven into the sediments under the force of the lead weights. Acoustic telemetry will indicate whether satisfactory penetration has been achieved. If not, the probe can be pulled-out of the sea-bed and re-entered. An acoustically controlled release will free the lead weights which will be recovered on the warp. The probe will then be left undisturbed to record pore-pressures over a period of up to 10 days. A second acoustically commanded release will then be used to separate the remaining two sections of the instrument. The buoyant head section will freely ascend to the surface where it will be recovered while the long disposable probe remains embedded in the sediment.

The mechanical design phase of this instrument has been completed and it is at present (February 1982) under construction. Meanwhile the differential-pressure transducer intended for the PUPPI has been mounted on the head of the Heat Flow Probe and is connected to a pore-pressure port at the tip of this device to enable the port and tip configuration to be tested at sea.

On Discovery Cruise 118 (February-March 1981) a range of different sediment types was collected using a Kastenlot corer (15 x 15 cm square section) with a 2m barrel. About one hundred 75 mm and 50 mm diameter samples were taken for consolidation and permeability tests. Results from these tests have demonstrated the wide range of permeability and void ratio depth-profiles that may exist in pelagic sediments ranging in lithology from nearly pure carbonate oozes to deep-sea clays. The permeability has been found to range from 10^{-7} m s^{-1} to 9×10^{-9} m s^{-1} with no overburden and from 10^{-8} m s^{-1} to 10^{-10} m s^{-1} at a void ratio equivalent to a depth of approximately 130m. A range of three orders of magnitude has therefore been recorded from these different samples with up to two orders of magnitude separating samples having the same void ratio. Some horizontal permeabilities

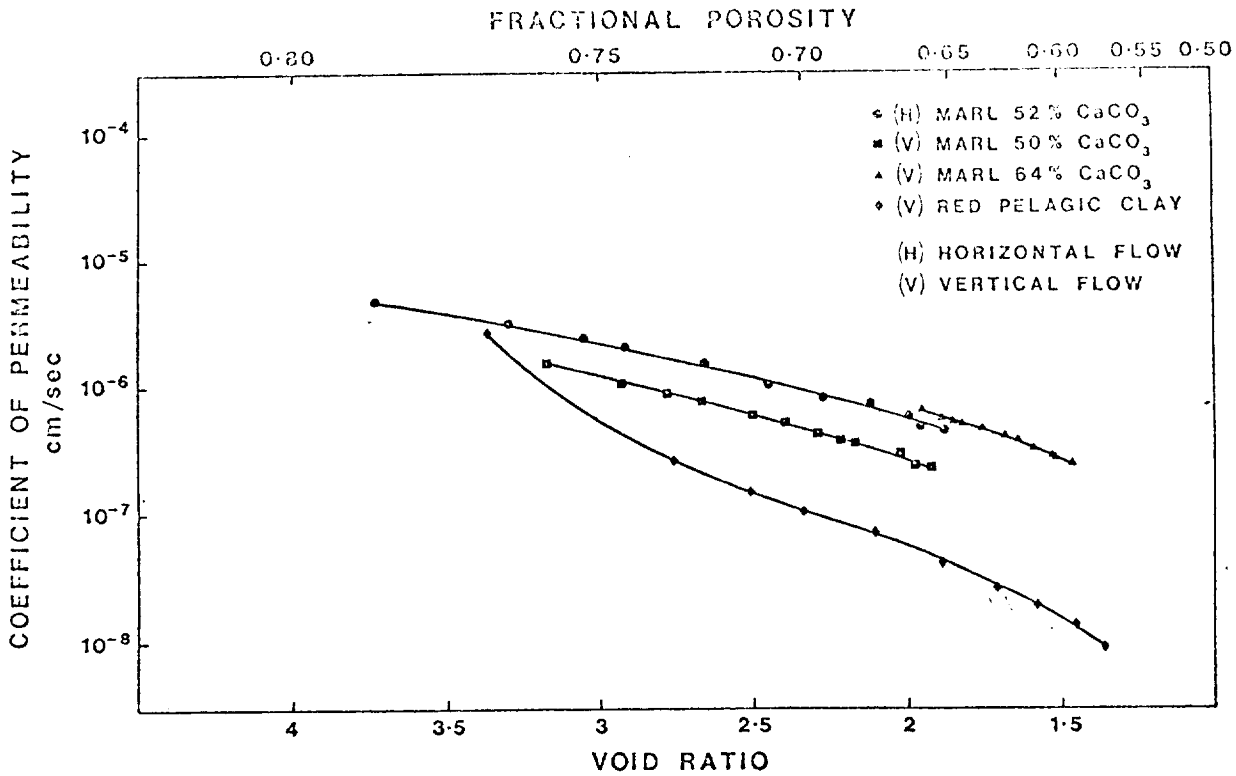


Fig. 2 Permeability versus void ratio of some North Atlantic Sediments

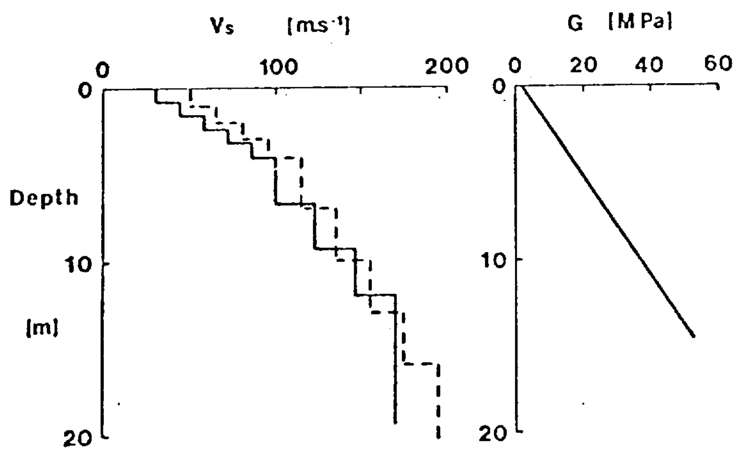


Fig. 3 The left hand figure shows two profiles of the shear-wave velocity as a function of depth beneath the sea-bed. The solid curve was obtained from observations of surface waves generated by dropping large weights onto the sea-bed and recording the resulting disturbances with ocean bottom seismographs. The right hand figure shows the corresponding elastic shear modulus calculated from the shear velocity assuming a constant sediment density of 1550 kgm^{-3}.

exceed vertical permeabilities by a factor of four in adjacent samples. Such a large anisotropy is expected to have a profound effect on pore-water speeds and directions of flow. However, since reliable pore-pressure measurements have yet to be made in deep-sea sediments it is not yet possible to estimate unambiguously what these speeds might be.

Magnetic susceptibility measurements on cores

The magnetic susceptibility of deep-sea sediments depends on the nature and proportions of the constituent minerals and particularly on the quantity of terrigenous material present. Continuous magnetic susceptibility profiles of deep-sea sediment cores can therefore be used to rapidly identify changes in lithology and as an aid to correlating lithologies of the same age between cores. During Discovery Cruise 118 the magnetic susceptibility of seven 5 cm diameter gravity cores and one 2 m long box core were measured using a new shipboard magnetometer recently built for this purpose at the Institute. The sensor comprises a balanced a.c. bridge and the results are shown as a continuous trace on an X-Y recorder. The data showed that low susceptibility was associated with carbonate material and higher values occurred within clay and marl bands. Several volcanic ash layers were identified in one core, two of which were not visible in the core but which were confirmed subsequently from a study of smear slides.

Elastic shear modulus

The elastic shear modulus of a sediment is an important parameter for predicting settlement under large engineering structures. It may also be possible to relate it empirically to the sediment shear strength. A new marine seismic technique has led to the modelling of shear-wave velocity/depth profiles in the top few tens of metres of the sea-bed. The shear modulus is calculated directly from the shear-wave velocity after making a suitable estimate of the sediment density. The technique involved dropping large weights onto the sea-bed and recording the resulting seismic disturbance out to a maximum distance of about 2 km from the point of impact.

B. TEMPERATURE CONDUCTIVITY AND HEAT FLOW

The possible mobility of pore water within deep sea sediments is an important aspect to be considered when assessing the suitability of this material as a potential disposal site for high-level radioactive waste. A consequence of any sustained vertical pore-water advection is a change in the overall conductive heat-flux and a curvature in the profile of sediment temperature with depth. Thus by recording the thermal structure accurately with a suitable probe it is possible, in the absence of other disturbing factors, to estimate the velocity of pore-water advection.

In 1980, the Institute took delivery of two 5m long marine geothermal heat flow probes from Applied Microsystems Ltd., Canada. This instrument measures *in situ* sediment temperatures using thermistors spaced at 1 metre intervals inside a tubular steel bowstring which is held taut alongside, and offset from, a solid steel strength member. Thermal conductivity can also be measured *in situ* by observing the decay of a heat-pulse generated by passing a current through wires within the bowstring after measurements of the ambient temperature have been completed. All data are recorded digitally on magnetic tape.

The instrument was initially tested in Loch Etive from the Scottish Marine Biological Association vessel "Callanus". Handling techniques were developed and the acoustic probe-to-ship telemetry link was checked at a range of a few hundred metres. Two successful penetrations were made in Airds Bay and good quality data were obtained.

During Discovery Cruise 118 (February/March 1981) the heat probe was deployed at five stations in the N.E. Atlantic. At two of these stations (Discovery stations 10318 and 10335) repeated temperature measurements were made along linear traverses using the 'pogo-stick' technique. In this technique the probe is periodically inserted into the sea-bed while the ship is underway at about 1 knot, and between insertions it is towed just above the sea-bed. From these experiments experience was gained in handling the instrument in water depths of up to 6060 metres and a number of weaknesses in the mechanical construction were identified. Nevertheless, data from a total of eighteen 5 metre penetrations were obtained. After correction for the effects of frictional heating several thermal profiles showed significant departures from linearity which possibly could be caused by pore-water movement. The results suggest upward velocities of the order of 40 cm/year.

Other mechanisms which also could be responsible for these non-linear temperature profiles are currently being examined. These include regular (seasonal?) or sudden changes in bottom water temperature, production of heat within the sediments and physical disturbance caused by the penetration of the probe. The importance of these factors with respect to the pore-water advection effect is being estimated in order that the reliability of the deduced pore-water velocities can be assessed.

A needle probe has been designed and constructed for measuring the thermal conductivity of deep-sea sediment cores in the laboratory. The results will be compared to in situ measurements made by the heat probe. A novel double-needle probe has also been made and will be used to measure the thermal conductivity anisotropy of the sediments.

