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DEEP SEA WASTE DISPOSAL

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OCEANOGRAPHY

related to

DEEP SEA WASTE DISPOSAL

A Survey commissioned by the Department of the Environment

Institute of Oceanographic Sciences,
Wormley, Godalming, Surrey GU8 5UB.

September 1978

CONTENTS

INTRODUCTION

The Sixth Report of the Royal Commission on Environmental Pollution (Cmnd 6618) recommended that a programme of research is needed to ensure that safe containment for an indefinite period of long-lived, highly radioactive wastes is feasible before a commitment is made to a large scale nuclear programme.

In response to the Commission's recommendations the Government decided to keep open and study further two options for the disposal of waste in the ocean (Cmnd 6820). They are

(i) disposal on the bed of the deep ocean
(ii) disposal within the deep ocean bed.

If either of these options are finally adopted, it is inevitable, in view of the long time scales over which the waste products will remain radioactive, that waste will be released from its primary containment before radioactivity ceases to be a hazard.

If waste material is placed on the bed of the deep ocean release will be directly into the seawater, through which the radionuclides may find a pathway to the marine and terrestrial biota. It is necessary to establish that dispersion and dilution will prevent any unacceptable concentration.

If waste is to be disposed of within the deep ocean bed it is necessary to be sure that any release from the containers will be localised within the sediment barrier for the remaining active lifetime of the waste products at least to the extent that any secondary release to the water will be sufficiently diluted.

Whichever option is chosen, accidents that could result in release to the seawater may occur during transport and emplacement of the waste containers. It must be established that any such release will be sufficiently diluted.

Research will be needed before any of these conditions can be satisfied. Preparation of this document was commissioned by the Department of the Environment as a step in defining the necessary programme. It attempts

a) to summarize the present state of knowledge of the deep ocean environment relevant to the disposal options and assess the processes which could aid or hinder dispersal of material released from its container.

b) to identify areas of research in which more work is needed before the safety of disposal on, or beneath, the ocean bed can be assessed.

c) to indicate which areas of research can or should be undertaken by British scientists.

The report is divided into four chapters dealing respectively with geology and geophysics, geochemistry, physical oceanography and marine biology. The chapters were written separately by different authors, or groups of authors, specialists in the different scientific fields.

Each chapter commences with a summary of its objectives and conclusions, provides a review of present knowledge in its particular discipline, and ends with recommendations for the research needed to assess the feasibility of the disposal options. Whilst intended to be a fairly complete survey of past and present research developments, the report naturally covers only work of which the authors were aware during the short period in which the reports were prepared, and they apologise to those whose research has been overlooked. References are given at the end of each chapter. The rapid rate of increase in relevant research and understanding is reflected in the number of references to work published in the present decade.

Naturally the approach to the problems and questions raised regarding the feasibility of the oceanic disposal options is different in the various chapters. Nevertheless, it should be appreciated that there is much common ground, especially among the recommendations for research. Some of the research in each of the four areas of science will rely heavily on information from research in the other fields of study.

The need for an increased research effort

Work in connexion with deep ocean waste disposal will be intimately related to other oceanic research undertaken for practical purposes or in quest of scientific understanding.

Many of the problems that must be solved before waste can be disposed of in the ocean are of great scientific interest and will undoubtedly be attacked in the course of time. One possible strategy would be to allow the present research effort to proceed, redirecting it where appropriate and possible. This approach may not however fit the timetable for necessary decisions about the future of nuclear power which requires a pilot disposal facility to be in operation by the early 1990s.

Of course scientists are naturally attracted to problems of great practical importance that lie within their sphere of interest and may well redirect their own interests. But the amount of redirection will be limited by a number of constraints, the most telling of which is the small number of people now working in marine science who are qualified to produce useful work in a short time. However hard the scientists try it is unrealistic to expect to achieve the results that are needed in the above timescale.

The only way to achieve what is desired is to expand the applied effort selectively bringing in new people with the right basic skills. This paper attempts to identify scientific projects that could be undertaken by the United Kingdom with this in mind, making use of advanced expertise already present, adding to it where necessary and reinforcing it by selective recruiting where appropriate.

International cooperation

Research by British scientists will depend on, and be closely related to, work being done abroad to the same general end. The United Kingdom is one of a small group of nations with the expertise and equipment to work effectively at sea. All will have to play their part if work on the many problems is to progress satisfactorily. Some types of research require a broad attack by many scientists, so that the same sort of activity will probably be needed in several countries simultaneously. Others require special knowledge or equipment available only in one or two places and are best left to the countries qualified to do them.

If all necessary work is to be done without wasteful duplication but with the required degree of joint effort it is necessary to ensure that there is a well coordinated international programme. Fortunately there are close informal links between ocean scientists the world over which will ensure that all are kept informed of plans and progress.

However, some degree of formal coordination is also necessary and to some extent already exists. Under the auspices of the NEA Radioactive Waste Management Committee, three international workshops have been held in the United States in 1976, 1977 and 1978 to discuss the problems arising from seabed disposal and to highlight the research required. The NEA Seabed Working Group was formed with membership from USA, UK, France, Japan and Canada, and between annual meetings works through correspondence in seven task groups:-

Physical Oceanography
Canisters
Waste Form
Biology
Sediment and Rock
Site Selection
Systems Analysis

The objective of the Seabed Working Group and its Task Groups are to:-

"Provide forums for discussion, assessment of progress and planning of future efforts;

Encourage and coordinate cooperative cruises and experiments among the member nations including the sharing of ship time between experiments from different nations;

Share facilities and test equipment;

Exchange information;

Maintain cognizance of international policy issues."

A restructuring of task groups has been suggested by the Systems Analysis Task Group Meeting in May 1978, together with a systems analysis model of an overall research programme.

These task groups have already provided an invaluable channel for communication on research programmes in other countries and are leading to cooperative research projects and coordinated cruises with the minimum of bureaucracy. Direct contact in this way between involved scientists may well be more productive than intergovernmental agreements.

Research programmes on land disposal and on the sea disposal of low level waste are at present discussed and coordinated through the IAEA and the EEC. However neither of these organisations has yet been active in considering the research required for high level disposal in the deep ocean.

The International Council of Scientific Unions has recently considered (at the 17th General Assembly) a report on the "Question of ICSU involvement in the problem of disposal of nuclear wastes" in which it was proposed to set up a steering committee and a series of working groups on different disposal options including the marine option. Their task would be to study existing and planned research and development programmes and to examine international coordination from a more academic viewpoint. A study group will be set up to explore ICSU's role in this field.

The principal recommendations

The recommendations of this report take into account the need to plan a United Kingdom research programme so as to take advantage of national needs and capabilities and to fit in with the work of other nations.

Each of the four chapters recommends a selective approach to support of research, making maximum use of existing expertise and facilities in government laboratories, universities and elsewhere.

All agree in one way or another that it is possible to identify types of research that will have to be done by any nation that is to be regarded as a serious contributor. This basic element includes the support of techniques needed for a range of research topics and the support of international research programmes aimed at the rapid joint acquisition of basic knowledge about the properties of the ocean and its floor worldwide.

In addition it will be necessary for each nation to carry out specialist or advanced studies, appropriate to its own capability, selected either because the expertise is already available or because expertise can be developed from skills already possessed.

The four chapters each recommend a programme of research for the United Kingdom combining these two sorts of elements. In addition to making a useful contribution to an international effort, the combined programmes should also meet the domestic requirement for the range of skills needed for participation in decision making at all levels and for knowledge about particular disposal areas of practical interest. Furthermore public acceptance in UK of a particular disposal option will require the demonstration of its safety through the advice and expertise of its own scientific community and not be dependent on foreign assessments. The proposed research programmes will create a body of scientists which the public will see to be independent of any nuclear lobby, who have great experience of problems of ocean disposal and who will be able to give such advice.

The principal recommendations chapter by chapter whether specifically included in the proposals for research or referred to in the body of the text, are here summarized and rearranged under basic, specialist or advanced and instrumental headings.

1. Geology and geophysics

a Basic programme

i Reconnaissance surveys (1-49)* of areas of the ocean floor which seem to be of a type that might be suitable for disposal, to determine bathymetry, sediment thickness, morphology of the seabed and nature of the superficial sediments on a regional scale. Estimation of geophysical parameters such as seismicity and heat flow. Some areas for reconnaissance may already be chosen from what is already known, others may come to be considered as more is learned of the processes affecting stability of the sea floor.

* refer to chapter and page numbers in this report.

The programme of reconnaissance surveys is, therefore, likely to be a continuing one; it is best fitted as logistic opportunity occurs, into the national oceanographic programme.

ii Routine sedimentological work (1-51) on ship or shore as appropriate including

Initial core description
Detailed sedimentological core analysis
Dating
Palaeoenvironmental studies
Geotechnical measurements
Heat source experiments

b <u>Specialist or advanced studies</u>

i Sea floor observations. As the problems of seabed disposal become more firmly identified it will be necessary to study certain aspects of the sea bed in greater detail, often using seafloor observations to obtain the required resolution. Topics in which UK might play a leading role or in which the development of a UK expertise is essential include: (1-50 and table 1.3).

Detailed heat flow determinations
Heat transfer experiments
Long term soil mechanics experiment
Detailed studies of local seismicity
Small scale seismic profiling
Detailed acoustic and seismic reflexion profiling using deep towed devices
Bottom photography
In-situ sedimentation studies

More advanced research studies in support of these topics might include work on the mechanisms of heat flow, on the fundamental basis for the soil mechanical properties of deep sea sediment and on the improvement of dating and palaeoenvironmental techniques (1-53).

c <u>Laboratory and field instruments for basic and advanced programmes (1-52)</u>

Because of the volume of work to be done, considerable extension will be needed of facilities suitable for routine work in the basic programme particularly for sedimentological use. This will not necessarily involve the development of novel equipment.

The acquisition of suitable coring and seabed sampling devices will start with purchase of the best available equipment and will lead on to programmes to develop appropriate specialist devices.

Other requirements in the early stages will include acoustic navigation systems for precise location of samplers and other instruments on or near the sea floor, apparatus for heat flow determinations and the improvement of cameras and ocean bottom seismic receivers.

Requirements for the advanced programme will include development of ocean bottom seismic sources, deep towed acoustic and seismic reflexion equipment and the apparatus required for in situ geotechnical measurements and sedimentation studies.

2. Geochemistry

a Basic programme. A general study probably lasting three to five years and including the following elements (2-52).

i Chemistry and mineralogy of sediments; collection and analysis of long core sections; characterisation of modern and Quaternary (glacial) horizons.

ii Accumulation rates of bulk sediments and heavy elements; dating of sediment sections; geological histories.

iii Chemistry of fission, activation product, and transuranic nuclides in the Irish Sea; a basic geochemical study of a point-source "experiment" provided by the Windscale outfall.

iv Chemistry of the pore waters of marine sediments.

b Specialist or advanced studies. These would follow from the basic work and would last at least a further decade.

Exchange properties of marine sediments, using radioactive and stable nuclides.

Behaviour of natural series actinides and lanthanides in marine deposits.

Sediment properties and stability of waste forms under elevated temperatures and pressures; studies of natural glasses.

Chemistry of suspended particles in the deep sea.

Migration in the pore fluid; thermodynamics and speciation of radionuclides.

Laboratory and field experiments on the interaction of transuranic nuclides and natural marine sediments.

Radiation effects on sediments, pore fluids and waste forms.

c Instrumentation

The geochemistry programme will share many of the requirements for new or improved sediment samples of the geology and geophysics programme outlined in section 1.

Special equipment will include traps for suspended particles (2-45), instrumentation for studying the effects of in situ releases (2-46) and equipment to work in the laboratory on the chemical behaviour of sediments at high temperature and pressure (2-44, 2-46).

3 Physical Oceanography

a Basic programme

A contribution by the United Kingdom - which is among the world leaders - to an international study of the abyssal currents and circulation of the ocean. The basic programme will include, at a later stage, studies to determine the potential behaviour of contaminants released at specific sites.

Its elements will include:

i Observation of the large scale current systems using neutrally buoyant floats to estimate long term advection (3-68).

ii Complementary observations using fixed moorings (3-68).

iii Study of mesoscale eddies in the ocean and particularly their effect on the benthic boundary layer (3-28).

iv Theoretical work on dispersal using numerical models (3-69).

v An overview of climatic modelling undertaken as part of the Global Atmospheric Research Project (3-70).

b Specialist or advanced studies

A long term study concentrating on the benthic boundary layer including

i Long term observations at a few sites to determine the turbulent structure of the boundary layer under different mean currents, thermal structure and bottom topography (3-67).

ii Associated numerical modelling.

iii Fundamental studies in the laboratory and at sea of special processes, for example double diffusive effects, likely to affect dispersion (3-22).

iv Fundamental studies in the laboratory and at sea of the stability, erosion and transport of fine grained sediments (3-68).

c Instruments and apparatus

Considerable effort will be required to develop the equipment for making observations close to the floor of the deep ocean. In the early stages this will include both static equipment to measure water movements and temperature and neutrally buoyant floats able to work within a few metres of the bottom. Special attention will be needed to the means of recovering instruments and to the accurate measurements of weak currents under severe conditions (3-61).

The most difficult instrumental development for work on the abyssal circulation will be of a neutrally buoyant float system for use over long time periods to define the mean circulation and diffusion in ocean basins where waste may be dumped (3-68).

4. Marine Biology

a Basic programme

Contributions to an international programme to fill in the most serious gaps in knowledge about the quantitative distribution of organisms in the ocean. Elements requiring UK participation include:

i A sampling and observational programme aimed principally at estimating the heterogeneity in the distribution of benthic and midwater animals (4-39).

ii A sampling programme using techniques developed in the UK to detect diurnal, ontogenetic and feeding migrations of animals below 1000m depth (4-43, 4-45).

iii Study of the statistics of catches and distribution of the larger animals (4-44).

iv Reinforcement of UK capability in taxonomy of deep sea species (4-39).

v Cooperation in an international programme of community analysis and zoogeography (4-41).

b   Specialist or advanced studies

i   Contribution to an international programme of quantitative studies of benthic micro-, macro-, and megafauna and of midwater macroplankton and nekton (4-41).

ii   Study of feeding and reproductive strategies of selected groups where UK has special expertise (4-42).

iii   Detailed study of migrations revealed by the basic programme.

iv   Mathematical modelling of the whole and parts of the oceanic ecosystem.

c   Instruments

The United Kingdom is among the leaders in quantitative sampling methods for deep ocean fauna. Among the systems needing further development are:

i   Longhurst Hardy Plankton recorder - modification to deal with low density of organisms below 600m.

ii   IOS RMT+8 Net. Development of a multiple sampling system to reduce ship time for deep hauls.

iii   Benthic sampling - development of quantitative methods.

CHAPTER 1: GEOLOGY AND GEOPHYSICS

SECTION NO. | CONTENTS | PAGE NO.

CHAPTER 2: GEOCHEMISTRY

CONTENTS

Chapter 3 PROBLEMS OF DISPERSION - PHYSICAL OCEANOGRAPHY

CONTENTS

CHAPTER 4

High level Radioactive Waste Disposal in the Ocean

Marine Biological Research Requirements

CHAPTER 1: GEOLOGY AND GEOPHYSICS

SECTION NO.	CONTENTS	PAGE NO.

SUMMARY

A review of present knowledge in marine geology and geophysics emphasises: firstly, the enormous increase over the past three decades in our general understanding of geological processes in the deep ocean; and secondly, the lack of detailed information with which to answer many of the questions posed by the proposal to embed radioactive waste canisters beneath the seabed.

Only in the past twenty years have abyssal ocean floors been recognised as other than tranquil regions of steady sediment accumulation. Sediment transport and deposition over huge areas of the ocean floor is controlled by bottom-flowing currents. Large-scale erosion of the seafloor also occurs. Submarine sediment slides and slumps can move enormous volumes of sediment on low angle slopes, demonstrating the need for research into earthquake hazard in likely disposal areas.

Practically no in-situ experimentation has been carried out on deep ocean floors; thus our knowledge of the controls on sedimentary processes is severely limited. Similarly there is almost no information on the physical properties of the medium into which the waste canisters might be emplaced. Recent studies have suggested the possibility of convective heat flow through deep ocean sediments, and illustrate the need for an understanding of physical processes within the proposed sediment barrier.

Changes observed in oceanic sediment cores provide a record of past environmental changes averaged over time scales similar to those involved in decay of the radioactive waste. Studies aimed at predicting future environmental changes will require a particularly refined knowledge of the recent history of a disposal location, built from a range of stratigraphic techniques.

We consider that the choice of study areas, and later of possible disposal sites, should rest on site criteria which are continually refined as the research progresses. The prime target of any U.K. research programme devoted to the beneath-the-seabed option should be the evaluation of the sediment barrier in a variety of environments.

Most of the research requirements that we have identified fall within the range of present expertise and technology. They call for a concentration of research effort in a small number of study areas with the emphasis on in-situ experimentation and evaluation of the sediments as a barrier.

1. INTRODUCTION

The purpose of this chapter is to identify the geological and geophysical factors relevant to the disposal of high level radioactive waste beneath the ocean floor. It is assumed that the waste will be processed into canisters and that these will be embedded in the sediments or underlying rock of the ocean floor. Thus a "multiple barrier" concept is assumed. From the geological and geophysical point of view the problem then is: can we predict, from our knowledge of the processes affecting the sediments and rock and from what we know of their physical properties, what will happen to the waste during the ensuing 10^6 years that it takes for the radioactivity to decay to background levels? The chemical aspects of the sediment and rock "barrier" are discussed elsewhere in the IOS Report. Here the factors controlling the effectiveness and endurance of the sediments and rocks as a physical barrier are considered.

No particular method of emplacement of the waste in the seabed is assumed. Although several emplacement techniques have been mooted, the choice of the actual method to be employed can only be made when the effectiveness of the sediment/rock barrier is understood, when the depth to which emplacement is necessary has been determined and when the physical properties of the sediment/rock have been considered. However, physical properties of the sediments and rock relevant to any emplacement process are discussed in this chapter.

Although concentrating on the "beneath-the-seabed" option, this chapter reviews current knowledge of the processes affecting the stability and resistance to erosion of the sediment barrier. Thus, in common with the later chapters, interactions with the overlying seawater are considered. Further studies on these processes are identified as research requirements in the last section.

2. THE GEOLOGICAL ENVIRONMENT

2.1 THE MOVING, COOLING PLATE

Geological and geophysical studies of the ocean floor over the past two decades have established that the older idea of continental drift is substantially true. The new theory of plate tectonics, now just over ten years old, summarises modern ideas about the evolution of the earth's surface. Rather like a cracked egg, the earth's surface is composed of a number of integral pieces or plates. The plates are not stationary, but are constantly moving relative to each other under the influence of forces, not yet fully understood, generated in the earth's interior. The total number of plates is small - there are only about a dozen major plates and a few minor ones - so that the distance across one is typically measured in thousands of kilometres. In contrast, their thickness is only about a hundred kilometres. Nevertheless, because the plates forming the outer hard shell (the lithosphere) of the earth are considerably more rigid than the underlying asthenosphere, they suffer very little deformation within their interior as they move about. However, the boundaries separating the plates are zones of considerable tectonic, volcanic and earthquake activity. So much so that a map of the earth's seismicity (1) is essentially a map of the plate boundaries (2) (Figure 1-1).

Three main types of plate boundary have been identified:

(1) The Spreading Axis - where the plates are moving apart and new plate material is formed by the upwelling of molten rock from within the earth. Because the rocks thus formed are denser and less buoyant than the granitic rocks which constitute the basement of the continents, the spreading axis is almost always found below sea level, except where rifting has just begun beneath a continent, and manifests itself as the axis of a mid-oceanic ridge. The Mid Atlantic Ridge and East Pacific Rise are examples.

(2) The Subduction Zone - where the plates are moving together and one of the plates is destroyed by passing down beneath the other and being assimilated

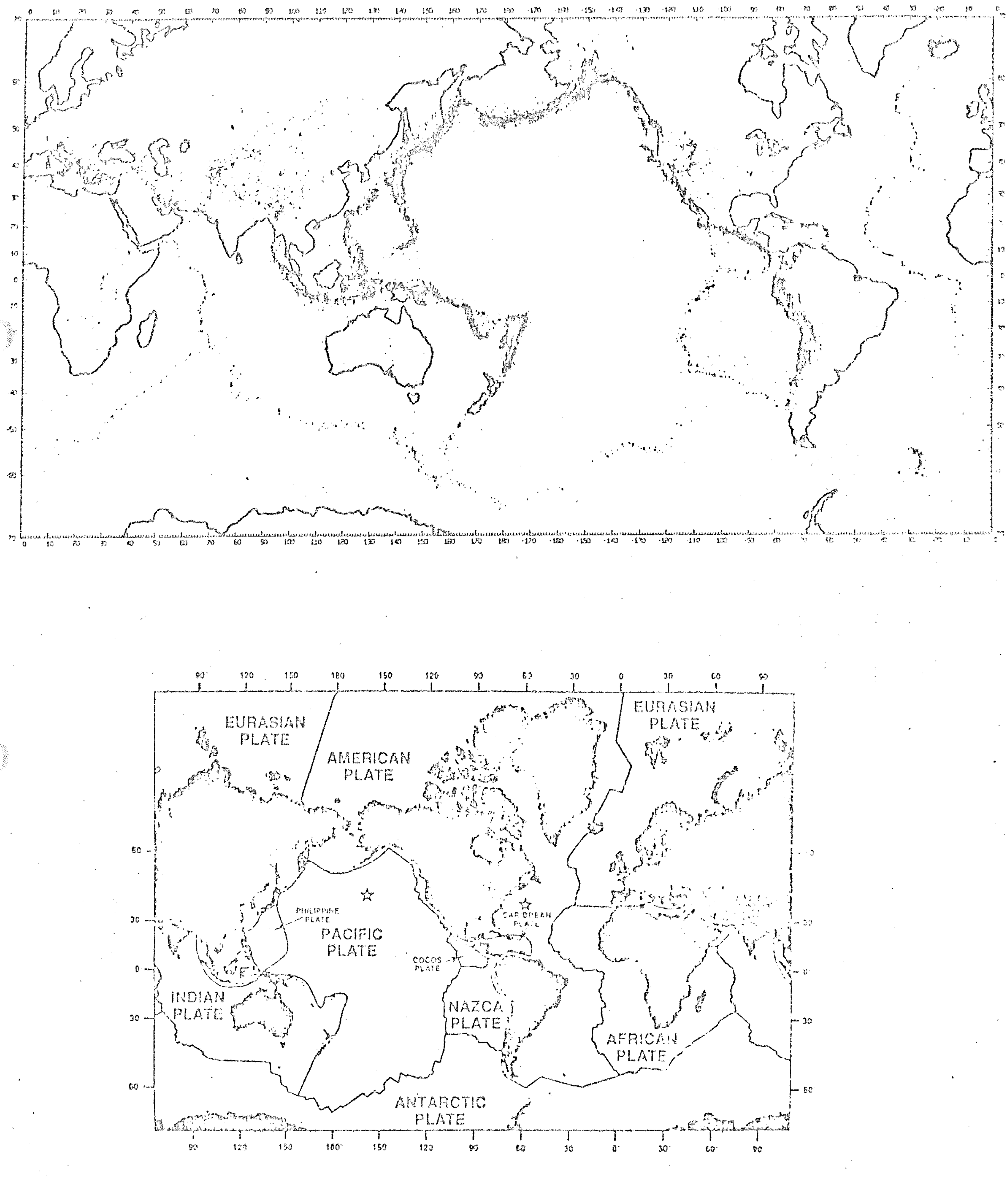


Figure 1 - 1 Seismicity of the earth (after Barazangi and Dorman, 1969) and plate tectonic map (after Hollister, 1977).

into the earth's mantle. Where an oceanic plate collides with a plate carrying a continent, the less dense continental mass remains on the surface while the denser oceanic plate is consumed. This process is taking place along the west coast of South America. (Note, however, that not all continental margins are plate boundaries. Frequently continent and adjacent ocean basin belong to the same plate, for example the eastern Atlantic Ocean south of the Azores belongs to the African plate, and they move together. In this situation the continental margin is called a passive margin (Figure 1-2)).

(3) The Transform Fault - where the plates are moving past each other and plate material is neither being created nor destroyed. Transform faults are found both on the ocean floor and on the continents. The Romanche Fracture Zone offsetting the Mid Atlantic Ridge near the equator and the San Andreas Fault in California are examples.

It is apparent from the above discussion of the processes taking place at plate boundaries that whereas oceanic crust is easily formed and easily destroyed, continental crust - once formed - remains at the earth's surface. Thus the rocks found on the continents, in particular the granitic basement rocks, are in general considerably older than those found on the ocean floor. The oldest rocks recovered from the ocean floor are approximately 200 million years old whereas rocks nearly 4000 million years old have been found on the continents. Furthermore, because, during their long history, the granitic basement complexes of the continents have suffered reworking and metamorphism, no simple pattern can be observed in their age distribution. In contrast the age distribution of the basaltic crust of the ocean floor forms a simple banded pattern, with the youngest rocks observed along the mid-oceanic ridges and the crust becoming progressively older with increasing distance from the mid-oceanic ridge at which it was formed. Only rarely does off-axis volcanism create a seamount or (more rarely still) an island, e.g. Hawaii, to disrupt this simple age configuration.

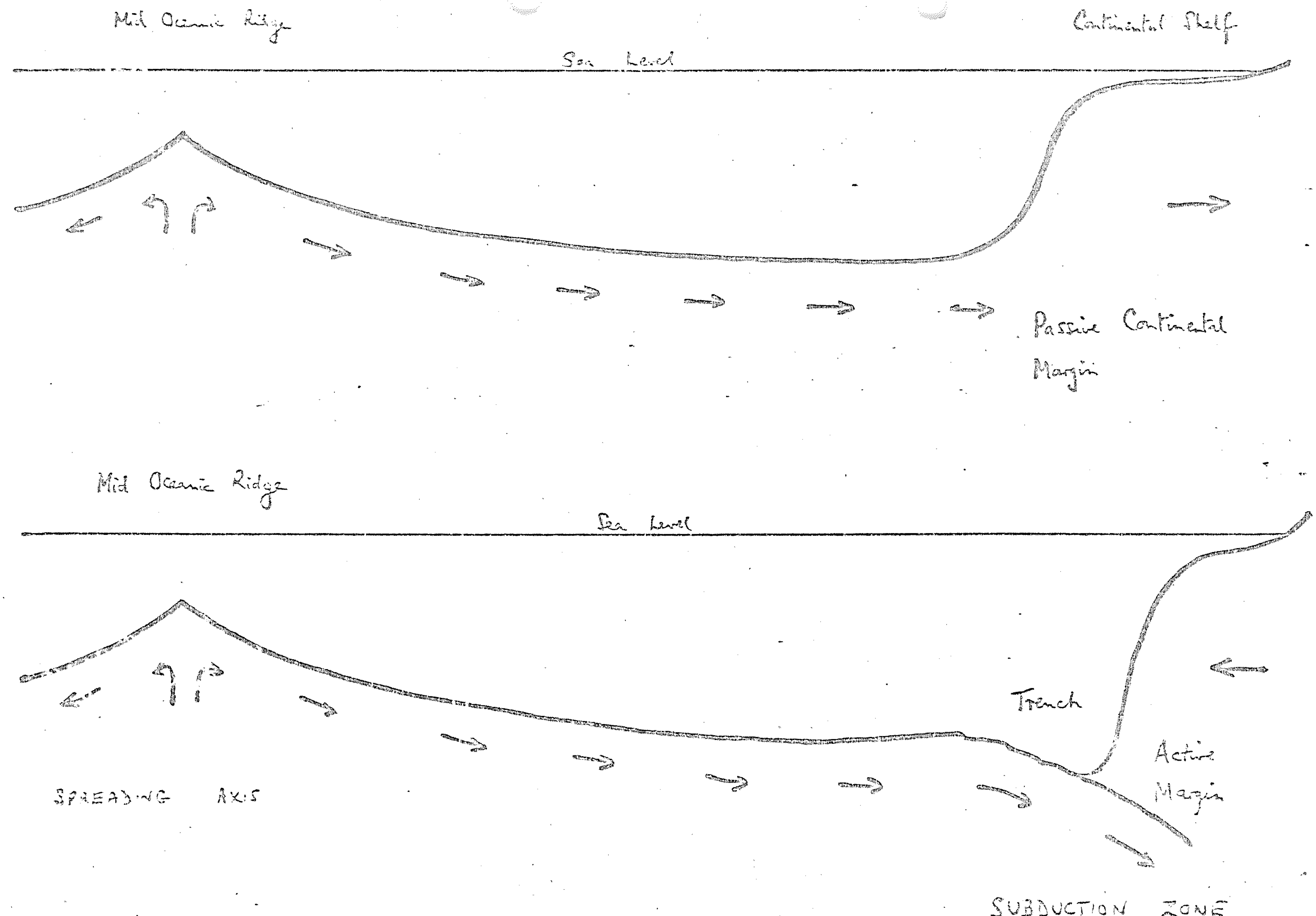


Figure 1-2 Profiles of the ocean floor from ridge to continent.

The simple age relationships of the ocean floor in turn allow simple methods to be used to determine its age. As new oceanic crust, formed from molten rock at the ridge axis, cools, it acquires the magnetization of the earth's field at that time. However, the earth's magnetic dipole, whilst remaining aligned with the axis of the earth's rotation, is known from paleomagnetic studies of rocks on land to change its polarity at intervals of 10^5 or 10^6 years. Thus the magnetized rocks of the ocean floor retain the polarity of magnetization appropriate to the time of their formation. And the moving ocean floor itself has been likened to an enormous tape recorder with the rocks alternately normally and reversely magnetised in bands parallel to the mid-oceanic ridge. These bands of varying magnetic polarity give rise to anomalies in the earth's magnetic field which can be detected by magnetometers towed behind ships or aircraft close to the sea surface/(3)/(Figure 1-3). A sufficiently detailed magnetic anomaly map allows the age of the ocean floor to be determined/(4)/. Understanding how to "read" the oceanic tape recorder was one of the outstanding discoveries of the nineteen sixties.

2.2 THERMAL CONTRACTION OF THE COOLING PLATE

The upwelling of hot molten rock to produce new plate material along the axes of the mid-oceanic ridges implies that the temperature of the newly formed plate is close to the melting point of upper mantle rock under low confining pressures - about 1200°C. As it moves away from the spreading axis it cools through its upper surface - maintained by the ocean at a temperature close to 0°C - and thickens at its lower surface. As the rock cools it contracts, so that the sea depth increases with increasing distance from the ridge axis. It has been found that when the sea depth (strictly speaking the depth to the basaltic basement, corrected for the effect of sediment loading) is plotted against age, all oceans follow a similar relationship. Out to about 70 my (equivalent to a distance from the ridge axis of from 1000 to 5000 km, according to spreading rate) the depth increases

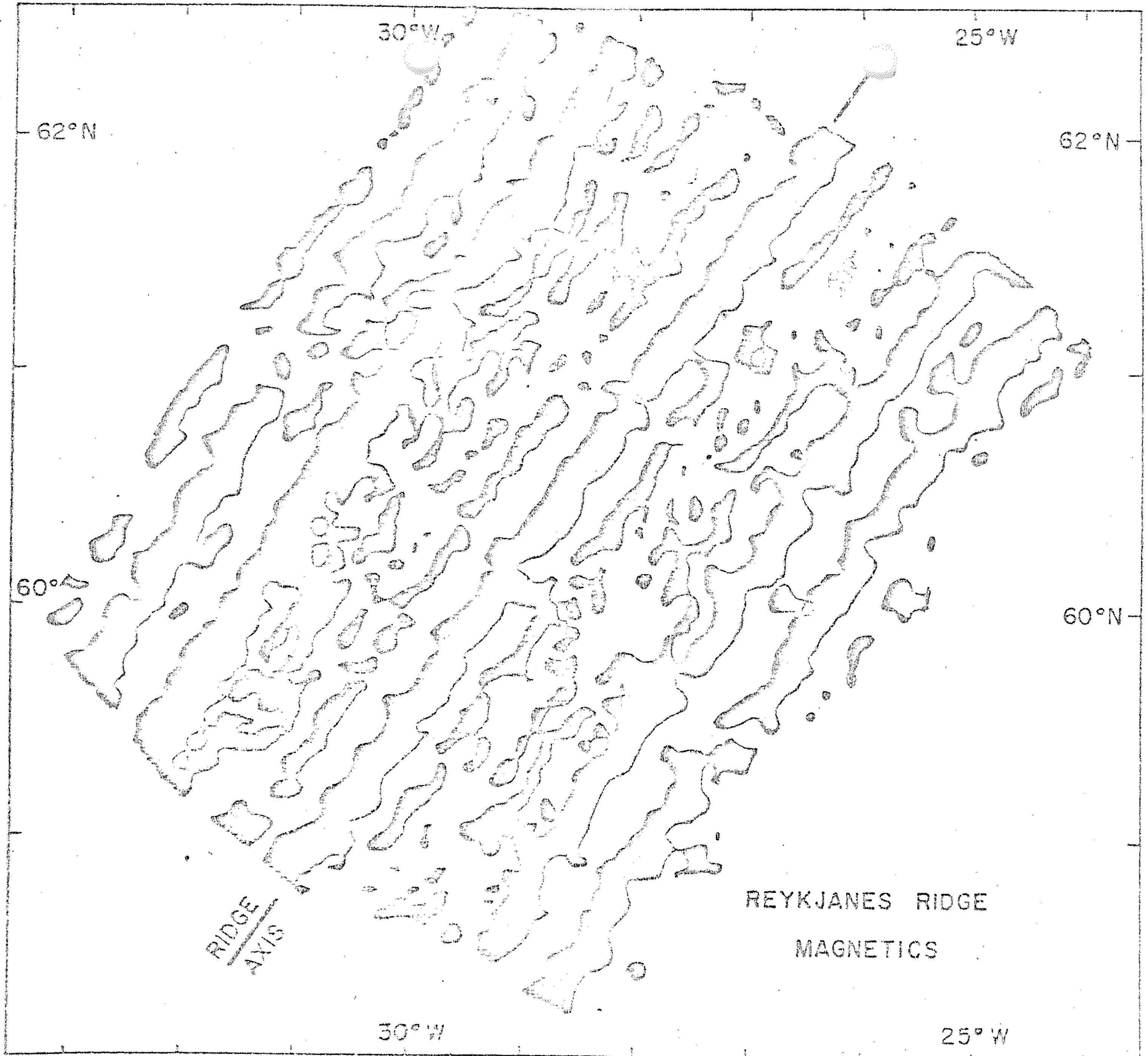


Figure 1-3 Magnetic anomaly map of the Reykjanes Ridge, a spreading axis (after Heirtzler, Le Pichon and Baron, 1966). Dark areas indicate areas of positive anomaly, where the observed total magnetic field exceeds the smoothed earth's field.

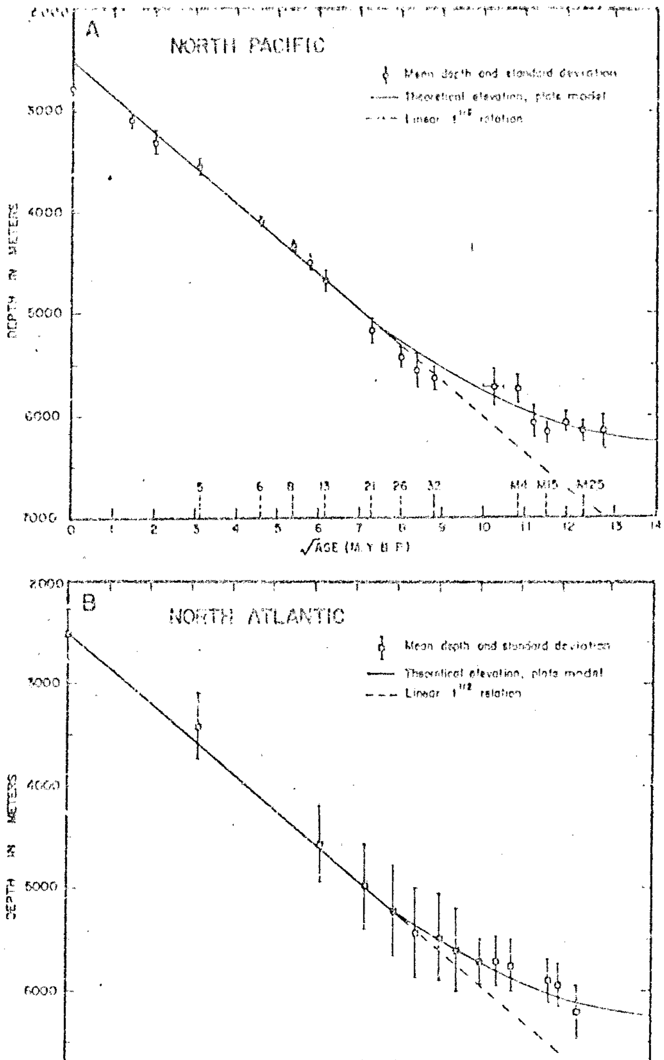


Figure 1-4 Mean water depths (with standard deviations) plotted against the square root of plate age for (a) the North Pacific and (b) the North Atlantic (after Parsons and Sclater, 1977).