Extensive modifications to the Applied microsystems heat probe have recently been completed at the Institute. These have involved strengthening the mechanical assembly and incorporating refinements to the electronics and acoustics which will improve the telemetry of sediment temperatures and positioning of the probe with respect to the bottom. A tilt sensor has been added to monitor the probe's attitude in the sediment in real time.

A theoretical study has just been completed on thermal expansion effects in deep-sea sediments[7]. The study neglects any chemical changes which heating a sediment might promote and concentrates on the physical effects. It is concluded that the temperature cycling of a sediment brought about by the emplacement and cooling of a hot radioactive waste canister would compact the sediment, a process has been called "thermal tamping". Thermal tamping would enhance the ability of the sediment to retain the radionuclides once the canister has corroded away.

C. SEDIMENT CHEMISTRY AND MINERALOGY

The first requirement of the sediment chemistry work has been reliable means of recovering undisturbed and uncontaminated sediment for study. In the first two years of the work considerable effort was devoted to the development and evaluation of a box corer to sample the uppermost metre of the sea bed with minimal disturbance, and a large section gravity corer - the Kastenlot - to sample the uppermost 2-4 metres.

Collections of sediment samples from different oceanic areas were carried out on Discovery Cruises 108 (Jan-Feb, 1980), 110 (May-June, 1980) and 125 (Jan-Feb, 1982). Samples of sediment have also been collected for other laboratories and groups within IOS engaged in radioactive waste disposal studies.

Laboratory procedures have also, meanwhile, been developed for chemical and mineralogical examination of sediments, based mainly on X-ray methods. Work to date has concentrated on Atlantic red clay sediments. Fluctuations in the solid phase composition and accumulation rates determined on material collected from the Nares Abyssal Plain, close to the areas favoured by the Site Selection Task Group, tend to demonstrate that lateral sediment redistribution, including turbidity current flow, has been an active process in this region over the past few hundred thousand years and has given rise to considerable vertical or horizontal variability on a local scale in the areas studied.

Six cores were selected for intensive study on the basis of their stratigraphy and the pore water investigations which were made immediately on retrieval. The pore water data indicate that, with only one exception, only very mildly reducing conditions prevail in these cores, and it is believed that no diagenetic remobilisation of metallic elements is presently active. On this basis it has been possible to differentiate and characterise the sediment types found by conjugate use of the mineralogical, chemical and radiometric data. Two major sediment types, a pelagic brown clay and a coarser gray clay turbidite clay have been described previously in the literature. Sections of both types have been identified and investigated, but a variety of other types, predominantly brown in colour, but not pelagic, have also been found.

In the cores studied, four sections of pelagic clay have been identified, although the sediment accumulation rates are higher than those previously quoted. An estimate of the long term mean flux of certain transition elements from the water column to the sediments over the Nares Abyssal Plain has been derived. The composition of this flux appears to bear some similarity to literature analyses of manganese nodules and micronodules found in the fracture zone area to the northeast of the Nares Abyssal Plain. The accompanying diagrams and tables illustrate some aspects of the interpretations made of the analytical data, which is in preparation for publication.

DISCOVERY STATION: 10164 # 1K

Depth Interval, cm.	Major Element Data, % wt.															Trace Element Data, ppm.										
	SiO_2	Al_2O_3	Fe_2O_{3T}	MnO	MgO	CaO	K_2O	Na_2O	TiO_2	P_2O_5	NaCl*	LOI	Total	CO_2	Org.C	Rb	Sr	Y	Zr	Nb	Ni	Co	V	Cr	Cu	Zn
26-28	49.09	17.51	8.11	0.35	2.79	0.85	3.71	1.53	0.82	0.15	2.25	9.59	96.75	0.43	0.13	166	120	32	141	19	56	21	157	102	43	132
32-34	49.58	18.01	8.11	0.32	2.81	0.83	3.81	1.58	0.83	0.16	2.19	9.45	97.68	0.44	0.16	169	126	34	143	20	56	24	162	105	37	125
38-40	52.49	16.59	7.58	0.48	2.56	0.99	3.57	1.64	0.84	0.15	1.99	9.04	97.92	0.42	0.33	163	120	32	139	18	58	22	167	106	36	122
44-46	50.91	16.99	8.49	0.30	2.78	0.86	3.79	1.65	0.84	0.16	1.97	8.71	97.45	0.58	0.25	161	132	31	160	21	56	23	158	99	81	123
50-52	48.66	17.55	7.99	0.12	3.10	1.10	4.00	1.19	0.81	0.15	2.33	10.08	96.48	0.82	0.37	174	119	33	135	19	51	22	163	99	37	127
55-57	49.32	17.89	8.21	0.06	3.10	1.15	4.15	1.15	0.81	0.14	2.04	9.53	97.55	0.97	0.32	177	120	33	137	21	50	20	162	98	27	125
65-67	50.08	18.39	7.81	0.07	3.52	2.11	4.13	1.02	0.81	0.13	2.19	10.17	100.43	1.67	0.47	180	139	34	137	19	52	20	170	100	65	127
84-86	48.97	17.96	7.35	0.09	3.64	3.90	3.75	0.80	0.78	0.14	2.95	11.87	102.20	2.56	0.64	172	183	29	139	17	52	20	156	96	42	113
104-106	45.20	16.64	7.00	0.10	2.90	3.90	3.60	0.88	0.77	0.13	2.43	12.27	99.02	3.11	0.44	165	177	30	135	16	47	20	151	92	39	114
124-126	52.52	15.85	6.25	0.10	3.24	4.41	3.27	1.28	0.51	0.13	2.11	11.25	100.92	3.78	0.67	148	182	32	156	18	48	23	142	84	34	104
135-137	62.08	12.75	4.38	0.06	2.55	4.16	2.44	1.98	0.72	0.13	1.73	9.14	102.12	3.78	0.44	107	170	30	211	18	68	30	102	68	25	80
144-146	50.39	17.85	7.70	0.11	3.48	1.23	3.99	1.19	0.79	0.14	2.29	9.62	98.78	1.02	0.30	169	121	30	135	16	57	27	171	98	101	123
164-166	52.61	16.76	7.28	0.10	2.96	1.28	3.65	1.29	0.90	0.15	2.02	9.47	98.47	1.28	0.46	163	120	33	160	18	64	31	155	98	32	121
184-186	50.00	16.89	8.09	0.20	3.16	1.28	3.67	1.37	0.78	0.15	2.64	10.36	98.59	1.30	0.33	150	132	29	135	16	67	35	149	86	58	122
196-198	49.23	17.53	7.80	0.24	2.95	0.99	3.49	1.37	0.81	0.15	2.75	10.45	97.76	0.49	0.21	147	135	29	137	17	68	50	148	93	127	123

* equivalent to total evaporated seawater salts, assuming Na/Cl = 0.555.

Table 1. Bulk sediment composition versus depth data sheet for Nares Abyssal Plain core - all data obtained from XRF analysis of fusion beads and powder pellets, except LOI, organic carbon and CO_2 which were determined gravimetrically.

Depth cm	U ppm	Th ppm	Th/U	$^{234}U/^{238}U$ activity	$^{230}Th/^{232}Th$ activity	^{230}Th dpm/g	^{234}U dpm/g	$^{230}Th_{excess}$ dpm/g
10164 # 1K								
26-28	2.36±0.08	13.2±0.9	5.6±0.4	0.94±0.04	1.19±0.06	3.81±0.26	1.66±0.06	2.15±0.27
32-34	2.37±0.08	15.7±0.7	6.6±0.4	0.93±0.04	0.96±0.04	3.66±0.17	1.64±0.06	2.02±0.18
38-40	2.49±0.09	14.8±0.6	5.9±0.3	0.92±0.04	1.03±0.03	3.72±0.14	1.71±0.06	2.01±0.15
44-46	2.54±0.06	12.3±0.3	4.8±0.2	0.95±0.03	1.23±0.03	3.66±0.09	1.81±0.04	1.85±0.10
50-52	2.48±0.11	14.8±0.7	6.0±0.4	0.96±0.05	1.51±0.05	5.45±0.24	1.78±0.08	3.67±0.25
55-57	2.72±0.09	15.4±0.8	5.7±0.3	0.84±0.04	1.09±0.05	4.06±0.21	1.70±0.06	2.36±0.22
65-67	3.31±0.08	13.8±0.6	4.2±0.2	0.94±0.03	1.03±0.03	3.45±0.14	2.32±0.06	1.13±0.15
84-86	4.00±0.09	14.1±0.4	3.5±0.1	0.95±0.02	1.01±0.02	3.46±0.10	2.85±0.06	0.61±0.11
104-106	2.87±0.10	13.7±0.7	4.8±0.3	0.98±0.04	1.01±0.04	3.37±0.17	2.12±0.07	1.25±0.18
124-126	3.18±0.09	11.6±0.4	3.6±0.2	0.91±0.03	1.00±0.03	2.83±0.11	2.16±0.06	0.67±0.13
135-137	2.87±0.07	9.58±0.28	3.3±0.1	1.06±0.03	1.19±0.03	2.78±0.08	2.27±0.07	0.51±0.11
144-146	2.87±0.10	14.8±0.6	5.2±0.3	0.99±0.04	1.36±0.03	4.89±0.18	2.13±0.07	2.76±0.19
164-166	2.81±0.07	13.2±0.4	4.7±0.2	0.88±0.03	1.60±0.04	5.11±0.14	1.84±0.05	3.27±0.15
184-186	2.19±0.07	14.4±0.7	6.6±0.4	0.95±0.04	4.07±0.12	14.2±0.6	1.56±0.05	12.6±0.6
196-198	2.21±0.05	10.7±0.3	4.8±0.2	0.90±0.03	3.05±0.06	7.97±0.18	1.47±0.04	6.50±0.18

Table 2. A complete radiometric data set for 2 metre Kasten core 10164 from the Nares Abyssal Plain. Such information is necessary to derive data for the $^{230}Th_{excess}$ method for estimation of accumulation rates, as well as providing information on uranium and thorium isotope geochemistry.

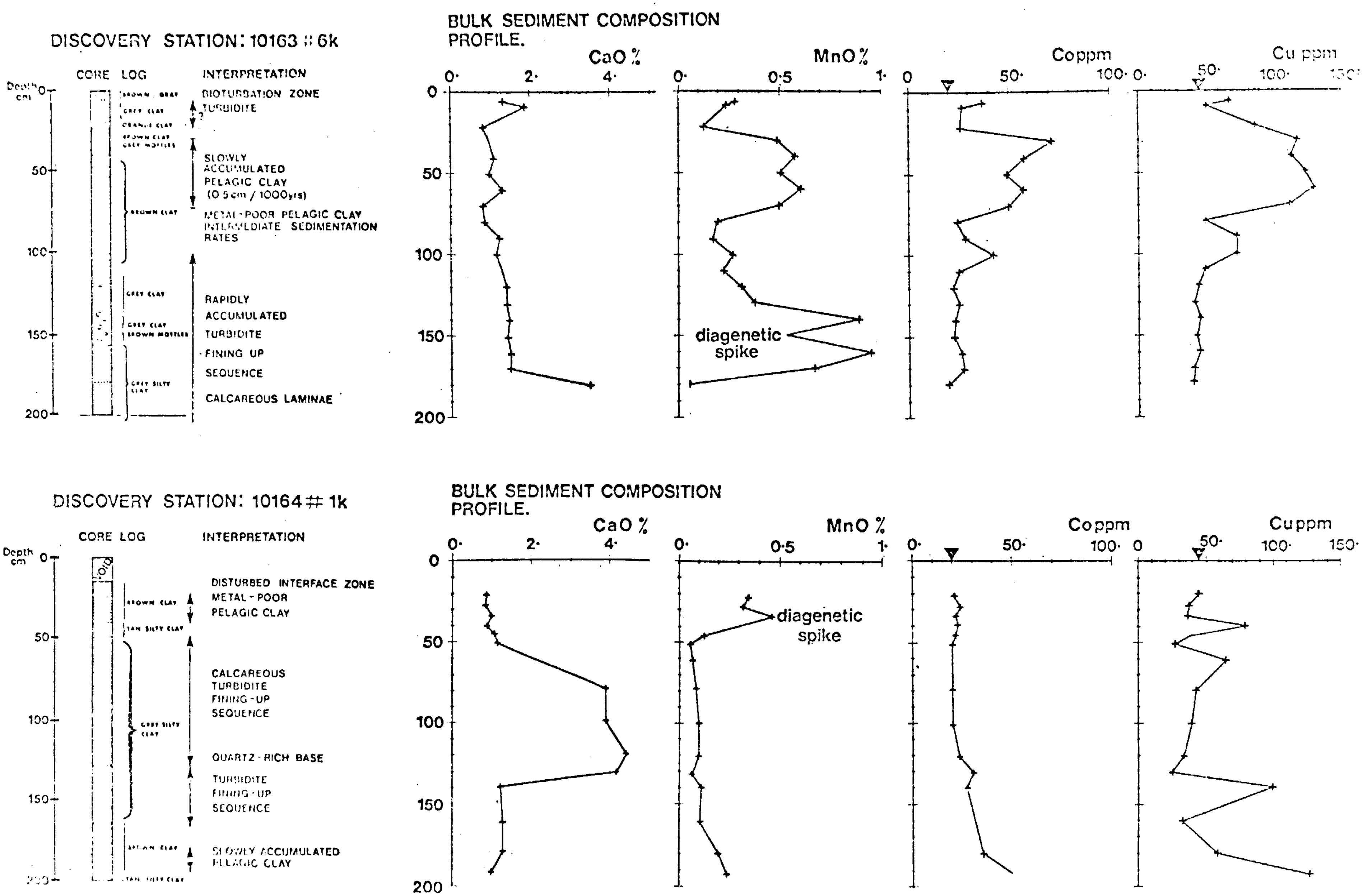

DISCOVERY STATION: 10163 # 6k
CORE LOG
INTERPRETATION
BIOTURBATION ZONE
TURBIDITE
SLOWLY ACCUMULATED PELAGIC CLAY (0.5cm / 1000yrs)
METAL-POOR PELAGIC CLAY INTERMEDIATE SEDIMENTATION RATES
RAPIDLY ACCUMULATED TURBIDITE FINING UP SEQUENCE
CALCAREOUS LAMINAE
BULK SEDIMENT COMPOSITION PROFILE.
CaO %
MnO %
Coppm
Cu ppm
diagenetic spike
DISCOVERY STATION: 10164 # 1k
Depth cm
DISTURBED INTERFACE ZONE
METAL-POOR PELAGIC CLAY
CALCAREOUS TURBIDITE FINING-UP SEQUENCE
QUARTZ-RICH BASE
TURBIDITE FINING-UP SEQUENCE
SLOWLY ACCUMULATED PELAGIC CLAY
Cuppm

Fig. 4

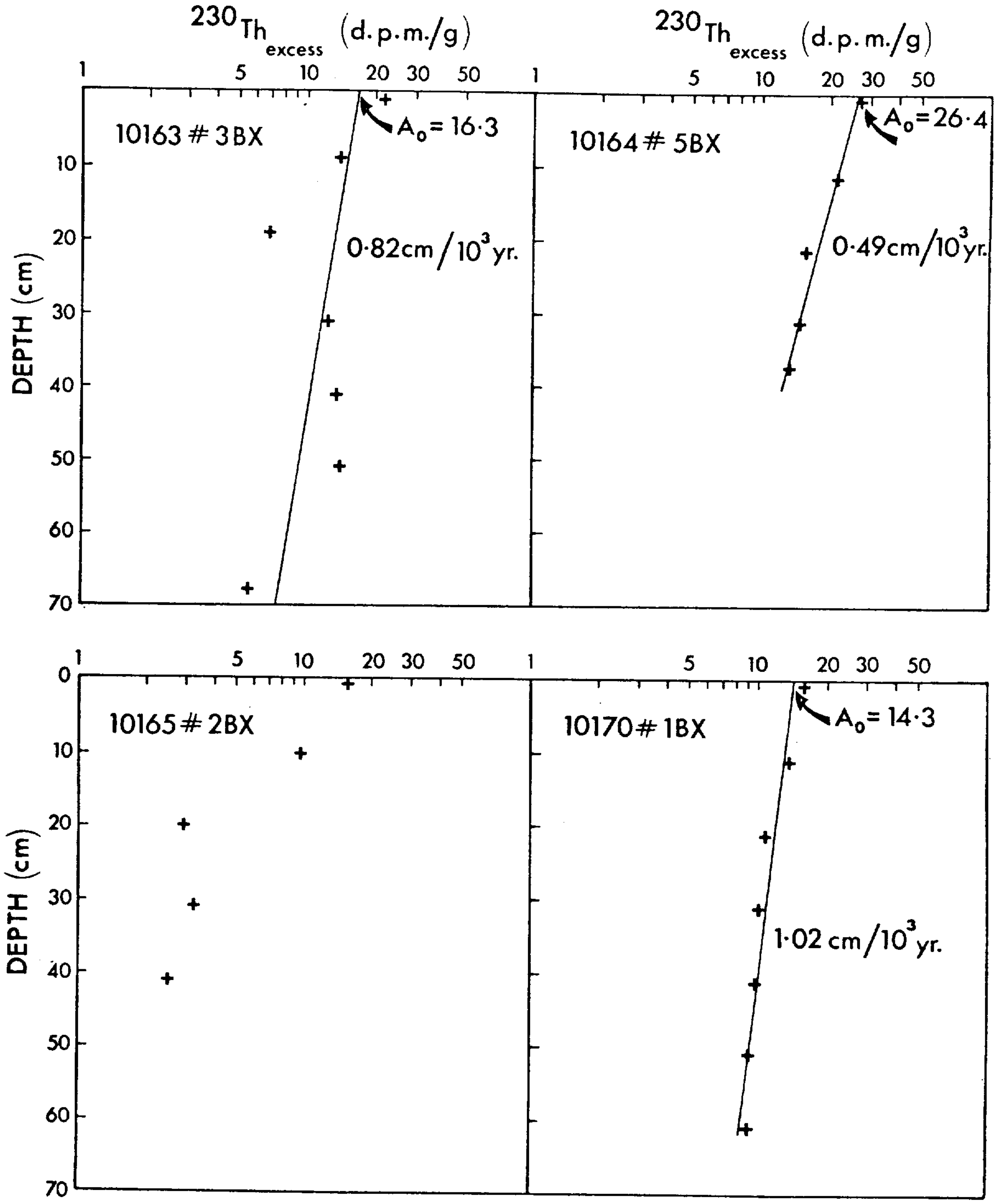


Fig. 5 $^{230}Th_{excess}$ data for four box cores from the Nares Abyssal Plain. Sediment accumulation rates can be estimated for only three of the cores as shown.

Average major and trace element composition of Nares Abyssal Plain bulk sediment samples (this study) compared with average shale composition (Wedepohl, 1967).

	Nares Abyssal Plain sediments: overall mean of 62 Analyses	Slowly accumulated brown clays. Group mean N=16	Metal-poor brown clays Group mean N=12	Grey clays Group Mean N=18	Average Shale Wedepohl (1967)
SiO_2	50.61 (2.25)	50.06 (0.57)	51.06 (1.39)	51.35 (3.18)	58.61
Al_2O_3	17.88 (1.12)	18.61 (0.72)	18.12 (0.74)	17.34 (1.41)	16.63
Fe_2O_{3T}	7.85 (0.65)	8.15 (0.14)	8.14 (0.43)	7.41 (0.90)	6.89
MnO	0.35 (0.20)	0.53 (0.14)	0.29 (0.10)	0.13* (0.08)	0.11
MgO	3.17 (0.26)	3.03 (0.13)	3.28 (0.25)	3.27 (0.28)	2.60
CaO	1.91 (1.59)	1.07 (0.28)	1.26 (0.37)	2.71 (1.36)	2.21
K_2O	3.55 (0.34)	3.33 (0.14)	3.66 (0.20)	3.64 (0.40)	3.61
TiO_2	0.82 (0.22)	0.81	0.82	0.88	0.77
P_2O_5	0.17 (0.00)	0.17	0.18	0.18	0.16
NaCl	2.41 (0.38)	2.69	2.81	2.15	0.92
Na_2O	1.45 (0.17)	1.55	1.50	1.40	2.10
LOI	9.33 (1.42)	9.22	8.64	9.76	
TOTAL	99.42 (2.13)	99.37	99.98	100.31	
CO_2	1.40 (1.10)	0.64 (0.40)	0.84 (0.40)	2.28 (1.33)	1.3
Org.C	0.27 (0.17)	0.17 (0.10)	0.16 (0.13)	0.40 (0.17)	
Rb	157 (13)	146 (3)	161 (6)	160 (16)	140
Sr	155 (19)	152 (12)	139 (14)	160 (31)	300
Y	31 (2)	32	30	31	41
Zr	135 (15)	130 (10)	135 (13)	142 (21)	160
Nb	17 (2)	17	18	17	18
Ni	78 (24)	107 (29)	79 (16)	60 (13)	68
Co	38 (17)	59 (13)	39 (14)	27 (9)	19
V	165 (12)	170 (9)	170 (7)	157 (17)	130
Cr	96 (6)	92 (3)	100 (3)	95 (8)	90
Cu	77 (15)	122 (20)	76 (2)	52 (23)	45
Zn	126 (9)	132 (4)	128 (4)	118 (11)	95

Nares samples are grouped into three main classes according to colour and inferred accumulation rate; N is total number of samples assigned to each group, and figures in brackets are standard deviations of the mean. *indicates 3 high values excluded from mean. Units: SiO_2 - Org.C, % wt; Rb - Zn, ppm (dry basis).