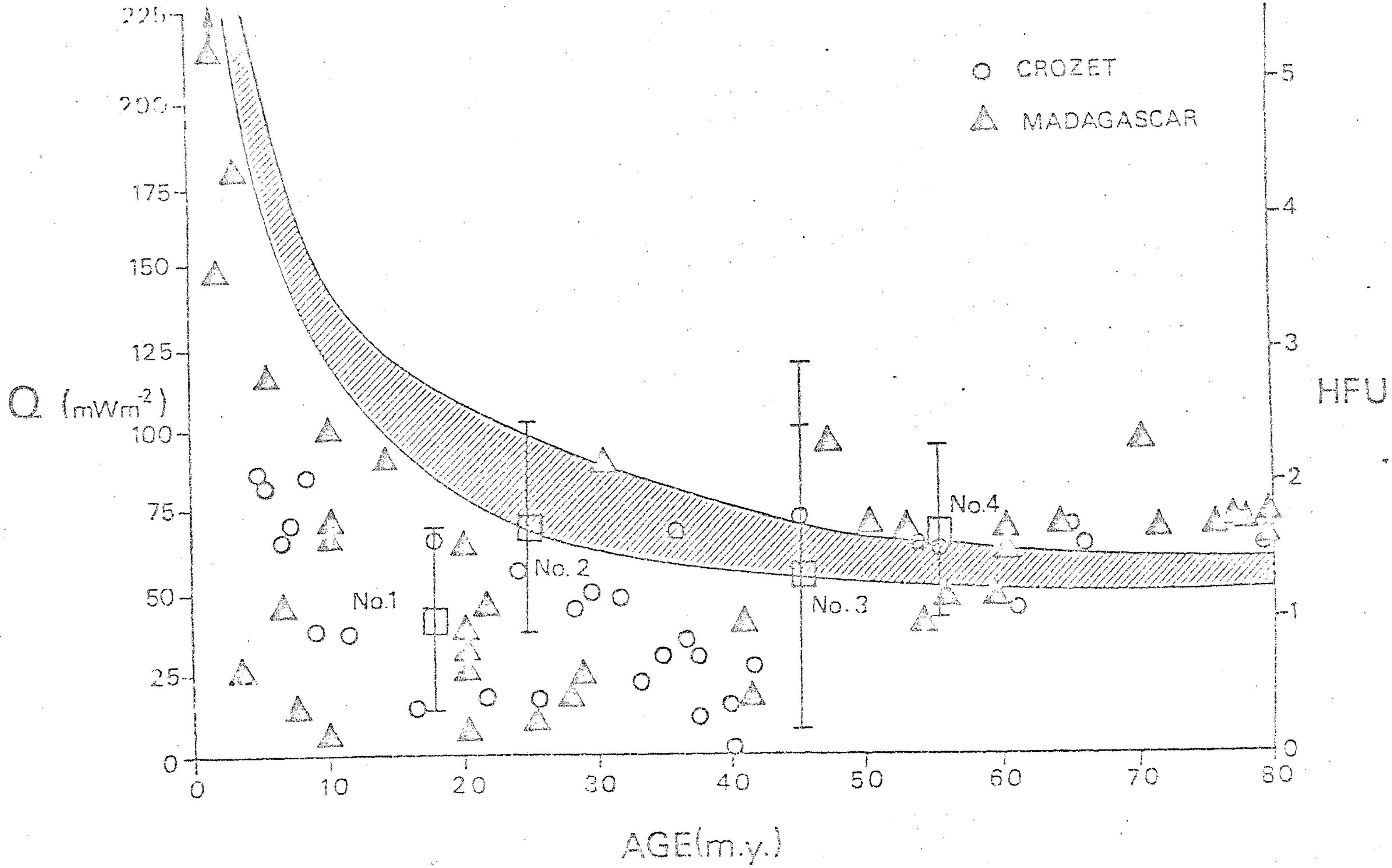


Figure 1-5 Heat flow versus age in the Crozet and Madagascar Basins of the Indian Ocean. Boxes are mean heat flow values (with standard deviations) from detailed surveys. The hatched area shows the range of values predicted by theoretical plate models (after Anderson, 1978) [1 Heat Flow Unit (HFU) = 10^{-6} Cal cm^{-2} sec^{-1} = 41.87 mWm^{-2}].

linearly with $t^{\frac{1}{2}}$, i.e. with the square root of the age of the plate (Figure 1-4).

A number of thermal models of the cooling plate have been developed (5). The models differ in the assumptions made about the lower boundary, but it has been shown that all give rise to the linear $t^{\frac{1}{2}}$ dependence of depth out to some age, for all are solutions of the same equation of heat transport. If the plate were a semi-infinite half space - the simplest model - the $t^{\frac{1}{2}}$ dependence would continue indefinitely. That this dependence breaks down beyond 70 my is an indication of the finite thickness of the plate and that the heat flux through its upper surface does not decay to zero but to a finite value, which is the sum of the background value through the base of the plate (0.8 HFU) and the heat generated by radioactive decay within the plate itself (0.2 HFU).

2.3 PROCESSES OF HEAT TRANSFER NEAR THE OCEAN FLOOR

The same cooling plate models which describe the variation of water depth with plate age also predict the variation of the heat flow through the ocean floor with age. Where the depth shows a $t^{\frac{1}{2}}$ dependence, the heat flow should vary linearly at $t^{-\frac{1}{2}}$. The success of the thermal models in fitting the depth data gives one confidence in their applicability to the heat flow data. However, the observed heat flow deviates considerably from the simple relation predicted. The observations show considerable scatter and only recently have the causes of this scatter been understood. The processes involved are best understood by considering the results of detailed measurements within a limited area - the Crozet and Madagascar Basins of the Southwest Indian Ocean (6,7). The same processes are involved elsewhere on the ocean floor, but the timescale varies.

Heat flow observations from the Crozet and Madagascar Basins are plotted against age (determined from the magnetic anomalies) in Figure 1-5. Most of these measurements were obtained by measuring the temperature gradient in the top few metres of the ocean floor and by measuring the

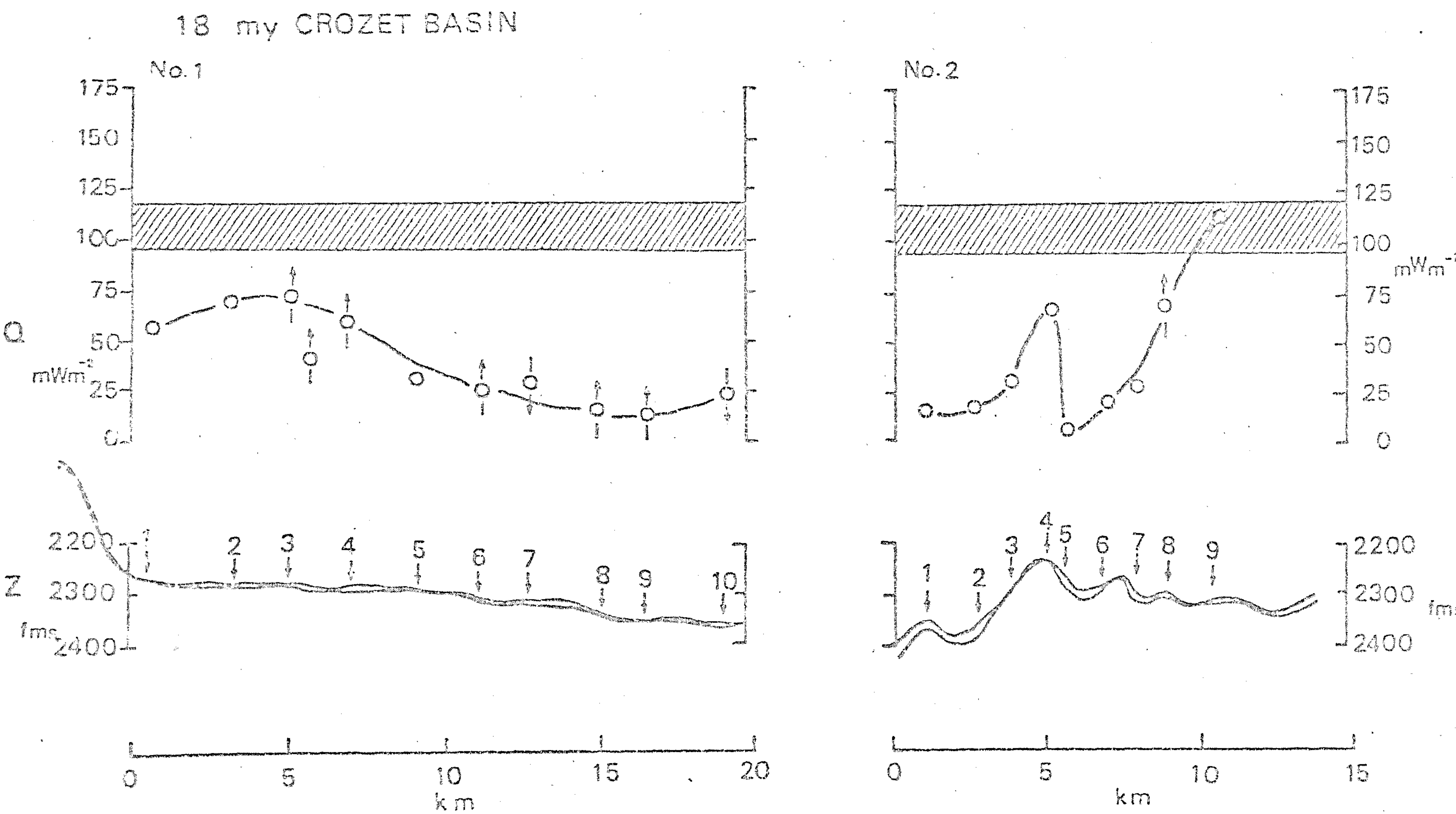


Figure 1-6 Detailed heat flow survey over 18 my old plate in the Crozet Basin, Indian Ocean (after Anderson, 1978). The hatched band indicates the range of heat flow values predicted from theoretical plate models. The deficiency between observed and predicted heat flow in this thinly sedimented region is believed to be due to the convection cells in the oceanic crust being open to the sea.

thermal conductivity of sediment samples on board ship. The divergence from the range of values predicted by theoretical cooling plate models is considerable. Broadly, the plot can be divided into three different areas according to age:

(1) At ages younger than about 40 my, observed heat flow invariably falls below the predicted value. Extremely low values are observed, even over young plate.

(2) At intermediate ages, approximately 40 to 60 my, the observed heat flow shows rough agreement with that predicted, but with considerable scatter.

(3) Beyond about 60 my, the scatter of the observations decreases and the observations tend to agree with theoretical predictions (some refinement of the models may be necessary in the case shown).

The above behaviour has been interpreted as follows. Young oceanic crust is highly cracked and fractured, extremely permeable and saturated with sea water. Thus the dominant process of heat transfer in the top few kilometres of young plate is not conduction through the rock but convection of seawater. Furthermore, until the crust is completely blanketed by an impermeable layer of soft sediment, the crustal convection cells are not closed but open to the sea itself. Thus much of the cooling of the young plate takes place by the mass transfer of seawater across the ocean floor. Heat flow values in this region (which can only be made when there is sufficient sediment to take the temperature probe) are consequently always less than that predicted by conduction models. The results of a detailed heat flow survey over 18 my old crust in the Crozet Basin illustrate this situation (Figure 1-6). The cyclical pattern of the heat flow observations with a wavelength considerably longer than fluctuations in the thickness of the sedimentary cover is thought to reflect the dimensions of the convection cells themselves.

When the sediment is sufficiently thick to form an impenetrable barrier to the passage of seawater and to seal off all rock outcrops from contact with the sea, the convection cells in the oceanic crust became closed systems. All the heat transferred convectively through the rock layer must now be conducted through the sediment blanket. This regime is applicable to the 40 to 60 my age range in the Crozet and Madagascar Basins. A detailed heat flow survey over 55 my crust in the Madagascar Basin illustrates the situation on a fine scale (Figure 1-7). Good agreement with the theoretical heat flow predicted by the conduction models is obtained. But the cyclical variation reflecting the convection cell pattern in the crust is still apparent.

The closed convection systems in the oceanic crust do not continue indefinitely. Ultimately they seal themselves up with hydrothermal minerals of their own making. Convection then ceases and heat is transferred by conduction throughout. This is thought to be the explanation of the smaller scatter of heat flow measurements in old plate (older than 60 my in Figure 1-5).

The processes outlined above are believed to occur in all oceanic crust. However, because there is considerable variation in sedimentation rates and in the degree of cracking and fracturing of the crust, the time scale varies. The behaviour of mean heat flow with age is shown in somewhat idealised form for all the major ridge segments in Figure 1-8. On the Galapagos spreading centre observed heat flow matches the theoretical in only 5 my. This is because this particular spreading axis lies beneath the equatorial high productivity zone in the eastern Pacific Ocean, where sedimentation rates are extremely high - about 50 m per million years. Elsewhere in the Pacific, the heat flow over plate created at the East Pacific Rise does not straddle the theoretical curve until about 15 my. In the Atlantic Ocean the same process takes nearly 80 my. The reason for this difference in the behaviour of mean heat flow between the East Pacific Rise and the Mid Atlantic Ridge is believed to be due to the much more rugged nature of the latter. Thus it takes considerably longer for

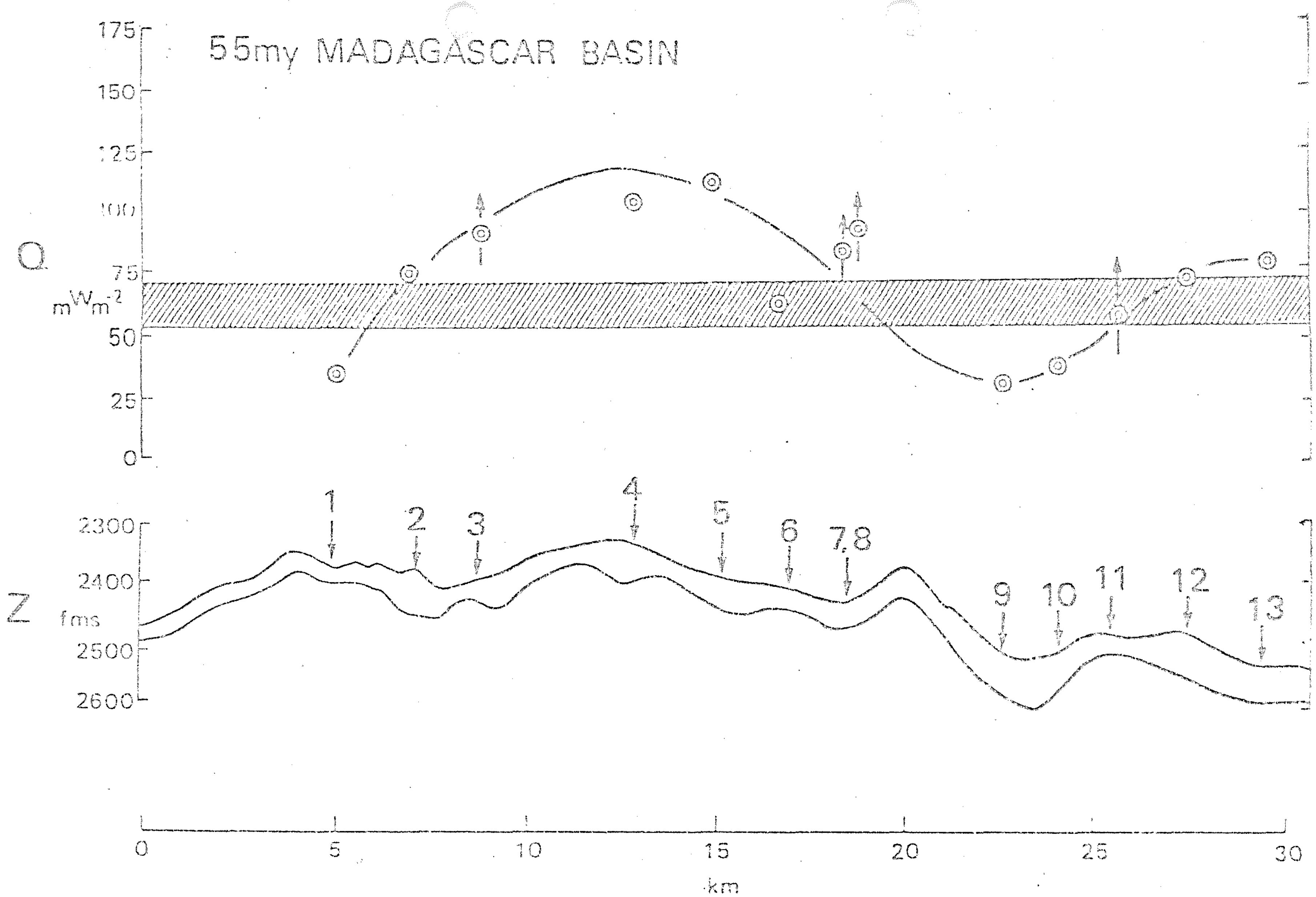


Figure 1-7 Detailed heat flow survey over 55 my old plate in the Madagascar Basin, Indian Ocean (after Anderson 1978). The hatched band indicates the range of heat flow values predicted from theoretical plate models. The mean heat flow observed here matches the theoretical because the sedimentary cover is now sufficient to isolate the crustal convection cells from the sea.

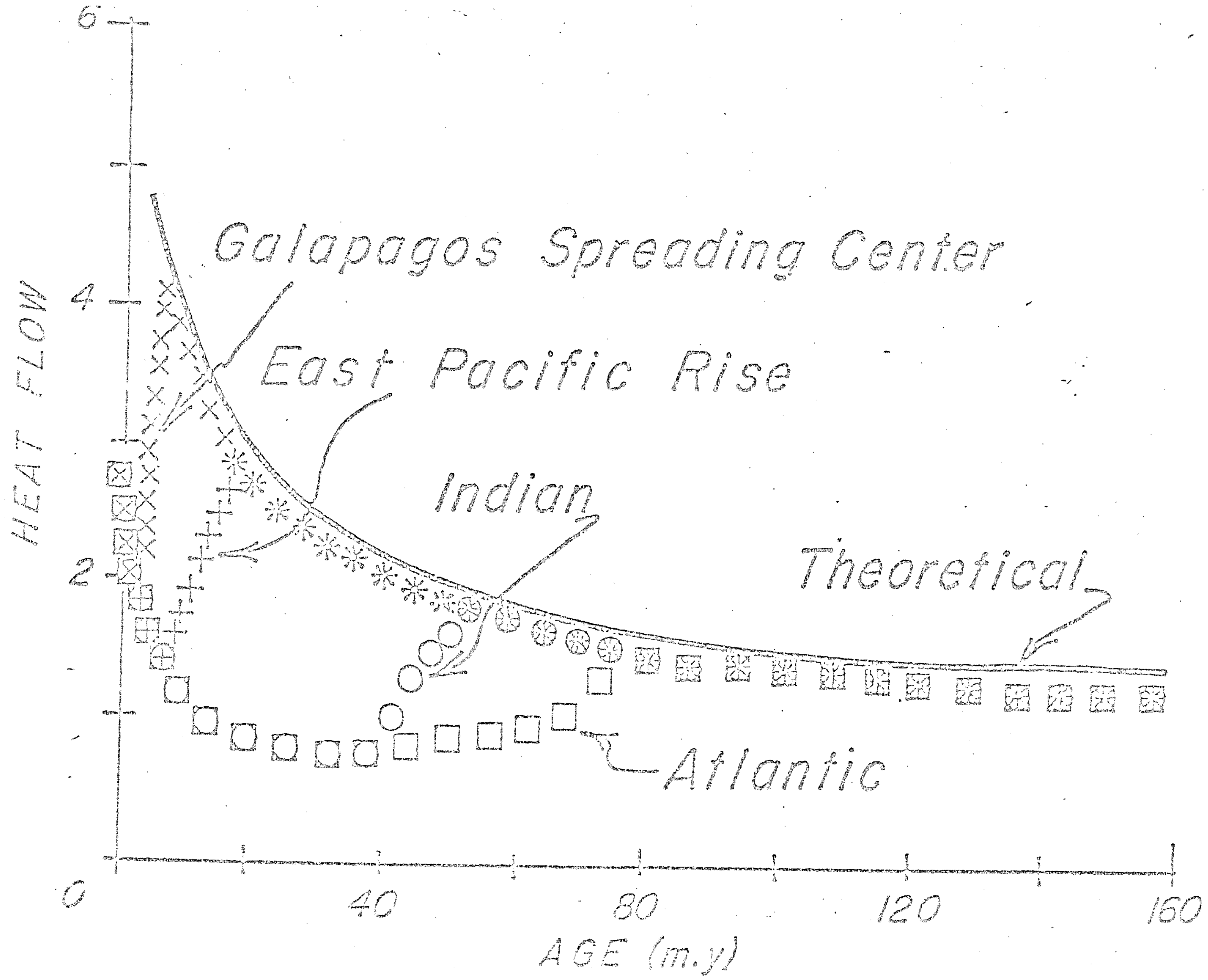


Figure 1-6 Variation in mean heat flow versus age for each of the major mid-oceanic ridge segments (after Anderson, 197[illegible]

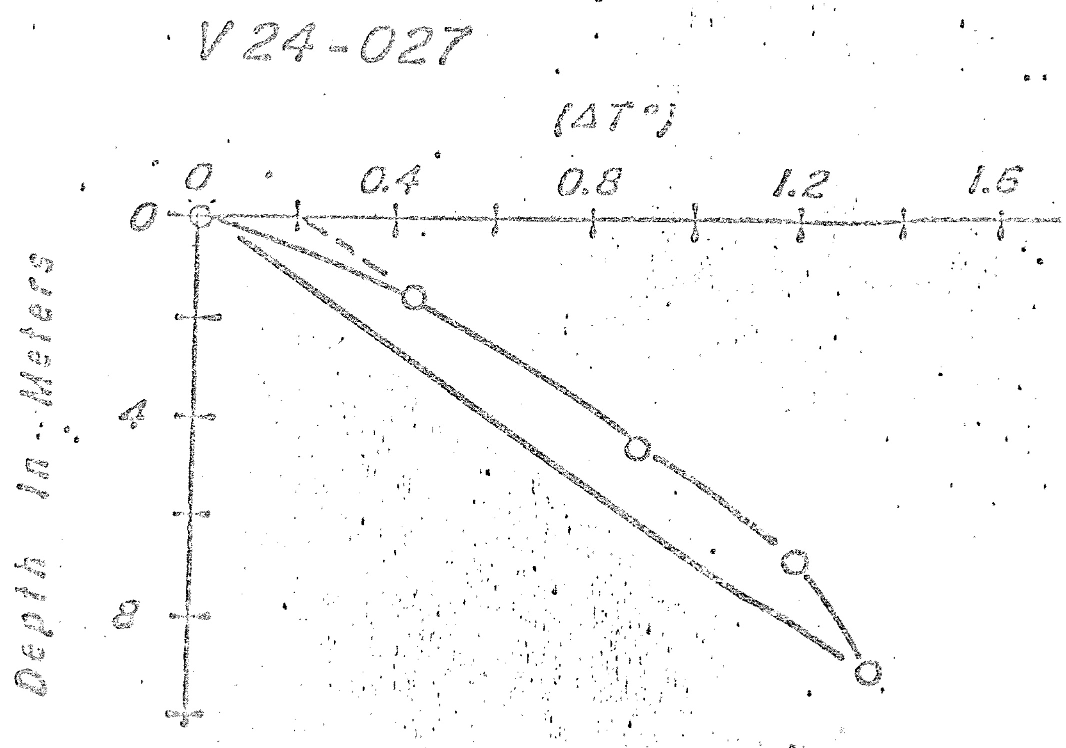


Figure 1-9 Non-linear temperature gradient observed at station V24-027 on the flanks of the East Pacific Rise. The curvature is thought to indicate the upward flow of pore water through the sediment (after Anderson, 1978).

sediments to completely blanket crust created at the Mid Atlantic Ridge (typical basement relief away from the axial region ~1000 m) than that created at the East Pacific Rise (typical basement relief ~200 m).

Finally the effectiveness of the sediment layer as an impermeable blanket isolating the rock from the sea must be considered. The temperature gradient measured in the top few metres of the sediment on the ocean floor is not always linear. Both concave-up and concave-down temperature-depth profiles have been observed. Though there are many possible explanations for this phenomenon, it has been suggested that flow of water into or out of the sediment may be taking place because the sediment blanket is not completely sealing the underlying convection cells from the sea (6,8). Upward flow of water would produce a concave downwards temperature profile, downward flow a concave upwards profile. An example of a non-linear temperature gradient observed on the flanks of the East Pacific Rise is shown in Figure 1-9. This profile has been interpreted to indicate a conductive heat flow of 2.65 HFU, a convective heat loss of 0.72 HFU and an upward flow of water at a velocity of 3.4×10^{-6} cm/sec. It is important to emphasise, however, that this interpretation is highly speculative and that many more measurements are needed to confirm or refute this hypothesis.

The possibility that in some areas water is being driven convectively through the sediments has important implications for radioactive waste disposal. Flow rates of 10^{-6} cm/sec would bring pore water from 100 m depth to the sediment surface in a few centuries. Thus detailed heat flow surveys over a wide range of sediment thicknesses and plate ages will form an important line of research.

2.4 AGING PROCESSES IN THE IGNEOUS CRUST

2.4.1 Rock Porosity and Seismic Velocity

Seismic refraction techniques have been employed for many years to determine the velocity structure of the oceanic crust[(9)]. Airgun or explosive sources near the sea surface are recorded by surface floating sonobuoys or bottom receivers. The travel time data thus obtained is interpreted in terms of the compressional velocity structure of the top few kilometres of crust. The technique yields little information about the sedimentary overburden, because of the latter's low seismic velocity. Most of the information concerns the hard rocks. The simplest method of interpreting the data is to regard the oceanic crust as a series of homogeneous layers and to calculate the velocities and thicknesses of these layers. When this is done, essentially four different layers can be identified, according to their seismic velocities, in the top few kilometres of the igneous crust (10).

Layer	Average Velocity
2A	3.6 km/sec
2B	5.2
2C	6.1
3	6.9

The structure of the upper oceanic crust in the Atlantic and Pacific Oceans, interpreted in this manner from a large number of airgun/sonobuoy records, is shown as a function of age in Figure 1-10. The low velocity layer 2A is found to be thickest on the ridge axis in both oceans but thins with age, disappearing at about 30 my in the Pacific Ocean and at about 60 my in the Atlantic. Whether it disappears completely is uncertain because layers thinner than about 100 m are unresolvable with the airgun/sonobuoy technique. Another change observed in layer 2A is that its velocity increases with age, from about 3.3 km/sec on the ridge axis to layer 2B values (more than 4.5 km/sec) at 40 my.

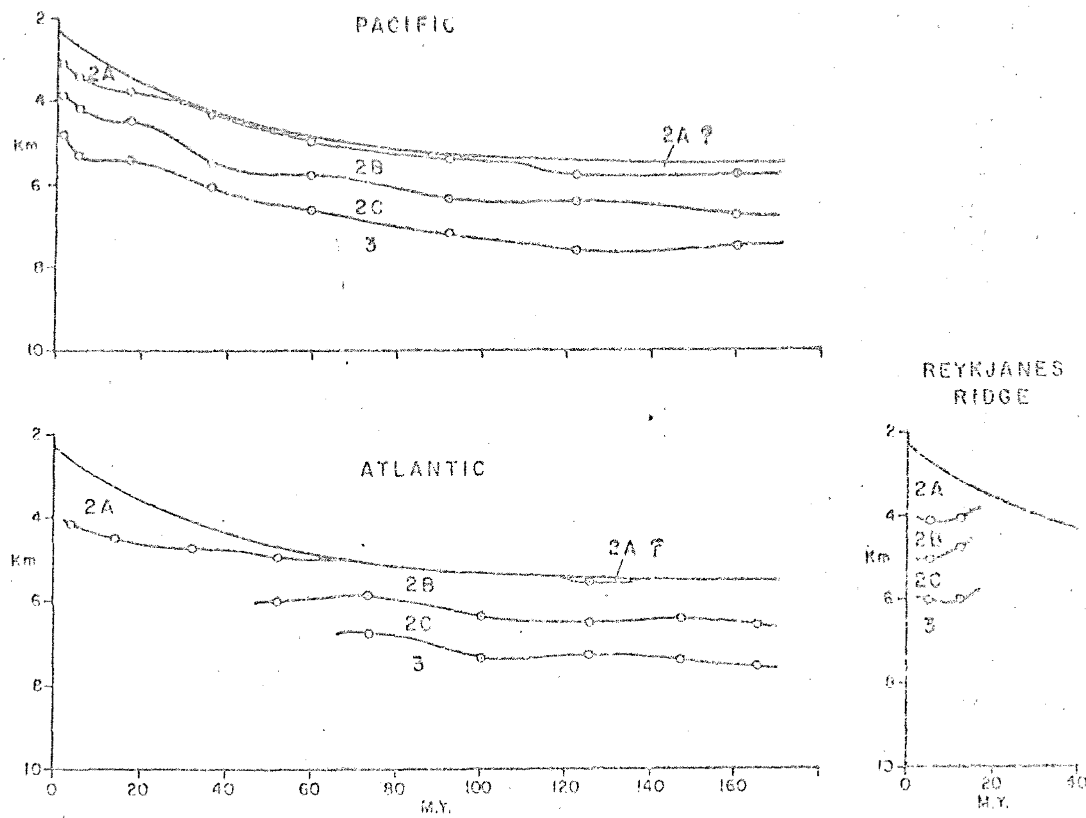


Figure 1-10 Velocity structure of the upper oceanic crust in the Atlantic and Pacific Oceans as a function of age (after Houtz and Ewing, 1976). The sediment layer has been removed. The average velocities of layers 2A, B and C are 3.6, 5.2 and 6.1 km/sec respectively. Note how layer 2A thins with age.

The low velocities observed at the top of the oceanic crust are believed to be due to its high porosity. The changes which occur in the thickness and velocity of layer 2A are thought to be the result of the filling of voids and cracks by hydrothermal mineralisation.

A more sophisticated method of interpreting seismic refraction data is to treat the velocity structure as a series of velocity gradients. The better quality data available from airgun/bottom receiver profiles merits this approach. It is thought that the velocity gradient model gives a better representation of the true velocity structure than the stack of constant velocity layers. Seismic velocity is not a unique indicator of rock type, but since the top few kilometres of the igneous crust are known with some confidence to be composed of basaltic lavas (except in the uppermost few hundred metres where sediments and basaltic rubble are often intermixed), the variations of seismic velocity can be interpreted in terms of the varying physical properties of the basalt rather than due to any compositional changes. The essential feature of the rock affecting its seismic velocity is its porosity. Porosity/depth curves for 4 my and 62 my old crust in the North Atlantic[(11)], inferred from the seismic velocity structure, are shown in Figure 1-11. These porosities are probably upper limits to the true porosity because of the simplifying assumptions made about the geometry of the water-filled voids.

In conclusion, seismic refraction measurements of the upper oceanic crust show that the young crust produced at the ridge axis is extremely porous, with porosities near its top surface in the region of 30-40%. As the crust ages and moves away from the ridge axis its porosity decreases due to the filling of voids and cracks by hydrothermal minerals. This process takes longer on the Mid-Atlantic Ridge than on the East Pacific Rise, probably because faulting and fissuring, which is more prevalent on the former, makes young MAR crust more porous.

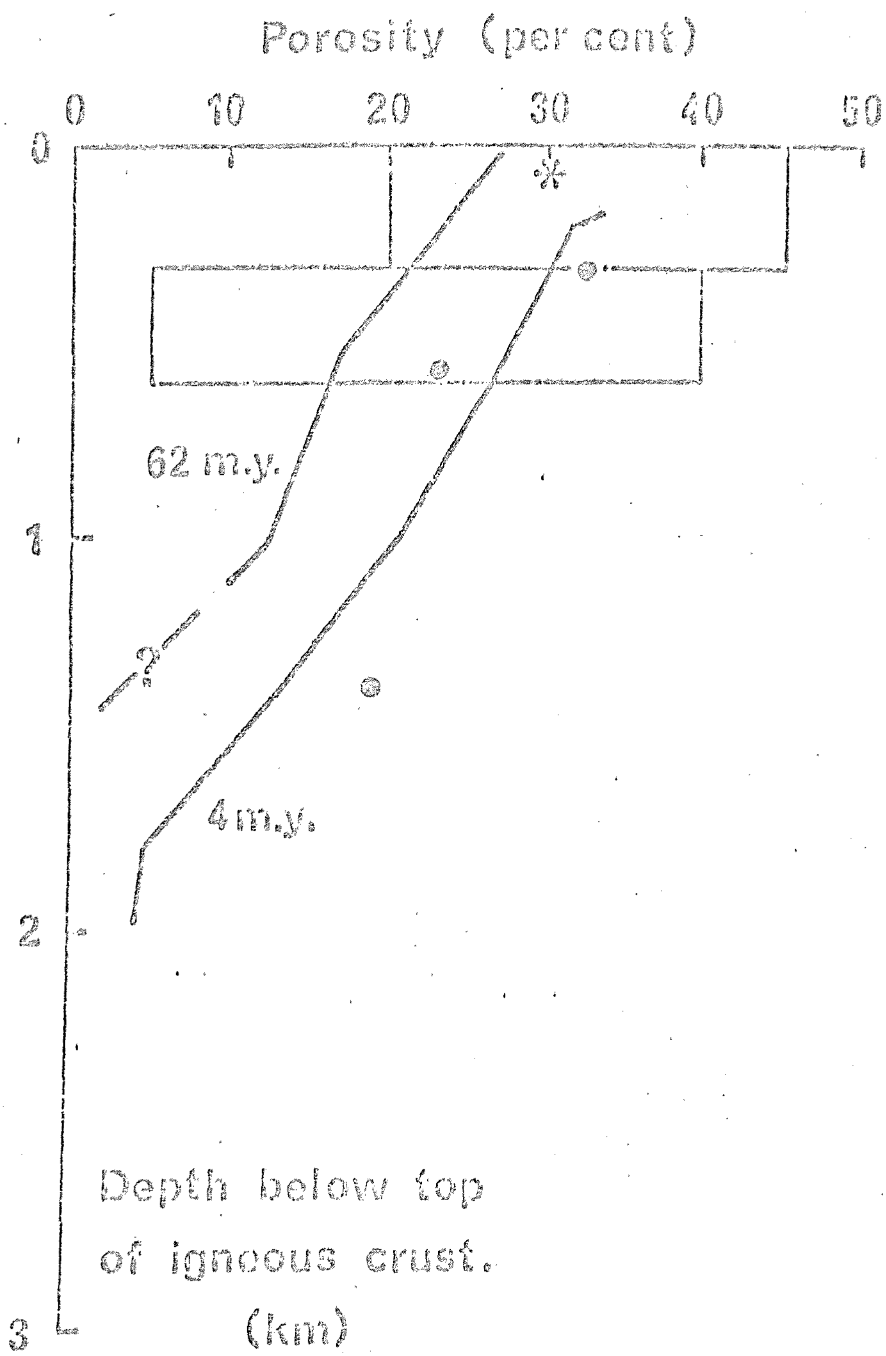


Figure 1-11 Porosity/depth curves for 4 my and 62 my old crust in the North Atlantic Ocean, inferred from seismic refraction observations (after Whitmarsh, 1978). The boxes, dots and asterisk are porosities of borehole samples from Hawaii, Iceland and the Reykjanes Ridge.

2.4.2 Permeability

No permeability measurements have been carried out on core samples of the igneous rocks of the ocean floor. Such measurements would be of little value, for it is known that the igneous crust is highly fractured and fissured during the process of its formation so that its bulk permeability is undoubtedly controlled by cracks and fissures. Theoretical models of the convective hydrothermal systems which have been observed indicate that the permeability of the crust lies in the range 10^{-3} to 10^{-1} darcy[(12)]. These values apply to the full thickness of rock in which convection is thought to be important - the order of 5 km. A constant value of permeability over this depth range is unrealistic because cracks and fissures tend to close with increasing pressure of overburden. Thus the permeability near the top of the igneous crust is probably greater than 10^{-1} darcy.

The permeability of the upper oceanic crust may be inferred from observations in Iceland and Hawaii. Hot-water convective systems are found in volcanically active parts of Iceland, a sub-aerial extension of the Mid-Atlantic Ridge. But vapour-dominated systems, such as found in Italy and New Zealand[(13)] are not found. This is thought to be due to the greater permeability of Icelandic rocks and to the abundant precipitation[(14)]. This suggests permeabilities in the region of 1 darcy.

The permeabilities of core samples obtained from a research drill hole penetrating more than a kilometre into the active volcano, Kilauea, on Hawaii, have been measured[(15)]. The rocks encountered were basalts, similar to those found in the oceanic basement. The permeabilities determined for cores from the top 500 m of the hole lay in the range 10^{-1} to 1 darcy. These values are probably lower limits to the bulk permeability of the rock in which fractures undoubtedly play a large part.

In conclusion, the permeability of the top few hundred metres of the young oceanic crust is very high, probably in the range 10^{-1} to 10 darcy.

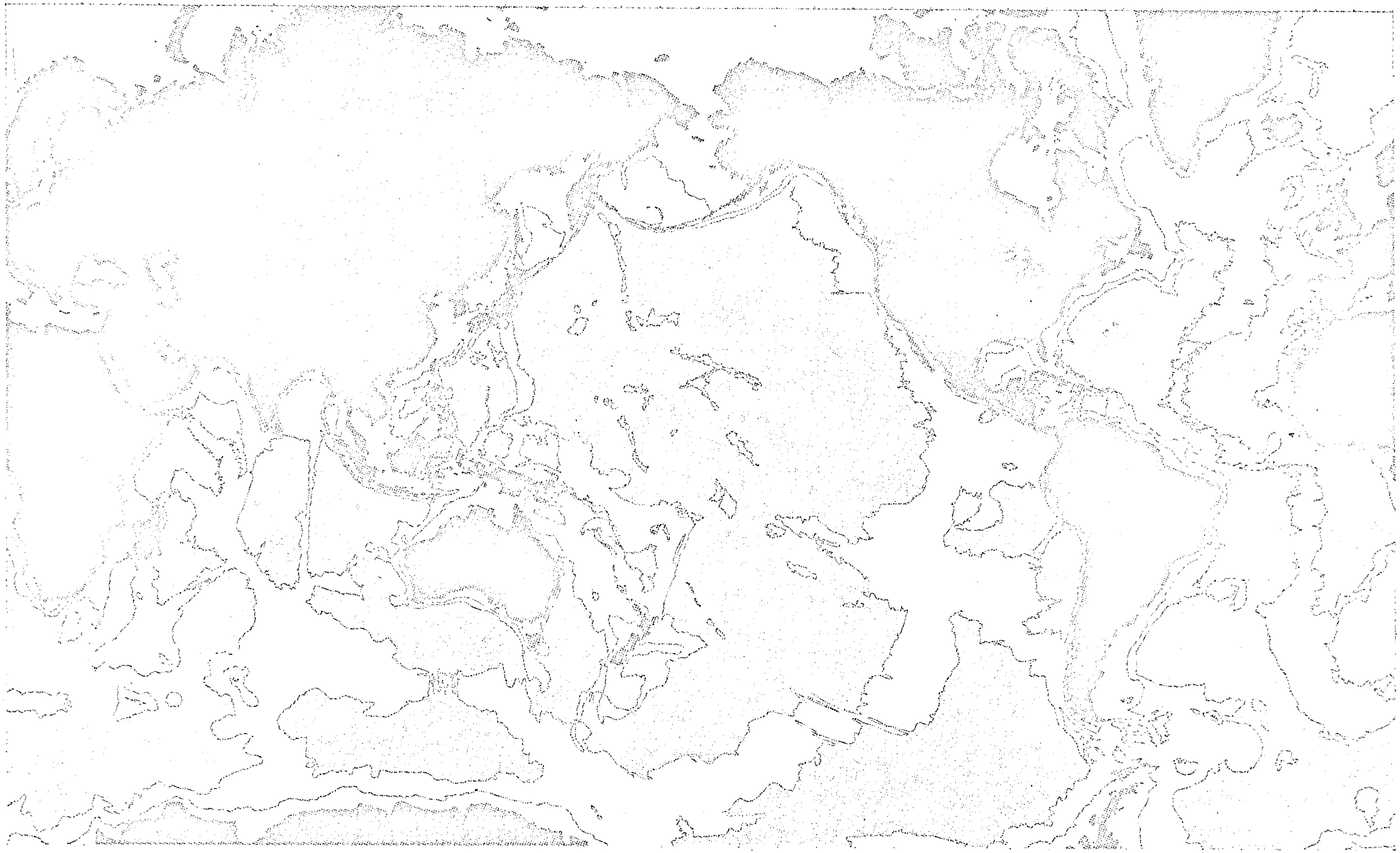


Figure 1 - 12 Principal bathymetric features of the World Ocean as defined by the 1000 m and 4000 m depth contours; the deep basins (>4000 m) are stippled.