Table 3.

A summary table showing average sediment composition in different sediment types from the Nares Abyssal Plain. Metal-poor brown clays are intermediate in composition between slowly accumulated brown (pelagic) clays and grey clays (turbidites). Grey clays are relatively rich in organic material and tend towards average shale compositions characteristic of near-shore environments.

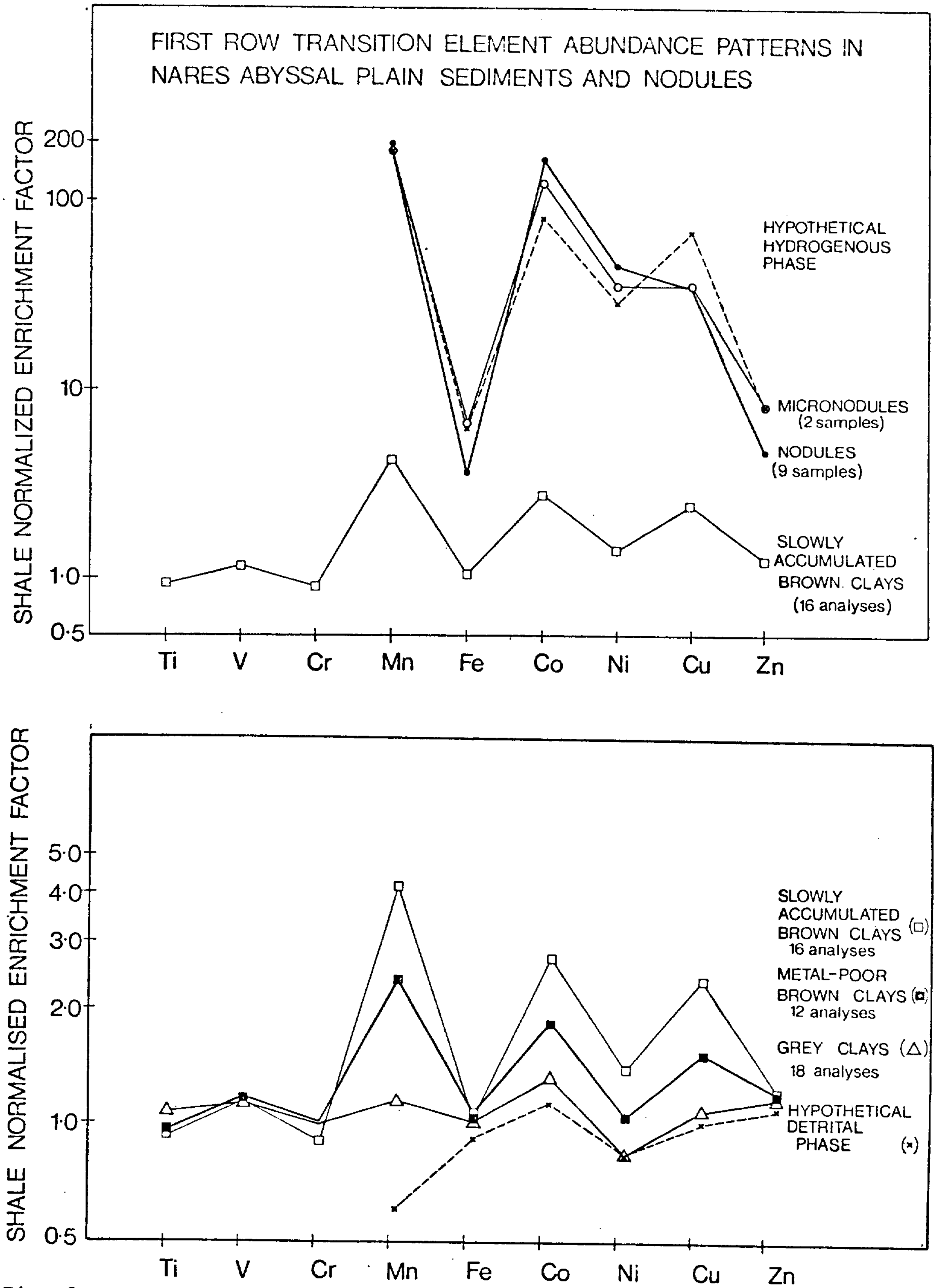


Fig. 6

An illustration of the element abundance patterns characteristic of different sediment types on the Nares Abyssal Plain. Enrichment of certain transition elements can be explained by mixing of a hydrogenous phase (c.f. manganese nodules) with a detrital phase similar to nearshore mud (shale). Slowly accumulated brown clays contain about 2% hydrogenous component which shows a positive Cu anomaly compared with micronodule composition.

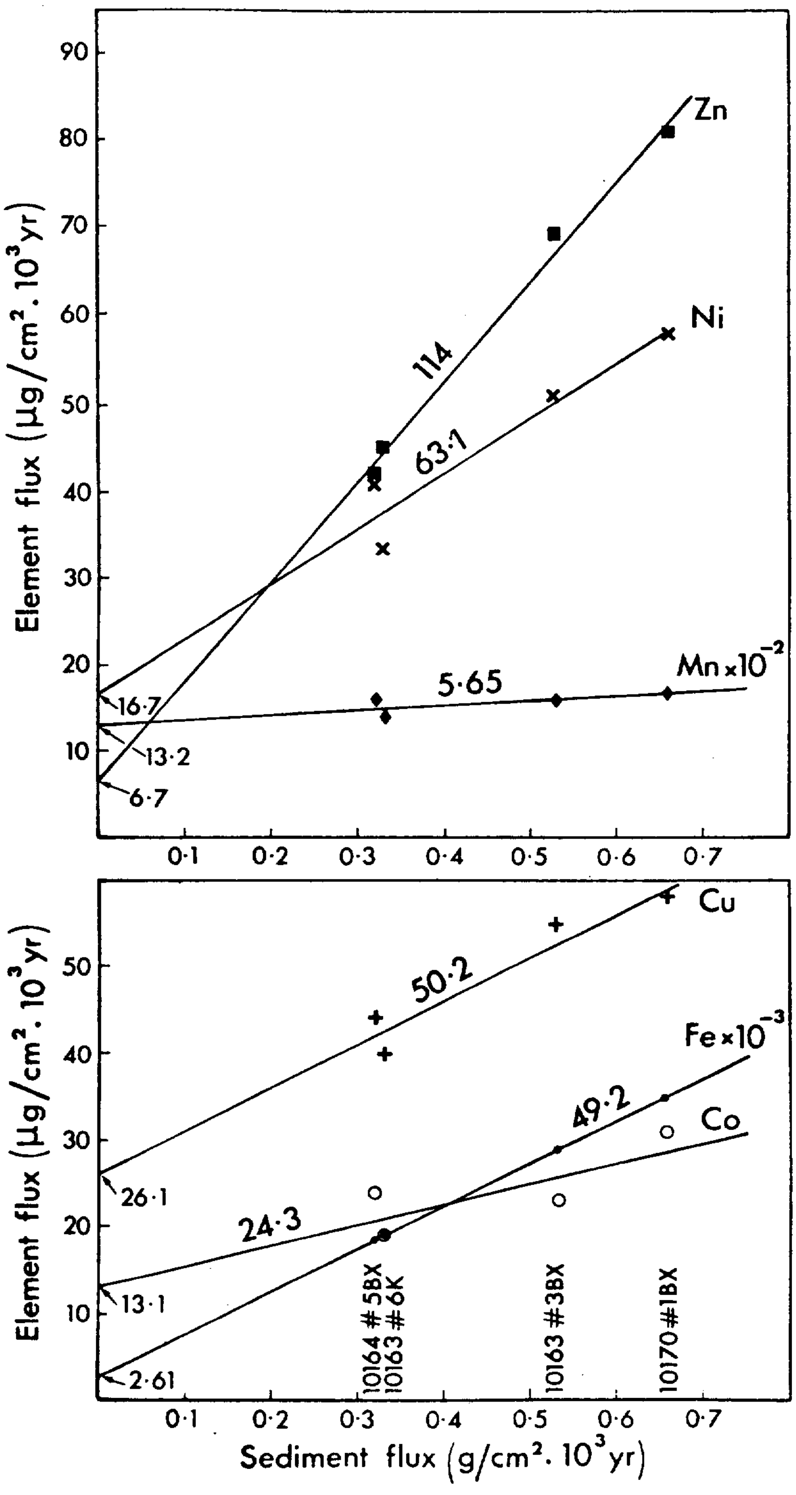


Fig. 7

Illustration of a model used to resolve the different components which comprise sediments. The model uses element concentration data and associated $^{230}Th_{excess}$ accumulation rates. The matrix concentrations of six transition elements (slope values) and of the superimposed hydrogenous fluxes (intercept values) are illustrated for four cores from the Nares Abyssal Plain. The values so obtained are compared with values from other work in the literature overleaf.

Comparison of estimated (i) pelagic brown clay detrital compositions and (ii) hydrogenous fluxes, of V, Mn, Fe, Co, Ni, Cu and Zn.

(i) Detrital compositions (p.p.m. by weight)

Element	Nares A.P. brown clay	Nares A.P. grey clay[a]	Bermuda Rise (GPC-5)[b]	North Atlantic average[c]	Pacific[d]	Average shale[e]
V	157±11	157	-	-	-	130
Mn	570±360	1100	600±300	582	2087	850
Fe ($x10^{-3}$)	49.2±1.2	51.8	51±3	-	38-43	68
Co	24 ±13	27	23±2	12	31-48	19
Ni	63 ±15	60	66±4	63	51-92	68
Cu	50 ±10	52	36±9	67	169-224	45
Zn	114 ±6	118	124±7	-	-	95

(ii) Hydrogenous fluxes ($\mu g/cm^2 . 10^3$ yr)

Element	Nares Abyssal Plain	Northwest Atlantic (Gulf Stream)[b]	Caribbean[f]	Pacific[d]
V	6±2	-	-	-
Mn	1300±50	4300±1100	-	500
Fe	2600±200	-	-	800
Co	13±2	7.2±5.7	7.4	5
Ni	17±2	46±16	10.7	10
Cu	26±2	76±26	19.2	8
Zn	7±1	17±20	-	-

a. Table X, this work.

b. BACON and ROSHOLT (1982)

c. CHESTER and MESSIHA-HANNA (1970)

d. KRISHNASWAMI (1976)

e. WEDEPOHL (1967)

f. TUREKIAN (1965)

Table 4 A comparison of estimated sediment detrital compositions and superimposed hydrogenous fluxes for Nares Abyssal Plain sediments with literature values.

A desk study has been made of the effects of bioturbation on the sedimentary record, because this results in presence of local channels of significant length. Thdse traces have been found with remarkable frequency but it does not appear at present that their influence on diffusion rates is likely to be significant.

Sampling of sediments, resuspended sediments and pore waters from different sedimentation regimes will continue in the future. One aim is to obtain as comprehensive a geochemical data set as possible on the sediment sections investigated to reduce ambiguity in interpretation. Two cruises are planned for 1982/83 to obtain cores of varying carbonate contents (N.E. Atlantic including areas designated by the Seabed Working Group) and redox potential (E. equatorial Atlantic). These will provide material for chemical and mineralogical characterization, measurement of accumulation rates and behaviour of U and Th, studies of diffusion rates and ion exchange capacity. Particular attention will be paid to the temporal stability of the redox and pH properties with the aim of defining the envelope of conditions which will be carried out on longer cores when these become available.

Studies of the association of trace metals with sediment components, using selective leaching techniques, are also being carried out at IOS. This work is not part of the RWD programme but will produce relevant information.

Contact has been established with workers at Imperial College, London, University of Manchester, AERE, Harwell and the International Laboratory of Marine Radioactivity, Monaco. Sediment samples will be supplied to these laboratories as required.

D. CHEMISTRY OF SEDIMENT PORE WATERS

This work is done for obvious reasons in close conjunction with the study of sediment chemistry and mineralogy. Because of the rapid changes known to occur in several pore water constituents on retrieval from the sea floor, it has, however, required development of its own in situ experimental systems and shipboard and laboratory study methods. Developments have included an in situ pore water sampler for studies of dissolved gases and major constituents involved in the carbon dioxide system. A second in situ pore water sampler suitable for collecting samples for studies of trace levels of transition elements involved in the oxidation/ reduction system is nearing completion.

The interpretation of Nares Abyssal Plain sedimentation reported above is supported by corresponding fluctuations in the pore water data from the same cores. Manganese and iodide/iodate ratios in the pore waters indicate mildly reducing conditions at a depth (10-25 cm) corresponding to an estimated burial age of 2-5 x 10^4 years and at one station clear non-steady state effects, which have been interpreted in terms of an organic-rich source at depth, were observed. It should be emphasized, however, that operational constraints prevented sampling in areas which have been identified subsequently as most suitable on the basis of geophysical measurements.

Laboratory studies of diffusion in plugs of sediment and on the determination of ion exchange capacity have been carried out. The former have been directed mainly at gaining experience necessary for designing future experiments while the latter will form part of our routine screening of sediments.

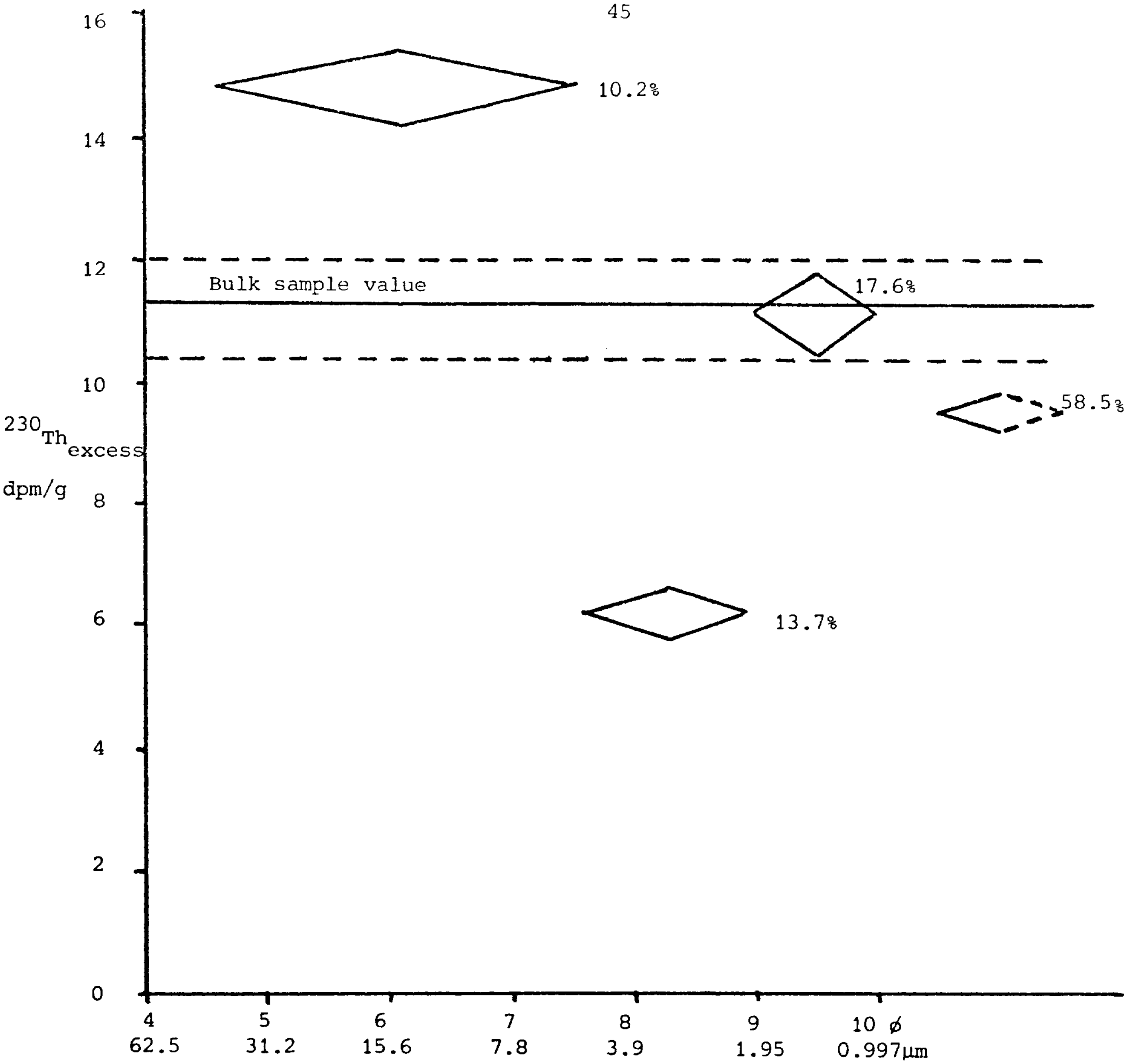
E. NATURAL RADIONUCLIDES IN SEDIMENTS

The use of natural radionuclides to determine sediment accumulation rates has been mentioned above, and it is this information which allows estimation of metal and mineral fluxes to the sediments from measured concentrations. Their behaviour is also studied as a analogue of that of the actinides likely to be present in waste.

Examination of uranium and thorium isotopes in four size fractions separated from bulk samples of Nares Abyssal Plain red clay of an inferred pelagic character revealed no clear relationship between specific activity and particle size (surface area). Similar work is planned on a different type of red clay from the Cape Basin whose accumulation rate has been determined for this purpose. Work has also commenced on a core from the Cape Verde Abyssal Plain area. This core shows a red clay overlying two separate carbonate-rich turbidites which are difficult to account for at the depth (6 km) and from the perceived topography. Besides determination of clay accumulation rate, work has concentrated on the possible geochemical controls operative on a marked (x8) uranium enrichment at the interface between the upper and lower turbidites.