The average permeability of the top few kilometres of the crust is thought to lie in the range 10^{-3} to 10^{-1} darcy. The permeability of the igneous crust appears to decrease with age and convection probably ceases when its average permeability falls below 10^{-3} darcy (see table in Section 2.14.5).

2.5 PRESENT STATUS OF OCEANIC SEDIMENTOLOGY

Despite the areal extent of the deep ocean basins on the Earth's surface (Figure 1-12), the practical difficulties of working in such regions have ensured that our knowledge of their sediment sequences is surprisingly recent. Systematic attempts to sample the sediment surface beneath the deep ocean began with the H.M.S. Challenger expedition of 1872-76 but most of the data now available have been collected since World War II (Figure 1-13). Only in recent years has this worldwide data base built up to the extent that general horizontal distributions of sediment types on the floors of the deep oceans could be mapped. These distributions have been coupled with new information from physical and chemical oceanography and marine biology to provide an insight into the present day deep marine sedimentary system (16,17).

The volume of sediment in the deep ocean basins has been determined more readily by seismic reflection profiling. Following an intensive period of study during the sixties, it became possible to draw generalised sediment thickness maps (18) (Figure 1-14) and to infer the sediment type from its acoustic signature. Sampling was, until mid-1968, restricted to coring the top ten metres or to dredging scarps where sections of the sedimentary layering might be exposed. Since then the Deep Sea Drilling Project has penetrated hundreds of metres to determine changes in sediment type with depth (and age). This information can be extended horizontally using seismic profiling to interpret the geological history of the deep ocean basins (19,20).

We must emphasise the recency of the available information and its patchy data coverage. Figure 1-15A illustrates seismic reflection profiling tracks in part of the Eastern Atlantic. Much of the profiling has been devoted to the continental margins, the plate boundaries or the detailed study areas. Typical coverage over an area that could be considered for disposal studies is shown in Figure 1-15B. Some short pieces of ship track

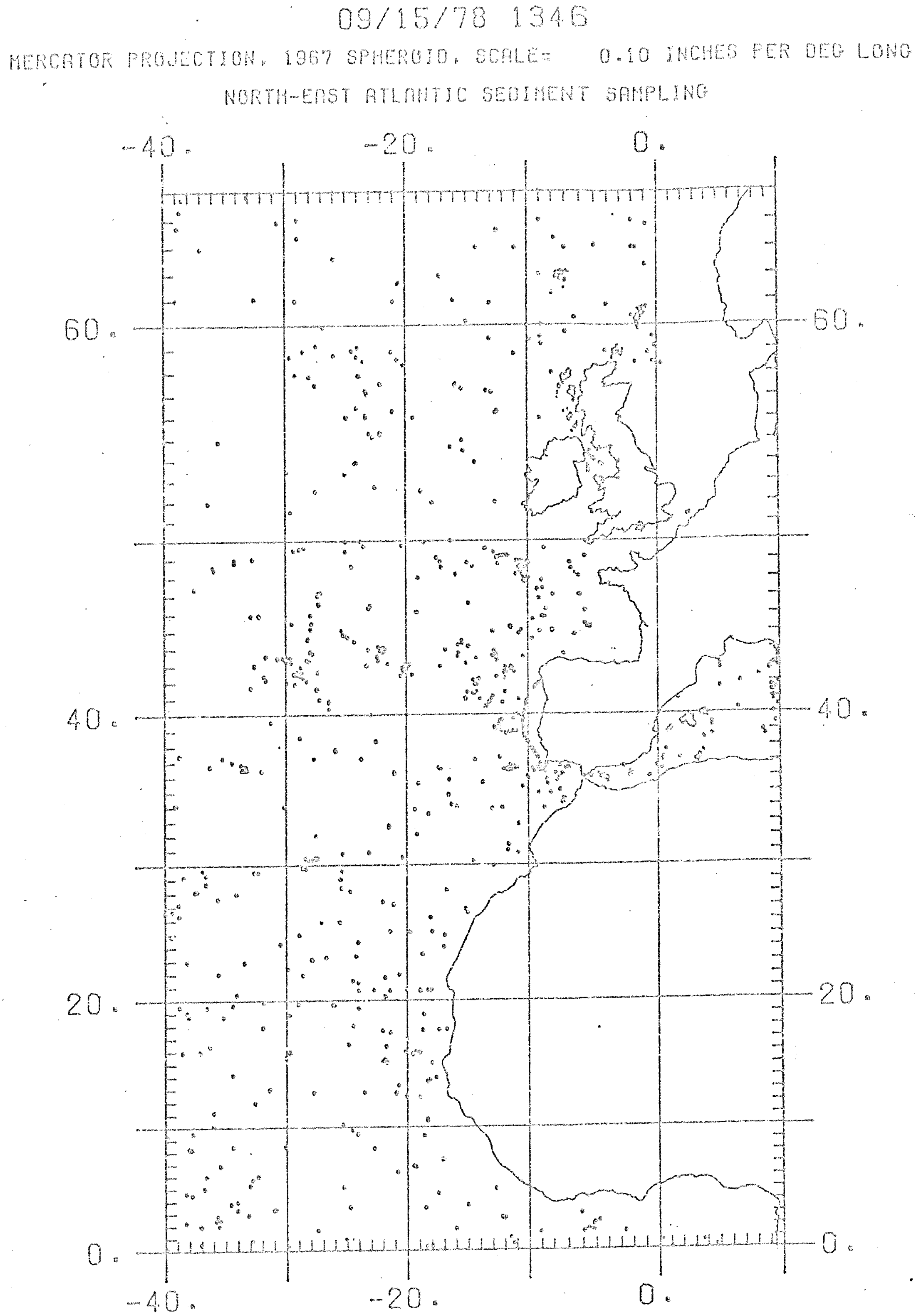


Figure 1 - 13 Sediment sampling sites in the Northeast Atlantic. This example shows the density of non-Russian sampling information that is available to [illegible] researchers. Note (1) the paucity of the data base relative to its areal extent; compare the size of land areas such as the UK; (2) the clusters of sampling sites in areas of particular geologic interest.

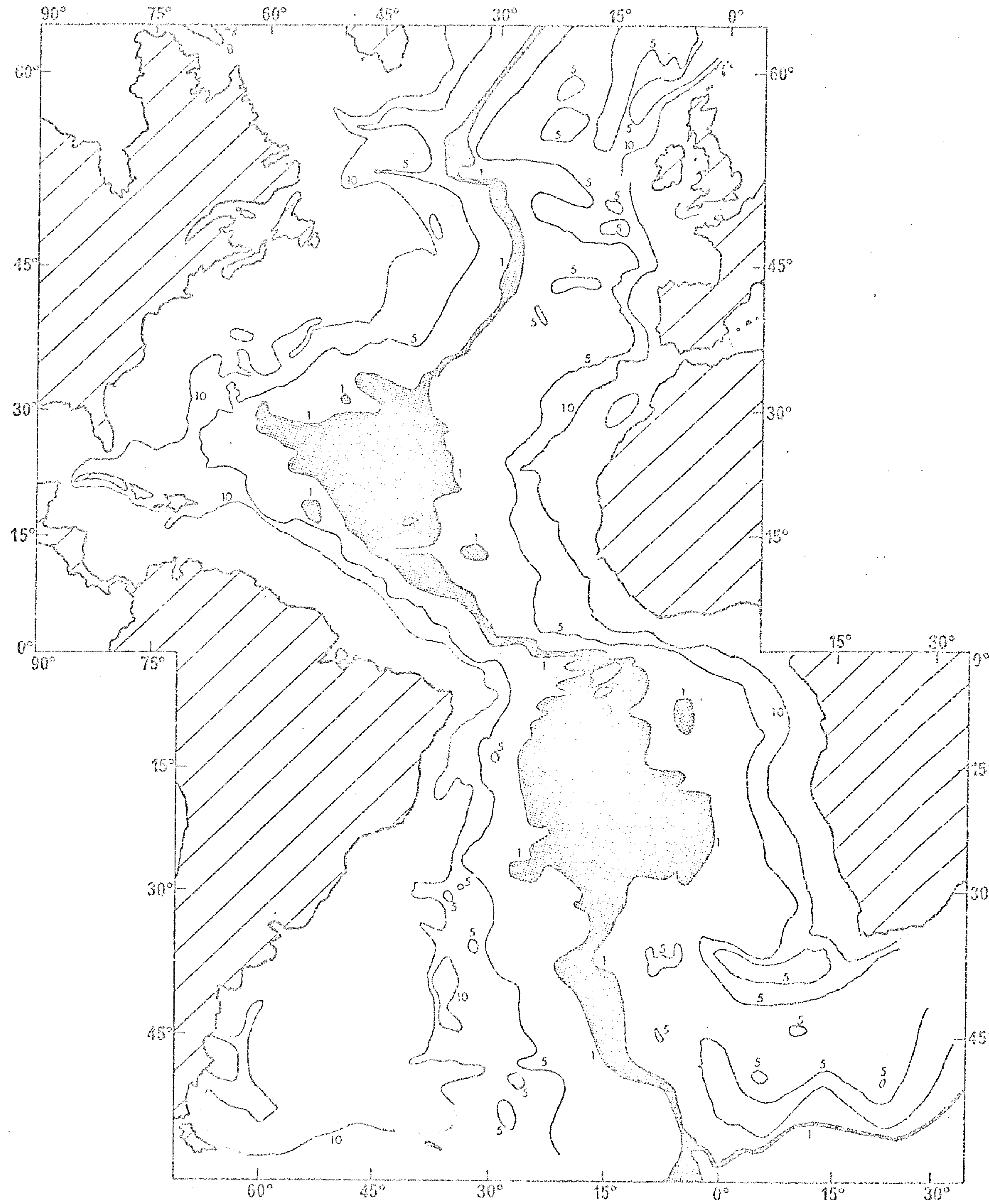


Figure 1 - 14 Generalized sediment thicknesses in the Atlantic Ocean based upon seismic profiling. (Simplified from Ewing et al 1973). Dark shaded areas have ≤1 sec (~100 meters) of sediment cover, light shaded areas have >10 sec (~1 km) thickness. The 5 sec (~500 m) thickness contour is also shown.

Figure 1 - 15A Seismic reflection profiling tracks between Western Europe and the Mid-Atlantic Ridge to 1975, with additional 103 tracks to February 1976. Closed boxes are areas of ... Shaded box shows area covered

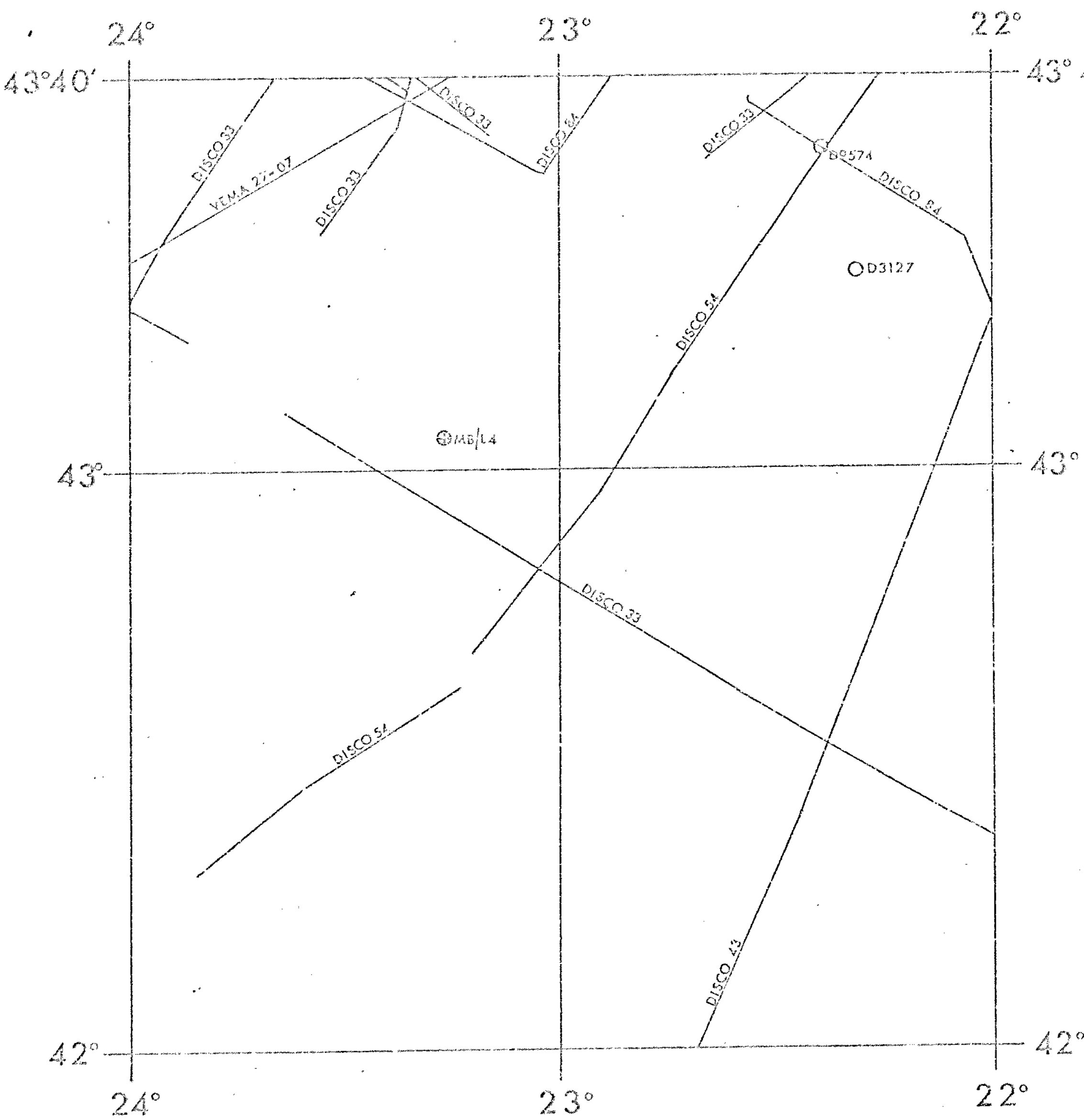


Figure 1 - 15B Typical coverage in an area that could be considered for initial disposal studies. Area is approximately 38,000 sq.km. Circles are coring stations; circle with a cross is a gravity core and camera station.

give the only information on the sediment cover, apart from three isolated core samples: this for an area about half the size of Scotland.

2.6 SEDIMENT SOURCES AND TYPES

The basic elements of all sedimentary systems are: (a) the source of the sedimentary material; (b) its transport and distribution; (c) its deposition or accumulation; and (d) any post-depositional effects such as erosion and redistribution, consolidation into rock, etc. Environmental constraints influence each of the basic elements referred to above. Factors such as climate, relief, regional geology or oceanographic conditions acting at the source for example, put constraints on the nature and amount of the sediment supply. Once deposited the sediments can still undergo erosion and redistribution by deep bottom currents if a change in oceanographic conditions occurs, or mass movements such as slumping if affected by earthquakes or other tectonic instability.

Deep sea sediments are usually named for their source material. Thus terrigenous sediments are made up predominantly of land-derived sediment; the biogenous oozes are composed of the microscopic remains of marine organisms. Other major types are the volcanogenic sediments and authigenic (chemical) precipitates, while a minor category is extraterrestrial in origin (i.e. meteorites and tectite swarms from outer space).

2.6.1 TERRIGENOUS SEDIMENT: The addition of terrigenous materials to the oceans from the land is about 250×10^{14} grams annually of which about 206×10^{14} g is solid, particulate matter.[21] Climate, relief and geology of the source areas are the principal factors which determine the sediment supply and the world's rivers are the most important dispersal agents, transporting 183×10^{14} g/yr of particulate matter[22] and 42×10^{14} g/yr of dissolved substances. Small changes in climatic factors can create large variations in sediment supply to the oceans, and thus can drastically change the sedimentary record of deep sea cores.

Four rivers, the Hwang Ho, Ganges, Bramaputra and Yangtze, at present account for 25% of the sediment transported to the world ocean. Of the top

Figure 1 - 16 Drainage basins of the rivers of the world that discharge more than 10^{14} grams of sediment annually (based on Holeman, 1960). Key to rivers (and average annual suspended loads in 10^{14} g/yr.): 1. Hwang Ho (13.9), 2. Ganges (14.5), 3. Bramaputra (7.3), 4. Yangtze (5.0), 5. Indus (4.4), 6. Amazon (3.6), 7. Mississippi (3.1), 8. Irrawaddy (3.0), 9. Mekong (1.7), 10. Colorado (1.4), 11. Red (1.3), 12. Nile (1.1).

twelve rivers by sediment discharge, only the Amazon, Indus and Ganges/ Bramaputra systems input into the open ocean (Figure 1-16). All of the others deposit their sediments in marginal seas, such as the Gulf of Mexico, the Mediterranean or the China Seas. More importantly, in all cases the bulk of sediment carried in by rivers is presently deposited nearshore in estuaries, deltas or offshore basins, and in only a few cases, such as the Congo, is it discharged directly beyond the continental shelf and margins into the deep basins of the open ocean. That this has been true for most of the geologic history of the present deep basins is shown by sediment thickness distributions (Figure 1-14). Probably no more than 20% of the total volume of sediment in the open oceans is located beyond the continental margins. However, lowered sea levels during glacial periods probably caused exposure and erosion of much of the continental shelf regime and thus more rivers to input directly into the deep basins.

Terrigenous materials can be eroded and transported into the deep oceans by glaciers and icebergs. After melting such materials presently contribute 19×10^{14} g/yr to the marine sedimentary system. Today, this is of significance only in polar regions, principally Antarctica, but again conditions were markedly different during the Quaternary glacial periods (Figure 1-17). Ice transport was of much greater importance and maximum deposition of ice-rafted materials shifted to the subpolar North Atlantic, south of Iceland.[23] As will be shown in section 3.4, ice-rafted debris is of particular significance in disposal considerations.

Coastal erosion and wind transport also deliver terrigenous material to the oceans but are insignificant compared to river and ice transport.

2.6.2 BIOGENOUS SEDIMENT: Biogenous sedimentary materials result from the fixation of mineral phases by marine organisms. In nearshore regions molluscs and coral produce their shells and other parts by fixing calcium

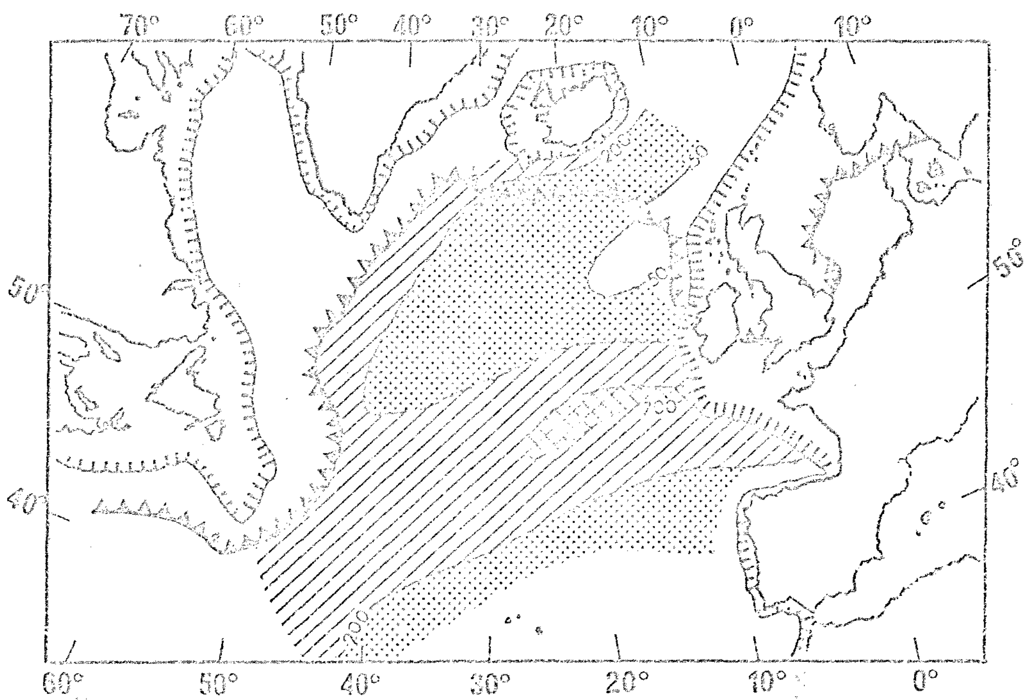


Figure 1 - 17

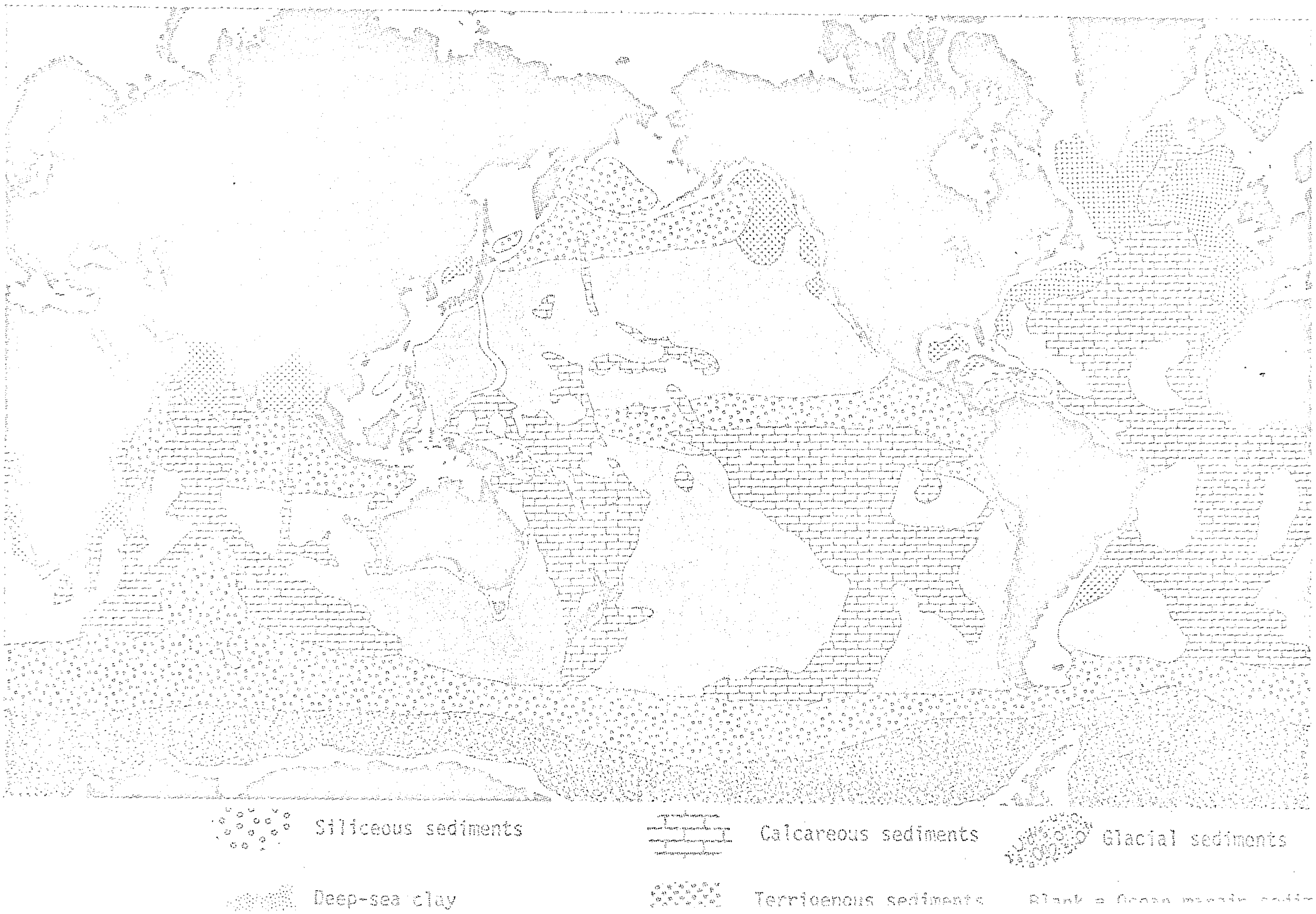
Inferred distribution of ice-rafted sand deposition in the North Atlantic during the last glacial maximum (from Ruddiman 1977). Line with triangles is ice sheet limit on the continents and its inferred limit over the ocean. Hachured line is the continental shelf/slope break. Cross hatching: areas with deposition rates over 700 milligrams of ice-rafted sand per sq.cm per 1000 yrs; diagonal lines: 200-700 mgms/sq.cm/10^3 yrs; stippled 50-200 mgm/sq.cm/10^3 yrs.

carbonate in the form of aragonite. These fossil remains can collect to form shell banks and barriers, and even islands and atolls in the tropics. In the open ocean, on the other hand, zooplankton (principally foraminifera and radiolarians) and phytoplankton (mainly coccoliths and diatoms) are responsible for fixing large amounts of calcium carbonate (as calcite) and silica (as opal) from the surface waters. Their fossil remains settle to form the oceanic oozes which blanket much of the deep seafloor. Fish and sponges are also capable of fixing various minerals. Many organisms in the surface layer of the deep ocean generate fecal pellets of silt size, composed mainly of biogenous material, which will sink to the seafloor much faster than the terrigenous suspended clays.

The production of biogenous sediment is determined by the surface biological productivity of the ocean. Very rough calculations (based upon the assumptions that the oceans stay in chemical equilibrium and that all of the calcium carbonate and silica removed as sediment is replaced by input of dissolved substances from the land) show that the amount of biogenous sediment produced annually is only about 10% of the terrigenous input(24). However, since most of the terrigenous sediment in the oceans accumulates on the continental margins, the spatial distribution of biogenous sediment is impressive(25) (Figure 1-18).

2.6.3 VOLCANOGENIC SEDIMENTS: These are the volcanic ashes (tephra) and their altered equivalents(26) which result from eruptions on the continents or the oceanic ridges or islands (Figure 1-19). They are carried by winds and become the next largest contributor to the deep marine sedimentary system. Altered volcanic ash is a major component of the Pacific red clays and may also be a source of manganese and iron precipitates, particularly in areas of submarine volcanism. Sediment sequences with highly porous layers of unaltered ash could present problems for disposal because they might provide easy patways to the surface.

Figure 1 - 18 Generalised distribution of the principal types of sediment on the floors of the oceans (modified from Davies & Gorsline 1976).



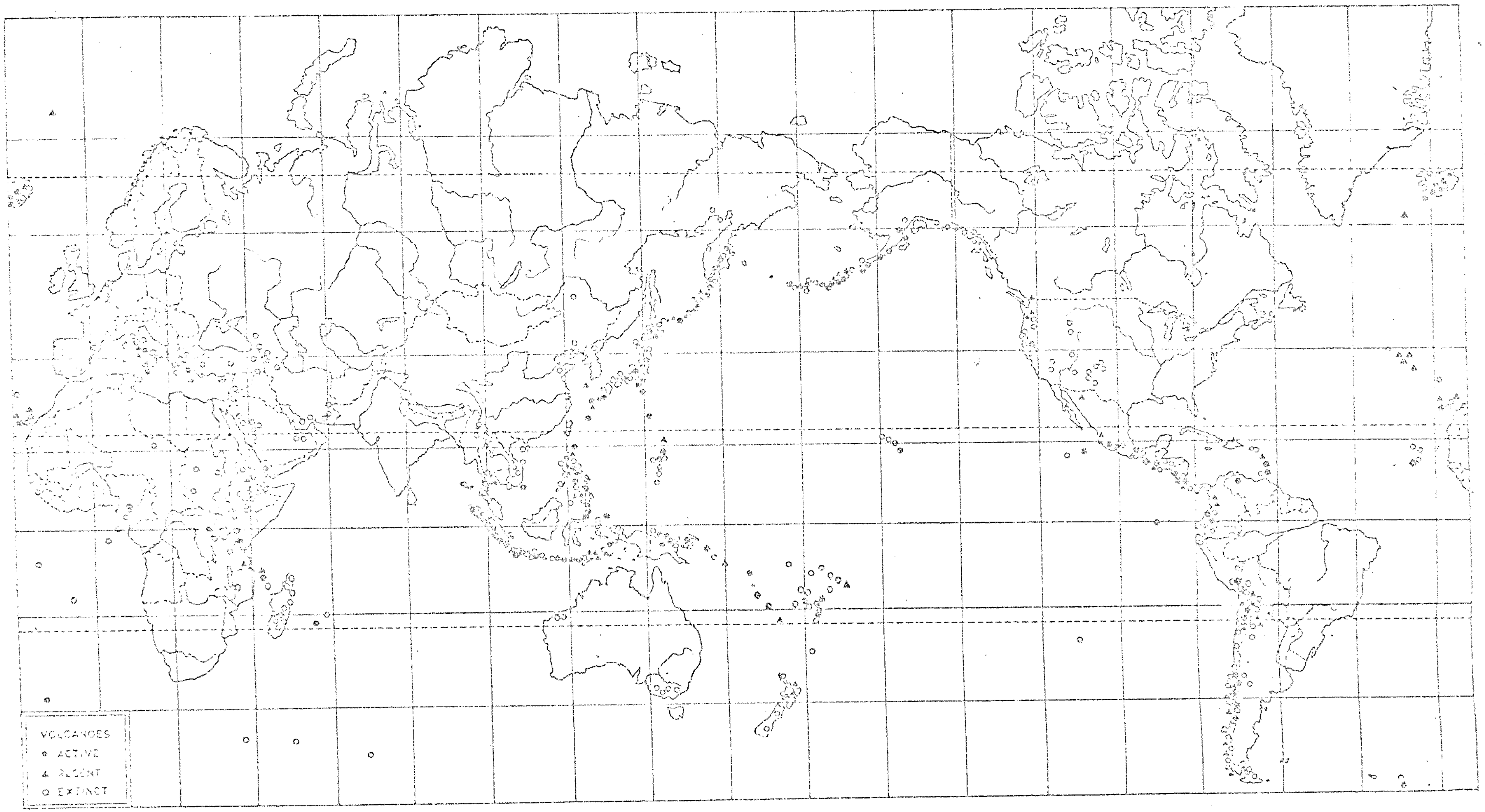


Figure 1 - 19   Distribution of the world's volcanoes (updated to 1970 from Vening Meinesz 1964) (52).

2.6.4 AUTHIGENIC SEDIMENTS: In the main, these are seafloor chemical precipitates but they may well be in part biochemically formed. Among the most widely known, because of their resource potential, are manganese nodules and shallow water phosphates. Manganese nodules cover wide areas of the deep ocean floors and techniques are in advanced stages of development to mine them.

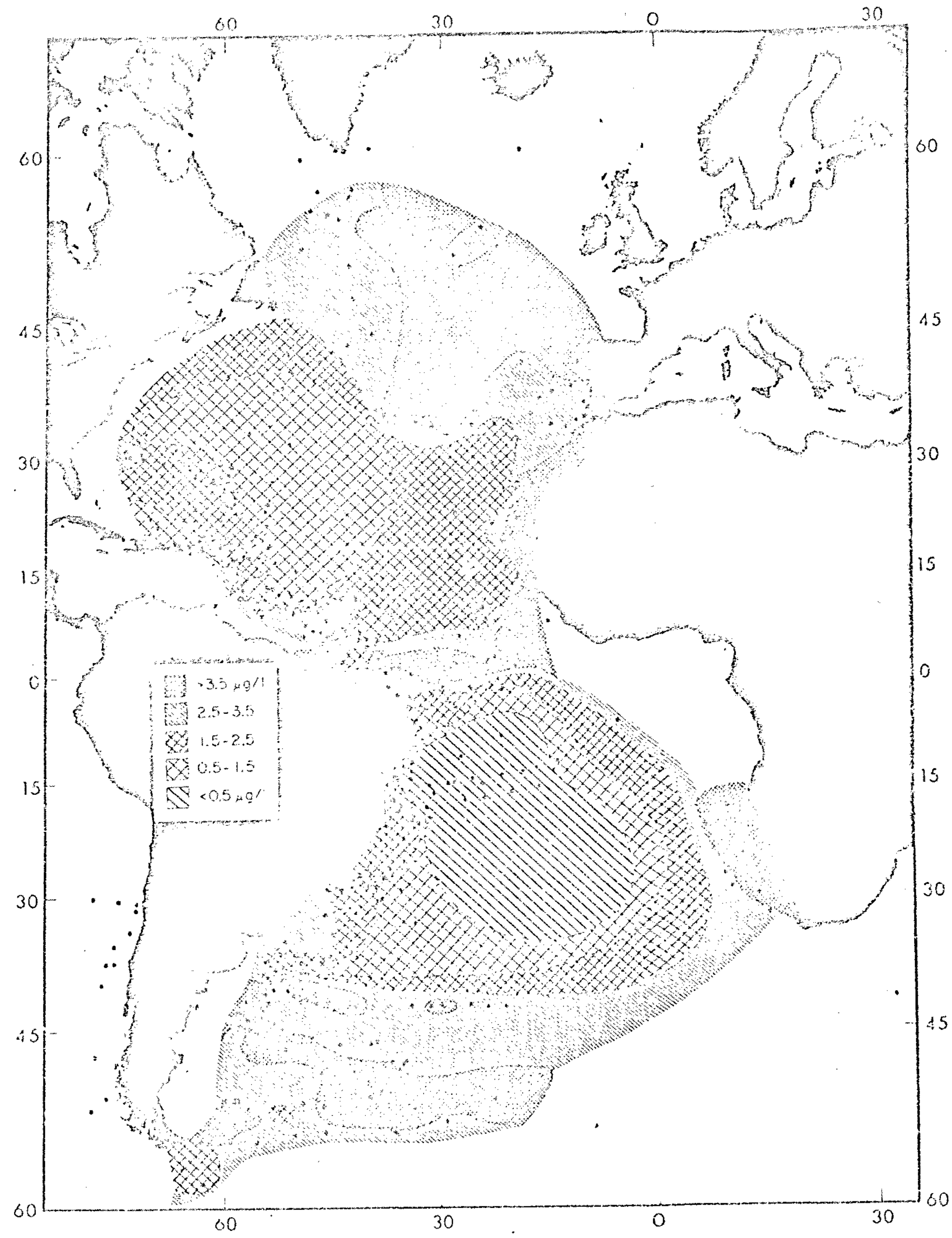
Man's activities in dumping waste materials into the ocean, although not yet of geological significance on a global scale, are locally important near densely populated, highly industrialised seaboards. It has been pointed out that New York City supplies more particulate matter to the ocean annually than any of the rivers of the eastern United States (27).

2.7 SEDIMENT TRANSPORT

Mechanisms that transport sediments in the marine system are all primarily responses to gravity. Deep water areas are influenced by density driven currents of various kinds as well as surface currents. The principal influence of the surface currents is to distribute the fine suspended load along with the biogenically produced sediment. Additionally surface currents distribute ice-rafted material and volcanic debris, especially floating pumice.

As suspended materials settle through the water column, concentrations are developed at density discontinuities where appreciable lateral movement can be initiated as sediment plumes, such as occur frequently at the permanent thermocline. Another concentration zone, located within a thousand metres of the bottom in all deep ocean areas, is known as the 'nepheloid layer'[28]. It is a zone in which upward mixing and resuspension of sediment from the bottom also occurs and its distribution (Figure 1-20) depends strongly on the effects of topography (downslope movement caused by excess of density) and bottom water circulation (lateral movement).

Downslope movement of sediment in the nepheloid layer is seen as a stage in a continuous spectrum of mechanisms for movement of sediment along the seafloor under gravity. The possible range is one of increasing scale



Suspended sediment concentrations in the Atlantic nepheloid layer (from Biscaye & Eittreim 1977).

Figure 1 - 20

and volume of entrained sediment, through density currents, grain flows, fluidised sediment flows to turbidity currents and debris flows and then perhaps on to mass movement processes, such as creep, slumping and sediment slides. Most of the above mechanisms are episodic in nature and are the cause of the marked vertical variability of sediment sequences found beneath the continental rise and the abyssal plains. The larger scale processes are able to transport coarse-grained sediment and thus will give rise to sand and silt layers in what would normally be clayey sequences. Tracing of these sandy layers (or turbidites) by seismic profiling reveals a general decrease in their occurrence away from the continental margins. However, any upstanding topographic feature can be the source of such flows should its sediment cover become unstable. In addition, the nature of the transport is such that flows are strongly controlled by topography and even on open, flat seafloor turbidity currents are known to create their own channel systems. Horizontal variability is therefore great and areas within reach of such sediment transport mechanisms are likely to prove impossible to model in terms of leakage pathways for emplaced wastes. Close to their sources some of these flow mechanisms may even be erosive, so that it will be necessary to locate disposal areas at least beyond layered turbidite distributions that can be inferred from seismic profiling.

Thermohaline currents are a component of the ocean's bottom water circulation resulting from density differences between water masses of differing salinity and/or temperature. They can rework or erode existing deep water deposits. Acceleration of currents around upstanding features may cause erosion of the surrounding sediment surface (Figure 1-22), while later deceleration will cause deposition. Modification of the sediment surface by bottom currents, producing characteristic bedforms in abyssal regions, has been widely recognized in recent years. These bedforms range from millimetres to kilometres in scale (Table 1-1). However, not infrequently even the largest bedforms are simply surface modifications of even grander

TABLE 1.1 - CHARACTERISTICS OF BED FORMS IN THE DEEP OCEAN

	Spacing	Relief	Width	Length	Conditions of formation
SMALL-SCALE FEATURES Lineations	Up to 10 mm	Up to 1-2 mm	Up to 1-2 mm	100-150 mm	Faint examples formed by very slow currents; increasing definition with increasing current
Scour and 'tails' around static obstacles	Depends on size of obstacle				Formed with pronounced lineations and at faster flow rates
Asymmetrical ripples	Proportional to 1000 times the grain diameter	Generally 40 mm	**	May be continuous for metres to tens of metres, or form a complex network	Caused by net movement of water in one direction
LARGE-SCALE FEATURES TRANSVERSE TO CURRENT Megaripples	0.6-30 m	0.4-1.5 m	**	Tens of metres to hundreds of metres	As for ripples above
Sand waves	Generally 30-500 m but up to 1 km	1.5-25 m (1/3-1/10 of flow depth)	**	Hundreds of metres to tens of kilometres	Beneath bed flow of 0.5-1 ms^{-1} (widespread on continental shelves but rare in the deep ocean
Transverse mud waves	2-6 km	20-100 m	**	Tens of metres to kilometres	Where appreciable bottom currents are accompanied by high suspended sediment concentrations
PARALLEL TO CURRENT Sand ribbons	Tens of metres to hundreds of metres	1 m	Tens of metres	Kilometres	(e.g. in water depth of 100 m with surface currents of 1 ms^{-1})
Furrows	Tens of metres	1-2 m	Metres	Kilometres	?
Longitudinal mud waves	2-6 km	20-100 m	**	Kilometres	As for transverse mud waves, but generally little known

GENERALLY INCREASING CURRENT VELOCITY

** Generally width and spacing same for wave-like structures scale depositional ridges, known as sediment drifts, that have been built by bottom current action over millions of years. An example is Feni Ridge, a wedge of sediment up to 1 km thick that has been built up over the past 20 million years against the south-eastern margin of Rockall Plateau (29) (Figure 1-21). Recent long range sonar mapping of its surface has revealed complex dune fields of longitudinal mud waves up to 30 metres high and over 26 km in length.

2.8 SEDIMENT DEPOSITION

Since practically no in-situ experimentation on sedimentary processes has yet been carried out on deep ocean floors, our knowledge of the controls on deposition of the major sediment types and their accumulation rates is severely limited.

2.8.1 Current Deposited Sediments: Infilling of seabed morphology by gravity-controlled processes has been the prime factor in producing the present, broad flat abyssal plains. Averaged accumulation rates in turbidite sequences on North Atlantic margins range upwards from 20 cm per thousand years. These rates however will vary spatially and in time. For example, Pleistocene sea level changes over the past 1.8 million years not only produced increased sediment supply but also lengthened (high sea level stand) or shortened (low sea level stand) the courses of submarine canyon systems on the continental slope and shelf. The canyons are major conduits through which turbidity currents and other gravity flows funnel sediment away from the continents. Thus the sea-level changes have influenced the patterns of sediment deposition on the continental rise (submarine fans) and the basin floor (abyssal plains).

On seismic profiles the deposits of deep ocean bottom currents (contourite sequences) are acoustically fairly transparent, lacking strong internal layering. They are not uniformly distributed in relation to the basement topography but are heaped into piles and ridges elongated parallel to the current. Their upper surfaces are commonly decorated with mudwaves and because they are built by geostrophic currents they are most common around the margins

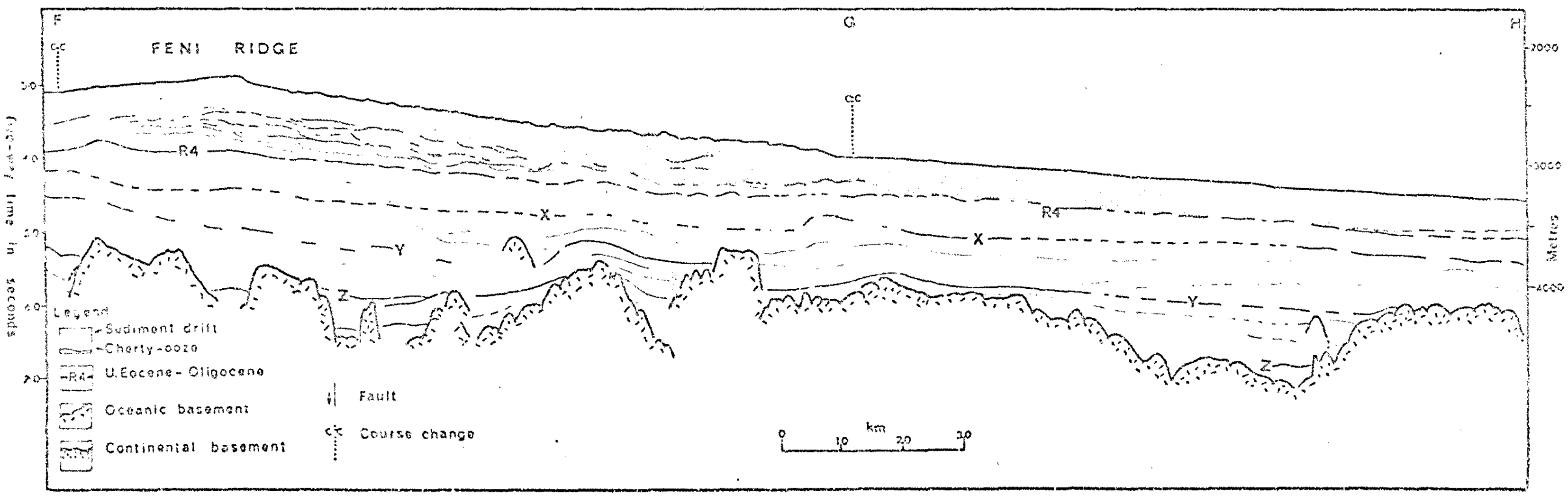


Figure 1 - 21 Cross section of the Feni Ridge sediment drift drawn from a seismic reflection profile. Note the discordance of layering between the drift and underlying sediments. (From Roberts 1975).

of thé ocean basins. Averaged accumulation rates lie between 5 and 15 cm/10^3 yrs.

2.8.2 Pelagic Sediments: In areas where bottom current activity is slight, such as the mid-gyre-regions central to the major bottom water circulation patterns, particles carried by currents in the surface layer settle out and cover the seafloor in a uniform blanket, irrespective of basement morphology. The terrigenous fine-sediment component, comprising mainly clays, volcanic debris and windblown dust, is distributed worldwide. The biogenous component on the other hand accumulates only where productivity exceeds dissolution. The surface oceans are undersaturated in silica and so siliceous biogenic remains begin to dissolve immediately. It has been estimated that only 4% of the skeletal silica formed survives to reach the seafloor and half of that is dissolved after deposition[30]. Thus, accumulations of siliceous sediment are found only beneath regions of high biological productivity, namely the equatorial (radiolarian oozes) and subpolar regions and those ocean margins where upwelling occurs (diatomaceous oozes). Diatom oozes have accumulated, over the past 2 million years on ridges and plateaus of the Aleutian Arc, at rates between 7 and 14 cm/10^3 yrs.

The accumulation of calcareous sediments is governed by similar factors, except that the oceans' surface waters are supersaturated in calcium carbonate and thus carbonate deposits (reefs, etc.) can accumulate in shallow seas the world over. The oceans become undersaturated with respect to calcium carbonate below a few hundred metres and dissolution commences, becoming particularly rapid below about 4000 metres water depth. Below 5000 metres virtually no undissolved carbonate can survive. Recent studies[24] have shown however that most solution occurs at the sediment water interface over long exposure times, rather than in the water column during sinking. The depth at which carbonate supply from the surface matches carbonate dissolution and there is no net accumulation of calcareous sediment is referred to as the carbonate compensation depth or 'CCD'. It tends to be depressed under the equatorial high productivity belt, but becomes shallower towards the ocean margins. In regions remote from the land, seafloors that stand above the CCD are usually blanketed in calcareous ooze. Below it only the residual component of fine terrigenous sediment is deposited; these are the pelagic clays. North Atlantic calcareous oozes have accumulated at average rates of between 2 and 3 cm/10^3 yrs since the last glacial period. Accumulation rates in Pacific deep sea clays are generally less than 0.1 cm/10^3 yrs and in many regions almost zero deposition has occurred over millions of years.

2.9 EROSION OF THE SEAFLOOR

Erosion by deep ocean current systems may occur on a large scale (Figure 1-22). On a regional scale deep sea drilling has shown that, over large areas of the Atlantic and Indian Oceans, sediments representing long periods of geologic history are missing; these breaks in accumulation (hiatuses) attest to the long term effects of current erosion (31,32).

Information on more local dynamic conditions that might be necessary for the erosion of sediment surfaces, in disposal study areas for example, is difficult to obtain. Fine grained marine sediments exhibit a resistance to erosion in excess of that which would be expected from considerations of the size and weight of the constituent sediment particles alone. This additional erosion resistance (or cohesion) could mainly be the result of both interparticle surface attractions

and organic binding. Thus simple relationships, such as those that can be measured in laboratory flumes for coarser sediments between grainsize and threshold erosion velocity, are not directly applicable. Neither are studies on the erosion of freshwater muds (33) since salt water flocculation strongly affects the behaviour of fine grained marine sediment surfaces. Cohesion and erosion resistance in marine muds are complex functions of a number of inter-related sediment properties including their water content, mineral and organic composition, grainsize, depositional history and their fabric (spatial arrangement of particles). Some useful information, such

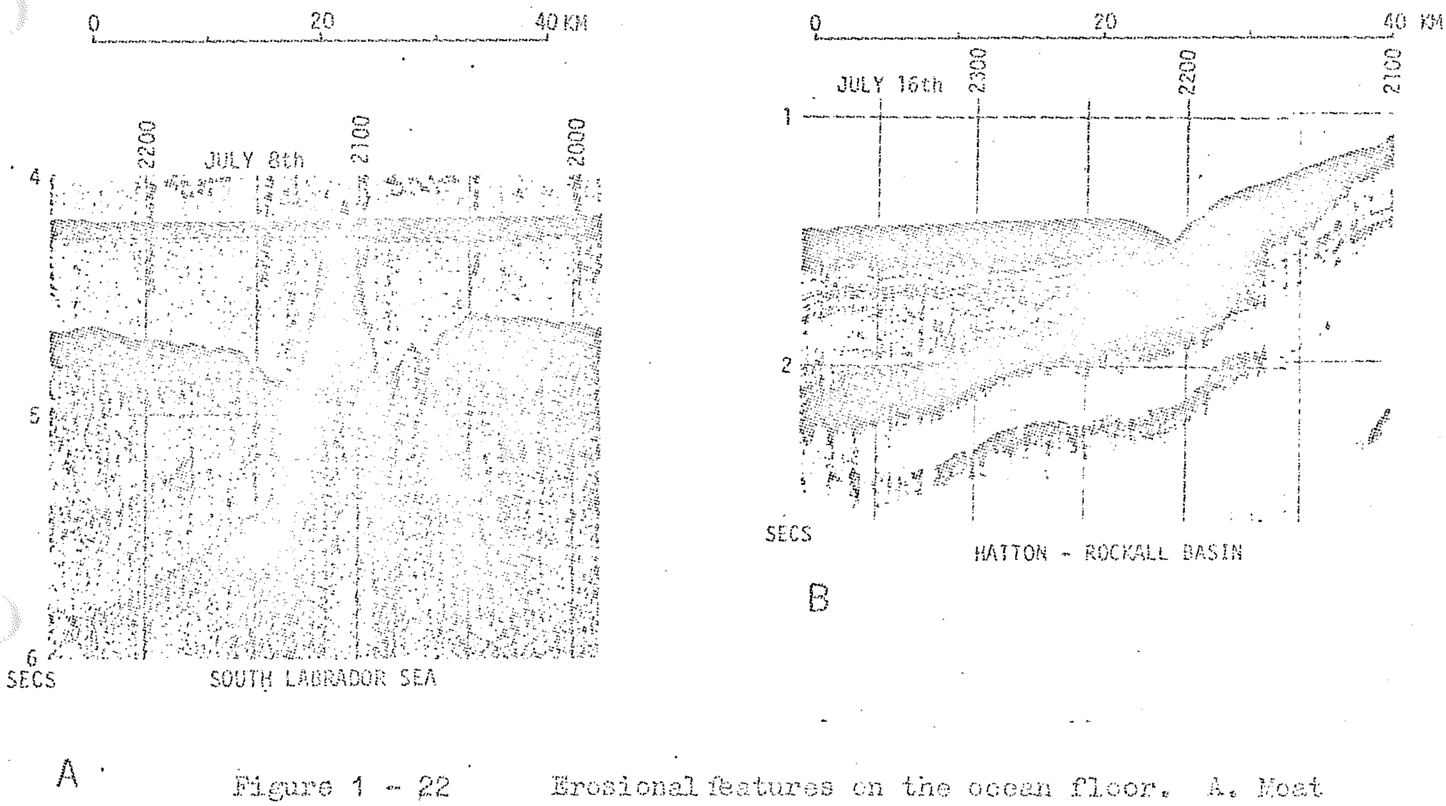


Figure 1 - 22 Erosional features on the ocean floor. A. Moat around a seamount in the South Labrador Sea. B. Marginal channel in the Hatton-Rockall Basin (from Davies & Laughton 1972) (63).

as the generally inverse relationship of water content changes to the threshold erosion velocity of marine clays, has resulted from investigations that involved laboratory experimentation on reconstituted marine sediments sampled at sea[34]. However, some of the complexly inter-related sediment properties are typically not reproducible for laboratory flume studies. Recent in-situ experiments[35] using a sea-floor flume in a shallow embayment off the U.S. coast have emphasised this point. The experiments also demonstrated that the intensity of bioturbation (biological reworking) can be a prime factor in destabilizing muddy sediments and decreasing their resistance to erosion. So far in-situ flume experiments have been conducted only in very shallow water (16 metres depth) but the SEAFLUME device[36] is designed to operate at any depth. Even at this stage it is clear that experiments with such equipment will be necessary in disposal study areas and should be linked to long term monitoring by bottom current meter arrays.

To Summarise:

Only in the past two decades have the abyssal ocean floors been recognised as other than tranquil regions with little to disturb the gentle rain of particles from the surface. To date we have only a general impression of the dynamic processes at work in these areas. A concentrated effort in nearbottom investigation over a number of small areas of the seafloor, employing a wide range of oceanographic techniques, is necessary before predictions can be made of the geologically short term stability of sediments in these basins.

2.10 GEOGRAPHICAL DISTRIBUTION OF SEDIMENT TYPES

Figure 1-18 presented earlier, serves to illustrate some basic differences in the patterns of sediment types through the three major oceans. These are the result of the range of depositional controls outlined above. In the Pacific and Indian Oceans, all four of the major sediment types, calcareous ooze, pelagic clay, siliceous ooze and terrigeneous sediment, are represented by extensive zones where they are the dominant sediment variety. The Atlantic differs in a number of respects as is discussed below.

Pelagic clay and siliceous ooze occurrence is strongly dependent upon the level of the CCD and the distribution of current-deposited (terrigenous) sediments. The CCD in the North Atlantic varies between 5000 and 6000 metres water depth. Some abyssal plains and small troughs do exist in the North Atlantic that are below the local CCD level, but in most cases, these are near enough to land areas to be reached by copious supplies of rapidly-depositing terrigenous sediment. Thus areas of pelagic clay in the Atlantic are sparser than in the Pacific, where pelagic clays cover enormous areas. Similarly, although surface productivity is high enough in a zone south of Iceland for considerable deposition of biogenic silica, calcareous plankton productivity is also very high and the seafloor is sufficiently elevated above the CCD that siliceous remains simply become a component of calcareous ooze. Consequently no high latitude siliceous oozes are present in the North Atlantic either. This leaves only two major sediment types: calcareous ooze and terrigenous sediments.

In both the Pacific and Indian Oceans, bottom water is produced at the southern ends only, in the Antarctic sink regions, and flows northwards. The Atlantic, on the other hand, has bottom water production at both its northern and southern ends. In the North Atlantic especially, few deep areas can be considered remote from either density currents or geostrophic current action. This means that whereas distinct sedimentary provinces exist in the Pacific and Indian Oceans, North Atlantic sediments are complex admixtures of two, biogenous and terrigenous, end members. This is particularly true at the latitude of the United Kingdom where nearly all of the sediments have been transported long distances by a wide range of mechanisms before becoming deposited.

2.11 POST-DEPOSITIONAL PROCESSES

Deposited sediment may be affected by erosion, redistribution, winnowing, episodic mass movements and turbidity current flow. Disruption of the sediment pile by the burrowing activity of organisms living in the upper metre of the seabed (bioturbation) is a redistribution process that occurs almost everywhere; regions under anoxic bottom waters being the only exception. Bioturbation is known to re-introduce large quantities of fine sediment to the nepheloid layer.

Sedimentary material that survives these redistributive processes begins to suffer diagenetic changes. Mineralogies alter with the formation of authigenic minerals; such as where a distinctive suite of clay minerals and zeolites are produced by the submarine weathering of volcanic materials. When the sediment pile begins to thicken, a series of physico-chemical changes are brought about by compaction and loading. Resulting physical changes in sediment and rock permeability, porosity and shear strength are dealt with in other sections of this chapter. Changes in chemical properties are referred to in Chapter 2: Geochemistry. Relatively few studies have considered the inter-relationship of changes in both chemical and physical properties, and these mostly have confined themselves to long-term changes in drill holes: the alteration of calcareous oozes to soft limestones, for example (37).

The mobilization of silica to form chert is one particular chemical process that may be of importance in disposal considerations. The discovery of extensive chert horizons within sediment sequences has been one of the surprises of deep sea drilling. These are analogous to the flint beds of the English Chalk. Incipient chertification in the upper layers could present major problems to emplacement and modelling of slowly deposited sediments, such as pelagic clays (81).

2.12 PREDICTABILITY OF SEDIMENT SEQUENCES

2.12.1 THE LAST 200 MILLION YEARS: The first sediments deposited on newly-created seafloor in a mature ocean are frequently volcanogenic but these soon become swamped by calcareous ooze as the seafloor spreads away from the ridge. Calcareous ooze will in most cases build up a considerable sediment cover on the oceanic basement before the seafloor has subsided below the CCD. Thereafter residual pelagic clays will be deposited. Fluctuations in the level of the CCD through geologic time (38), due to changing oceanographic conditions, will produce layering variations in the sediment column (Figure 1-23). Should a sub-CCD site pass into high productivity zones, siliceous oozes will begin to appear in the column. Alternatively passage into volcanically active regions, such as near subduction zones, could cause volcanogenic sediments to be deposited. In addition, at any time in its geologic history a site could come within reach of terrigenous sedimentation, which is dominant on passive ocean margins. Local tectonic events or current erosion will cause gaps in the sedimentary record preserved at a particular location. Thus the development of ocean basin sediment columns is fairly predictable (20).

At the other extreme in terms of predictability are changes that occur at the seafloor on a time scale of months to years. Many of the current-produced bedforms known from the deep ocean floors are thought to result from episodic changes in sedimentary regimes, since current meter monitoring over periods of up to a month has so far failed to record conditions that could cause such bedform developments. Monitoring equipment is presently being developed in the United States that may be capable of recording such 'events', but again this field of in-situ experimentation requires urgent attention.

2.12.2 THE LAST 1.8 MILLION YEARS: Between the above extremes lies the time scale covered by surficial sediment core sampling. Generally the upper 20 to 30 metres of cover represents no more than the last 3 million years of deposition for most sediment types, but similar thicknesses can represent up to 70 million years in the extremely slowly accumulated pelagic clays (2).

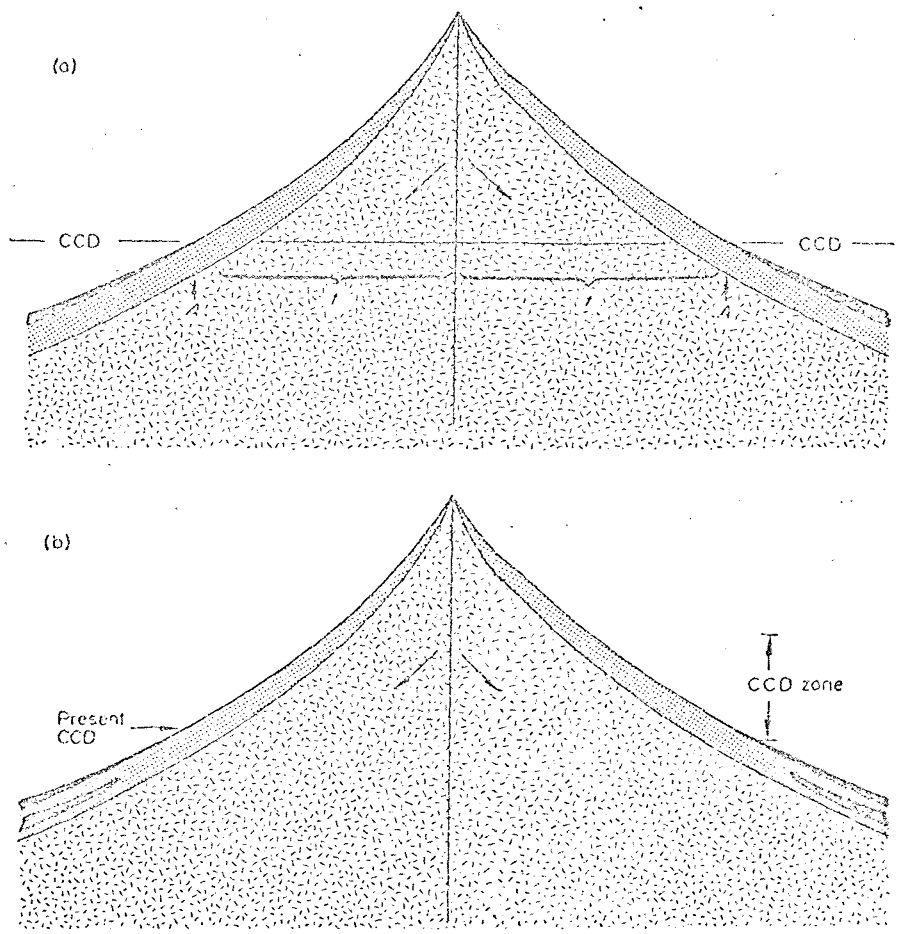


Figure 1 - 23 Carbonate deposition on spreading and subsiding ridge flanks for (a) stationary and (b) fluctuating CCD levels. Stipples: calcareous ooze; block: pelagic clay; t: distance from ridge crest corresponding to time t; A: final thickness of carbonate corresponding to time t; CCD zone: range of fluctuation of local CCD level (from Berger & Winterer 1974).

A great deal of research effort is necessary to date sedimentary sequences over this shortened timescale. Evolutionary changes of micro-fossil groups have not been rapid enough to apply the standard micro-paleontological techniques that divide up (relatively coarsely) the Cenozoic timescale (the last 64 million years). Some major paleontological events are correlated with reversals of the Earth's magnetic field as measured in paleomagnetic studies. Variations in bulk carbonate content in sediments, caused by differing foraminiferal productivity, reflect climate changes (39), as also do differing oxygen isotope ratios in the shells of planktonic foraminifera (40,41). Measurements of these parameters are taken together and correlated with the paleomagnetic changes to provide a reference stratigraphy for deep sea cores based on glacial cycles (42). Absolute dating of marine cores is tackled by geochemical measurements, either on bulk sediments, using radiocarbon (C^{14}) or uranium series methods (thorium, Th-230 and proactinium, Pa-231), or on individual volcanic ash layers, using the potassium-argon method. Unfortunately absolute dating is not always reliable (17). Carbonates older than 20,000 years may give erroneous C^{14} dates caused by contamination with recent carbon; many cores do not yield ideal Th-230 versus depth curves; and volcanic ash layers may already be contaminated by old material at the source eruption. Similarly bioturbation by benthic fauna can have a marked effect on the stratigraphic record held by cores (43). Although recent studies have shown that bioturbation is confined to the upper tens of centimetres of deep ocean sediment and that rates of mixing are lower than in shallow environments, biological effects are constant over all sedimentary environments irrespective of surface productivity and local sedimentation rates. Thus stratigraphies will be 'blurred' over a greater time range in slowly deposited red clays than in carbonate oozes; perhaps 25,000 years as opposed to 2,500 years. Also, since the surface sediment being mixed will maintain the signature of the contemporary magnetic field, the magnetic reversal sequence will be offset by the amount of 'blurring'.

Disposal studies aimed at predicting environmental changes will require then particularly a detailed knowledge of the recent history of a location. Reliable stratigraphies such as this can only be built up when the whole range of micropaleontological, paleomagnetic and geochemical dating techniques are employed and compared with one another. Any coordinated sampling programme for disposal studies will require the services of a number of specialist laboratories, groups and individuals to provide this basic information. In addition, certain techniques that may enable refinements to be made to any stratigraphy determined by established methods should be encouraged. These include the use of secular variation to refine the paleomagnetic timescale (44,45) over the past 10-20 thousand years and measurement of magnetic fabrics to establish changes in current regimes through time (46,47).

Major environmental changes have been recognised in deep marine sediment sequences linked to the main advances of glacial ice during the last 1.8 million years of Quaternary time. Recent paleomagnetic and oxygen isotope studies have shown that glacial/interglacial fluctuations have characterised the Earth's climate for at least the past 3.2 million years; only their scale has increased in the past 2.5 million years (41). Our present climate most probably represents an interglacial rather than post-glacial condition. Some of the effects of glacial climatic and sea-level changes on sediment supply and distribution have been outlined in earlier sections of this chapter. An understanding of regional changes in water mass circulation over the past 200,000 years is being gained through application of multivariate statistical studies of planktonic microfossil populations from sediment cores (48). This information has already been linked to regional changes in sediment composition and rates of accumulation (23,49). Intensification of bottom water circulation has been suggested as an explanation of widespread erosional events on the deep seafloor (32). To date, detailed paleo-environmental information such as that published by the CLIMAP group (48) is available for no more than 50 core locations worldwide;

very few of these are less than 100 km apart. In order to estimate the predictability of disposal areas, such techniques will need to be concentrated on closely spaced suites of long cores.

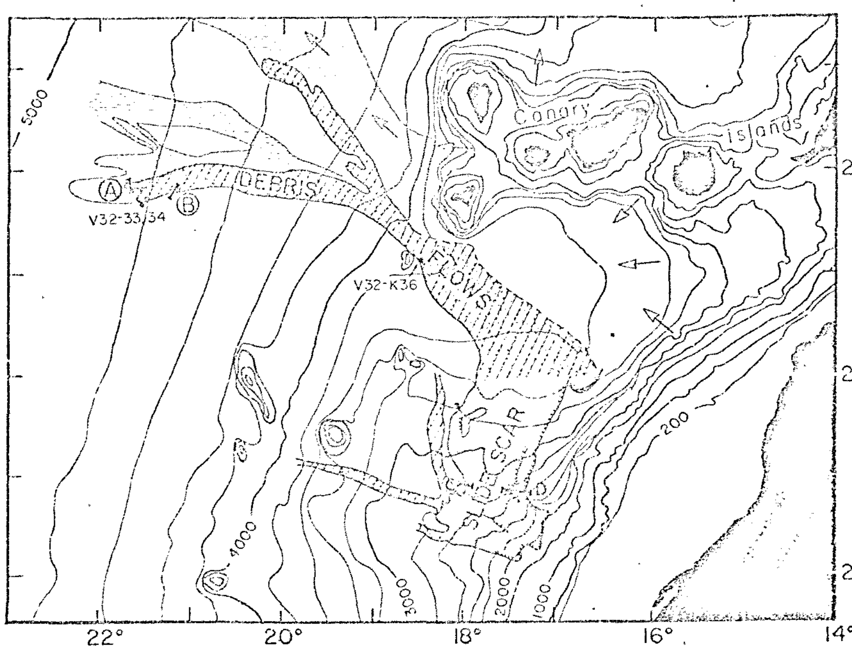
2.13 STABILITY OF THE SEABED

2.13.1 MECHANISMS OF SEDIMENT FAILURE

There is an obvious hazard of the sediment barrier becoming stripped off by erosive bottom currents or breached by mass sediment movement. Sediment on any slope is liable to failure under conditions controlled by the steepness of the slope, the sediment type, and on occasion the occurrence of earthquakes. The mechanisms of sediment failures on land have been intensively studied by civil engineers. In contrast, the 'state of the art' for submarine environments beyond the shelf break has barely gone further than description of seabed morphology left behind after mass failure. Waste canisters carefully emplaced at some optimum spacing could become concentrated under the effects of creep, slumping or sliding; or at worst even become exposed at the sediment/water interface, thus negating the effectiveness of the sediment barrier.

A submarine sediment slump is defined as a slope failure in which the sediment has been down-dropped and rotated, but whose actual mass translation and internal contortion are minimal. A slide is a failure in which the sediment has translated along a glide plane and moved downslope, usually transforming into a debris flow in which semi-consolidated lumps of slide sediment become mixed with surficial materials downslope (50). In most cases, as for example in the 1929 earthquake-induced Grand Banks failure which broke a number of submarine telephone cables south of Newfoundland, turbidity currents are initiated, which extend depositional effects onto abyssal plains well beyond the immediate locality of the mass movement (51).

Submarine mass movements can involve enormous volumes of sediment (Figure 1-24). At least a dozen localities on North Atlantic margins have



The Spanish Sahara sediment slide and associated debris flow deposits. Stippling: area of sediment removal; diagonal lines with circles: extent of debris flows; dashed lines: main turbidity current deposits; hatching: 20-100 m scarps; arrows: probable routes for Pleistocene and Holocene turbidity currents (from Embley & Jacobi 1977).

Figure 1 - 24

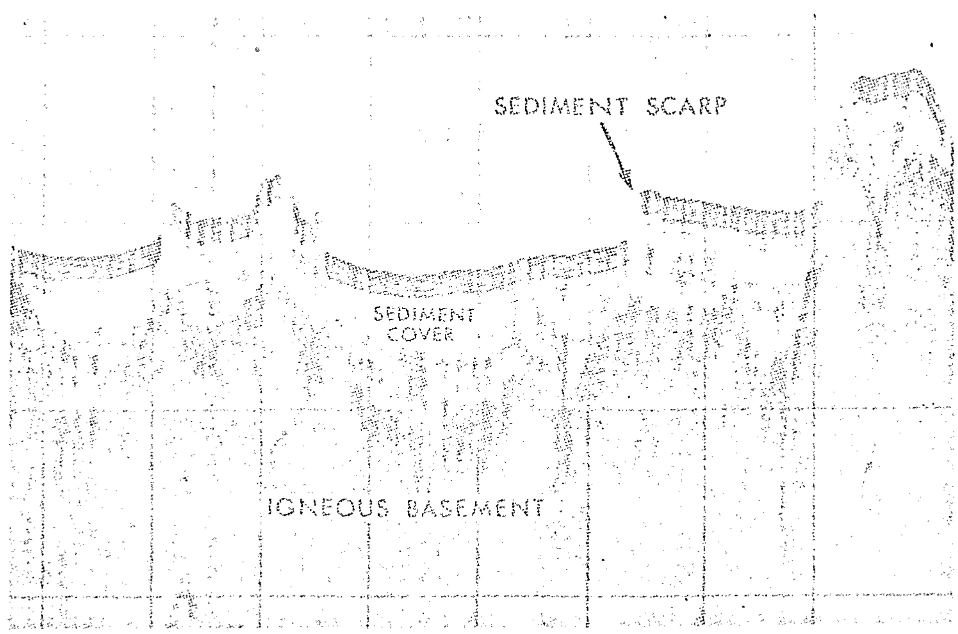
slides and slumps ranging upwards from 200 km² in areal extent. Some of these are known to have occurred on slope angles of as little as 0.5°.

Suggested mechanisms for slope failure are: (1) tectonic,- involving earthquakes or long-term tilting; (2) overloading, due to high sedimentation rates near the shelf edge; (3) progressive failure, caused by lower slope erosion by geostrophic currents; (4) in-situ changes in internal pore pressures, related to gas generation. We note here that many of the large slides that are thought to have been earthquake-induced, occurred on continental margins that would be considered aseismic in the short term (<100 years).

If it is assumed that the continental margins will be avoided as possible disposal sites because of factors like resource potential and that disposal areas will be located beyond the range of debris flows initiated by known margin slides and slumps, we are still left with the knowledge that causes (1) and (3) above are capable of initiating large scale mass movement on very low regional slopes.

Isolated oceanic rises like the Madeira Rise and Great Meteor Seamount might also be avoided as potential sites, but this still leaves wide areas where the microtopography is such that local slopes of greater than 1.5° do occur.

More important perhaps in deep seafloor regions might be small scale effects of mass movement, such as creep. This has been detected in shelf areas such as the Gulf of Mexico but nothing is known of whether it exists on the deep ocean floor. Similarly very little is known of mid-plate tectonism and its effects on sediments. Closely-spaced seismic profiling surveys frequently detect what, depending upon interpretation (Figure 1-25), may either be recent faulting of the sediment cover (that is, mid-plate tectonism) or the building up by pelagic sedimentation of a depositional sediment scarp above an old basement fault. Clearly there is a need to link long-term monitoring of earthquake (and microearthquake) activity in



'RRS Discovery' seismic reflection profile
about 100 miles northeast of the Azores showing
fault scarps of problematic age (from Searle 1977) (65).

Figure 1 - 25

any disposal study areas to experiments on sediment mass movement on local low-angle slopes (Table 1.3.3f).

As well as the above natural effects on local sediment stability, responses to container emplacement itself or other artificial effects such as sudden loading by a sunken ship should also be considered. Also, an emplaced heat-producing waste canister could cause stresses that exceed the shear strength of its host sediment and thus initiate mass fluidisation. Research into sediment mass movement should also attempt in-situ measurements of the effects of emplaced heat sources (Table 1.3.2).

2.13.2 SEISMIC HAZARD

Although most earthquakes occur at plate boundaries, intra-plate earthquakes do occur. At any particular location large intra-plate earthquakes are infrequent and may not have occurred during the last two decades - the brief period during which an efficient worldwide seismic monitoring network has existed. For example, the largest known British earthquake (m_b = 5.5), which occurred in 1931, was an order of magnitude more energetic than anything which has been detected since (53). Even at active plate margins, seismically quiet periods have prevailed in some regions for several decades. Furthermore, the detection threshold of the present earthquake reporting network is not uniform over the earth's surface, but is biassed by the distribution of stations to greater sensitivity over the land masses of the northern hemisphere. Thus the lack of reported earthquakes from a region of the ocean floor cannot be taken to mean the absence of earthquakes in that region.

Earthquakes occurring beneath the ocean floor could affect the environment in which waste canisters were emplaced in two ways:

(1) By affecting the physical properties of the sediment itself. Even on gentle slopes this could initiate sediment failure. In flat-lying areas it might speed up the process of compaction and hence the rate at which sediments dewater.

(2) By altering the topography of the ocean floor through faulting. This could lead to waste canisters being exposed at the sediment surface directly, or indirectly by altering the depositional/erosional regime at the seabed. Faults are commonly observed on seismic reflection profiles of the seabed and it is not always clear from the sedimentary structure whether these are active or merely the fossil record of the creation of igneous crust at the ridge axis (Figure 1-25).

Microearthquake surveys on the ocean floor with Ocean Bottom Seismographs could indicate whether such faults are seismically active at the present time and whether the ocean basins are as inactive as current seismicity maps suggest (Table 1.3.6).

2.14 PHYSICAL PROPERTIES OF DEEP SEA SEDIMENTS

2.14.1 THE SOFT SEDIMENT KNOWLEDGE GAP

The superficial sediments of the ocean floor are generally found to be soft, often plastic and with low shear strength. With time soft sediments compact under the overburden of more sediment and processes of diagenesis cause the component particles to be cemented together. Thus when the sedimentary column is old enough or thick enough the material at the bottom has become lithified into a rock. The process of lithification is complicated and need not be entered into here. Suffice to say that the thickness of the superficial soft sediment, while showing considerable variability, is of the order of 100 m. Determining the properties of this soft sediment layer has proved more difficult than finding out those of the lithified sediments beneath. In particular information relating to the depth range 30-100 m is difficult to acquire both from the point of view of sampling and of making in situ measurements.

Difficulties in Sampling The capabilities of modern sampling techniques are summarised in the section on sediment shear strength. The largest corer now in use can penetrate soft sediment to a depth of 30 m/(2,54). This is too big for conventional oceanographic ships to deploy in oceanic depths and probably represents the limit of development of this technique. Sediment samples from deeper than 30 m beneath the ocean floor have practically all been obtained by the Deep Sea Drilling Project Ship Glomar Challenger. The latter process involves considerable disturbance to the sediment, which is particularly great near the top of DSDP holes because oscillations of the drill pipe are not damped out until a considerable length is buried in the seabed. Furthermore, recovery is often incomplete, particularly where layers with contrasting physical properties are interbedded.

Difficulties in Measurement In-situ measurement of such parameters as compressional and shear wave velocity, electrical résistivity and shear strength have been made in the top few metres of the sediment. Below this depth, down to about 100 m, only spot temperature measurements have been made in DSDP holes, with a probe pushed ahead of the drilling bit into undrilled sediment[55,56]. Below 100 m, provided the sediment is sufficiently lithified, the whole range of well logging tools have been employed to measure the properties of the rock. Among the properties measured have been sonic velocity, density, porosity, electrical resistivity, natural γ radiation.

Seismic techniques might provide a way to study some of the in-situ properties of the soft sediments. For this to work however, both sources and receivers must be deployed on the ocean floor. Ocean floor receivers have been operated with success for many years, but little effort has so far been devoted to the development of ocean floor seismic sources. With air gun or explosive sources fired near the sea surface, information relating to the sedimentary column is usually limited to interval time and sounding velocity - averages which may embrace a wide range of properties within the column. Furthermore, purely compressional sources near the sea surface produce little converted shear energy in the sediments and rocks. With sources on the ocean floor it should be possible to generate more shear wave energy. Shear wave velocity is a more sensitive indicator of the physical properties of sediments than is compressional wave velocity (Table 1.3.3).

2.14.2 POROSITY

The porosity of a rock is defined as the volume of voids expressed as a percentage of the total volume. The unconsolidated sediments of the ocean floor have porosities ranging from about 40% to 90%, but typically lie in the region of 70%. Porosity is found to correlate with grain size, the fine grained sediments composed of clay-sized particles being the most porous. This is a consequence of the shape of the particles. The platy clay-sized particles form open "house-of-cards" structures; the coarser particles, being more rounded, form more close-packed structures. Porosity decreases with depth below the bottom due to compaction, but not necessarily in a simple way and porosities in excess of 50% are commonplace at subbottom depths of 200 metres.

Because the density of the solid particles in the sediments recovered from the ocean floor is usually close to 2.7 gm/cm³, other physical parameters such as wet bulk density (ρ) and water content (w) (pore water expressed as a fraction of the wet weight) can be calculated from the porosity. Thus

$$\rho = 2.7 - 1.67\phi$$

$$\rho^{-1} = 0.37 + 0.63w$$

In soil mechanical studies the parameter void ratio (e) is often used, defined as the ratio of the volume of voids to the volume of solids. Hence

$$\phi = \left(\frac{e}{e + 1}\right) 100\%$$

The following table indicates how porosity and its related parameters vary with the grain size of a sediment. (Real sediments, of course, cover a range of particle size).

	Very fine sand	Silt	Clay
Grain diameter	0.1 mm	0.01 mm	0.001 mm
Porosity	45%	60%	75%
Wet bulk density	1.95 gm/cm³	1.7 gm/cm³	1.45 gm/cm³
Water content	0.24	0.36	0.53
Void ratio	0.82	1.5	3.0

The porosity of a sediment sample is measured in the laboratory either by gravimetric or by gamma-ray attenuation methods. In-situ determinations of the porosity of ocean floor sediments have been made by measuring their resistivity and by gamma-ray scattering techniques.

2.14.3 THERMAL PROPERTIES

Thermal Conductivity The thermal conductivity of a sediment is controlled primarily by its porosity or water content[57]. Laboratory measurements have shown that the thermal resistivity (the reciprocal of the conductivity) is approximately linearly related to water content and, at the temperature and pressure of the ocean floor ($3^{o}C$, 5×10^{7} Pa), the following relationship has been proposed[58].

$$\frac{1}{k} = 168 + 678w$$

where w is the water content expressed as a fraction of the wet weight, k is thermal conductivity in cal $cm^{-1} sec^{-1} {}^{o}C^{-1}$.

However, no relationship of this sort can be entirely adequate, for the mineral particles from which a sediment is composed have an effect on its conductivity. In particular, calcareous sediments are found to have greater than average conductivities, and the expression above has been found to underestimate the in-situ conductivity of some sediments by up to 20%[59]. Nevertheless, porosity or water content is the dominant influence on conductivity. Furthermore, since porosity correlates strongly with grain size - finer grained sediments being more porous - arenaceous sediments such as abyssal turbidites are more conductive than finer grained clays.