F. CHEMISTRY OF SUSPENDED SEDIMENTS

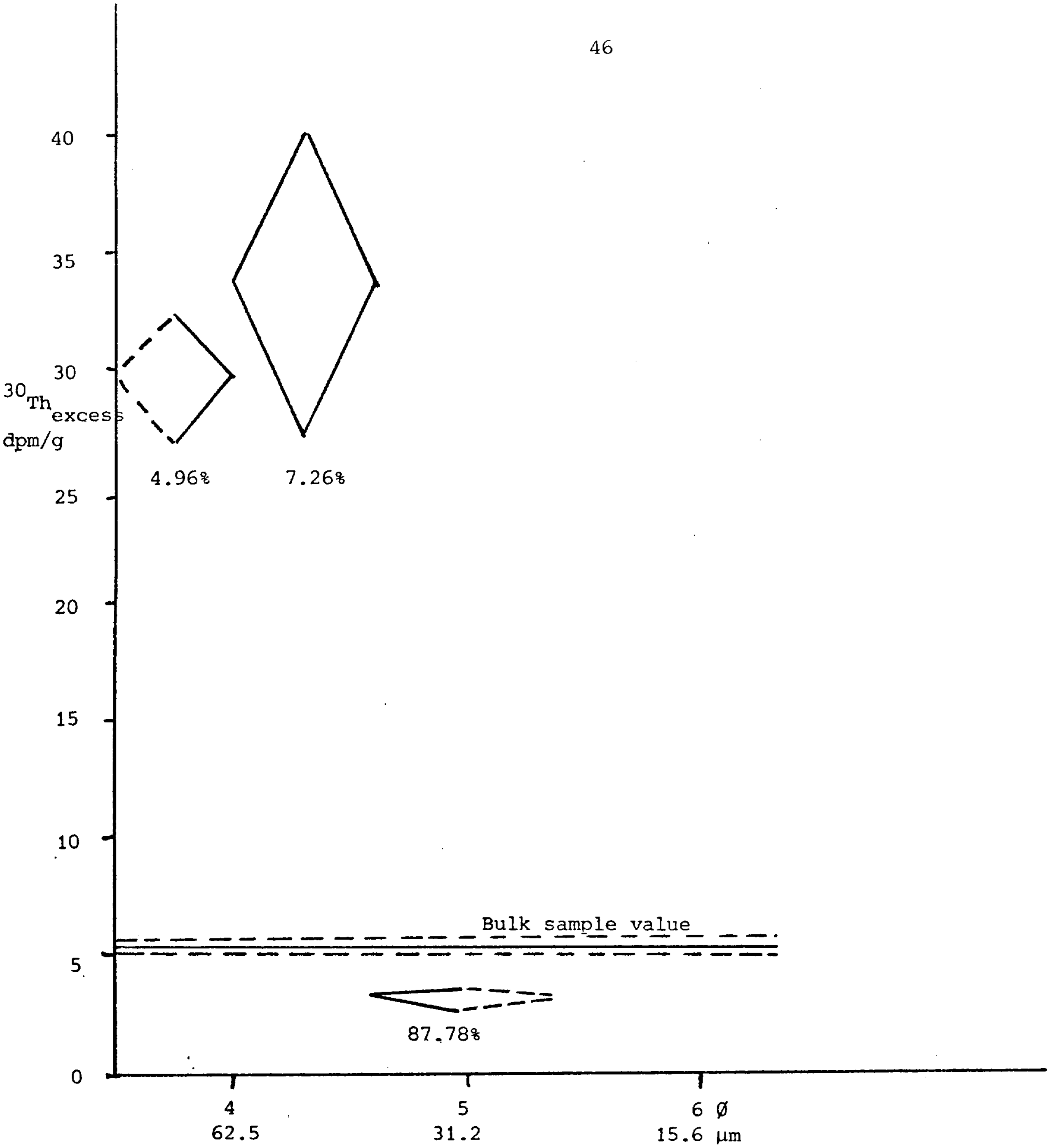
Work during the first year of this project has concentrated on the development of an instrument capable of *in situ* filtration of the particulate material in seawater at all depths, and on methods for analysis of the recovered particulate material. The greatest effort was devoted to one design, construction and testing of the *in situ* filtration system. This device incorporates sensors for several seawater parameters which transmit back to the ship on an outboard cast, thus allowing selection of depths for filtration on the inboard cast. Its first deep sea deployment on *Discovery* Cruise 125 was technically successful and particulate samples from a wide range of depths were obtained. These samples are now being examined by a variety of chemical and electron microscope methods.



Size fraction µm	Percentage of total sediment	^{230}Th contribution (dpm/g) from each size fraction
5-40	10.2	1.51±0.06
2-5	13.7	0.85±0.05
1-2	17.6	1.95±0.12
<1	58.5	5.56±0.18

Diagram to show $^{230}Th_{excess}$ measurements on size separated fractions from a sample taken from 38-48cm in core 10163#6K from the Nares Abyssal Plain. The proportions of the total sediment made up by the different size fractions are shown, as is a $^{230}Th_{excess}$ value (with error) for the bulk sample. A mass balance is calculated for the total sediment from the size fraction data.

Fig. 8



Size fraction µm	Percentage of total sediment	^{230}Th contribution (dpm/g) from each size fraction
>63	4.96	1.47±0.14
40-63	7.26	2.45±0.3
<40	87.78	2.94±0.14

Diagram to show $^{230}Th_{excess}$ measurements on size separated fractions from a sample taken from 25-52cm in core 9940 BX from the Cape Basin. The proportions of the total sediment made up by the different size fractions are shown, as is a $^{230}Th_{excess}$ value (with error) for the bulk sample. A mass balance is calculated for the total sediment from the size fraction data.

Fig. 9

3. BIOLOGICAL TRANSFER

OBJECTIVE

To identify and if possible to quantify potential biological transport routes by which radioactive material might move from the sea bed to the surface.

INTRODUCTION

The work is divided into two areas, each dealing with quite different kinds of animals in quite different environments and each studied with different methods and apparatus. 'Midwater' work is concerned with the animals that float or swim in the main body of the ocean free from the sea floor, for the most part being independent of any substrate throughout their lives.

'Benthic' work is concerned with the animals living on or in the sea floor which are dependent on a substrate for all or at least most of their lives.

That these two divisions have common ground is implicit in the contract objective and the relationship between benthic and midwater organisms is an essential part of the study. However, it has so far been convenient to consider the work under the two headings 'midwater' and 'benthic'.

At the outset there was some background information available. For example it was known that certain biological pathways existed which transferred material from the seabed to the sruface even in oceanic cepths; it was believed that the amount of material so transferred was small.

The midwater work has as its objectives to determine whether there are other pathways, undetected at the outset of the contract, how much material is transferred and how long the transfer processes take.

It was accepted that, however small the transport might be it could, in the event of radioactive materials being transferred to the surface, be significant in causing concern to the public and that the mechanisms and quantities should be understood so as to be able to allay any concern.

The benthic part of the contract also began with a certain amount of existing background information. It was already known, albeit in rather vague terms, that the biomass varied considrably from place to place, both on a scale of metres and on a scale of thousands of kilometres. It was known that large mobile animals, apparently scavengers, existed even at abyssal depths. It was known that a potential ladder existed in certain slope regions which might transfer materials from the sea floor in abyssal depths to the shallow seas of the continental shelf.

The benthic work aims to determine the biomass of the larger benthic organisms, which have not been much studied previously, the rates of movement of these organisms, their reproductive strategies and their trophic relationships.

Much of the contract work fits very closely with the science vote programmes, and both support each other. Nevertheless, the needs of the Department had called for more and earlier emphasis on the quantitative rather than the qualitative aspects whereas in the normal way both aspects would have been given equal importance. To understand food webs it is of course essential to know precisely what species are involved and although this does not necessarily mean all the species present it is likely to take longer, for this as well as for other reasons.

Midwater Work

There are several ways in which material could be transferred by biological means from the sea floor to the surface. An organism can swim or float up directly to the surface and indeed a number do so as part of their life history. The young of several species of fish and the larvae of some echinoderms and some coelenterates are examples. More examples have come to light since this study began and undoubtedly the catalogue is far from complete. We do not have any idea of the amounts of biomass involved, though clearly it is small compared with that normally resident in surface waters, nor of the time taken except to say it must, by analogy with known life histories of similar organisms, be in the order of days or perhaps one or two weeks rather than months or longer.

Another way involves transfer of prey to predator via a ladder of vertically migrating organisms. This method could potentially move a much larger biomass since, at least in the top 1000m or so, a large number of species are known to be migrating daily over considerable ranges. Work at IOS over the last fourteen years or so has investigated the uppermost 1000m in great detail and as the technical capabilities of the sampling improved the investigations were extended to depths of 2000m and occasionally 2500m. Work has now been extended to the sea floor at depths down to 4000m (the limits of the trawl warp available) and biomass measurements made (1). These show that the biomass between 2500m and the sea floor is small in comparison with the biomass above that depth. Only a few observations have been made below 2500m and these are not at present sufficient to examine migratory patterns if any exist at those depths. A set of repeated observations was therefore made at a depth of 1000m over two days to try to detect migratory behaviour and to try to determine the significance of single observations. The results (2) suggest that little migration took place beyond that depth and that the samples did not show much variability. Subsequent work has demonstrated daily migration between 1700m and the near surface in at least one species of fish and it has been suggested that some vertical migration may be taking place below 1000m which would not be detected by the analyses we are able to make.

As a result of the contract work on the deep water column a further transport mechanism has been detected. Occasionally large benthic organisms have been caught in midwater at depths between 1500m and the sea floor; although the occurrences are few the number of net hauls from these depths are few also. It is impossible at present to specify the reasons for these occurrences of benthic animals or to say if any midwater animal could prey upon them and so initiate a further upward transport. It is hoped that more evidence will be collected in the future sampling programme due to begin in late 1982.

One further route which needs to be considered is that due to daily migrators in depths of about 1500m or less reaching the sea floor, certainly we have demonstrated that benthic fish at these depths feed largely on such organisms and it has been shown that some midwater organisms prey on benthic organisms. For this route to be of any importance to the RWD investigations horizontal transport along the sea floor has to be assumed or demonstrated.

Benthic work

There are a number of ways in which the animals on or in the sea floor can be important to waste disposal. For example, they could be a stage in the path to upwards transport through the water column and they can be a way of dispersing materials horizontally along the sea bed either by direct migration or by the agency of large mobile scavengers.

Whereas the science vote supported benthic programme at IOS sets out to discover as much as possible about the ecology of the benthic region, the contract work has concentrated on three aspects, the macrofaunal biomass, the rates of movement of animals and the relationship between sledge catches (made as part of the science vote work) and photographs taken during these hauls by a sledge mounted camera. The last is an attempt to see if camera surveys could be a cheaper substitute for the use of catching devices as a way of quantifying the nature of benthic communities.

Published estimates of the biomass of the deep sea benthic fauna have been in terms of wet weight. This is an unsatisfactory measurement for comparative purposes because of substantial differences in the water and ash content of different animals. A programme was therefore started using the epibenthic sledge to obtain estimates of the biomass of macrobenthic invertebrates in the Porcupine Sea Bight which would demonstrate real differences between stations at different depths and between taxonomic groups. It is significant that the preliminary results show a big decline in biomass at about 2000m, which is the depth where a similar decline occurs in the midwater fauna.

Work on the rates of movement of animals has involved an autonomous camera system 'Bathysnap', six successful casts have been made so far with this gear at depths between 512 and 4009m and the results are being analysed. The apparatus photographs $2m^2$ of sea bed every sixteen minutes as well as recording temperature and current speed and direction. Megabenthic animals are present on many of the photographs and from several series of frames rates of movement have been calculated and behaviour observed.

A paper is in preparation describing the gear with a note on the foraging behaviour of a decapod *Glyphocrangon sculpta*.

Work on the sledge photographs has continued and has now reached a stage when a general assessment of the value of the method can be made. A comparison between the organisms seen in photographs and those present in simultaneous net catches has been made. (3). From this some of the shortcomings of the purely photographic survey can be seen. A brief report (not intended for publication) has been written on the use of transect photography. This suggests that if the frame capacity of the camera was increased and if some net samples were used to obtain 'ground truth' the photographic survey method might have value perhaps for monitoring an already surveyed area, and for determining localised distributions of easily seen and easily identified animals.