The thermal conductivity of sediments has been measured both in the laboratory and in situ on the ocean floor[60]. Good agreement is obtained between the two techniques. Since the effect of pressure is to increase the thermal conductivity by 1% for every 1000 fm (1829 m) of water depth and the effect of temperature is to decrease the conductivity by 1% for every $4^{o}C$ drop in temperature, laboratory measurements must be reduced by approximately 4% to obtain in-situ values.

Maps of the thermal conductivity of the superficial sediments of the ocean floor show considerable uniformity over large regions[61]. Most values lie in the range 1.8 to 2.25 mcal $cm^{-1} sec^{-1} {}^{o}C^{-1}$ (0.75 to 0.94 $Wm^{-1}K^{-1}$).

The thermal conductivity of the rocks composing the igneous crust has been determined from laboratory measurements on drilled samples (62). The average conductivity of young basalts is 4.0 mcal $cm^{-1} sec^{-1} {}^{o}C^{-1}$ (1.7 $Wm^{-1}K^{-1}$). With age the conductivity of the uppermost basalts decreases due to weathering to about 3.5 (1.5), whilst that of the deeper basalts increases as a result of hydrothermal alteration to about 5.0 (2.1).

Thermal Diffusivity If the thermal conductivity, k, of a sediment has been measured, only its water content need be known for its thermal diffusivity, $\frac{k}{\rho\sigma}$, to be calculated, for both the density, ρ, and specific heat, σ, are more closely related to water content than is k.

Assuming the grain density to be 2.7 gm cm^{-3}, the bulk density of a sediment is given by

$$\rho^{-1} = 0.37 + 0.63w$$

where w is the water content expressed as a fraction of the wet weight, ρ is density in gm cm^{-3}.

The specific heat of the high porosity sediments found in the deep oceans is dominated by that of water, so that it is sufficient to take the specific heat of the mineral grains as 0.18 cal $gm^{-1} {}^{o}C^{-1}$. Hence the specific heat of the sediment is given by

$\sigma = 0.18 + 0.82w$ where w is the water content (58).

2.14.4 SHEAR STRENGTH

Study of the geotechnical properties of ocean floor sediments has grown considerably in the past two decades, principally in the USA. The original inspiration for this work was the naval interest in placing anchors and defence installations on the ocean floor. The possibilities of manganese nodule mining and radioactive waste disposal have broadened this interest. The parallel growth in geotechnical studies of continental shelf sediments, associated with oil and gas installations, has been of less relevance to the deep ocean work, because the continental shelf sediments are in general much coarser-grained and because the problems encountered are different (being principally associated with wave-induced loading and current scour).

Nevertheless, some of the equipment developed for in-situ measurement of geotechnical properties on the continental shelf might be adaptable for deep water operation.

A limited number of in situ measurements of sediment shear strength and other geotechnical properties have been made from submersibles and by unmanned equipment. These have not penetrated more than a few metres into the sediment. Most measurements have been conducted in the laboratory (either shipboard or on land) on samples obtained by coring or drilling. This immediately introduces a problem because most of the sediments found on the ocean floor are highly sensitive, meaning that their strength is considerably reduced by working or remolding. Undisturbed samples of ocean floor sediments can only be obtained with the right type of equipment and the exercise of considerable care. The table below summarises the capabilities of various sampling techniques currently in use.

Method	Lateral dimensions of core	Penetration	Effect on Sediment Shear Strength
Spade Box Corer	20 cm × 30 cm	<1 m	Minimal. 0.7 kPa (.007 kg cm^{-2}, 0.1 psi) strength sediment has been recovered with worm burrows intact (64).
Giant Piston Corer	11.5 cm dia	<30 m	Less disturbance than with smaller diameter corers.
Conventional Corer	5 to 8 cm dia	<10 m	Piston cores more disturbed than gravity cores. Both often too disturbed for geotechnical purposes.
Drilling (DSDP)	6.6 cm dia	Complete penetration of soft sediments.	Soft sediments always highly disturbed.

In addition to the disturbance introduced by the sampling techniques, all deep-sea sediment samples are subjected to a rapid reduction of pressure of approximately 5×10^7 Pa (500 bar) in being brought to the surface. Since water is more compressible than rock-forming minerals (it expands 2% in being raised from ocean depths to the surface), this causes the pore water to expand more than the sedimentary minerals so that some dewatering of the sediment or disruption of its fabric is inevitable.

The effect of this on the bulk density, porosity and related parameters is small, but on the shear strength can be considerable. Temperature changes are also involved in sampling, but have less effect than the pressure changes.

Attempts have been made to correct laboratory measurements of sediment strength to their in situ values by using the residual pore water pressure measured in a sample as an index of the degree of disturbance it has suffered. The method has been applied to DSDP cores (Leg 19) to estimate the shear strength profile to a depth of two hundred metres (66) but the validity of these estimates is questionable.

Recent studies of the shear strength of sediments are summarised in Figure 1-26. At the sediment surface the shear strength of ocean floor sediments is often very low, sometimes due to bioturbation, but within a metre is usually in the region of 10 kPa (0.1 kg cm^{-2}, 1.4 psi). In the top 20 metres the variability shown in the figure probably represents the actual variability on the ocean floor. The extrapolations to greater depths may be considerably in error, since the only measurements available are on highly disturbed DSDP samples. Vane shear measurements on DSDP samples, while showing increasing strength with depth, also show considerable scatter (66,67). For samples from 100 m depth, shear strength ranges from 10 to 100 kPa (0.1 to 1.0 kg cm^{-2}).

The shear strength of sediments depends very much on the rate at which shearing stresses are applied. Because of this the dynamic rigidity derived from in situ observations of seismic shear or Stoneley waves (68) on the ocean floor (typically 10^7 Pa) is found to be three or four orders of magnitude greater than the shear strength determined for the same site by in situ or laboratory soil mechanical tests (typically 10^3-10^4 Pa) (69). Nevertheless the shear velocity profile of the sediment determined from close range seismic observations might be used to determine the profile of shear strength if the

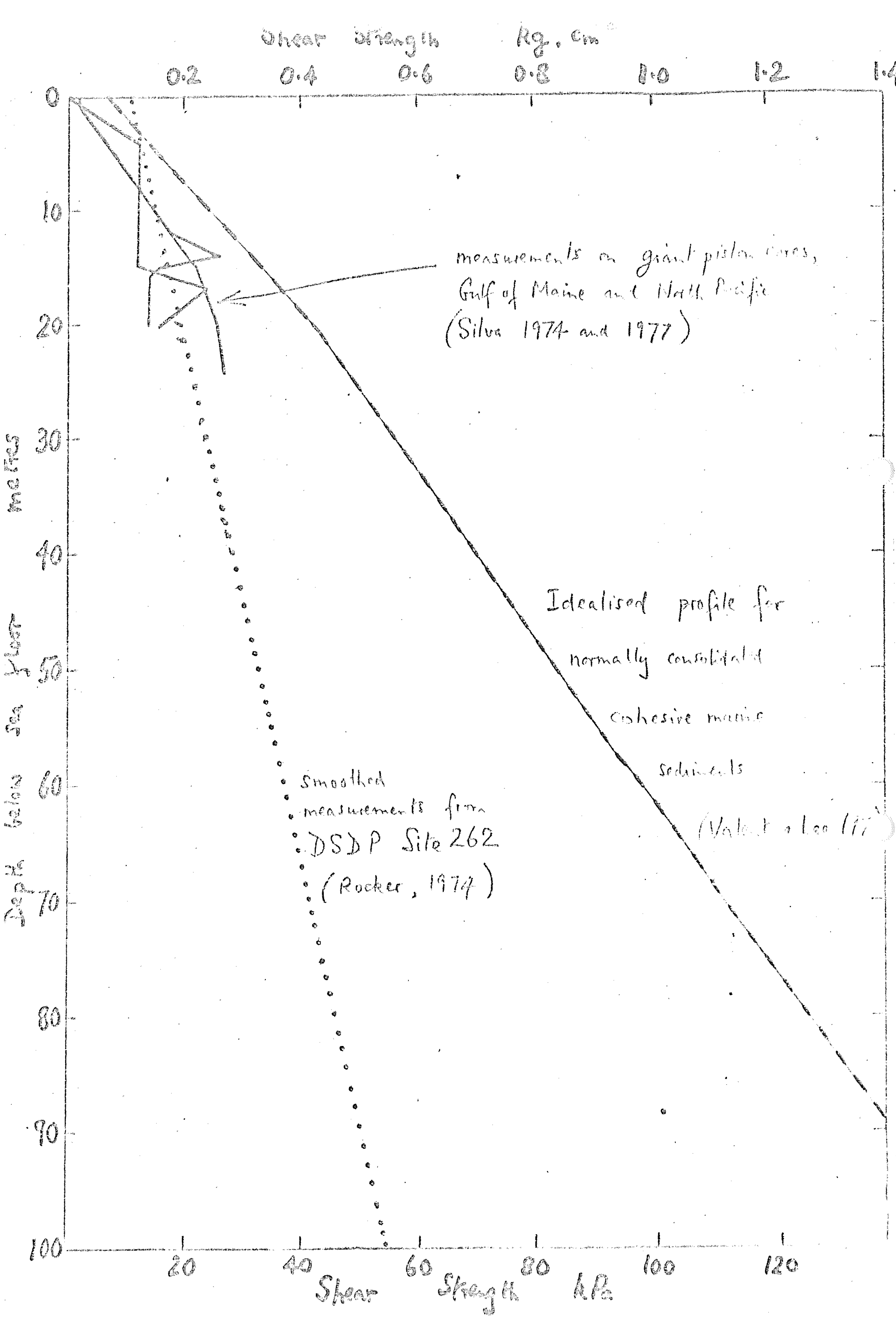


Figure 1-26 A summary of shear strength measurements of ocean floor sediments.

initial value at the sediment surface were calibrated by soil mechanical measurements. Compressional wave velocities are too insensitive to the low rigidity of the sediments for them to be a useful indicator of sediment strength. However, lithification of the sediment is usually associated with a marked increase in compressional velocity, so that compressional wave observations can be used to indicate the thickness of soft sediment.

Another indication of the dependence of shear strength on the rate of shearing comes from studies of the penetration of projectiles into sea floor soils. It has been found empirically that the effective shear strength experienced by projectiles is about twice that determined under static conditions by soil mechanical tests (70).

2.14.5 PERMEABILITY

No in situ measurements of the permeability of the rocks or sediments of the ocean floor have ever been made. It is important therefore to consider first the whole range of permeabilities found in earth materials and geological formations. These are summarised in Table 1.2.

Information on the permeability of unconsolidated soils and sediments comes mainly from soil mechanical studies. A wide range of permeabilities is found in nature, from the order of 10^4 darcy for a clean gravel (e.g. a shingle beach) to values ranging from 10^{-4} to 10^{-8} darcy for clays [71]. To a first order permeability is a function of the grain size of the sediment, the finer grained the sediment the lower the permeability. Since the porosity (and void ratio) of unconsolidated sediments generally increases with decreasing grain size, the permeability tends to decrease with increasing porosity. However, when sediments of a limited range of grain size are studied in laboratory consolidation tests, permeability is observed to decrease with decreasing porosity or void ratio. Here the effect of compaction, closing up the holes between particles, is being observed. Laboratory tests on a range of carbonate and clay sediments from the deep

NB The coefficient of permeability only applies when the fluid is water at moderate temperatures.

Coefficient of Permeability				k	cm sec^{-1}							Log Scale	
10^{2}	10^{1}	1	10^{-1}	10^{-2}	10^{-3}	10^{-4}	10^{-5}	10^{-6}	10^{-7}	10^{-8}	10^{-9}	10^{-10}	10^{-11}
Permeability				K	cm^2							Log Scale	
10^{-3}	10^{-4}	10^{-5}	10^{-6}	10^{-7}	10^{-8}	10^{-9}	10^{-10}	10^{-11}	10^{-12}	10^{-13}	10^{-14}	10^{-15}	10^{-16}
Permeability				K	Darcy							Log Scale	
10^{5}	10^{4}	10^{3}	10^{2}	10^{1}	1	10^{-1}	10^{-2}	10^{-3}	10^{-4}	10^{-5}	10^{-6}	10^{-7}	10^{-8}

Drainage	Good		Poor		Practically Impervious
Soil Type	Clean gravel	Clean sands, sand and gravel mixtures	Very fine sands, organic and inorganic silts, mixtures of sand, silt and clay		Clays
Methods of Measurement	Direct testing of soil in-situ - pumping tests				Derived from consolidation tests

Terzaghi and Peck, 1948

Range of producing oil and gas formations
Schlumberger Ltd, 1972

Oil rocks
Bear, 1972

N.Atl.cores
UCNW 1971

Pacific Red Clay (Illitic)
Silva, 1977

Geothermal Steam Areas
Elder, 1965

Deep Water Sediments from Gulf of Mexico
Bryant et al, 1974 $k = 10^{-9}e^{5}$ cm/sec

Kilauea Hole (Top 500 m)
Zablocki et al, 1974

Oceanic Crust
Anderson et al, 1977

TABLE 1.2 Summary of the Permeabilities found in Earth Materials and Geological Formations waters of the Gulf of Mexico have yielded the following relationship between coefficient of permeability (k) and void ratio (e) (72).

$k = 10^{-9} e^5$ $0.4 < e < 4.0$

Similar tests on one particular sediment type, an illitic clay from the deep Pacific (54), are summarised by the following equation

$e = 11.04 + 1.27 \text{ Log } k$ $1.0 < e < 2.7$

The permeabilities of the bulk of the unconsolidated pelagic clays and oozes found on the ocean floor probably lie in the range 10^{-4} to 10^{-5} darcy. Higher permeabilities are likely to be found in turbidite sequences (73), particularly in the coarser grained beds at the bottom of individual turbidite flows. Indeed these may allow the easy lateral flow of pore water whilst flow across the beds is inhibited by the less permeable finer-grained beds.

No permeability measurements appear to have been made on lithified sediment samples recovered from drill holes in the ocean floor. However, their permeabilities may be inferred from those of their soft sediment analogues and from the range of permeabilities encountered in oil and gas formations (74,75). The process of lithification is unlikely to produce any reduction in permeability because inter-particle cementing will tend to seal up the holes in the sediment matrix. Once a sediment is lithified, however, it loses its plastic properties and may be fractured. The bulk permeability of the sedimentary formation may then be controlled by the fractures and faults it contains. No amount of laboratory testing of drill hole samples can determine the bulk permeability of such a formation. (The drilling process itself introduces numerous fractures into the core samples in addition to those already there). It can however be determined by downhole pumping experiments, or at least an upper limit to the bulk permeability can be obtained. The technique is commonplace in the oil industry. Permeability experiments have been proposed for DSDP drill holes in the ocean floor, but have not yet been attempted.

2.15 GAS HYDRATES

Under the temperature and pressure conditions prevailing in the top few hundred metres of the deep-sea bed, many common gases combine with water to form solid gas hydrates, one class of a group of compounds called clathrates (76). Methane is the most important gas that does this. At greater depths below the seafloor the temperature is too great for hydrates to exist and methane, for example, would be present as a gas. Evidence for the existence of hydrates has been found on seismic reflection records and in core samples from the continental slope off the eastern United States. Their distribution in the superficial sediments of the ocean basins is difficult to predict on present knowledge, but could be extensive if the methane available from biogenic sources is supplemented by that outgassed from the earth's interior (77).

Solid gas hydrates present within a sediment increase its strength and inhibit the percolation of gas and pore water. Heat from a radioactive waste canister buried within such a sediment would mobilise methane gas in a zone around the canister. The presence of free methane gas is likely to enhance the mobility of the pore water and might induce more rapid transport of radionuclides than laboratory measurements of permeability on gas free samples would indicate.

3. CHOICE OF AN OPTIMUM ENVIRONMENT

3.1 INTRODUCTION

The many parameters involved in defining sites suitable for radioactive waste disposal beneath the ocean floor make it unwise at the outset of this research to concentrate too closely on a limited number of areas or to be too restrictive in our concepts of what might eventually make a good disposal site. It is clear from our foregoing review of relevant knowledge in marine geology and geophysics that our understanding of many of the processes taking place on, and in, the ocean floor is inadequate. Thus, highly detailed work in a few areas would, at this stage, do less to improve our knowledge than the same effort spread over a large number of locations. Indeed, it will be necessary to study areas that from the outset have no potential for waste disposal. Similarly, a requirement of some of the early research will be to examine closely some of the criteria that are currently being proposed to select potential sites. Sections 3.3 and 3.4 below discuss some examples that will require investigation.

At the present time the only coordinated programme of research into the problems of high-level radioactive waste disposal beneath the deep ocean floor is the United States Seabed Disposal Program which began in 1974 (78). Its basic approach has been: (1) development of criteria with which to choose oceanic sites for emplacement; (2) evaluation of the effectiveness of sediments as a barrier to the mobility of radionuclides; (3) development of the necessary emplacement engineering. Although these three steps overlap considerably in timescale, the first has already tended to place constraints on the directions in which the remaining research effort is moving[(2)]. We consider it particularly important that evaluation of the sedimentary barrier in a variety of environments becomes the prime target of any U.K. research programme devoted to the beneath-the-seabed option.

3.2 THE M.P.M.G. STRAIT JACKET

Much of the US research which has been conducted so far into the problems of high-level radioactive waste disposal in the oceans has revolve around the "mid-plate, mid-gyre" concept. This does not appear to be a particularly useful approach. Indeed, it might impede the discovery of the optimum sites. Although we consider the mid-plate component of this concept to be sound, the mid-gyre component can be criticised on the following grounds:

1. Within the "multiple barrier" scheme the time constant associated with the oceanic barrier is likely to be very short. Much physical oceanographic and biological work is needed to define this oceanic time constant, but it is unlikely to be greater than 10^3 years and may be much shorter. Since this is a much shorter time than the sediment barrier might provide, the ocean can effectively be regarded as a short circuit and effort should be concentrated on as wide a range of geological environments as appear suitable. Thus a "good" sediment on the edge of the ocean could provide more effective containment of waste than a "bad" sediment in the middle of an oceanic gyre. The protection provided by the remoteness of a mid-gyre region such as the mid-North Pacific is an illusion.

2. The MPMG approach has tended to concentrate effort into regions where pelagic clay is the dominant sediment type. This may yet prove to be the most effective sedimentary barrier to the migration of radioactive waste. However the total thickness of sediment in regions of such cover is often very thin (<50 m) so that the thickness of the available barrier is limited. Furthermore, slowly deposited red clays are often quite strong,

which will inhibit penetration if the waste is packaged into free-fall projectiles. The most suitable sediment type is likely to have the right combination of properties - good sorption characteristics, low permeability, low shear strength, large formation thickness. Thus it might be more effective to emplace waste 100 m deep in soft ooze rather than 30 m deep in stiff clay. Not enough is yet known about the range of properties of the sediment types involved for this kind of judgement to be made.

3.3 DISTAL ABYSSAL PLAINS

Primarily because of their marked vertical and horizontal variability, and possibility of active erosion, turbidity current-deposited sequences would appear to have little potential as media for waste emplacement. On the other hand, the wide flat abyssal plains away from the main geostrophic bottom water flow of the basin margins, are attractive in terms of sediment thickness and probable lack of post-depositional mass movement or current erosion.

'Distal turbidites are those turbidity current deposits most seaward from margin sources or downslope from channel sources(79,80). Sedimentation models suggest that turbidity currents entering the distal environment should already have lost most of their coarser-grained sediment and the resulting unchannelised deposition would be a sheet of fine grained silt and clay. Such layers would be undetectable on seismic profiles. When distal depositional events follow one another relatively rapidly the slowly depositing pelagic sediment would be only a small component of the sediment column. Thorough mixing of indigenous pelagic and exotic turbidite material means that it frequently becomes impossible to differentiate individual distal turbidites even in recovered cores.

It is possible that, with increased research effort, clayey distal turbidite sequences may prove sufficiently predictable in time and space for emplacement modelling. Thus the distal abyssal plains should not be ignored at this stage as a possible environment for disposal studies.

3.4 AREAS WITH GLACIAL ERRATICS

Ice transports sediment with no regard of particle size and thus it becomes possible that even enormous boulders (up to the size of a house) can occur as erratics in areas where local hydraulic energy levels provide only for fine-grained sedimentation. The resulting sediment columns are a random mixing of clays and coarse sediments. Emplacement of waste canisters into such media, that might even have a boulder strewn surface, would be relatively difficult and probably hazardous. Similarly, after emplacement, the predictability of the effects of the canister on the sediment 'barrier' would be relatively poor.

During glacial maxima, fields of sea ice and icebergs migrate to lower latitudes than in periods such as the present interglacial. Most dredge hauls recovered from scarps and seamounts in the Northeast Atlantic are dominated by glacial erratic boulders even as far south as the latitude of

North Africa[63]. Little is known of the distribution of glacial rock debris on the open abyssal plains which have not been dredged. Bottom photographs identify recently deposited rock debris in polar regions, but it is likely that a thin sediment cover would mask older Pleistocene rock accumulations on open plains beyond polar regions. Layers of ice-rafted sand recovered in sediment cores are a better guide to the distribution of Pleistocene glacial debris, and have been used (Figure 1-17) to outline changing patterns of ice-rafted sand deposition over the past 120,000 years[23]. The distributions extend south of Spain. However, this study is based on only 32 cores covering the whole North Atlantic and clearly the distribution maps are rather generalised.

It has been suggested that the presently inferred limits of Pleistocene ice-rafted sand and erratic transport away from polar regions should stand as the boundaries of exploration for disposal areas. Since this criterion would confine exploration to subtropical and equatorial regions in the Atlantic and exclude huge areas of seafloor that might in other respects be perfectly suitable for disposal evaluation, we suggest a concentrated research effort to investigate this site criterion and extend its data base. Shallow dredging and sonar and photographic investigations of surficial sediments on open abyssal plains could ascertain whether glacial rocks and boulders that could be an emplacement problem are indeed widely distributed there; whether they follow distinct 'iceberg paths', or even whether such glacial erratics as have already been dredged are unusually concentrated around upstanding seafloor features (because of grounding or circulation effects). Benthic net sampling by biological research groups frequently recovers pebble and other rock debris on open abyssal plains. Analysis of these 'residue' collections should provide additional data. (It is worth noting that the majority of benthic biological hauls in the I.O.S. 'Discovery' collections record 'clinker' in their inventory. This waste from coal-fired shipping is likely to be confined to the major shipping lanes, but it could present similar emplacement problems for disposal canisters to surface ice-rafted debris).

Thorough analysis of presently existing cores in repositories at the major marine geological centres for ice-rafted sand layers would enable more reliable quantitative estimates to be made of their regional extent in subpolar areas. Precision CLIMAP-type dating would be unnecessary in this review, since changing patterns through glacial cycles are not required, simply a knowledge of the extent and thickness of sediment sequences that contain the layers.

4. RESEARCH NEEDS

4.1 RECONNAISSANCE GEOLOGICAL AND GEOPHYSICAL SURVEYS

Some areas suitable for detailed study can be chosen from what is already known of the ocean floor. Others may come to light after reviewing site suitability problems, such as the hazard presented by ice-rafted debris (see 3.4) or after geochemical studies aimed at choosing the most efficient sediment types in terms of absorbtive capacity (see Chapter 2) Nevertheless, the choice will be limited by the coverage provided by existing data, much of which has been biassed towards the solution of problems quite different from the one with which we are now faced.

Bathymetric and seismic profiling coverage in many potential waste disposal areas will probably be sparse (Figure 1-15). Reconnaissance surveys are therefore required at the outset of this work. The goal of these surveys would be to determine bathymetry, sediment thickness, morphology of the seabed and nature of the superficial sediments on a regional scale. Techniques to be employed include precision echo sounding (PES, 10 kHz and 2 kHz), seismic reflection profiling (SRP), large scale side scan sonar (GLORIA) and coring. Much of this reconnaissance could be accomplished through a coordinated international effort.

Surveying can locate large scale depositional and erosional features resulting from current flow and allow subdivision of proximal and distal turbidite environments. Coring and shallow surface dredging will tackle such problems as delineation of regional CCD levels, determination of local grain size variability, refinement of regional distributions of ice-rafted debris, volcanic ash layers, and manganese deposits, etc.

Improvements to the range of sampling devices can be made and supplemented through the purchase of commercially available equipment. However, a start should be made on the development of more advanced and specialised sampling methods.

4.2 SEAFLOOR OBSERVATIONS IN STUDY AREAS

Once an area has been reconnoitered by observations from close to the sea surface, it becomes necessary to place instruments close to, on or beneath the seafloor, both to improve the resolution of near surface observations and to make measurements which can only be conducted in-situ. A wide range of projects are envisaged at this stage. Details of the individual projects, their objectives and their relevance to radioactive waste disposal are given in Table 1.3. References to specific text sections should allow assessment of the international status of such work at present. The table also includes a note of UK centres of which we are aware that are engaged in relevant work. Many of these projects must await the development of new instrumentation (see later section), but all lie within the scope of existing oceanographic technology.

Initially, some degree of exchange of equipment and expertise could be possible in a coordinated international programme; for example, reconnaissance long range side scan sonar (GLORIA) coverage of a study area for detailed short range nearbottom side scan (Deep Tow) surveys.

4.3 LABORATORY MEASUREMENTS ON SAMPLES

Sediment sampling will constitute a major part of the research programme. Thought must be given to the handling and curation of the core samples so that they suffer as little disturbance as possible during transport and storage. It is important that shore-based facilities are available to match the volume of sediment collected.

Some observations will need to be made in shipboard laboratories, when the samples are as little disturbed and as fresh as possible. These

TABLE 1.3

Project	Objective	Relevance to Radioactive Waste Disposal	Status of this type of work in UK*
1. Heat Flow Detailed temperature gradient and conductivity measurements within limited areas, covering different plate ages and sediment thickness.	To determine the natural processes of heat transfer through the sediments and the underlying crust.	The dewatering of sediment due to compaction is one cause of moving pore water. In some situations it may also be driven into movement by convective processes of heat transfer (2.3; 2.14.3).	Little if any work on oceanic heat flow during the last ten years. However, the equipment required is simple. The expertise to carry out this type of project exists within IOS and a number of University departments.
2. In-situ heat transfer experiment (envisioned as the culmination of extensive laboratory experimentation on the effects of heat on deep-sea sediments)	To observe temperature changes in the vicinity of an artificial heat source (radioactive?) embedded in the sediment. Pre- and post-emplacement sediment sampling could determine the effects of an isolated heat source on rates of diagenesis, cementation as well as on physical properties of the sediment.	To study processes of heat transfer when high temperature and temperature gradients prevail, as they would around a radioactive waste canister. Sediment reconstitution processes could affect integrity of the barrier and its susceptibility to mass movement (2.13.1).	None at present. Considerable equipment development and laboratory testing needed. In UK, IOS has oceanographic expertise, Harwell the experience in handling radioactive material. Many University departments have the petrological expertise to study sediment changes for geotechnical aspects, see below.

*Not intended to be a comprehensive listing of relevant UK study centres.

TABLE 1.3 (contd)

Project	Objective	Relevance to Radioactive Waste Disposal	Status of this type of work in UK*
3. <u>In-situ measurement of geotechnical properties</u> (a) Electrical resistivity probe. (b) Acoustic probe to measure compressional wave velocity and attenuation. (c) Shear velocity probe. (d) Cone penetrometer (vane shear apparatus?) to measure shear strength. (e) Projectile experiment. Monitoring the deceleration of a projectile fitted with acoustic transmitter (CW 10 kHz) by shipboard recording of signal received at deep hydrophone. (f) Monitoring for mass movement on low-angle slopes using acoustically positioned markers and bottom explosive sources to trigger sediment motion. (g) Gamma-ray probe to measure density.	To determine sediment porosity, density and shear strength of the top few metres of sediment. Acoustic attenuation is indicative of grain size distribution. Measuring a range of geophysical properties allows better definition of some of the mechanical properties. Only the projectile experiment could provide information on shear strength to depths greater than 10 m into the sediment. The same projectile might prove useful as a source of P and S waves for close range seismic profiles (2.14.1).	Knowledge of the in-situ physical properties of the sediment to as great a depth as possible is required. Comparison of parameters measured in the laboratory with those determined on the ocean floor will guide the extrapolation of the more detailed laboratory measurements to in-situ conditions. Experience of the penetrability of ocean floor sediments by projectiles is needed before this technique can be employed for waste disposal. Mass movements could affect the integrity of the sediment barrier and concentrate waste canisters (2.13.1).	(a)(b)(c). Electrical resistivity/acoustic probe for use on the continental shelf has been developed at Marine Science Laboratories, UCNW, Menai Bridge and used by IGS Engineering Geology Unit. Modification needed for deep ocean work. Shear velocity probe under development at UCNW for continental shelf use. Considerable acoustic and resistivity experience also exists within IOS. (d) In-situ shear strength apparatus has been developed commercially for continental shelf use. (e)(f) New projects. IOS has the acoustic expertise to develop acoustically monitored equipment, but lacks the soil mechanics experience needed to interpret the results fully. See project 5 for bottom explosive sources.

TABLE 1.3 (contd)

Project	Objective	Relevance to Radioactive Waste Disposal	Status of this type of work in UK*
4. Buoyant Pinger, long term soil mechanics experiment.	To investigate the bearing strength of sediments under a range of loading conditions. Each buoyant pinger is moored to a heavy sinker lying on the seabed. Its height above the bottom will be acoustically monitored over a period of years.	If waste canisters are disposed onto the seabed, it is important to know whether they remain there or whether they slowly sink into it. Short term measurements of sediment strength may overestimate its long term properties (2.14.4). It may also be necessary to conduct this experiment with hot, radioactive canisters.	A buoyant pinger has been under development at IOS with a scientific objective to investigate whether, under certain conditions, earthquakes liquefy deep sea sediments.
5. Small Scale Seismic Profiles with bottom sources and receivers. Seismic refraction and Stoneley wave experiments at ranges up to 5 km.	To determine the compressional and shear velocity structure in the sediment.	The results can be interpreted in terms of the thickness of the soft sediments and of the variation of shear strength with depth. The latter can be used to extrapolate other types of shear strength measurement to greater depth (2.14.4).	The expertise to deploy and recover ocean bottom seismic receivers already exists at IOS. Development work is required for bottom sources (explosive, projectile, other?).

TABLE 1.3 (contd)

Project	Objective	Relevance to Radioactive Waste Disposal	Status of this type of work in UK*
6. Long term monitoring with Ocean Bottom Seismographs	To determine seismicity in the vicinity of potential disposal sites. Observations of microearthquakes allow the frequency of larger, more hazardous, events to be assessed.	Although most earthquakes occur at plate boundaries, intra plate earthquakes do occur. At any particular location large intra-plate earthquakes are infrequent and may not have occurred during the existence of efficient world-wide seismic monitoring. But microearthquakes, too small to be detected at land based stations, can indicate areas of tectonic instability even when this is still latent. Such areas could be susceptible to mass sediment movement (2.13.2).	The expertise to record earthquakes on the ocean floor already exists in IOS. Instrument development is required to extend the recording period of existing instruments.
7. Deep towed Seismic Reflection Profiling and Side Scan Sonar with acoustic navigation.	To elucidate the fine structure of the sediments; and to locate targets not resolvable from the surface (e.g. erratics, wrecks). To study large scale surface bedforms and relate these to current meter and nephelometer measurements (project 9). To elucidate stability of sediments on slopes.	Once characteristic bedforms are related to particular current regimes in a study area, they can be traced horizontally to establish the spatial continuity of sedimentation processes (2.7). Location of erratics and wrecks must be known to ensure safe emplacement of canisters (3.4).	IOS has considerable experience of seismic reflection profiling, side scan sonar and acoustic navigation, but needs to obtain the equipment necessary to exploit these techniques close to the ocean floor. At least 7 km of armoured electrical cable (well-logging cable) mounted on its own winch is needed for this work.

TABLE 1.3 (contd)

Project	Objective	Relevance to Radioactive Waste Disposal	Status of this type of work in UK*
8. Bottom Photography with acoustic navigation.	To classify acoustically detected targets and to observe targets below resolution of sonar, e.g. small erratics. To study small scale surface bedforms and relate these to current meter and nephelometer measurements (project 9). To determine the areal extent of bioturbation.	Once characteristic sediment surface features are related to particular sedimentary regimes, they can be traced horizontally to establish spatial continuity (2.7).	IOS and a number of University groups have experience in underwater photography. Ability to occupy predetermined positions requires a sophisticated real-time acoustic navigation system (now under development at IOS).
9. Nephelometer and Current Meter Measurements	To establish bottom current regimes and sediment movement in the nepheloid layer. To relate these to sediment type and structure and surface bedforms.	Results would relate to projects 7, 8, 10 and 11. They would also establish the stability of the sediment surface and the distribution and composition of the nepheloid layer (2.7, 2.9). Paleocurrents might be inferred by comparison with core structure and fabric.	IOS has considerable experience in deep ocean current meter studies. Nephelometers could be bought or modified from existing designs. A sophisticated bottom acoustic navigation system would again be necessary.

TABLE 1.3 (contd)

Project	Objective	Relevance to Radioactive Waste Disposal	Status of this type of work in UK
10. In-situ flume studies	To determine the erodability of various sediment surfaces.	Results would establish the resistance of the sediment barrier to current erosion (2.9).	None at present. A 'SEAFLUME' device could be developed from existing shallow water designs for operation on the deep ocean floor. IOS should by then have the necessary bottom navigation system. A number of universities have the necessary laboratory flume expertise to interpret the results.
11. In-situ studies on rates of bioturbation by the introduction of sediment surfaces containing natural or artificial tracers.	To study the rates and depths of biological mixing.	Results would relate to projects 8 and 10 and would also determine likely rates of re-introduction of sediment to the nepheloid layer by bioturbation (2.7, 2.9). Bioturbation limits resolution with which sediment stability/history can be determined (2.12.2).	None at present. Again a precise bottom navigation system is required. Emplacement mechanisms that preserve the sediment surface need development along with recovery or sophisticated box-coring apparatus.

will include:

(a) Initial core descriptions and preliminary dating, to control subsequent sampling;

(b) Some geotechnical and physical property measurements that might change in transit - density, porosity, water content, compressional and shear velocity, shear strength.

The bulk of the work on sediment samples can be done at shore-based laboratories.

These will include:-

(c) Detailed sedimentological study:- sedimentary structures, lithostratigraphy, grain size, bulk mineralogy, carbonate content, etc.

(d) Dating,

micropaleontology, paleomagnetism, isotope dating, etc.

(e) Paleoenvironmental studies - magnetic fabrics, oxygen isotopes, studies on environmentally sensitive microfaunas for comparison with living forms, e.g. benthic foraminifera, and ostracodes, CLIMAP-type statistical techniques on faunal populations.

(f) Geotechnical measurements - consolidation tests, ..., flume studies, etc.

(g) Geochemical studies (see separate report).

(h) Heat source experiments.

Not all the samples need to be collected in the same manner. For geotechnical measurements they must be as little disturbed as possible; this will require the use of box and large diameter corers. Sedimentological studies require a representative sample of the whole column penetrated, for which conventional corers and giant piston corers are necessary. Some of the land-based experiments may merely require a large volume of sediment which can be collected with grabs.

Shipboard and shore-based studies will be undertaken as part of the basic programme in many countries. Each will require the full range of facilities implied above.

4.4 INSTRUMENT DEVELOPMENT

None of the projects which have been proposed is beyond the scope of present day oceanographic technology. But being able to say that a particular project is feasible does not mean that it can be carried out immediately. A considerable amount of instrument development will be necessary before many of the near-seafloor measurements can be made on a routine basis. In some cases this process will take several years. Much could be accomplished within the framework of an international programme. The following development work will be necessary:

(a) Development of acoustic navigation systems for precise location of instruments close to the seafloor;

(b) Development of heat flow instrumentation and apparatus for in-situ heat transfer experiments;

(c) Improvement of sampling techniques, especially for deep coring and shallow dredging;

(d) Improvement of existing ocean bottom seismic receivers;

(e) Development of bottom sources (explosives, projectile, other?) for close range seismic studies;

(f) Development of near-bottom seismic reflection profiling and side-scan sonar equipment;

(g) Development of nephelometers and improvement of bottom camera systems and current meter arrays;

(h) Development of instruments for in-situ geotechnical measurements, and sedimentation studies.

4.5 SUPPORT FOR SPECIALISED OCEANOGRAPHIC PROGRAMMES PARTICULARLY RELEVANT TO RADIOACTIVE WASTE DISPOSAL

Although great advances have been made in oceanography in the past few decades, considerable ignorance of many of the processes taking place in and beneath the oceans remains. Some of these processes are directly relevant to the problem of radioactive waste disposal in the oceans. Our understanding of these processes may not be appreciably advanced if waste disposal research is too site specific. It is appropriate therefore that more general support be given to research programmes which could yield relevant results. Examples of these are:

(a) Heat flow studies

The possibility that the pore water of sediments is moving convectively must be explored (2.3).

(b) Soil mechanical studies of deep sea sediments

The effect of compaction on the movement of sediment pore water must also be resolved. Consolidation tests on sediments from a range of depositional and erosional environments could aid our understanding of this process (2.14).

(c) Downhole logging in IPOD holes

Downhole measurement of the physical properties of both sediments and igneous crust of the ocean floor will improve our understanding of the processes which take place there. Porosity and permeability measurement are particularly relevant (2.14).

(d) Improvement of dating and paleoenvironmental techniques

In order to predict likely stability of the sediment barrier over the period of waste decay, it will be necessary to have a detailed knowledge of its recent geological history. This will require more refined dating of the cored sequences than is presently available and developmer of appropriate techniques should be encouraged (2.12.2).

LIST OF REFERENCES

1. BARAZANGI, M. and DORMAN, J., Bull. Seism. Soc. Am., 59, 369-380 (1969).
2. HOLLISTER, C.D., Oceanus, 20, 19-25 (1977).
3. HEIRTZLER, J.R., LE PICHON, X. and BARON, J.G., Deep-Sea Res., 13, 427-443 (1966).
4. VINE, F.J., In The History of the Earth's Crust (ed. R.A. Phinney), 73-89 (Princeton University Press, 1968).
5. PARSONS, B. and SCLATER, J.G., J. Geophys. Res., 82, 803-827 (1977).
6. ANDERSON, R.N., In The Sea, Vol. 7 (in the press).
7. ANDERSON, R.N., LANGSETH, M.G. and SCLATER, J.G., J. Geophys. Res., 82, 3391-3409 (1977).
8. ANDERSON, R.N., HOBART, M.A. and LANGSETH, M.G., Science (in the press).
9. LUDWIG, W.J., NAFE, J.E. and DRAKE, C.L., In The Sea, Vol. 4 (ed. A.E. Maxwell), 53-84 (Wiley-Interscience, New York, 1970).
10. HOUTZ, R. and EWING, J., J. Geophys. Res., 81, 2490-2498 (1976).
11. WHITMARSH, R.B., Earth Planet. Sci. Lett., 37, 451-464 (1978).
12. RIBANDO, R.J., TORRANCE, K.E. and TURCOTTE, D.L., J. Geophys. Res., 81, 3007-3012 (1976).
13. ELDER, J.W., In Terrestrial Heat Flow (ed. W.H.K. Lee), 211-239 (Amer. Geophys. Union, 1965).
14. PALMASON, G., In Geodynamics of Iceland and the North Atlantic Area (ed. L. Kristjansson), 297-306 (Reidel Co., Dordrecht, 1974).
15. ZABLOCKI, C.J. et al., Geophys. Res. Lett., 1, 323-326 (1973).
16. BERGER, W.H., Geol. Soc. Amer. Bull., 81, 1385-1402 (1970).
17. BROECKER, W.S., Chemical Oceanography (Harcourt Brace Jovanovich, New York, 1974).
18. EWING, M., CARPENTER, G., WINDISCH, C. and EWING, J., Geol. Soc. Amer. Bull., 84, 71-88 (1973).
19. VAN ANDEL, T., HEATH, G.R. and MOORE, T.C., Geol. Soc. Amer. Memoir, 143 (1975).

20. KIDD, R.B. and DAVIES, T.A., Mar. Geol., 26, 49-70 (1978).

21. GARRELS, R. and MACKENZIE, F.T., Evolution of the Sedimentary Rocks (Norton, New York, 1971).

22. HOLEMAN, J.H., Water Resources Res., 4 (1968).

23. RUDDIMAN, W.F., Geol. Soc. Amer. Bull., 88, 1813-1827 (1977).

24. BERGER, W.H., In The Geology of Continental Margins (eds. C.A. Burk and C.L. Drake), 213-241 (Springer Verlag, New York, 1974).

25. DAVIES, T.A. and GORSLINE, D.S., In Chemical Oceanography, 2nd edition (eds. J.P. Riley and R. Chester), 1-180 (Academic Press, London, 1976).

26. VALLIER, T.L. and KIDD, R.B., In Indian Ocean Geology and Biostratigraphy (eds. J.R. Heirtzler et al.), 87-118 (Amer. Geophys. Union, Washington D.C., 1977).

27. GROSS, M.G., Water Resources Res., 6, 927-931

28. BISCAYE, P.E. and EITTREIM, S.L., Mar. Geol., 23, 155-172 (1977).

29. ROBERTS, D.G., Phil. Trans. Roy. Soc., A278, 447-509 (1975).

30. HEATH, G.R., In Studies in Paleo-Oceanography (ed. W.W. Hay), Spec. Publs. Soc. Econ. Paleont. Miner., Tulsa, 20, 77-93 (1974).

31. BERGGREN, W.A. and HOLLISTER, C.D., In Studies in Paleo-Oceanography (ed. W.W. Hay), Spec. Publs. Soc. Econ. Paleont. Miner., Tulsa, 20, 126-186 (1974).

32. DAVIES, T.A., WESER, O.E., LUYENDYK, B.P. and KIDD, R.B., Nature, 253, 15-19 (1975).

33. EINSELE, G., OVERBECK, R., SCHWARTZ, H.U. and UNSOLD, G., Sedimentology, 21, 339-372 (1974).

34. LONSDALE, P. and SOUTHARD, J.B., Mar. Geol., 17, M51-M60 (1974).

35. YOUNG, R.A. and SOUTHARD, J.B., Geol. Soc. Amer. Bull., 89, 663-672 (1978).

36. YOUNG, R.A., Mar. Geol., 23, M11-M18 (1977).

37. SCHLANGER, S.O. and DOUGLAS, R.G., In Pelagic Sediments on Land and under the Sea (eds. K.J. Hsü and H.C. Jenkyns), Spec. Publs. Int. Ass. Sedimentol., 1, 117-148 (Blackwell Scientific Publications, Oxford, 1974)

38. BERGER, W.H. and WINTERER, E.L., In Pelagic Sediments on Land and under the Sea (eds. K.J. Hsü and H.C. Jenkyns), Spec. Publs. Int. Ass. Sedimentol., 1, 11-48 (Blackwell Scientific Publications, Oxford, 1974).

39. OLAUSSEN, E., In Progress in Oceanography, 4, 245-265 (1967).

40. EMILIANI, C., In Progress in Oceanography, Vol. 4 (ed. M. Sears), 219-224 (Pergamon Press, London, 1967).

41. SHACKLETON, N.J. and OPDYKE, N.D., Nature, 270, 216-219 (1977).

42. BROECKER, W.S., WALLACE, S. and VAN DONK, J., Rev. Geophys. Space Phys., 8, 169-198 (1970).

43. TUREKIAN, K.K., COCHRAN, J.K. and DE MASTER, D.J., Oceanus, 21, 34-41 (1978).

44. BLOW, R.A. and HAMILTON, N., Earth Planet. Sci. Letts., 22, 417-422 (1974).

45. CREER, K.M., GROSS, D.L. and LINEBACK, J.A., Geol. Soc. Amer. Bull., 87, 531-540 (1976).

46. REES, A.I., VON RAD, U. and SHEPARD, F.P., Mar. Geol., 6, 145-178 (1968).

47. HAMILTON, N. and REES, A.I., In Paleogeophysics (ed. S.K. Runcorn), (Academic Press, New York, 1970).

48. CLINE, R.M. and HAYS, J.D., eds., Investigation of Late Quaternary Paleoceanography and Paleoclimatology, Geol. Soc. Amer. Memoir, 145 (1976).

49. HEATH, G.R., MOORE, T.C. and DAUPHIN, J.P., In Investigation of Late Quaternary Paleoceanography and Paleoclimatology (eds. R.M. Cline and J.D. Hayes), Geol. Soc. Amer. Memoir, 145, 393-409 (1976).

50. EMBLEY, R.W. and JACOBI, R.D., Mar. Geotechnology, 2, 205-228 (1977).

51. HEEZEN, B.C. and EWING, M., Amer. Journ. of Science, 250, 849-873 (1952).

52. VENING MEINESZ, F.A., The Earth's Crust and Mantle (Elsevier Pub. Co., Amsterdam, 1964).

53. LILWALL, R.C., Seismol. Bull. Inst. Geol. Sci., 4, 1-9 (1976).

54. SILVA, A.J., Oceanus, 20, 31-40 (1977).

55. ERICKSON, A.J., VON HERZEN, R.P., SCLATER, J.G., GIRDLER, R.W., MARSHALL, B.V. and HYNDMAN, R.D., J. Geophys. Res., 80, 2515-2528 (1975).

56. HYNDMAN, R.D., VON HERZEN, R.P., ERICKSON, A.J. and JOLIVET, J., J. Geophys. Res., 81, 4053-4060 (1976).

57. RATCLIFFE, E.H., J. Geophys. Res., 65, 1535-1541 (1960).

58. BULLARD, E.C., In The Sea, Vol. 3 (ed. M.N. Hill), 218-232 (Wiley-Interscience, New York, 1963).

59. LACHENBRUCH, A.H. and MARSHALL, B.V., J. Geophys. Res., 71, 1223-1248 (1966).

60. SCLATER, J.G., CORRY, C.E. and VACQUIER, V., J. Geophys. Res., 74, 1070-1081 (1969).

61. LANGSETH, M.G. and VON HERZEN, R.P., In The Sea, Vol. 4 (ed. A.E. Maxwell), 299-352 (Wiley-Interscience, New York, 1970).

62. HYNDMAN, R.D. and DRURY, M.J., J. Geophys. Res., 81, 4042-4052 (1976).

63. DAVIES, T.A. and LAUGHTON, A.S., Init. Rep. Deep Sea Drilling Project, 12, 905-934 (U.S. Government Printing Office, Washington D.C., 1972).

64. HAGERTY, R., In Deep Sea Sediments, Physical and Mechanical Properties (ed. A.L. Inderbitzen), 169-186 (Plenum Press, New York, 1974).

65. SEARLE, R., Mar. Geol., 25, 299-320 (1977).

66. LEE, H.J., Init. Rep. Deep Sea Drilling Project, 19, 701-719 (U.S. Government Printing Office, Washington D.C., 1973).

67. ROCKER, K., Init. Rep. Deep Sea Drilling Project, 27, 425-432 (U.S. Government Printing Office, Washington D.C., 1974).

68. DAVIES, D., Bull. Seism. Soc. Amer., 55, 903-918 (1965).

69. HAMILTON, E.L., BUCKER, H.P., KEIR, D.L. and WHITNEY, J.A., J. Geophys. Res., 75, 4039-4049 (1970).

70. VALENT, P.J. and LEE, H.J., Mar. Geotech., 1, 267-293 (1976).

71. TERZAGHI, K. and PECK, R.B., Soil Mechanics in Engineering Practice (Wiley & Sons, New York, 1948).

72. BRYANT, W.R., DEFLACHE, A.P. and TRABANT, P.K., In Deep Sea Sediments, Physical and Mechanical Properties (ed. A.L. Inderbitzen), 209-244 (Plenum Press, New York, 1974).

73. BUCHAN, S., DEWES, F.C.D., JONES, A.S.G., McCANN, D.M. and TAYLOR-SMITH, D., Acoustic and Geotechnical Properties of North Atlantic Cores (Univ. Coll. North Wales Geol. Rept., 1971).

74. BEAR, J., Dynamics of Fluids in Porous Media (Elsevier, New York, 1972).

75. SCHLUMBERGER, Log Interpretation, Vol. 1, Principles (Schlumberger Ltd., New York, 1972).

76. TUCHOLKE, B.E., Lamont-Doherty Geological Observatory Yearbook, 4, 45-48 (1977).

77. PATERSON, D., New Scientist, 78, 896-898 (1978).

78. BISHOP, W.P. and HOLLISTER, C.D., Nuclear Technology, 24, 425-443 (1974).

79. NELSON, C.H. and KULM, V., In Turbidites and Deep Water Sedimentation, Soc. Econ. Paleont. Miner. Short Course, Anaheim, 39-78 (1973).

80. BOUMA, A.H. and HOLLISTER, C.D., In Turbidites and Deep Water Sedimentation, Soc. Econ. Paleont. Miner. Short Course, Anaheim, 79-118 (1973).

81. KEENE, J.B., Init. Rep. Deep Sea Drilling Project, 32, 429-520 (U.S. Government Printing Office, Washington D.C., 1974).

CHAPTER 2

GEOCHEMISTRY

CONTENTS

Summary

1. The geochemistry of marine sediments is reviewed, stressing those aspects relevant to the disposal of high level radioactive waste on the deep-sea floor or by burial in sea-floor deposits.

2. Sediments accumulating in the deep sea by the rain of mineral particles derived from the continents and by the settling of biological debris formed in the sea, the pelagic sediments, are fine-grained, are highly oxidised and have high specific surface areas.

3. Chemical reactions in the sediments after deposition lead to alterations in the solid components and to changes in the composition of the water trapped within the sediment (the pore water).

4. The adsorptive and exchange properties of fine-grained marine sediments are poorly known. Available information suggests that significant amounts of ions can be removed from solution by association with sediment particles. This also applies to fallout radionuclides and to discharged fission and activation product nuclides in the sea. On present understanding, it is not possible to predict the degree to which various nuclides will be associated with sediment particles from a knowledge of other physical or chemical properties of the sediment.

5. Recent experimental work on borosilicate glass, the presently favoured disposal medium for high level waste, shows that considerable alteration of the glass and migration of contained nuclides can occur under moderately high temperature and pressure conditions.

6. Simple estimates of the migration of dissolved constituents in unconsolidated sea-floor sediments, assuming available effective diffusion coefficients are applicable, show that a column of fine-grained clay of the order tens of metres thick might be adequate to isolate high level waste for time periods of the order required.

7. Research requirements fall into two parts: a) a phase of basic studies aimed at an understanding of the chemistry and mineralogy of pelagic sediments and the composition of pore waters, and (b) a phase of special studies of the

exchange properties of pelagic sediments, the stability of waste forms and sediments under conditions of high temperature, pressure and radiation intensity, the thermodynamic properties of pore waters and the speciation and migration of radionuclides in this environment, and the interaction of fission and activation product and transuranic nuclides with natural sediments.

8. Relevant work in marine geochemistry presently being carried out in the U.K. and abroad is briefly reviewed. A possible U.K. programme is described.

1. Introduction

High-level radioactive waste may be disposed of on the sea floor or by burial within sea floor sediment. Chemical reactions between waste and sediment could play an important part in decreasing or increasing the rate of migration, and in determining the migration pathways, of radionuclides released from a mass of waste. The geochemical environment of possible disposal sites must therefore be fully described so that the potential of the sediment as a barrier to migration can properly be assessed.

Research aimed at understanding the processes governing the chemistry and mineralogy of sea floor sediments has only been undertaken during the last few decades. Before the Second World War it was mainly concerned with establishing a catalogue of the composition of different types of sea floor materials. Information on geochemical reactions, and the ways in which the composition of sea water and sediments have reached their present composition over geological time, has only become available in the last decade. The information is still fragmentary in the extreme, but this is an area of active research and some rapid progress at the present time in the U.K. and elsewhere.

Because of the rudimentary state of knowledge of the geochemical environment of the deep ocean, it is necessary at the moment to have stringent criteria for selecting specific disposal sites in the deep ocean, either in or on the sea bed. Few sites would be selected on the basis of present information and understanding. Research in marine geochemistry pertinent to this problem may, in future, permit relaxation of some of the criteria. But it is essential to approach the problem from a general point of view before potential disposal sites are selected. Site-specific investigations will naturally follow, guided by the information provided by long-term research into the chemical nature of the sea floor environment.

This section of the report appraises the information on the geochemistry of the deep ocean and attempts to identify the problems on which more work is required. It begins with a general review of the make-up of marine sediments and proceeds to a discussion of the chemical reactions on the sea floor which are known or suspected to bring about alterations in the original material. The available information on the reaction between radionuclides and sedimentary materials is outlined before a final account is given of the research needed to assess the effectiveness of oceanic sediments as a barrier to radionuclide migration.

2. Composition of Sea Floor Deposits

2.1 Introduction

The floor of the deep ocean, lying on average 4 km below sea level, is mostly covered with a blanket of fine-grained sediment. This material is derived by slow gravitational settling of particles through the water column and by bottom reworking and down-slope movement (See Chapter 1). Sediments composed of fine particles from the incessant rain of material from the near-surface layers, the pelagic deposits, are more widespread than are those supplied by down-slope movement of continental material. They are more relevant to the problem addressed herein. Areas of bare rock outcrops, consisting in the main of basalt, are also widely distributed on the ocean floor. They are most common in the central ridges of the oceans, where new crust is formed (see Chapter 1), but are also represented by isolated seamounts and the pedestals of oceanic islands.

Pelagic sediments have thicknesses above solid rock basement ranging from a few tens of metres to about 1 km (see Chapter 1). Thicker sections are found close to the margins of the ocean basins where slope-drived material is added to the rain of pelagic sediment particles. The oldest unconsolidated pelagic sediment is perhaps 50 to 60 million years old; more consolidated and lithified sedimentary rocks (see 2.3) are found below the unconsolidated overburden, and above the igneous (basaltic) basement.

The accumulation rate of modern pelagic sediments ranges between about 0.5 mm per 1000 years in the clays of the South Pacific to roughly 25 mm per 1000 years in the calcaerous oozes (see 2.2) of the North Atlantic. The accumulation is by no means uniform, 50 million year-old sediment being found at the sea floor in some parts of the Pacific.

2.2 Composition and distribution

Pelagic sediments are rather complex mixtures of components from a number of different ultimate sources (Fig. 2.1). The major components are (a) detrital particles, represented by mineral and rock grains supplied from the land or derived from sea-floor rocks; (b) biogenous particles, represented by the empty shells of planktonic algae and protozoa, composed of calcium carbonate and silica; and (c) authigenic constituents, which are compounds or minerals precipitated, or derived from the alteration of other solids, within the sediments.

The classification of pelagic sediments is based on the relative proportions of these major components, or end-members, in the mixture. Pelagic clays are sediments composed of detrital minerals and authigenic phases, and containing only minor amounts of biological debris. Calcareous oozes are sediments composed predominantly of carbonate shells (foraminifera and coccolithophorid plates). Siliceous oozes are sediments containing a significant fraction of silica shells (radiolarians and diatoms). The distribution of these pelagic sediment types is shown in Fig. 2.2.

The distribution of calcium carbonate on the sea floor appears to be related in a complex way to the water depth (see also Section 3.1.3). The planktonic shells may well settle to the sea floor in all depths, but they are preserved on more elevated parts and dissolve on the deeper ones, because the undersaturation of sea water with respect to calcium carbonate increases with decreasing temperature and increasing hydrostatic pressure and because active bottom water flow enhances dissolution. The boundary between sediments rich in carbonate and those with only a few percent carbonate defines the carbonate compensation depth; its actual depth is variable and depends on the balance between the rate of supply of carbonate shells and their rate of solution on the sea floor (see Section 3.1.3).

Size frequency distributions of the three main classes of pelagic sediments are shown in Fig. 2.3. Pelagic clays have the finest sizes, some Pacific samples containing more than 80% by weight clay grade ($< 4\mu m$ diameter) material. Calcareous oozes are coarser-grained, containing a significant sand fraction ($> 62\mu m$ diameter) composed of whole and fragmented shells of foraminifera. Siliceous oozes have size distributions somewhat similar to those of the clays, siliceous shells being smaller than foraminifera.

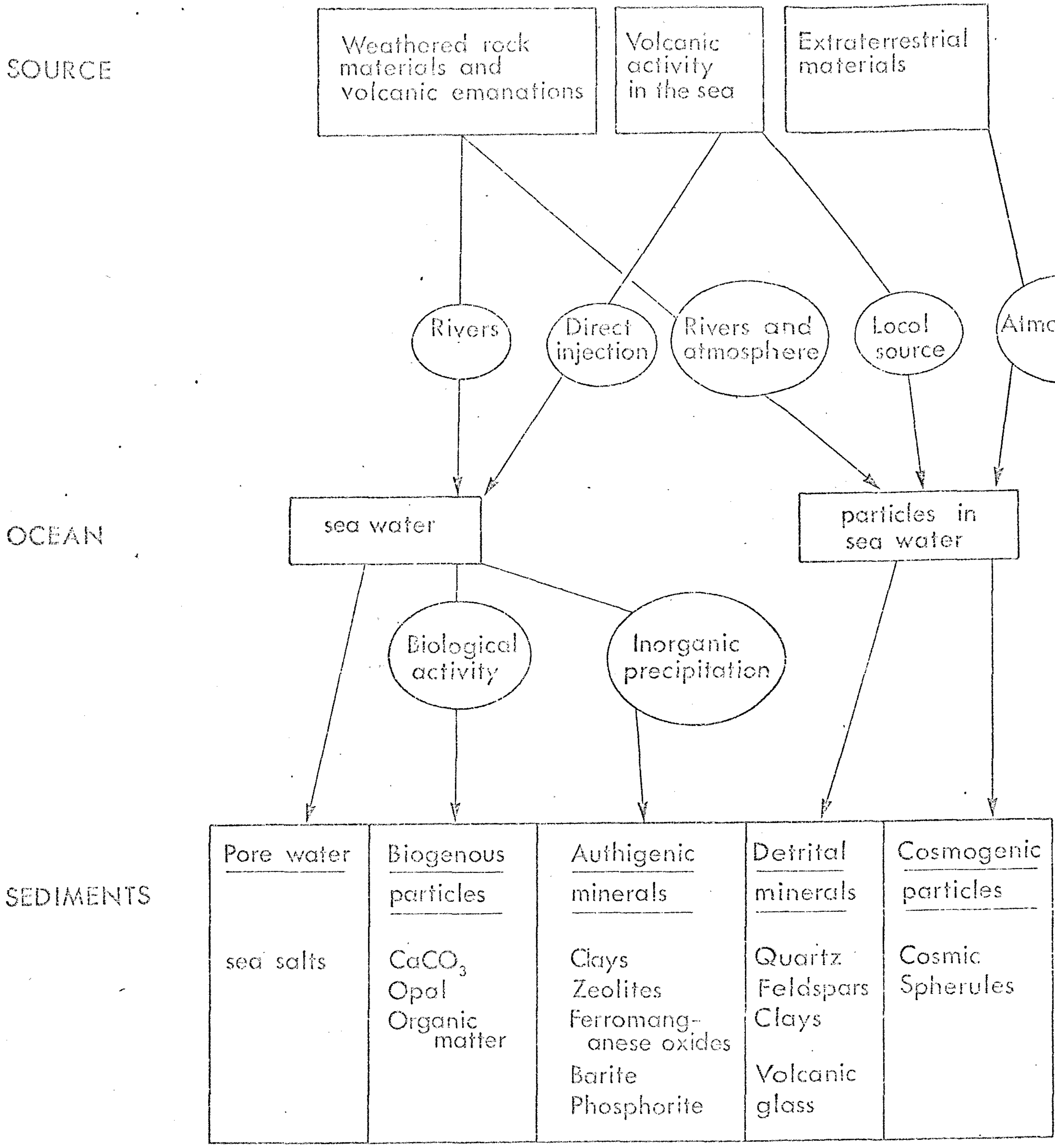


Fig. 2.1 Sources of components in marine deposits.

Pelagic Sediments

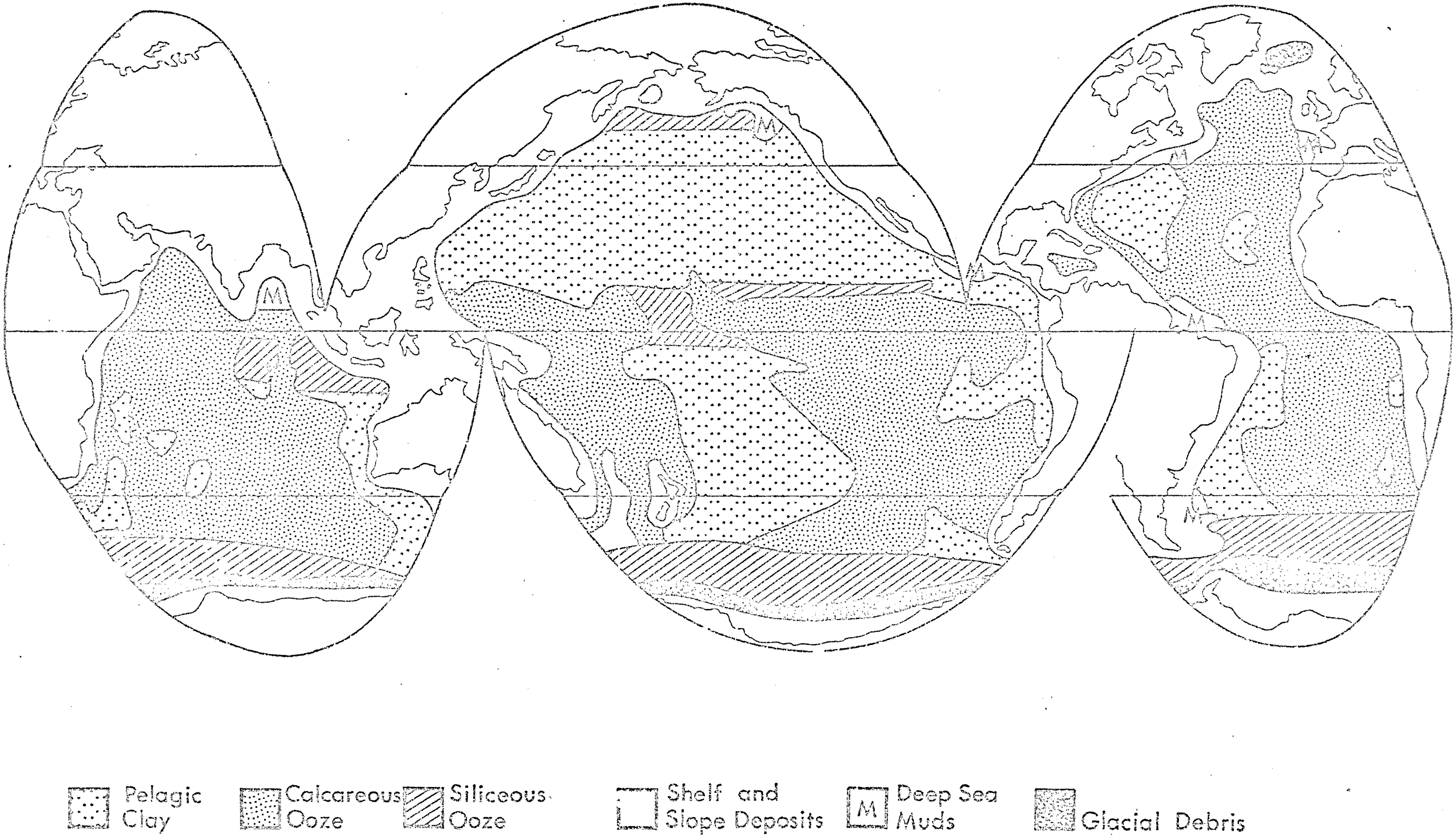


Fig. 2.2 Distribution of pelagic sediments on the deep-sea floor.

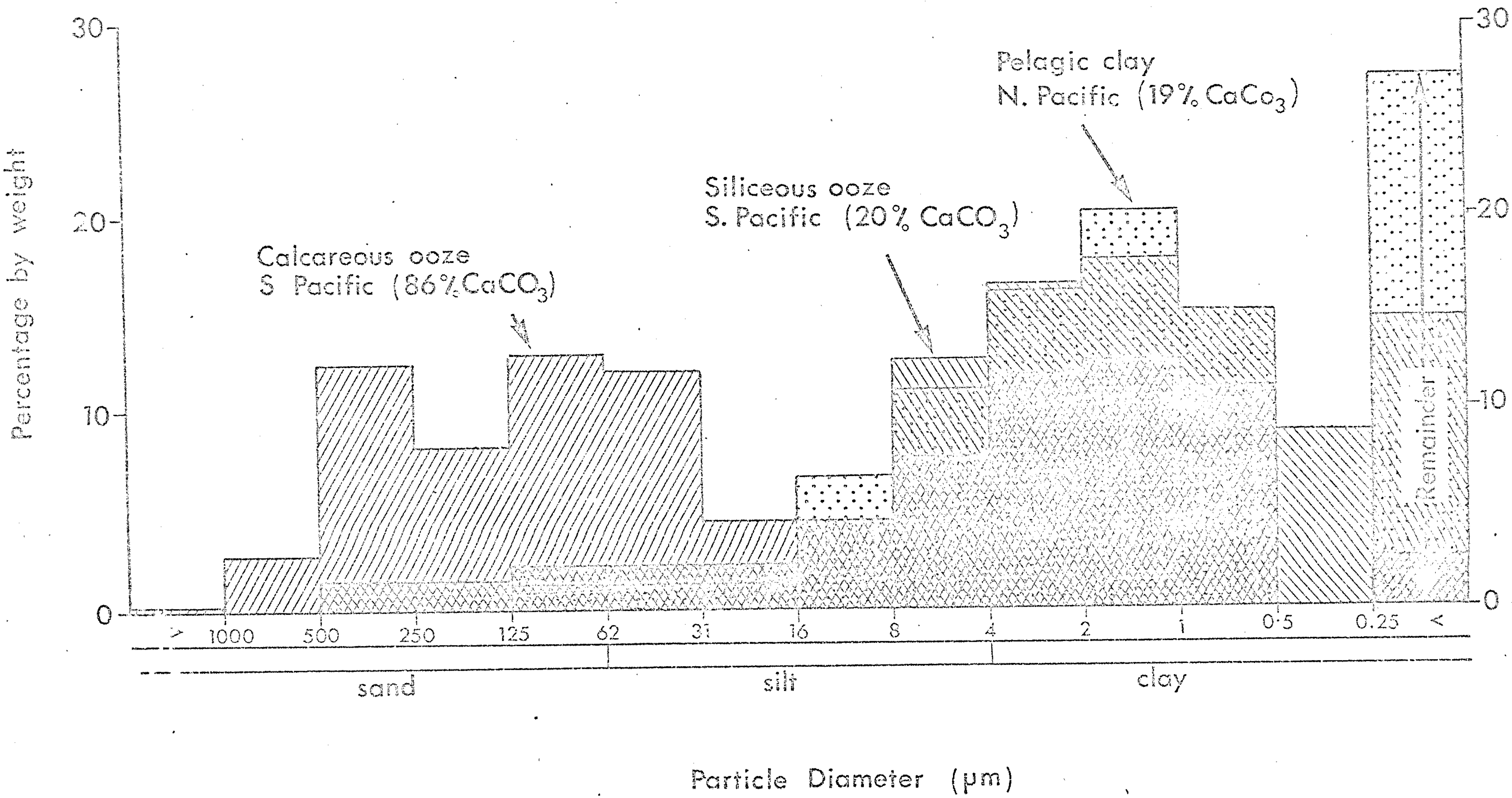


Fig. 2.3 Size frequency distributions of pelagic sediments from the Pacific Ocean

Because of the fine-grained nature of pelagic sediments their specific surface areas are high. Values range between 60 and 150 $m^2 g^{-1}$ (1). Such sediments are therefore highly surface-reactive (see Section 4).

2.2.1 Mineralogy

The mineralogical composition (Table 2.1) of pelagic sediments is determined by the composition of the source material and chemical reactions in the sediments after deposition. Silicate minerals make up the bulk of the material derived from the continents or from within the ocean basins themselves. A further silicate fraction is formed by the reaction between freshly erupted volcanic rock and ash with sea water and is represented principally by a range of zeolites and a layer silicate, montmorillonite. Biogenous shells are composed of calcite or aragonite, both polymorphs of $CaCO_3$, and amorphous hydrated SiO_2 (referred to as opal).

The remaining common minerals in pelagic sediments are authigenic and can form large concentrations in some areas. The ferromanganese minerals are particularly important; they are ubiquitous, forming amorphous coatings on grain surfaces and occurring in high concentrations as concretions and nodules, mainly as pavements on the sediment surface (see Section 2.2.2).

The distribution of the main silicate minerals in pelagic sediments provides clues to the origin of the different mineral species. The clay minerals (layer-lattice silicates, mainly formed in the soil profile) and quartz have been studied most extensively. Quartz is known to be more abundant in middle latitude zones of the oceans corresponding to the arid climatic zones of the continents (2) and it seems clear that the bulk of this mineral in pelagic deposits is delivered to the oceans by the wind. The distributions of the clay minerals support this conclusion. Thus illite is the dominant clay mineral in the North Pacific and the North Atlantic (Fig. 2.4), where quartz is also abundant, and is also thought to be continentally derived via the atmosphere (3). This has been corroborated by mineralogical analyses of atmospheric dusts collected over the oceans (4). On the other hand, montmorillonite is the dominant clay species in the South Pacific where it is thought to form by the alteration of abundant volcanic rock debris. The remaining two important clay minerals, kaolinite and chlorite, are also

Table 2.1

General Mineralogy of Pelagic Sediments

Mineral	Abundance	Source
Silicates		
Quartz	Common	Continents
Feldspars	Common	Continents; ocean floor basalts
Clay minerals	Abundant	Continents; alteration of volcanic debris in the ocean
Zeolites	Rare (locally abundant in Pacific)	Alteration of volcanic debris in the ocean
Volcanic glass	Rare	Ocean floor basalts
Opal	Common	Planktonic diatoms and radiolarians
Carbonates		
Calcite (hexagonal $CaCO_3$)	Abundant	Foraminifera (protozoa); coccolithophoride (algae)
Aragonite (orthorhombic $CaCO_3$)	Rare	Pteropoda (mollusca)
Sulphates		
Barite ($BaSO_4$)	Rare	Authigenic
Phosphates		
Carbonate Fluorapatite	Locally abundant as phosphorites	Authigenic
Oxides/Hydroxides		
MnO_2 (variants)	Locally abundant	Authigenic (coatings and concretions)
$Fe(OH)_3$ (variants)	Locally abundant	Authigenic (coatings and concretions)

derived from the continents, kaolinite from intense chemical weathering in the tropics and chlorite from physical weathering in high latitudes (Fig. 2.4).

A different clay mineral suite is found below the modern assemblage in the North Pacific (5), indicating a distinct change in the source or in the mechanism of sedimentation in this part of the ocean. This important observation provides evidence of varying sedimentation conditions in the remote parts of the sea floor.

2.2.2 Chemical Composition

A limited number of chemical analyses of pelagic sediments are available which serve to show the degree of variability in composition which is in turn brought about by the complex mixture of different mineral components discussed in Section 2.2.1. Hence carbonate-poor pelagic clays yield major element analyses similar to those of fine-grained crustal materials; minor variations in this end-member are produced by variations in the composition of the various clay mineral species, by the presence of unaltered volcanic ash and by the presence of authigenic zeolites and iron and manganese oxyhydroxides (see below). Calcareous oozes are predominantly composed of $CaCO_3$ with proportionally lower amounts of the detrital and/or authigenic silicate fraction. Siliceous oozes contain amorphous silica shells and have higher silicon contents than the other two main types of pelagic sediment.

The presence of certain other components in pelagic sediments assumes an importance, in terms of their influence on the chemical reactivity and the interstitial environment of a sediment, out of all proportion to their abundance. They include:-

a) Organic material

This fraction is derived overwhelmingly from the plankton and represents only about 1% of the total organic material produced by photosynthesis in the surface layers of the sea. Although it has survived complete alteration during descent through a deep column of oxygenated seawater, it does support a bacterial population and further breakdown and alteration within the sediment does take place (see Section 3.1.1).

Organic material is much more abundant in nearshore sediments than in

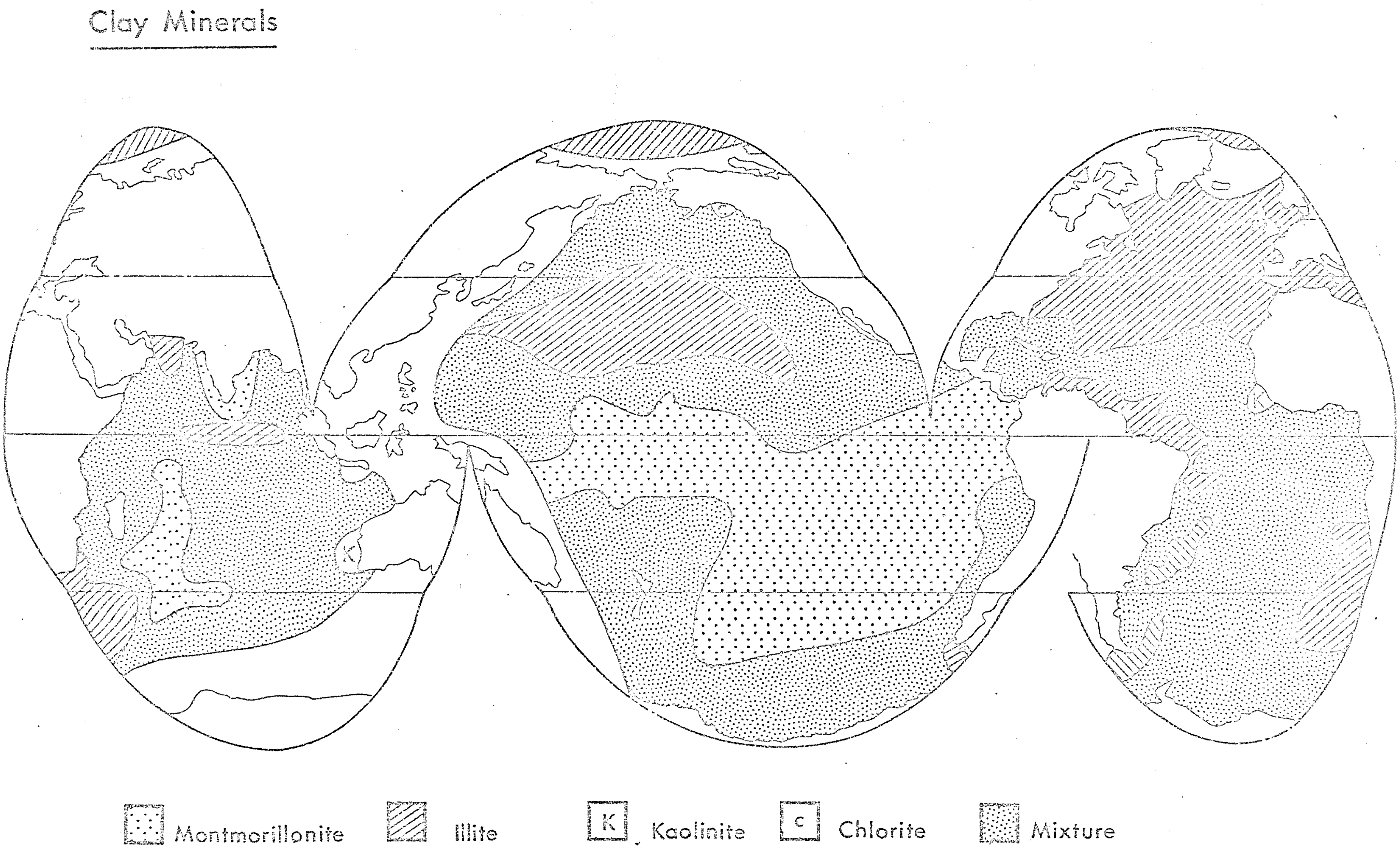


Fig. 2.4 Distribution of clay minerals in pelagic sediments

pelagic environments because: (a) there is a higher rate of primary organic production around the margins of the ocean (see Chapter 4), (b) the transit time from the sea surface to the bottom sediments is shorter, and (c) material is more rapidly buried by sediment derived from the land. Values of organic carbon (being roughly 60% of, and providing a useful measure of, total organic material) in pelagic sediments are between less than 0.1% and 2% (6). Calcareous oozes contain more organic carbon than the clays because the carbonate shells carry an organic coating. Some very slowly-accumulating clays in the North Pacific have carbon contents lower than the detection limits of the analytical methods available.

The concentration of organic carbon in surface sediments is positively correlated with the accumulation rate of the total sediment (6) because the carbon accumulating in slowly deposited pelagic sediments is efficiently utilised or degraded. In shallower environments, where deposition rates are faster, more is preserved.

In modern pelagic clays there is an exponential decrease in carbon with depth in the sediment, which reflects degration during burial, with an apparent half life of between 15000 and 50000 years. In Quaternary (glacial) sediments, encountered at variable depths below modern deposits, organic carbon contents are generally higher; carbon was apparently delivered to the sea floor during these periods at perhaps 2 to 40 times the present rate (6).

The presence of organic material in marine sediments is important from three different points of view:-

(i) Partially degraded and polymerised organic material has a high exchange capacity (see Section 4.1.3) and is thought to be responsible for binding (complexing) many metals in some deposits (7,8).

(ii) During the further degradation of this material, dissolved complex organic molecules may be produced (9) which may be capable of complexing and transporting a wide range of elements in the pore solution (see Section 3.2).

(iii) Respiratory decomposition of the organic material by micro-organisms near the sediment surface can consume all molecular oxygen in the pore water. At this point reduced substances are produced (see Section 3.1.5) and the behaviour of a wide range of elements is radically altered.