The use of the sledge mounted camera will be continued and there can be no doubt that useful information will be gained from it.

Summary

1. One new biological pathway from sea floor to surface has been observed.
2. The relationship between biomass and depth has been quantified albeit for a rather small number of samples.
3. It seems unlikely that diurnal migration occurs at all below 1700m and very little can be observed at 1000m.
4. The reliance which can be put on single samples at 1000m and below has been established.
5. The megabenthic biomass of a small series of samples has been measured by the dry weight method.
6. The rates of movement of some benthic animals has been directly measured.
7. Some measure of the reliance which can be placed on purely photographic surveys of the benthos has been made.

4. STUDIES OF THE BENTHIC BOUNDARY LAYER

OBJECTIVE

To examine the processes which control the characteristics of the benthic boundary layer and would control the dispersal of dissolved radioactive material released into it.

A. PHYSICS OF THE BENTHIC BOUNDARY LAYER

and

B. NEAR BOTTOM FLOATS

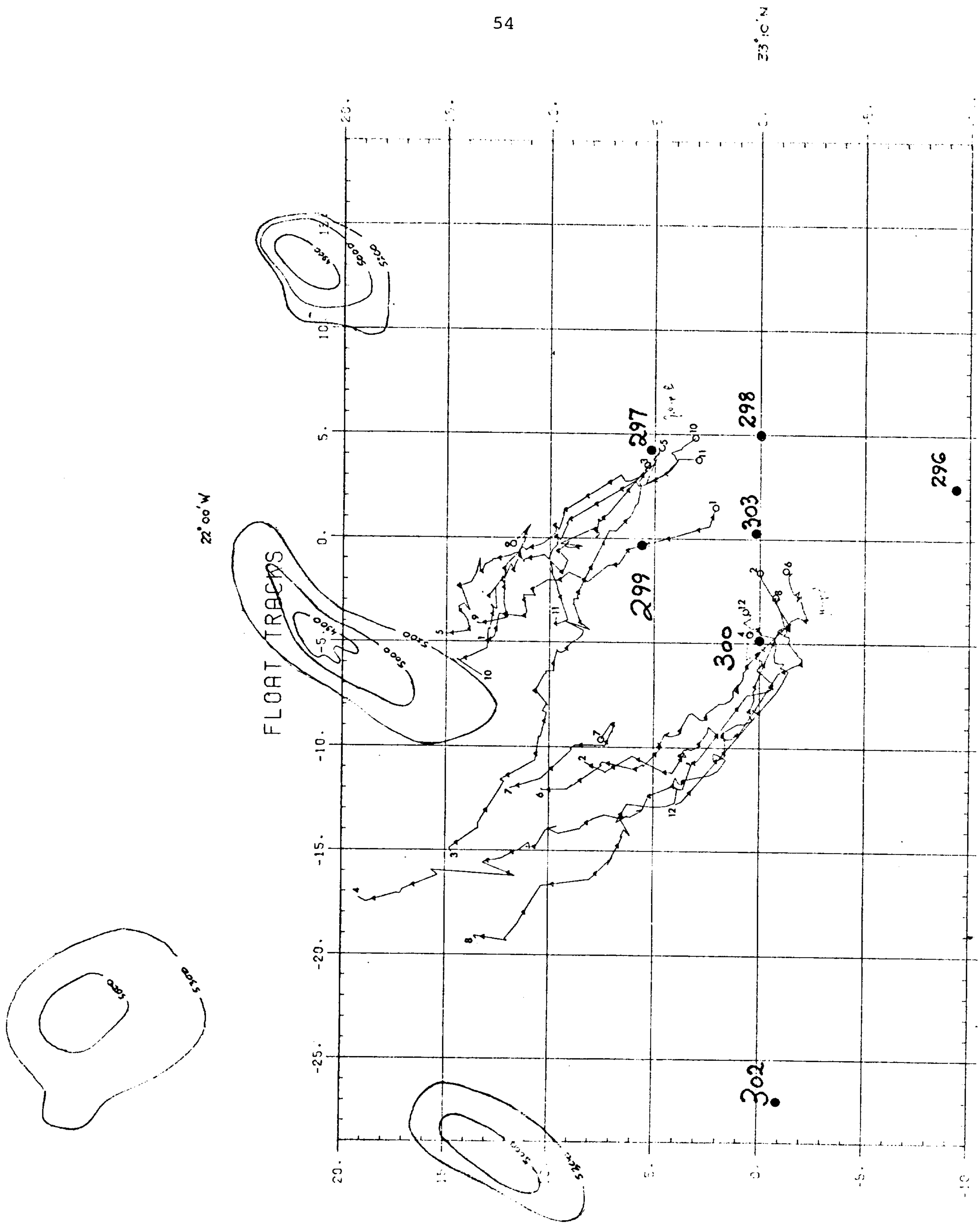
INTRODUCTION

The benthic boundary layer is a layer of water, typically 100-200m thick, immediately above the sea bed. It is stationary at the bed and moves with velocity and turbulent characteristics more nearly approaching those of the main flow as distance from the bed increases. The shear within it will cause dispersion of any dissolved material: it is necessary to know and understand the turbulent mixing processes within it in order to estimate its capability for initial dispersion of possibly highly concentrated released material.

Work at sea and analysis of the results

The principal experimental methods for studying the turbulent structure are neutrally buoyant floats, current meters and lowered profilers (CTD) and specially developed apparatus for near bottom measurements.

On Discovery Cruise 117 (January/February 1981) a float cluster experiment was performed near 33'N 22^{o}W. Two small clusters of floats (not echosounding) were released, both about 5000m depth, 300m above the bottom, and tracked for 10-17 days. Average dispersion rates of .1 to .3 km/day were measured for separations of 2-5 km, representing the first such measurements (20)



Constant depth float tracks superimposed on the bathymetry of the Madeira abyssal plain. Floats were near 5000m, approximately 300m above the bottom, and in 15 days their r.m.s. separation increases by a few kilometres.

Fig. 10

Measurements with a salinity and temperature profiler have revealed the presence of recently mixed water in the lee of abyssal hills[21]. This is seen to be a potentially important agent for transferring material out of the benthic boundary layer into the deep ocean interior.

Current measurements from the same abyssal areas made on a Science Vote project have been analysed. Space-time correlations have been deduced and the spreading of fluid particles inferred. Since the current records exceed 200 days duration, dispersion estimates have considerable statistical weight: in the mean we find particles with 3 km separation spread at rates of somewhat less than 0.1 km/day.

A benthic tripod that carries a current meter and a camera system was launched into water more than 5,000m deep on the Madeira Abyssal Plain during November of 1980 and recovered in Discovery Cruise 117. The peak current during the 64 day experiment was only 7.5 cm/s, and the currents were below the threshold of the current meter (1.3 cm/s) for almost 50% of the time. A demodulation technique was used to separate the flow into tidal, inertial and low frequency components, giving mean amplitudes of about 3 cm/s, 2 cm/s and 1 cm/s respectively. The temperature increased steadily by about 10 millidegrees during the measurement period, although there were frequent sudden changes of 2-3 millidegrees which suggested the advection of benthic fronts past the tripod. Detailed examination of one front showed it to have a horizontal thickness of a few hundred metres and the maximum gradient across the front to be of the order of 25 millidegrees/km. The tripod also carried a time-lapse 16 mm camera with flash unit to determine the character of the sediments and to look for evidence of bioturbation. No sediment movement due to the action of the currents was observed; however, although only one digging event was photographed, the sediment surface showed signs of bioturbation.

A mooring containing 5 Vector Averaging Current Meters at heights 10,20,30,50 and 70m above the bottom was deployed on the Madeira Abyssal Plain during the January cruise and recovered during July of the same year. Analysis of the records has so far shown little variation of the currents over this depth range although the currents were stronger than those recorded earlier by the benthic tripod. The peak flow reached a maximum of about 10 cm/sec, of which about 5 cm/sec was contributed by the low frequency flow. The tidal component had an amplitude of 3-6 cm/sec, and the inertial flow an amplitude of around 2 cm/sec. Work is now in progress to look for vertical phase differences in the flow structure, and to examine the vertical temperature variability.

Instrument development

For this program a new generation of echosounding floats has been developed, tested and constructed: along with range they telemeter height above bottom to a listening ship.

Development of BENCAT (an instrument to measure BENthic Currents And Temperatures) took place during most of 1980 with tank tests of the sensors being done in the first half of the year and shallow water trials taking place in the second half before the system went to sea for deep water trials in April of 1981. Unfortunately, although the instrument was successfully launched into water 4,000m deep near the Mid-Atlantic Ridge, it could not be recovered and attempts to drag for it failed.

A Mark II BENCAT has been designed and a 1/4 scale model tank tested.

A thermistor chain is being developed to measure the temperature at 20 depths within the benthic boundary layer. An initial version, which measures at 10 depths, is now nearly complete.

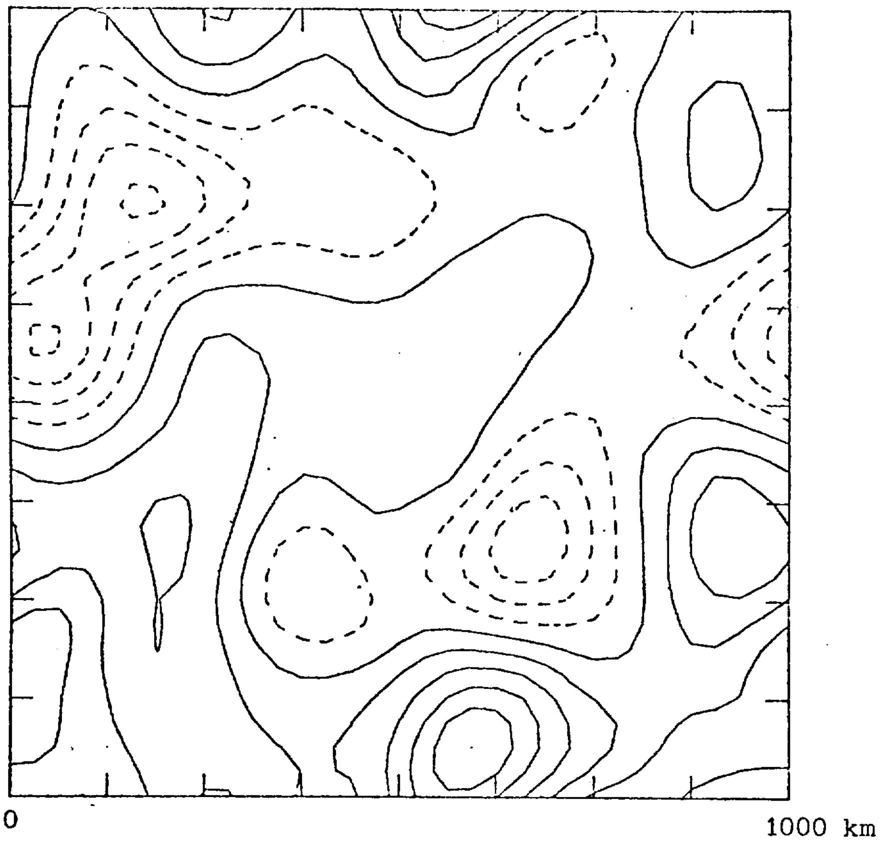
C. MODELS OF THE BENTHIC BOUNDARY LAYER

The object of this project is to investigate theoretically the physical processes on the benthic boundary layer that may be important in the dispersion of radioactive material. The work to date has concentrated on providing theoretical models to assess the importance of different physical processes in determining the height of the boundary layer and the horizontal transport of material within and above this layer.