Oxygen-deficient conditions are common in rapidly-accumulating nearshore and some hemipelagic deposits where a significant amount of organic material is available for post-depositional reactions. In pelagic deposits, such conditions are not common, although they are met in two sets of circumstances: (a) relatively small reduction zones have been reported in some organic-rich calcareous oozes (10) and (b) as noted above, glacial sediments generally contain more carbon than modern sediments, and oxygen-poor conditions may be found below modern oxidised deposits.

b) Oxyhydroxides

Uniformly oxidised pelagic sediments contain a small fraction of dispersed, amorphous manganese and iron oxyhydroxide, which is present as a fine coating on grain surfaces and as ferromanganese micro-concretions. Amounts of manganese and iron in this form, determined by selective leaching, are approximately 1% by weight of the total sediment (11). In some marginal oceanic environments, post-depositional reactions within the sediment, leading to the production of oxygen-poor conditions (see Section 3.1.5), can lead to an increase in precipitated ferromanganese oxyhydroxides in the surface layers.

The important of this minor sediment fraction lies in its surface chemistry and adsorptive capacity. Iron and manganese oxyhydroxides have both positive and negative surface charges under environmental conditions and are capable of specifically adsorbing a wide range of cations and anions from solution (12). Pelagic sediments have relatively high concentrations of a wide range of metals when compared with near-shore sediments (Table 2.2) and this is possibly due to their adsorption by the oxyhydroxides.

c) Ferromanganese Nodules

The well-known ferromanganese nodules represent a special case of the oxyhydroxide component discussed above. Such nodules are widely distributed on the sea floor of all the ocean basins, being most abundant in remote areas of the Pacific where sediment accumulation rates are very low (16). They are composed of crystalline manganese oxyhydroxides and largely amorphous iron oxyhydroxides together with admixed silicate and biogenous debris. They are distinguished by very high minor metal contents (Table 2.3) and are thought to

Table 2.2

Minor metal composition (ppm) of pelagic and nearshore sediments.

Element	1	2	3	4	5
Ba	690	5640	600	516	580
Co	190	280	290	44	19
Cu	300	700	200	110	45
Mo	40	40	15		3
Ni	260	400	80	105	68
Pb	90	45	100	31	20
Sr	170	320	1190	125	300
Zn	200	270	110	99	95
Zr	190	200	30	188	160

1 North Pacific pelagic clay (13)

2 North Pacific siliceous ooze (13)

3 South Pacific calcareous ooze (13)

4 North Atlantic pelagic clay (14)

5 Nearshore muds (15)

form extremely slowly by precipitation from sea water and from sediment pore waters, the minor metals being taken up by adsorption and coprecipitation by the oxyhydroxide phases. Such deposits are now considered to be a potential ore reserve, especially for copper and nickel (18).

2.3 Sedimentary Rocks

Recent drilling in the deep ocean from Glomar Challenger (19) has provided information on the distribution and composition of the consolidated and lithified equivalents of the unconsolidated sediments sampled by conventional coring methods.

2.3.1 Shales

Shales represent the lithified equivalents of clays. They are formed by gravitational compaction of the clays where the fine-grained clay mineral assemblage is oriented perpendicular to the confining overburden pressure. The porosity and permeability of such rocks are consequently very low. They have been sampled below the sea floor under a few hundred metres burial and may be up to 100 million years old.

2.3.2 Chalks and Limestones

Chalks and limestones are the lithified equivalents of calcareous oozes. They are formed by solution, reprecipitation and recrystallisation, in addition to gravitational compacting, of biogenous carbonate. Porosity, the proportion of void space in the sediment, is reduced from a value of approximately 70% in ooz to values of around 10% in cemented limestones. Available information suggests that calcareous ooze is transformed into a chalk under a few hundred metres burial while limestones are produced by further cementation under about 1 km burial. Calcareous rocks have been drilled in all ocean basins and are 20 to 120 million years old.

2.3.3 Cherts

Cherts, representing the lithified equivalents of siliceous oozes, and possibly the precipitates from hydrothermal solutions, are very compact beds of cristobalite and quartz (both SiO_2 polymorphs) derived from the reprecipitation of amorphous silica. The rocks are very well cemented and porosity is extremely low. They were a serious impediment to deep drilling in the ocean floor prior to the

Table 2.3

Bulk chemical composition (major elements wt. %; minor elements ppm) of ferromanganese nodules, having minor metal contents presently considered to be ore grade, from a survey area in the northern equatorial Pacific (17).

Element	Concentration (wt%)
Si	5.40
Al	2.00
Ti	0.56
Fe	6.40
Ca	1.60
Mg	1.70
K	1.00
P	0.19
Mn	24.90
	Concentration (ppm)
Ba	2420
Co	2400
Cu	10100
Mo	610
Ni	12500
Pb	560
Sr	530
Zn	860
Zr	290

development of re-entry techniques. Cherts have been sampled in all ocean basins, generally several hundred metres below the sea floor, and are 20 to 150 million years old.

2.4 Suspended Material

Reference has already been made to the derivation of the bulk of the detrital mineral components of deep sea clays from land via the atmosphere and the formation of biogenous oozes by the accumulation of settling planktonic shells. There is evidence that this material reaches the sea floor in organic aggregates (mainly faecal pellets) which settle more rapidly than the individual particles (20). Once on the sea floor, the fine-grained material is released by the disaggregation and breakdown of the larger particles.

In addition to the downward flux of primary particulate material from the surface layers, fine particles are also resuspended from the bottom by benthonic organisms and by fluid shear and maintained in suspension by strong turbulence in the boundary layers. (see Chapter 3). A near-bottom layer of increased particle concentration, called the nepheloid layer, is therefore present over large areas of the sea floor (21). The particles are most likely recycled between the sediment surface and the water column, providing a mechanism for extensive redistribution of sedimented material by currents (see Chapter 1). Since the particles have very fine grain sizes, of the order of a few micrometres, and therefore have a high specific surface area, they have a high adsorptive capacity for dissolved and colloidal constituents in the bottom water that may be derived from the sediment. The fluxes of particles from the sea surface and through the nepheloid layer are poorly known, as is the composition and the surface chemistry of the material.

3. Diagenesis in Marine Sediments

3.1 Chemical Reactions in Sediments

Diagenesis, the alteration of the solid phase components of a sediment after deposition, occurs universally in marine sediments. The processes of diagenesis can involve all of the components discussed in section 2 above, and may continue to operate throughout the whole depositional history of the sediment. Certain changes, such as the dissolution of calcium carbonate below the carbonate compensation depth (Section 2.2), can occur with great rapidity and are essentially complete before burial. Others, such as the devitrification of volcanic glass, are slow. Another important group of reactions occurs within the sediment in response to changes in environmental conditions after burial. Reaction sites within the sediment are supplied with dissolved reactants by the pore-water (see Section 3.2), which also serves to remove any soluble reaction products. The predominant mechanism for such supply and removal is molecular diffusion, which is a slow process; consequently, the concentration gradients of dissolved constituents in the pore fluids are relatively high even for reactions which do not occur rapidly. Study of such concentration gradients provides important clues to the nature of the diagenetic processes which are occurring.

3.1.1 Degradation of organic material

In open ocean areas much of the organic material which reaches the sediment is supplied by the fall of 'fast particles' from the surface waters (Section 2.4). These particles are mainly the faecal pellets of herbivorous zooplankton, and their organic content is derived from the phytoplankton overlying the site of deposition. The organic material so supplied supports the benthic community (See Chapter 4), which includes a large bacterial population at the sediment-water interface. The bacteria obtain their energy by the oxidation of organic material to carbon dioxide (CO_2) using the oxygen dissolved in sea water. At the same time they fix CO_2 to form their own cellular structure. Thus some fraction of the carbon which arrives at the bottom is converted into new organic molecules while another fraction is released from the sediment surface as CO_2. This process is rapid in geological terms, so that by the time the sediment is buried to a depth of a few centimetres only the more refractory organic material survives. Consequently, there is a rapid decrease in the numbers of bacteria with depth in the sediment, with cell counts falling by several orders of magnitude in the first metre (22).

In rapidly-accumulating sediments with a high organic content the oxygen demand may persist deeper into the sediment. If this demand exceeds the supply by molecular diffusion from the sediment surface the oxygen content of the pore water will fall to zero. However, bacteria exist which are able to utilise nitrate, and these remain active and multiply. When all nitrate has been converted into more reduced forms of nitrogen, other bacteria able to reduce sulphate to sulphide become predominant. After all the sulphate ion has been reduced bacterial activity falls essentially to zero (see Section 3.2). Any organic material not utilised at this point is preserved in the sediments because of the cessation of biological activity and because the remaining organic compounds cannot be metabolised.

Most pelagic sediments do not show such rapid oxygen depletion. This is because the organic supply to the sediment is too low to sustain the required high oxygen demand. Only refractory organic substances remain, and these at concentrations of a fraction of one percent by weight (see Section 2.2.2). Although direct evidence is lacking, it is likely that such sediments contain dissolved oxygen to considerable depths. They may indeed never become anoxic, so that the reactions characteristic of reducing environments (see Section 3.1.5) do not occur.

3.1.2 Dissolution of silica

Silicon is removed from sea water by several groups of marine organisms mainly as structural support for cell walls. After the death of these organisms the amorphous silica (opal) can reach the sediments. Planktonic diatoms, radiolaria, and siliconflagellates and benthic sponges are all known to contribute silica in this way (23).

The interstitial waters of most sediments are enriched in dissolved silica and this is generally ascribed to the dissolution of biogenous material. There is evidence to suggest that several factors are important in determining the degree of enrichment. Among these, the productivity of the overlying water, the degree of bioturbation (see Chapter 4) and the solubility of the silica are significant. Less than 10% of the material produced by animals and plants in the ocean will undergo burial, considerable dissolution occurring in the sea water itself and at the sediment-water interface. Dissolution continues after burial, and it is possible that as little as 0.1% of the total silica produced by organisms is finally incorporated in the sediment (23).

3.1.3 Dissolution of carbonate

The most common carbonate mineral produced in the ocean is calcite (Table 2.1). Lesser quantities of aragonite, a more soluble form of $CaCO_3$, are also formed. Calcite is produced by coccolithophores and by foraminifera, while the winged structures of the pteropods (pelagic molluscs) are supported by aragonite.

After the death of the organism, degradation of the organic coatings exposes the $CaCO_3$ to direct contact with sea water. However, since surface sea water is supersaturated with respect to both aragonite and calcite, it is probable that erosion of the carbonate does not commence until the particle has sunk to deep water, where the low temperature and high pressure act to increase the solubility of both polymorphic forms (24). The smallest particles (a few μm in diameter) probably dissolve in the water column, but larger ones (several hundred μm in diameter) appear to reach the sea floor before erosion has progressed very far. Rapid transport by the faecal pellets of marine zooplankton can also supply material directly to the sea floor (Section 2.4).

In an environment of low deposition rate, where the surficial sediments are exposed to waters undersaturated with respect to calcium carbonate, the tests and fragments so exposed dissolve before burial. The survival of carbonate depends on the activity of carbonate ions, which is a complicated function of temperature, pressure and pH, and on the rate of supply of fresh calcareous material to the sea bed. Consequently, the depth below which the calcium carbonate content of sediments falls to low levels (the carbonate compensation depth) varies widely over the world ocean. In the North Pacific this depth is as shallow as 3000 m, while it varies in the Atlantic from about 5500 m depth in the north to less than 5000 m in the south. Hence a high proportion of the Atlantic floor is covered with carbonate-rich sediment, and at all water depths Atlantic sediments contain more calcareous material than other oceans of the world (25).

It must be emphasized that our present understanding of the behaviour of carbonate materials in the ocean is only qualitative. In particular, it is not at present possible to predict the effect on the ocean of fossil fuel combustion, except to say that the activity of carbonate ion will, eventually, be reduced throughout the world ocean. This will cause a compensating dissolution of calcareous sediment. It has been shown that the burning of all fossil fuel reserves would produce enough CO_2 to dissolve all calcareous sediment accessible to the direct action of the waters of the world ocean (26). The inference to be drawn from this is that the carbonate compensation depth will become shallower in the relatively near future and some modern surficial sediments will dissolve. Uncertainties are too great to permit a precise prediction of the magnitude of this dissolution.

In the longer term calcareous sediments are vulnerable to dissolution resulting from changes in ocean circulation and from climatic changes. Any variation in the several parameters which control carbonate ion activity can vary the effective compensation depth, and the sedimentary record bears much evidence that such variations have occurred in the past.

3.1.4 Formation and recrystallisation of silicates

The bulk of the silicate fraction of marine sediments originates from the mechanical and chemical weathering of terrestrial source rocks. Clay minerals are important components of this fraction (Fig. 2.4) and are formed under conditions quite different from those encountered on the deep sea floor. It has been postulated that "reverse weathering" takes place in the marine sediments whereby amorphous and poorly-crystalline detrital clay particles take up cations from the pore-water to produce more ordered crystalline clays (27). Such reactions are important in the overall geochemical balance, but could also alter the exchange capacity of the sediments (see Section 4.1).

A further source of clay minerals is the *in situ* alteration of volcanic glass. In the South Pacific in particular, abundant rocks and glasses produced by the myriad volcanic archipelagos are thought to be the source of the montmorillonite in the sediments (see Fig. 2.4). On the other hand, there are also reports of basaltic glass fragments up to 3.5 million years old which appear to be totally unaltered (28). The stability of volcanic glasses of a variety of compositions, and their alteration reactions, are poorly understood.

3.1.5 Changes in Redox Potential

The balance between the degree of oxidation and reduction in a system is measured by the electron activity and is designated the redox potential. In the uppermost horizons of oceanic sediments, the potential has a value of about +400 mv because free oxygen is present as the favoured oxidant. When the oxygen has been consumed, as described in Section 3.1.1, the redox potential falls and nitrate is used as an oxidant. Thereafter, sulphate is reduced, which leads to the production of sulphide ions, and the redox potential falls further to about - 150 mv.

The gradient of electron-availability thus established has a considerable influence on the behaviour of many elements. For instance, iron and manganese are present as their oxidised species (Fe^{3+} and Mn^{4+}) in the oxidised surface layer (Section 2.2.2.b). They are present almost entirely as amorphous, insoluble hydrated oxides. As the redox potential falls with increasing burial, manganese is reduced to Mn^{2+} and, a little later, iron is reduced to Fe^{2+}. These ions are much more soluble and enter the pore water. Typically, therefore, a stepwise increase in these ions is seen when pore water concentration-depth profiles are plotted (29). Many other elements of the transition series presumably follow this behaviour.

The higher concentration of dissolved iron and manganese at depth in the sediment will cause upward diffusion of these species into the oxidised layer, where the higher redox potential will cause their precipitation. This phenomenon has been suggested as a mechanism for the formation of some ferromanganese nodules (30). Although this mechanism operates mainly in nearshore areas where reducing conditions are found close to the sediment-water interface, there is also some recent evidence suggesting that manganese is also mobile at the surface of oxic pelagic sediments presumably due to subtle changes in the redox conditions within the sediment (13).

3.2 Pore Waters

Sea water is trapped within the sediments as they accumulate. The composition of this pore water is altered by the processes of organic matter degradation (Section 3.1.1), mineral dissolution (Sections 3.1.2 and 3.1.3), the diagenesis of minerals (Section 3.1.4) and the exchange between solid and aqueous phases (Section 4.1). Because the ratio of solid to liquid in the sediment is high, such subtle reactions produce large changes in the chemical composition of the pore water; because the movement of solutes is by molecular diffusion rather than by turbulent mixing, concentration gradients of chemical species in the pore waters are marked. They provide valuable information on the types of reactions, the depths of reaction, the rate of supply of reactants and removal of products and the influence of the reactions on the composition of sea water.

Examples of the changes in the composition of pore waters relative to sea water are provided by:-

(a) the oxidation of organic material. Fig. 2.5 shows a schematic representation of the changes in concentration of some of the major redox indicators in pore waters. Consumption of oxygen in the upper layer is followed by the reduction of nitrate and finally sulphate. Iron and manganese are taken into solution from the solid phase as the redox potential falls.

(b) the dissolution of skeletal material, either siliceous or calcareous. Fig. 2.6 shows the influence of dissolution on the contration-depth profile of dissolved silicon in a marine sediment, calculated for differing dissolution rates.

(c) The formation of authigenic mineral phases. Fig. 2.7, containing data gathered by the Deep Sea Drilling Project, shows considerable change in the composition of pore water possibly due to the formation of dolomite ((Ca, Mg) CO_3) from calcite.

Studies of the concentration of major and minor constituents in the pore waters of marine sediments are providing valuable information on the subtle chemical reactions that take place in marine sediments and on the role that these reactions have on the overall geochemical balance in the ocean. In many situations, such reactions can only be detected by looking at the pore waters

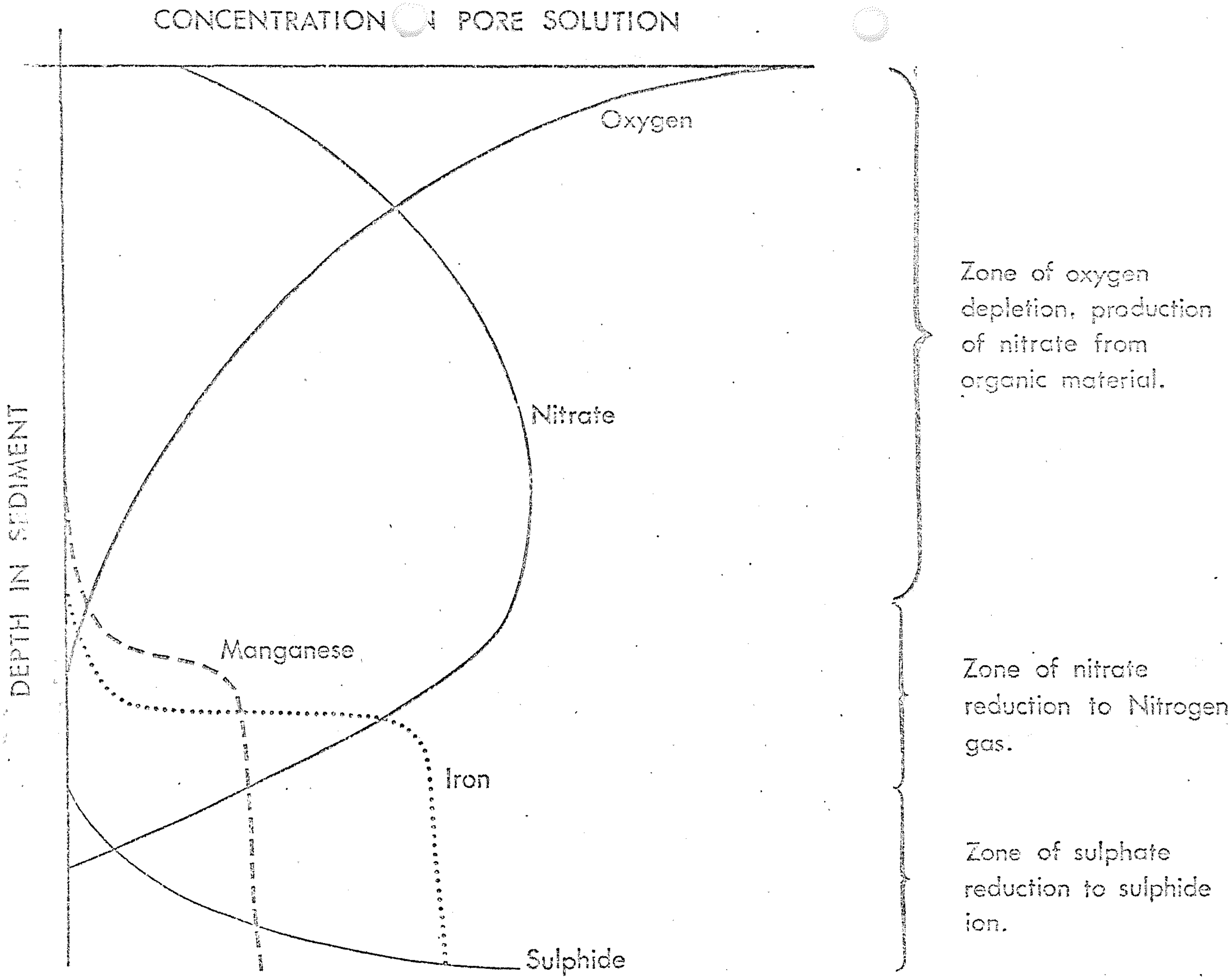


Fig. 2.5 Idealised schematic diagram of changes in concentration of pore water constituents which result from organic diagenesis. Concentration scales are arbitrary for each constituent.

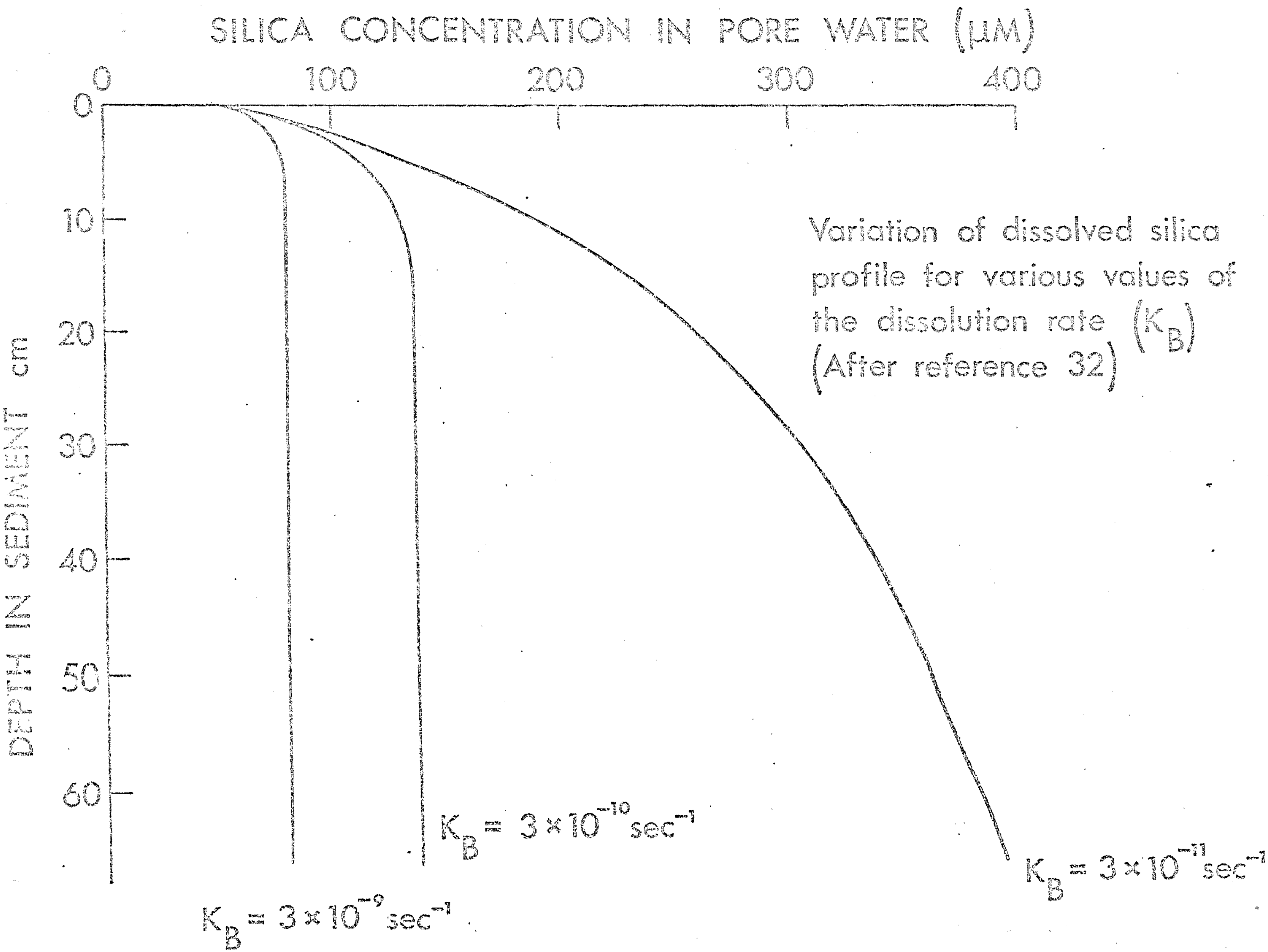


Fig. 2.6 Effect on dissolved silica concentration profiles of various rates of dissolution of biogenic silica. Results are derived from a mathematical model of early diagenetic processes, including bioturbation (32).

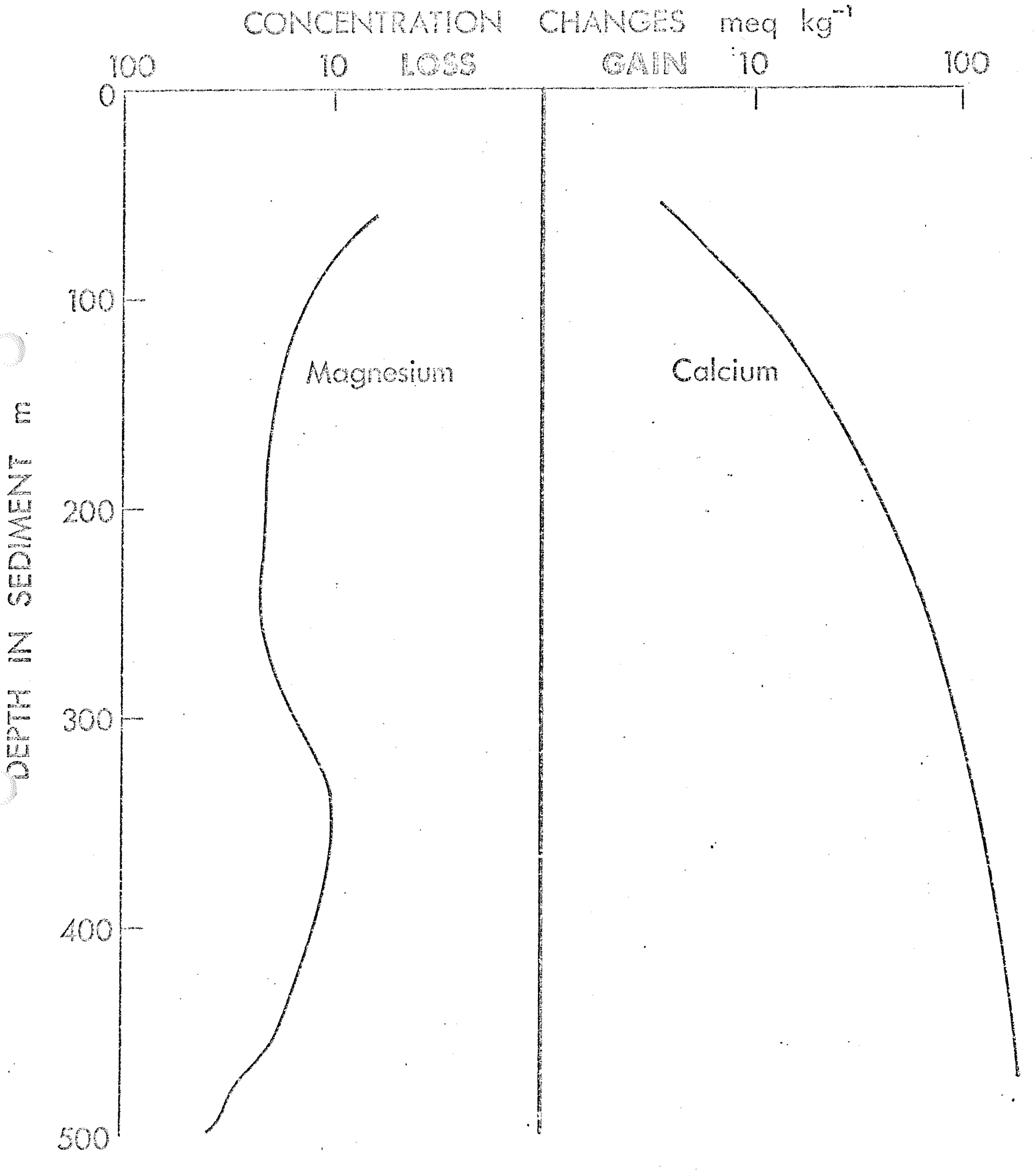


Fig. 2.7 Changes in concentration of dissolved calcium and magnesium ion in pore waters. DSDP Site 217, Ninetyeast Ridge, Indian Ocean. Gains or losses are relative to surficial pore water concentrations (33).

which are very sensitive to changes in the composition of the solids. In environments where the sedimentation rate is low, such as in pelagic clays, these reactions are important; their potential influence on the disposal of radioactive waste is discussed more fully in Section 5.

4. Interaction of Radionuclides with Sediments

4.1 Introduction

Sedimentary particles possess an exchange capacity or ability to adsorb ions from and to release ions to solution. This adsorption may or may not be reversible. The irreversible reactions are thought to be important in controlling the chemical composition of sea water. Over geological time, the soluble products of continental denudation have reacted with solids and have thereby been removed from seawater into the bottom sediments where other reactions may occur (34).

Three general categories of pelagic sediment components are known to be important in this respect and some background information is available on the importance of this phenomenon.

4.1.1 Clay Minerals

The so-called ion exchange capacity of the clay minerals has been known for a long time. Although anion exchange is also known to be important, by far the main emphasis has been on the behaviour of cations in clay-water systems. This is important in agriculture where the uptake and release of potassium and ammonium ions, for example, by soil clays play important roles in determining soil fertility.

Pelagic sediments contain a mixture of clay minerals (see Section 2.2.1), each type of clay having a different cation exchange capacity (C.E.C.). Montmorillonite, for example, has a CEC up to 8 times greater than that of illite, which in turn has a CEC at least twice that of kaolinite (35). This contrast is caused by the difference in structure of the various clay mineral species. Montmorillonite has the property of expansion along basal planes where an interlayer population of exchangeable ions, depending on the immediate aqueous environment, resides. Illite has an interlayer population of potassium ions in non-expandable layers, whereas kaolinite has no interlayers at all. The exchange sites in the latter two minerals are therefore mainly on the crystal surfaces and the total CEC is much lower.

The population of exchangeable cations in terrestrial and marine clay minerals are quite different and they change when terrestrial clays are transported into the sea. In terrestrial clays, the dominant exchangeable cation is calcium followed by magnesium. Sodium and potassium are minor components. On entering sea water, the calcium and magnesium are replaced by sodium which then becomes the dominant exchangeable ion. It should be pointed out that this general conclusion has only been arrived at in the last year following a study of CEC of river and marine clays (36). This has necessitated a reappraisal of conventional methods for determining this property which were developed for a different ionic medium. The available information on the exchange properties of different types of clay minerals concerned, and the different types of pelagic clays, is consequently rudimentary.

Although adsorbed cations can be replaced by other cations, it is well known by soil scientists that certain cations can be sorbed by certain clays from solution and remain in a non-exchangeable state. A good example is provided by potassium which can become "fixed" to a considerable degree in the soil profile. Geologists have also noted that the clay mineral composition of thick sections of shales changes in a regular way because of the uptake and fixation of potassium and magnesium ions (37).

The CEC is known to be changed by heating. Although the speed of the exchange reaction is increased at higher temperatures, the CEC decreases markedly. Thus, the CEC of montmorillonite decreases by a factor of 10 after exposure to a temperature rise of 700°C (35).

The cation exchange capacity of marine sediments is therefore a fundamental property, depending on composition, grain size and previous history. It is quite different for different clay mineral species and is known to change naturally over geological time. It is also drastically altered at high temperatures. Some further work on pelagic sediments is urgently required in view of the methodolical problems mentioned above, in order to place the available information on a firm basis. In addition to the cation exchange capacity, fine-grained clays are also potentially important in adsorbing elements from solution because of their high specific surface areas. Here, electrostatic attraction between ions and charged surfaces lead to large changes in solution compositions in the presence of clay minerals.

4.1.2 Oxyhydroxides

This ubiquitous component (Section 2.2.2b), although occurring in low concentrations, is thought to play an important role in the minor element composition of pelagic deposits. The main process is one of surface adsorption, to some extent by electrostatic attraction of opposite charges but mainly by chemical reaction or specific adsorption on mixed manganese and iron oxyhydroxides. The evidence for adsorption comes from observations of statistical correlations between certain minor elements and either manganese or iron in ferromanganese nodules, and marked enrichments of metals in oxide-rich sediments on some parts of the ocean floor (38). Reference has also been made (Section 2.2.2) to the unusual minor metal composition of pelagic sediments generally, a phenomenon which can be explained by invoking adsorption onto finely dispersed oxyhydroxides. The exchange capacity of soils may also be dominated by the presence of fine coatings of oxyhydroxides on otherwise fine-grained mineral particles (39).

Although a certain amount of circumstantial evidence for such adsorption is available, the hypothesis has yet to be tested. Neither an understanding of the mechanism of adsorption for different elements nor a means of predicting the degree of adsorption under different conditions is available. A great deal of laboratory work on the surface chemistry of hydrous manganese dioxide and precipitated ferric hydroxide has been carried out but it does not seem possible at the present time to extrapolate such data to the marine environment.

4.1.3 Organic Material

Partially degraded and polymerised organic material, derived as discussed in Section 2.2.2a, has a high exchange capacity. Evidence from soils suggests that the humus fraction, which is derived from the breakdown of lignin and other plant macromolecules, has a CEC at least two to three times greater than montmorillonite, the clay mineral with the highest CEC. This material apparently forms especially stable complexes with transition metals.

There is limited evidence that the organic fraction of marine sediments also has a high exchange capacity. In the Hudson River estuary, for example, measurements of the CEC before and after the removal of the bulk of the organic material by hydrogen peroxide suggest that up to 80% of the total CEC is due to the organic fraction, which constitutes roughly 5% of the total sediment (40). Moreover, some unpublished experimental results suggest that the organic material in estuarine sediments has quite different exchange properties from the inorganic fraction. In equilibrium with sea water, roughly 80% of the inorganic exchange sites are occupied by monovalent ions, whereas only 30% of the organic sites are occupied by monovalent ions. While magnesium cannot be detected on the inorganic sites, this ion is the dominant species on the organic exchange sites.

The exchange properties of the organic fraction of pelagic sediments are unknown. The organic material in such sediments is derived overwhelmingly from the plankton of the open sea, and consequently may have properties different to those of the organic fraction of the nearshore environments studied this far, where an input from land is dominant. Nevertheless, the complexing capacity of this planktonic material, especially for transition metals (7,8), and the possible preservation of organic material in some glacial deep-sea sediments (see Section 2.2.2a), means that a knowledge of the exchange properties of this minor sediment fraction will be essential.

4.2 Radionuclides and Sediments

The possible use of the property of ion-exchange for the immobilisation of radionuclides has been recognised (41). A considerable amount of attention has been devoted to the fixation of exchanged and adsorbed radionuclides on soils and by clays. The importance of montmorillonite as an adsorbing medium is well established.

Natural marine sediments also have considerable potential to remove radionuclides from seawater, and this aspect has been the subject of various studies. Two different approaches have been employed; firstly, laboratory experiments using natural sediments interacting with tracer solutions, and, secondly, field observations of sediment activity in response to release of radionuclides. The results of these studies are most significant. The scavenging properties of suspended particles and the diffusion velocity of radionuclides within a sediment are both directly related to the distribution coefficient of the nuclides (the ratio of the activity on the solid to that in solution). Considerable progress has been made in recent years in development of theoretical models to describe these processes. If these models are to give realistic results it is important that the correct distribution coefficients are incorporated.

4.2.1 Experimental Results

There exists considerable laboratory data on the interaction of (principally) fallout nuclides with sediments from various water depths and depositional regimes (42). These results indicate that the distribution coefficient (K_D) is insensitive to the particle size or to the lithological composition of the sediments; this finding is surprising in view of experience from soil chemistry, and warrants further investigation.

The degree of adsorption of nuclides by sediments found in these experiments is in the following order:-

$^{45}Ca < ^{90}Sr < U, Pu, ^{137}Cs < ^{86}Rb < ^{65}Zn < ^{59}Fe < ^{95}Zr / ^{95}Nb < ^{54}Mn < ^{106}Ru < ^{147}Pm.$

The evidence from these operational laboratory evaluations, that the sorption process is dominated by factors other than bulk lithology, suggests that we are dealing with a variety of sorption mechanisms; they may follow stepwise reaction pathways which are due to competing processes operating at different rates. These reactions may also not be reversible with the same kinetics. The trace components (organic matter and oxyhydroxides) associated with natural sediments may be important in causing these features, but this has not been demonstrated experimentally. In a study on the seepage of activity from a waste site at Oak Ridge, however, it was demonstrated that ^{60}Co and other nuclides were adsorbed by oxides of manganese in the surrounding shale and soil, rather than by any major components (43).

As would be expected, K_D values found for ^{90}Sr and ^{137}Cs (in the range 100-1000) are markedly less than those found for the trace metals, lanthanides or actinides, which lie in the range 5,000-100,000. These values are reflected in the effective diffusion coefficients of the nuclides in sediments, about 10^{-8} cm^2/sec for ^{90}Sr and ^{137}Cs and in the range 10^{-10} to 10^{-11} cm^2/sec for the lanthanides. As a comparison with these values, the diffusion coefficients of ions in free solution are around 10^{-5} cm^2/Sec.

4.2.2 Field Results

Interactions of fission product and transuranium nuclides with the environment have been studied in the main in connection with the global fallout resulting from surface and atmospheric testing of nuclear bombs and devices, and site specific releases from nuclear reactors, weapons and their associated fuel and waste processing facilities. Examples which have received attention in the marine sphere include releases from coastal processing plants and activity distributions at Pacific test sites.

One important result of these site specific release studies is the dependence of the distribution of activity on the physical and chemical condition of the discharge. This is particularly true for the transuranic elements, which have received increasing attention in recent years partly because of their high radiological damage potential and partly because of their persistence and increased importance at high reactor fuel burnup. From experimental evidence it is found that plutonium (also neptunium and americium) has various possible valency states in aqueous solution (44). A characteristic of Pu chemistry is the formation of colloidal products of hydrolysis.

a) Nearshore Environments

Relatively few studies appear to have been made of the vertical distribution of artificial activity (i.e. its record in time), and on how this inventory of activity changes with time in response to input. A major problem in assessing the post-depositional behaviour of radionuclides in the marine environment, particularly nearshore, is the separation of effects caused by geochemical factors from those caused by physical and biological agents. Physical disruption, such as caused by bottom currents or winnowing, can cause translocation and change local inventories of the deposited nuclides. Biological effects include bioturbation, where sediment is worked vertically downwards by organisms into the sediment column, resulting in a greater penetration of activity than that due to geochemical processes, although the site inventory remains unchanged. Although some of this information provides useful background to the problem of seabed waste disposal, it is not clear how much is directly relevant to vitrified waste emplacement in a sediment column.