To investigate the relevant length and time scales that are important in the development of the boundary layer a horizontally homogeneous one-dimensional model of a tidally driven boundary layer has been developed. The results of the model have shown when particular methods of modelling the turbulence within the layer are appropriate and how quickly the layer will reach an equilibrium height. The model suggests[17] that even in the eastern Atlantic basin, where near the bottom the stratification of the water column is slight, this small amount of stratification has a significant effect on the development and expected height of the boundary layer. The time scale for the development of the layer is found to be of the order of 10 days.

A major influence on the dynamics of the boundary layer on horizontal scales of 100 km or less, and a factor which makes the comparison of the one-dimensional model with observation difficult, is the forcing due to mesoscale eddies. The eddies will distort the height of the boundary layer and will advect material within it. These effects are being investigated using a two-layer quasi-geostropic ocean model which incorporates a simple boundary layer model that includes the limiting effect of stratification on its height. A linear stability analysis of the system has been carried out[18,19] and it has been found that the specification of the boundary layer can have a surprisingly large influence on the dynamics of the ocean as a whole.

a



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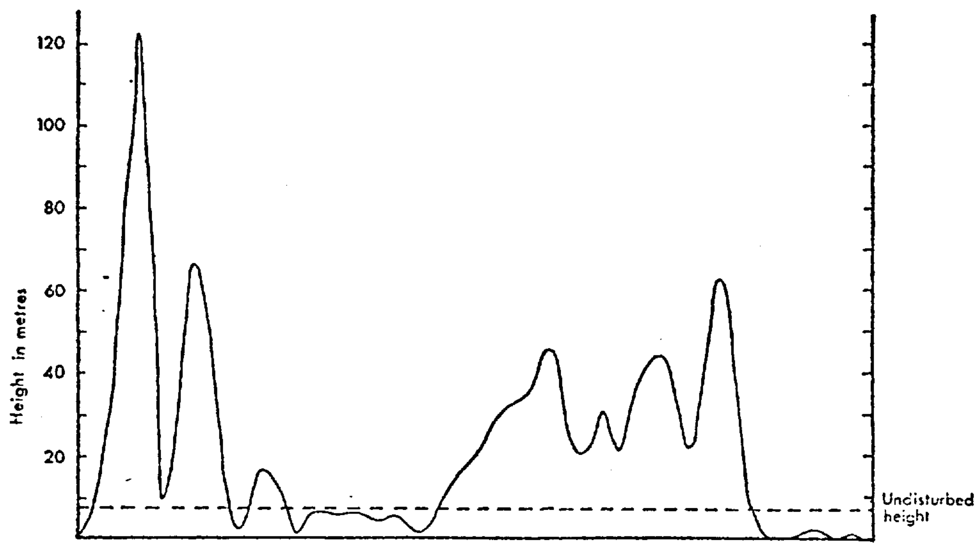


Fig. 11

Model results for the benthic boundary layer.

(a) Flow above the boundary layer is parallel to contours and anticlockwise around dashed vortices: velocities average 10 cms^{-1}.

(b) A cross section of boundary height beneath flow (a).

When startification limits the height of the boundary layer an unstable mode can exist which may well provide a source for synoptic scale motions within the ocean. In some instances this mode takes the form of a large wave on the boundary layer.

A numerical model has been developed to study the non-linear effects of mesoscale forcing. Tests have been carried out to ensure the model propagates Rossby waves correctly and that the numerical scheme conserves energy and enstrophy. These have proved successful and the model is now ready to use. It is hoped to use the model in the near future to study the dispersion of particles due to mesoscale eddies both within the boundary layer and above it. The statistics of the data obtained from the neutrally buoyant floats and current meter array of the experimental programme can be used as a test of the model, with the model being able to extend these to longer spatial scales and longer times.

5. DISPERSION IN THE DEEP WATERS OF THE EASTERN NORTH ATLANTIC

OBJECTIVE

To understand quantitatively those aspects of the ocean circulation most relevant to dispersion of material released into the water. In particular, the capacity of the circulation to advect materials to distant places will be assessed by studying, over a period of several years, the trajectories of a series of constant pressure floats.

Description

This work draws on understandings of the nature of ocean circulation developed over many years, and makes use of longstanding IOS expertise in the design, manufacture and deployment of neutrally buoyant floats to track water movements. It will be done in close collaboration with programmes to be mounted by the Woods Hole Oceanographic Institution, USA, COB Brest, France, and the MAFF Fisheries Laboratory, Lowestoft, and will share logistics and facilities where possible. A member of staff has worked closely for three months with colleagues engaged in the related programmes in the USA where the system was developed.

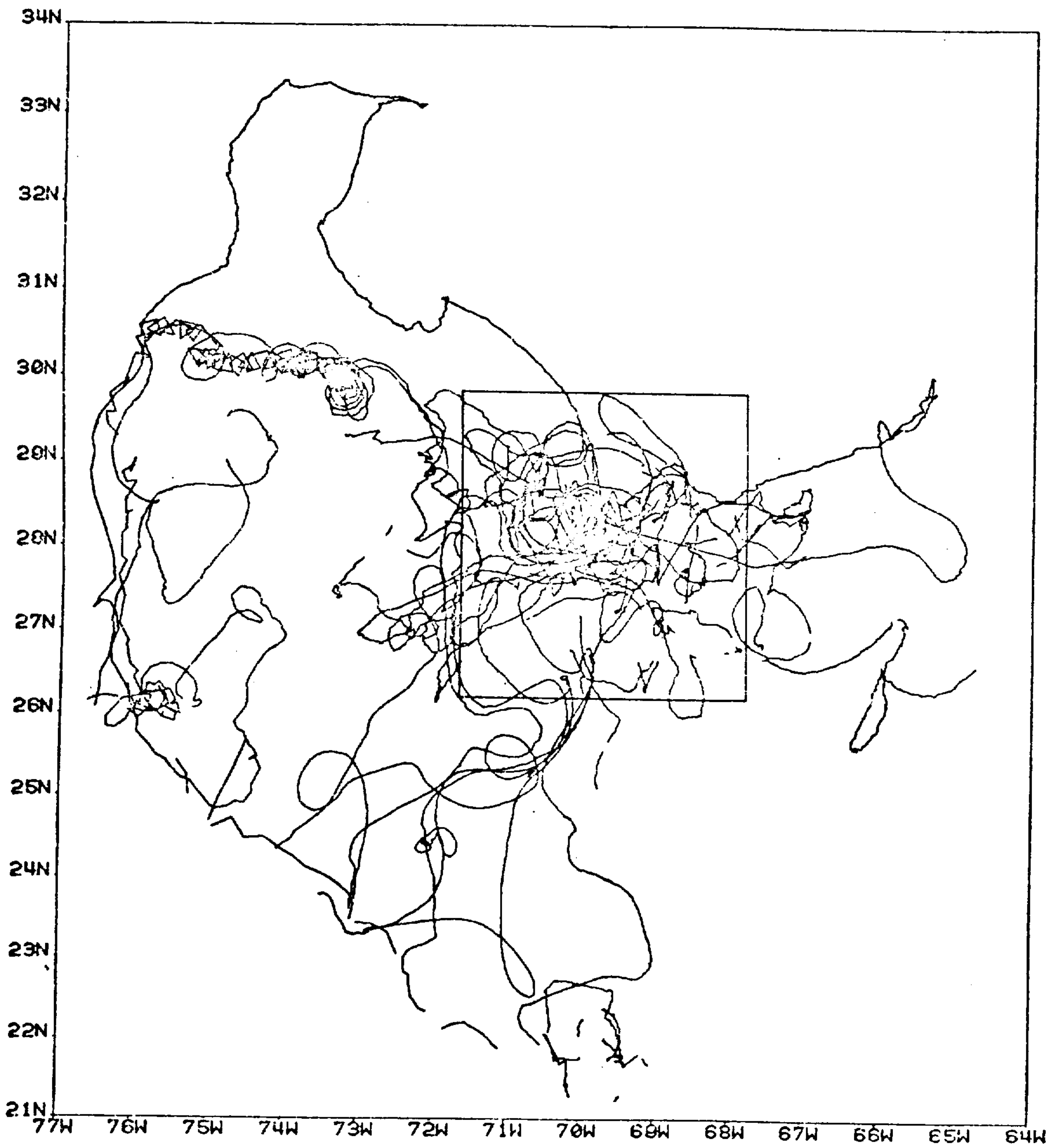
The work commenced during 1981/82 with the assembly of specialised hardware. In particular, four sound sources employing transducers of the same design as will be used in the floats, have been constructed. The sound source design has many similarities with the ultimate float design.

In the summer of 1982 extensive sound ranging trials were carried out using moored sound sources. The results have shown the feasibility of carrying out float tracking at depths of 3500m in the eastern basin of the North Atlantic. This necessary preliminary to the regular deployment of listening stations and floats has shown that acoustic ranges of at least 1000km will be achievable.

A batch of five floats and three listening stations will be built for use in a first tracking experiment in the summer of 1983.

Fig. 12

Tracks of SOFAR floats launched in the thermocline in the NW Atlantic. The period covered is from Sept 1972 to June 1976. The box is 400 km square. Of the 20 floats released in the box in the summer of 1973 ten persisted to the end of that year, six to the end of 1974 and 3 were still working in 1976. The picture shows large scale dispersion and a general westward advection.



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