The monitoring of radioactivity discharged from the Windscale reprocessing plant indicates that several elements have an affinity for sediments (45,46). Here the expected relationship between uptake and sediment particle surface area is found. For plutonium as an example, about 95% of the discharged activity is lost rapidly from the effluent to the sediments, while the remainder is found in seawater. An appreciable fraction of this residual plutonium in seawater (70%) passes a fine filter as would both a colloid and a true solution (47). Analyses of americium in parallel with those for plutonium demonstrate differences in geochemical behaviour, in that americium is more radidly removed by filtration and sedimentation. Reported experience from Trombay, India is similar to that at Windscale, 99% of the plutonium being taken up by sediments with a mean K_D of 90,000 (48).

On the basis of a time sequence of analyses on cores collected between 1964 and 1973 from the same location in Buzzard's Bay, U.S.A., it has been claimed that some remobilisation or solubilisation of fallout plutonium has occurred (49). This is based on evidence of a decreasing Pu inventory accompanied by a relatively constant ^{137}Cs inventory. The $^{241}Am/^{239,240}Pu$ activity ratio also remains constant with depth. This process, which implies plutonium (and presumably americium) migration against the concentration gradient, is postulated to occur in reduced sediments with low sedimentation rate. In contrast, a study of annually layered deposits from a nearshore basin off California, U.S.A., found no evidence for plutonium migration (50).

b) Deep-sea Environment

A large number of samples of sediment and water have been analysed in connection with programmes on the behaviour of long lived fallout nuclides (51). For soluble species, such as ^{90}Sr and ^{137}Cs, it is found that the activity remains predominantly in the top few hundred metres of the ocean water column, while other nuclides such as $^{95}ZR/^{95}Nb$, ^{106}Ru and the lanthanides largely become associated with particulate material and sink.

In recent years the distribution of fallout actinides in the oceanic water column has also been studied (52). In the mid-1970's, about 10% of the cumulative overland plutonium fallout was found in the sediments at ocean depths around 4000 m, and a model for this removal based on a particle association mechanism has been developed. The distribution of plutonium (and americium) in the sediments indicates the importance of bioturbation in the deep sea, as penetrations of activity to around 10 cm have been found in water depths of 5000 m, where this sediment depth represents tens of thousands of years of sedimentation.

4.2.3 Natural Series Nuclides

Nuclides of the natural radioactive series provide an opportunity to examine the long term behaviour of the heavy elements (atomic number > 82) in deep sea sediments. Most work has been performed on the natural actinides, thorium, protoactinium and uranium because of their relatively long half-lives. In the past 25 years an appreciable body of data has been gathered using the known decay rates to date sediment horizons and to estimate geochemical rates (53).

The geochemical mobility of these nuclides is found to be affected by their mode of supply to the sediments, and isotopes of the same element may behave differently in the same sediment column depending on their production and incorporation mechanisms. Such information is relevant to the possible behaviour of fission products and transuranics on release to pore water from buried waste in sediments, at least at normal ambient temperatures.

a) Uranium

Under the oxidising conditions in most pelagic deposits, there is little evidence for mobilisation of the primordial isotopes, ^{238}U and ^{235}U, from the detrital minerals of a sediment, the main vehicle of supply. The valency of uranium in the sediments is thought to be predominantly U(IV), perhaps as a substitute for calcium which has a similar ionic radius (54). In seawater, uranium is highly conservative with a mean residence time of 200,000-400,000 y. Here it is thought to exist as the U(VI) complex $UO_2(CO_3)_3^{4-}$.

In a small number of homogenous red clay cores, however, it has been observed that ^{234}U can migrate out of the sediment column through the sediment-water interface, where it helps maintain the $^{234}U/^{238}U$ activity ratio of 1.15 found throughout the open ocean (55). Although the phenomenon has not been observed in other types of pelagic sediment, where compositional inhomogeneity often occurs, a supply rate from the entire ocean floor of around 0.3 dpm $^{234}U/cm^2/1000y$ is found necessary to maintain the observed uranium content of the ocean. Two mechanisms for this process have been proposed. From studies on marine phosphorites, the mechanism is postulated to be oxidation of 30% of the in situ ^{234}U production in the sediments to U(VI), the ^{234} having been made more labile by the decay energies associated with preceeding alpha and beta emissions, and subsequently migrating as the uranyl carbonate complex (56). The second mechanism is alpha recoil of ^{234}Th from the decay of ^{238}U from the solid phase into solution, as demonstrated by laboratory experiments on the mineral zircon (57). Whatever the mechanism, the value of the effective diffusion coefficient is of the order $10^{-[illegible]}$ cm^2/sec.

b) Thorium and Protactinium

There is only one valency state of thorium, Th(IV), and this species is readily hydrolysed. The concentration of the primordial isotope, ^{232}Th, in seawater is extremely low, probably less than 0.01μg/1000 litres (58). ^{232}Th finds its way into sediments in detrital minerals whereas ^{230}Th is supplied to the sediment by scavenging from the overlying water column following its production from ^{234}U. To a first approximation, ^{231}Pa produced from ^{235}U behaves similarly to ^{230}Th. This mode of production has been the basis of various dating methods based on ^{230}Th and ^{231}Pa.

Large scale mobility of thorium isotopes in sediments has not been demonstrated.

The standing crop of ^{230}Th and ^{231}Pa in many sediment columns is often found to be balanced by the supply from the uranium isotopes in the overlying ocean column. However, there is strong evidence that some short scale mobility is possible, perhaps as $Th(OH)^{o}_{4}$. This is demonstrated by the isotope concentrations in some authigenic minerals (59), and in concentrations in relict fish teeth greater than those found in the living animal (60). Related evidence has been furnished that authigenic ^{230}Th becomes progressively less soluble in acid at greater depths in sediment cores, while yields of detrital ^{232}Th are unaffected (61).

The authigenic minerals in which the thorium enrichments have been observed are found in areas of slow sedimentation. However, the times for the thorium incorporation are short (of the order 100,000 yr) compared with the likely required periods for containment of radioactive wastes.

c) Radium

^{226}Ra and ^{228}Ra are produced in sediments by decay from their respective parent nuclides, ^{230}Th and ^{232}Th. As might be anticipated for an alkaline earth element, Ra^{2+} has a marked tendency to migrate in sediments, as shown by the fact that 99% of the ^{226}Ra input to the ocean is derived from the sediments (62), and that the bottom water content of ^{226}Ra is a factor of 2 or 3 greater than that found in surface water (63). Values of around 10^{-8} cm^2/sec have been found for the effective diffusion coefficient.

5. High Level Radioactive Waste and Marine Sediments

5.1 Introduction

The effects produced by placing radioactive waste on the deep sea floor, or by burying such waste in sea floor sediments, with respect to the behaviour of the sediment and the short- and long-term behaviour of the waste itself, are unknown. These effects will be better understood by acquiring more extensive information on the form and properties of the waste and from studies of the geochemistry of pelagic sediments. In discussing the interactions between waste and the sediment medium, we have emphasised the option of burial in sediment; the problems involved will be equally relevant to the alternative of placing the waste on the sea floor.

5.2 Form and Properties of the Waste

Present plans are that the high level radioactive waste originally in liquid form is solidified by fusion into a borosilicate glass (64). In the FINGAL process (65), cylinders 150 cm long and 15 cm in diameter have been produced, and in the later HARVEST Programme, cylinders 300 cm long and 50 cm in diameter will be produced (66).

Several properties of the glass are still poorly known. In particular, leach rates for the radionuclides under conditions on the deep sea floor are not available. Although a 10-year old sample of FINGAL glass is apparently stable in a short-term exposure to distilled water at 90°C (65), it is not clear how it would react in seawater (pore water) in contact with sediment at a mugh higher temperature and pressure. It has been recently shown (67) that simulated waste borosilicate glass, containing 13% fission product oxides, became extensively altered when reacted with water at 300°C and 300 bar pressure over a 2 week period. Moreover, new uranium-and caesium-bearing minerals were formed on the surface of the altered glass.

Reference has already been made (Section 3.1.4) to the apparent stability of some basaltic glasses on the deep sea floor. Further information on these natural occurrences, and on the products of hydrothermal reaction between rocks and seawater (for example in the geothermal system in Iceland), would be useful.

An alternative to vitrification of the radioactive waste has been recently suggested by workers at the Australian National University (68). They suggest that the radionuclides should be contained in the lattices of crystalline minerals and not in "solid solution" in a glass. A synthetic rock ("Synroc") has been prepared containing a group of minerals, which are also known to occur naturally, the minerals each having the ability to act as hosts for a different group of fission product and transuranic nuclides. Once confined to the minerals, it is argued that the nuclides would be stable for very long time periods; naturally-occurring uranium isotopes, for example, are known to be stable in crystal lattices of rocks, admittedly at lower temperatures and at lower radiation intensities than would be present in a waste block, for time periods of the order of 2000 to 3000 million years.

Support for this interesting suggestion comes from information on the natural nuclear reactor at Oklo, Gabon Republic (69). A natural chain reaction in a mass of uranium ore took place some 2000 million years ago and was detected by the anomalous isotopic composition of the uranium and by the presence of long-lived fission products and their daughters in some of the ore samples. It appears that most of the products of the reaction were remarkably immobile; the most mobile nuclide was apparently ^{90}Sr, but even in this case very little escaped the reactor zone (a few metres) before it decayed away to undetectable levels. The heavy elements (including the lanthanides and the actinides) remained relatively fixed; plutonium nuclides in particular were completely immobilised for time periods comparable with the half-life of ^{239}Pu (24,400 years) and apparently fixed in the crystal lattices of the ore minerals, mainly pitchblende.

Whatever the final form of the waste, it will be essential to know the chemical form of the radionuclides that are released into sea water or into the sediment pore water as a result of leaching. The behaviour of an element will depend on whether it is present in true solution or as a colloid; moreover, different valency states of the same element have quite different properties and can behave quite differently under environmental conditions. The transuranic nuclides are known to have variable valencies and plutonium in particular characteristically forms colloidal hydrolysis products.

5.3 Properties of the Sediments

Some of the sediments on the deep sea floor have physical and chemical properties which may make them suitable as a barrier to radionuclide migration once some of the activity is eventually released from its container. It is recognised that borosilicate glass will not confine the radionuclides for periods in excess of 1000 years so that the properties of the sediment barrier will become crucial.

The deep sea pelagic clays (Section 2.2) are probably the most suitable candidates for an effective sediment barrier, for the following reasons:-

a) they are very fine-grained (most constituent particles are less than 1 μm in diameter) and consequently have high specific surface areas (Section 4.1.1) and low permeabilities (Chapter 1)

b) they consist for the most part of clay minerals which have a relatively high cation exchange capacity (Section 4.1.1) and are therefore potentially capable of adsorbing some radionuclides from solution

c) they are highly oxidised (because they have accumulated slowly in well-oxygenated sea water) and therefore contain very little reactive organic material which could render radionuclides more soluble. In addition, they contain a very fine-grained oxyhydroxide fraction (Sections 2.2.2 and 4.1.2) capable of chemically adsorbing ions from solution. Reference has been made (Section 4.2.1) to the adsorption of ^{60}Co and other nuclides by the solid manganese oxide fraction of the shale and the soil in a radionuclide waste site. As a result of this finding, it was suggested (43) that finely-ground manganese oxides be added to high-level waste before it is solidified or that the waste is coprecipitated at high temperature with manganese oxide so that the migration barrier of the waste form is enhanced.

An extensive research programme into the chemistry and mineralogy of pelagic clays from the north Pacific is being carried out in the U.S. under contract from the Energy Research and Development Administration (70).

The emplacement of highly active waste into pelagic clays will cause other effects, including :-

a) alteration of the adsorption or exchange of ions from solution by the sediment particles at higher temperatures,

b) alteration of the sediment by recrystallisation at higher temperatures, possibly leading to an increase in grain size and a concomittant change in the exchange capacity, and by the formation of new mineral phases

c) alteration of the sediment by radiation.

5.4 The Pore Water

Two aspects are important in considering the role of the pore water environment on the emplacement of high level waste in marine sediments. The first involves the ultimate control of the composition of the pore water which may change drastically in the presence of waste canisters at a high temperature and will determine the chemical form of any released redionuclides. The second is concerned with diffusion of ions within the sediment and the consequent migration of radionuclides released from solid waste.

Among other important variables, the rate of leaching of radionuclides from a waste matrix will be a function of the environmental hydrogen ion concentration or pH. In sea water, the main control of pH, at least in the short-term, is the carbonate system. This maintains the pH at around 8. Pore waters are somewhat more complicated, and the buffer system here is not yet fully understood. The pH could be considerably perturbed in the vicinity of a waste canister where the temperature would be much higher than normal. The consequent corrosion products could further alter the composition of the pore fluid.

The degree of oxidation or reduction (the redox potential) of a sediment is largely controlled by the presence of free oxygen or reduced substances in the pore waters (see Sections 3.1.1 and 3.1.5). The processes determining the redox potential are not as yet well defined, and the extent to which the system is buffered against a change in redox is unknown. For reasons outlined in Section 5.3, it will probably be best to choose an oxygenated environment for the disposal of high level waste. It will be essential to predict the extent to which such an environment will be altered by the presence of the waste; it is known, for example, that the reaction between sea water and hot rock in the upper part of the ocean crust (Chapter 1) leads to the formation of deoxygenated seawater containing hydrogen sulphide (71). Under these conditions, the chemical behaviour of many constituents in the water and the leaching behaviour of solid waste are likely to be drastically altered.

The pore waters of marine sediments contain high levels of dissolved constituents, both organic and inorganic, capable of forming complexes which alter the behaviour of other constituents. Many radionuclides can exist in different chemical forms (Section 6.2) and these will react in various ways to the complexing agents. Consequently the geochemical behaviour of any given radionuclide in a sediment may be highly variable depending on the chemical species present. Although some progress has been made in predicting the chemical speciation of sea water, the more complicated system in the pore water is almost entirely unknown. It will not be possible to make predictions about the behaviour of any given nuclide released to the pore fluid until considerably more information on the thermodynamic properties of pore waters is available.

The vertical migration of chemical constituents in pore waters is by molecular diffusion (see Section 3.2) at a rate which is slower by a factor of about 10^6 than turbulent diffusion. Profiles of chemical constituents in pore waters are considered to represent diffusional gradients reflecting processes occurring over long time periods; quite significant concentration gradients can result from slow reactions.

From simple diffusion theory, the flux of a dissolved constituent in a porous medium is proportional to the concentration gradient through the medium and to the porosity of the medium. A knowledge of the proportionality constant, the diffusion coefficient, is required in order to evaluate fluxes within sediments and across the sea-floor into the ocean. This has been done for a number of non-radioactive substances and it is clear that the process is important in the global geochemical balance of many elements.

Assuming a very simple diffusional mechanism for transport through a sediment barrier, a breakthrough time can be defined as follows:-

$$t = \frac{Z^2}{D_e}$$

where Z is the barrier thickness and D_e is the effective diffusion coefficient. An empirical expression for D_e has been derived (72) which allows values of t for various values of K_D (the distribution coefficient of a nuclide between solid and aqueous phases) to be estimated (Fig 2.8). It is seen that the distribution coefficient must be at least 10^3 if the breakthrough time is to exceed 10^6 years. For any given value of K_D, an increase in barrier thickness by a factor of ten increases the time to breakthrough by a factor of 100.

These rudimentary considerations, taken together with the few distribution coefficients which have been measured for actinide and fission product nuclides,

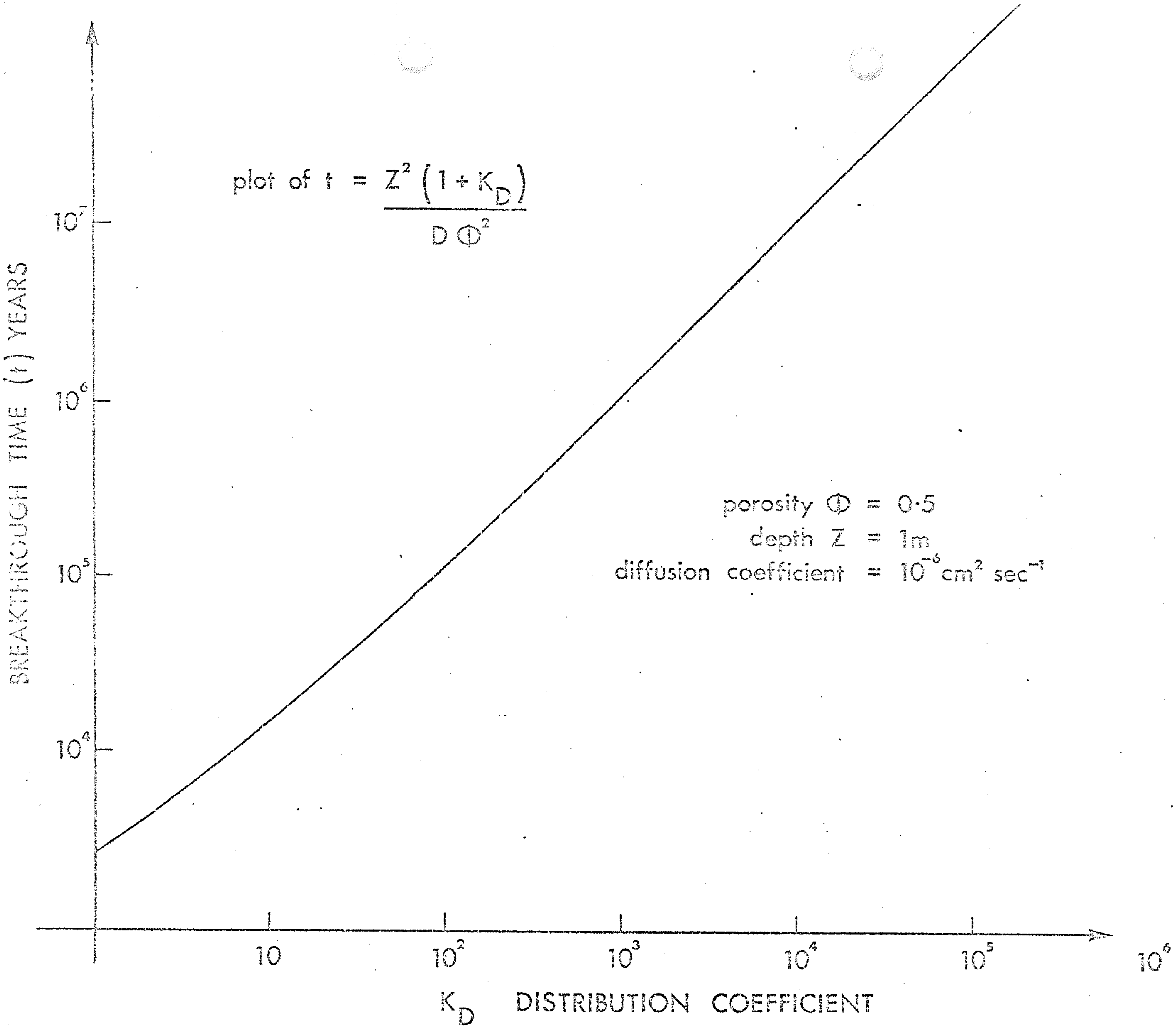


Fig. 2.8 Breakthrough time for various values of distribution coefficient. A 1m thickness of sediment, porosity 0.5, is assumed (72).

suggest that a barrier thickness of the order of tens of metres of pelagic sediment might be adequate to isolate high level waste. Although this is encouraging, it must be amphasised that the treatment is excessively simplistic and that the results shown in Fig. 8 can only be taken as a starting point for further work.

Perturbations to the sediment system caused by the presence of a mass of high level radioactive waste will certainly have profound effects on its physical and chemical properties. Indeed it is possible that gross convective overturn of sediment and pore water might occur. The implications for predictions of nuclide migration rates cannot at present be assessed even qualitatively. Also, the simple diffusional model mentioned above ignores several possible natural processes, including pore water advection, the importance of which is not yet clear. Quantitative assessment of all these factors will be necessary before realistic estimates of migration rates can be obtained.

6. Research Requirements

6.1 Introduction

The previous sections of this part of the report make it clear that it will be necessary initially to approach the problem of the disposal of high level radioactive waste in the ocean in a very general way. Decisions based on present knowledge will be far too restrictive to give an adequate range of options for disposal strategy. Moreover, it will be essential to work on the basic assumptions involved and to show that they have been questioned fully.

The areas requiring further work are therefore both fundamental and highly specialised. While we are able to identify with some confidence those areas where the background information is inadequate, we are not able to specify nearly so completely or so confidently the specifically applied research tasks that are required. This report should be viewed, therefore, as a basis for the planning of a long-term research programme in the course of which more specific questions could arise, requiring new approaches for their solution.

6.2 Basic Information

6.2.1 The chemical and mineralogical make-up of pelagic sediments

This is a necessary starting point for the work. The bulk composition and the chemistry and mineralogy of the major end-members of the sediments are required before other properties of the sediments, or experimental work on adsorption, are understood. Information on the variability in the chemical composition of the sediments over long time periods (long core sections) will provide additional information on the long-term geological conditions at different sites (see Chapter 1).

6.2.2 Accumulation rates of the bulk sediment and the metal fraction

An insight into the natural or man-made fluxes of chemical constituents in the ocean can be provided by determinations of the accumulation rates of metals, notwithstanding the fact that they may not be radioactive. The present state of ignorance about many natural processes makes a degree of redundancy highly desirable. Information on the bulk accumulation rates of the sediments will be useful in an assessment of long-term geological stability at different sites (see Chapter 1).

6.2.3 Chemistry of the pore waters of marine sediments

As discussed in Sections 3 and 5, the pore waters represent the most important migration medium for constituents recycled through the sediments, both natural and otherwise, and they are a very sensitive indicator of chemical change in the sediments as a whole. It will be essential to have a broad knowledge of the composition of natural pore waters in different types of pelagic sediments in order to provide a basis for recognising man-made perturbations to this system. Estimates of diffusion in the pore water, derived from the profiling of natural constituents, will be required for an assessment of natural migration rates and will provide a basis for designing experiments to measure such rates both vertical and horizontally (see 6.3.8).

6.3 Special Studies

6.3.1 The exchange capacity of marine sediments

The cation exchange capacity of marine sediments is a basic property that may give clues to the likely behaviour of such sediments towards introduced ionic species. The methods presently used to measure this property require stringent re-evaluation and the exchange capacities of a wide variety of sediments for a range of major and minor elements are required so that they can be related to other physical and chemical properties of the sediments (see Section 6.2.1). Use can be made of radioactive tracers of the stable elements, as well as lanthanide and actinide analogues of the transuranic elements. Experiments under different temperatures, pressures, redox conditions and pH will be essential.

6.3.2 Identification of the sediment components responsible for the bulk exchange capacity

As an outgrowth of 6.3.1, it will be necessary to identify the components (mineralogical or chemical) of the sediments which account for the exchange properties of any given sediment type, and to understand the surface chemistry of these components under varying environmental conditions. This will provide the data on which a prediction of likely exchange capacity of any sediment type, from other properties, can be based.

6.3.3 Chemistry of authigenesis and its products

It will not be possible to assume that the exchange properties of sediments will be invariant over long time periods. Authigenesis will bring about important alterations to the make-up of sediments and will lead to the production of new solid phases in sediments after burial. An example is the formation of silicates having relatively high exchange capacities or the recrystallation of some minerals to produce phases with a low exchange capacity. Reactions under oxic and anoxic conditions will require evaluation; the alteration of deposited organic material will follow different routes under these contrasting conditions, yielding products having different complexing capacities.

In parallel with this problem it will also be necessary to study the effects on the exchange properties of sediments at high temperatures. It seems likely that a certain amount of recrystallisation of amorphous and poorly crystallised material in the sediments will take place because of the high temperatures generated by waste placed on the sea floor or buried. This could produce better crystallised silicate minerals, iron and manganese oxyhydroxides and cherts, the latter from the accelerated alteration of amorphous silica. The exchange properties of these new phases are likely to differ significantly from the original material; intuitively they will probably be much lower. On the other hand, it is possible that some incorporation of radionuclides might take place on recrystallisation.

6.3.4 Chemistry of suspended particles

The chemical composition and the adsorptive capacity of suspended particles in the deep ocean will be required in order to evaluate the effectiveness of such fine particles in dispersing radioactivity around disposal sites. Sampling will have to be carried out with newly-designed traps which can be placed in the deep sea to distinguish between the steady vertical flux of particles and the recycled component from the bottom.

6.3.5 Migration in the pore fluid

As an outgrowth of 6.2.3 it will be necessary to attempt to model the diffusive and advective movement of radionuclides in the pore fluids. Research into the thermodynamic properties of the pore fluid and the speciation of dissolved constituents, including radionuclides, will be required. Information on the perturbations to the sediment/pore water system (see Section 6.3.8) will also be needed.

6.3.6 Behaviour of actinides in marine sediments

Some insight into the likely behaviour of transuranic nuclides in pelagic sediment can be gained by two approaches. Firstly, by evaluating the available data, and extending the research, on the distribution and behaviour of fallout and discharged radionuclides in the ocean (for example, an expanded programme of research into the distribution of discharged nuclides from the Windscale plant into the Irish Sea would be valuable). Secondly, studies are required of the geochemistry of the lanthanides and uranium and thorium nuclides in pelagic sediments. Such investigations of analogues of the transuranic nuclides could begin much earlier than, and could guide, experimental or in situ studies (Section 6.3.8) of, say, plutonium and americium. Work is also required on the geochemistry of fission product nuclides in marine deposits, including ^{137}Cs and ^{90}Sr, among others, because of their high initial activities in the waste, and ^{99}Tc among others, because of their long half-lives.

6.3.7 Experimental work on the adsorption of transuranic and fission product nuclides by sediments

This requires the use of appropriate plutonium, americium, curium and fission product nuclides and samples of the various types of pelagic sediments to conduct a series of experiments on adsorption and its relationship to other properties of the sediment. It will be essential to pay particular attention in these experiments to the speciation of the nuclides and to the effects of relatively high temperatures.

6.3.8 Experimental work on radionuclides and sediments under in situ conditions

A certain number of in situ releases of transuranic and fission product nuclides are probably justified towards the end of the research programme in order to examine likely behaviour under disposal site conditions and in order to test mo s and predictions arising from the experimental programme.

6.3.9 Effects of high temperatures and high radionuclide activity

Included here is a group of problems directly connected with the effects produced by the emplacement of a mass of highly radioactive material at a high temperature (ca. several hundred degrees centigrade). It is not exhaustive and will be amended frequently during the research programme.

a) effects of high temperature on advection/convection in the sediment and its effect on transport through the pore water

b) effects of high temperatures on the sediment (recrystallisation) and the effect of this on heat dissipation around a canister

c) effects of high temperatures and pressures on the chemical makeup of the sediment (formation of new mineral phases) and on the stability of the waste form itself.

d) radiation effects on the waste, sediment and sea water; radiation damage to solid phases, and the resulting changes in physical and chemical properties, and radiolysis of the aqueous phase.

7. Research Programmes

7.1 Existing Programmes

With one exception (see 7.1.1a)) research into the geochemistry of sea floor sediments relevant to the problem of the disposal of high level radioactive waste in the deep sea is being conducted in several laboratories as part of other research programmes. Included here is a brief annotated check-list of the principal programmes, emphasising work on the deep sea environment. This list is not claimed to be comprehensive; it is derived from an appraisal of the (western) scientific literature and from personal contact.

7.1.1 Sediment Geochemistry

a) Oregon State University (U.S.A.) (formerly at the University of Rhode Island): Part of the Seabed Assessment Programme under contract from the U.S. Environmental Research and Development Administration (70). A study of the chemistry of North Pacific pelagic clays and experimental determination of the adsorption of europium and thorium from NaCl solutions by these clays.

b) Oregon State University (U.S.A.): Part of NSF-supported research project on the sediments of the south-east Pacific emphasising metal-rich deposits and the composition and origin of the oxyhydroxide fraction.

c) U.S. Geological Survey, Menlo Park, California (U.S.A.): Part of the Deep Ocean Mining Environment Study (DOMES) of NOAA on the chemistry of pelagic sediments from areas of metal-rich ferromanganese nodules.

d) Oregon State University (U.S.A.): Part of NSF-supported Manganese Nodule Programme (MANOP) on the fluxes of chemical substances within pelagic sediments, using a remote bottom-lander vehicle.

e) Imperial College, London University: Part of a NERC-supported project on the applied geochemistry of sea-floor metal deposits in the Pacific and Indian Oceans.

f) Leeds University: NERC-supported projects on the geochemistry of the lanthanide metals in the ocean and on the geochemistry of Indian and Pacific Ocean sediments, the latter in collaboration with Liverpool Univesity.

g) Yale University and University of Southern California (U.S.A.) and Glasgow University: A number of research projects on the accumulation rates of marine sediments, using radiometric methods, and the geochemistry of the natural uranium and thorium series nuclides.

h) Woods Hole Oceanographic Institution and U.S. Geological Survey, Menlo Park, California (U.S.A.): Projects concerned with the exchange capacities of sediment particles, mainly in fresh-water and near-shore marine environments.

i) University of Utrecht (Netherlands): Chemistry of pelagic sediments from the Atlantic and experimental work on the adsorption of transition metals by manganese oxyhydroxides.

j) University of Göttingen, (W. Germany): Chemistry of pelagic sediments, including rocks recovered by the Deep Sea Drilling Project.

k) Centre des Faibles Radioactivités, France: Accumulation rates of pelagic sediments and ferromanganese nodules using radiometric methods.

l) Scripps Institution of Oceanography, Woods Hole Oceanographic Institution, Texas A and M University, Lawrence Livermore Laboratory (U.S.A.); International Laboratory of Marine Radioactivity (Monaco), Ministry of Agriculture, Fisheries and Food and Lancaster University: Studies of the behaviour of transuranic and fission product radionuclides in the marine environment.

At the Institute of Oceanographic Sciences, research is presently carried out on: the chemistry and mineralogy of pelagic sediments from the Atlantic and Pacific Oceans, the geochemistry of ferromanganese nodules, the behaviour of uranium- and thorium-series nuclides and on the accumulation rates of sediments and constituent elements in pelagic sediments.

7.1.2 Pore Waters

a) Woods Hole Oceanographic Institution (U.S.A.): major ion chemistry of pelagic sediment pore waters using methods for collecting in situ samples. Plans have been formulated for work on trace metals to begin shortly.

b) University of Washington, (U.S.A.): Transition metal and nutrient chemistry of pelagic sediment pore waters using methods for collecting in situ samples.

c) University of Rhode Island (U.S.A.): Part of the MANOP project (see 7.1.1d)) on the transition metal and nutrient chemistry of pelagic sediment pore waters using samples collected by separating water from sediments collected by conventional coring methods.

d) Texas A and M University (U.S.A.): Various projects on the nutrient chemistry of pelagic sediment pore waters emphasising the role of biological mixing on the concentration profiles observed; use is made of natural ^{222}Rn measurements in the pore waters.

e) Yale University (U.S.A.): Long-term interest in the chemistry of anoxic (near-shore) sediment pore waters and the mathematical modelling of concentration profiles.

f) Northwestern University (U.S.A.): Mathematical modelling of concentration profiles from pore waters.

g) Leeds University: NERC-supported project on the transition metal chemistry and the behaviour of iodine in the pore waters of pelagic sediments from the Pacific and Indian Oceans.

h) Kiel University (W. Germany): Extensive experience in the nutrient and trace element chemistry of pelagic and near-shore sediment pore waters from the Atlantic and Pacific Oceans.

i) Edinburgh University: NERC-supported project on the chemistry of anoxic (near-shore) sediment pore waters with emphasis on the role of dissolved organic substances on the behaviour of trace metals.

j) Imperial College, London University: Experimental studies of the composition of pore waters and rocks at elevated temperatures and pressures.

At the Institute of Oceanographic Sciences, work on pore waters is concerned with the chemistry of some of the major constituents and nutrient compounds, including gases. Use is made of an instrument to collect samples at in situ conditions at all oceanic water depths.

7.1.3 Suspended Particles

a) Woods Hole Oceanographic Institution (U.S.A.): Long-term research into the flux of particulate material to the deep-sea floor (PARFLUX Experiment) emphasising transport in large biological aggregates, and using moored traps.

b) Woods Hole Oceanographic Institution, Lamont-Doherty Geological Observatory Scripps Institution of Oceanography (U.S.A.), Centre des Faible Radioactivité (France) and Physical Research Laboratory (India): Part of the Geochemical Ocean Sections (GEOSECS) project into the chemistry of suspended particulate material in the open ocean.

c) Woods Hole Oceanographic Institution (U.S.A.): Co-ordination of a multi-institutional experiment on the flux of particulate material to the sea floor in the Low Energy Benthic Boundary Layer Experiment (LEBBLE) using moored traps.

d) Oregon State University (U.S.A.): Flux of biologically-associated metals to the deep-sea floor, as part of the MANOP project (see 7.1.1d)), using moored traps.

e) Scripps Institution of Oceanography (U.S.A.): Various projects on the flux of particulate material to the floors of the Southern California offshore basins, using moored traps, as part of the Institute of Marine Resources programme.

f) Marine Laboratory, Aberdeen (DAFS): Research into the supply of organic material to the sea floor, mainly around U.K., using moored traps.

g) Edinburgh University: NERC-supported projects on the chemistry of suspended particulate material in oceanic waters, using large volume water samples.

At the Institute of Oceanographic Sciences, work on suspended particulate material forms part of a project on the chemistry of the surficial sediment layers in the deep sea. Use is made of large volume sampling and a newly-designed particle trap for use in deep water.

7.1.4 Hydrothermal Reactions

There is considerable interest in the chemistry of reactions between seawater and ocean crustal rocks at high temperatures since this bears on the evolution of seawater and crustal rocks over geological time. This work is carried out by many University groups and at other institutions. The work is relevant to the proble of the long-term stability of buried waste forms (glass, ceramic or "synroc") and of the alteration of barrier sediments. Some of the most interesting work is carried out at:-

a) U.S. Geological Survey, Menlo Park (U.S.A.): mainly experimental investigatio using seawater and basalt.

b) National Energy Authority, Iceland: Geochemistry of the sea water and rocks in the Reykjanes and Svartsengi geothermal fields.

c) Woods Hole Oceanographic Institution (U.S.A.) and Newcastle University: Composition of sea-floor basaltic glasses and their alteration products and the geochemical mobilities of major and minor constituents of seawater and rocks during cooling.

d) Geophysical Laboratory of the Carnegie Institution, Washington (U.S.A.): Long and distinguished history of research into experimental approaches to the origin of igneous and metamorphic rocks and their alterations.

e) Edinburgh and Manchester Universities: Centres of NERC-supported research into the origin of igneous rock series by means of high temperature and pressure experiments.

7.2 A U.K. Research Programme

It was pointed out in Section 1 of this Chapter that research on the chemistry and mineralogy of sea-floor sediments is relatively new. The body of relevant information on geochemical cycles in the marine environment has been acquired only during the last decade or so. Section 7.1 identifies some of the research now being done and where it is being carried out both in the U.K. and abroad. If there were no acceleration in the research effort, it seems most unlikely that the additional basic knowledge would be sufficiently detailed for this problem before a further decade has elapsed; this would further delay the more specific studies which should follow the acquisition of the basic information.

Although a certain amount of this information is being provided in other research programmes, notably under the contract from ERDA to the Sandia Corporation in the U.S.A. (70), a large amount of additional research will be required on a wide range of pelagic sediment types and their pore waters from different marine environments. A substantial part of the necessary expertise in the Western World is in the U.K; it is essential that U.K. scientists play their part in an international programme if the research that is required is to be completed in good time.

The objectives of a U.K. programme should be:-

a) to accelerate the international programme by taking a share of the work in the basic studies requiring effort by many scientists working on a broad front,

b) to undertake some research that can only or best be done by U.K scientists because of some special expertise or facility,

c) to maintain a broad U.K. expertise as a basis for future programmes and to make possible a meaningful British participation in international planning and decision-making.

A brief outline of a possible collaborative programme can be given as follows. It would involve many of the U.K. groups identified in Section 7.1 as well as others whose expertise has not been recognised here but who would be identified in the planning phase of the programme.

7.2.1 Basic Studies

These would last 3 to 5 years.

a) Chemistry and mineralogy of sediments; collection and analysis of long core sections; characterisation of modern and Quaternary (glacial) horizons.

b) Accumulation rates of bulk sediments and heavy elements; dating of sediment sections; geological histories.

c) Chemistry of fission, activation product and transuranic nuclides in the Irish Sea; a basic geochemical study of a point-source "experiment" provided by the Windscale outfall.

d) Chemistry of the pore waters of marine sediments.

7.2.2 Special Studies

These would follow from the basic work and would last at least a further decade.

a) Exchange properties of marine sediments, using radioactive and stable nuclides (special expertise available in U.K.).

b) Behaviour of natural series actinides and lanthanides in marine deposits (special expertise available in U.K.).

c) Sediment properties and stability of waste forms under elevated temperatures and pressures; studies of natural glasses (necessary expertise must be acquired).

d) Chemistry of suspended particles in the deep sea (special expertise available in U.K.).

e) Migration in the pore fluid; thermodynamics and speciation of radionuclides (necessary expertise must be acquired).

f) Laboratory and field experiments on the interaction of transuranic nuclides and natural marine sediments (necessary expertise must be acquired).

g) Radiation effects on sediments, pore fluids and waste forms (necessary expertise must be acquired).

8. References

(1) Duursma, E.K. and Eisma, D. Neth. J. Sea Research 6, 265-324 (1973).

(2) Rex, R.W. and Goldberg, E.D. Tellus, 10, 153-159 (1958).

(3) Griffin, J.J., Windom, H. and Goldberg, E.D. Deep-Sea Res. 15, 433-459 (1968).

(4) Chester, R. In: Changing Chemistry of the Oceans (D. Dryssen and D. Jagner editors) Almgvist and Wiksell, Stockholm, 291-305 (1972.

(5) Heath, G.R. Geol. Soc. Amer. Bull., 80, 1997-2018 (1969).

(6) Heath, G.R., Moore, T.C. and Dauphin, J.P. In: The Fate of Fossil Fuel CO_2 in the Oceans (N.R. Anderson and A. Malahoff, editors) Plenum Press, N.Y., 605-625 (1977).

(7) Nissenbaum, A. and Swaine, D.J. Geochim Cosmochim. Acta., 40, 809-816 (1976).

(8) Calvert, S.E. and Morris, R.W. In: A Voyage of Discovery (M. Angel, editor) Pergamon Press, Oxford, 667-680 (1977).

(9) Krom, M.D. and Sholkovitz, E.R. Geochim. Cosmochim. Acta., 1565-1574 (1977).

(10) Arrhenius, G.O.S. Rept. Swedish Deep-Sea Exped., 5, Part 2, 227p. (1952).

(11) Unpublished I.O.S. data.

(12) Stumm, W. and Morgan, J.J. Aquatic Chemistry, Wiley-Interscience, N.Y., 583p.

(13) Calvert, S.E. and Price, N.B. Marine Chem., 5, 43-74 (1977).

(14) Unpublished I.O.S. data.

(15) Wedepohl, K.H. In: Origin and distribution of the elements (L.H. Ahrens, editor) Pergamon Press, Oxford, 999-1016 (1968).

(16) Cronan, D.C. In: Marine Manganese Deposits (G.P. Glasby, editor), Elsevier, Amsterdam, 11-44 (1977).

(17) Calvert, S.E., Price, N.B., Heath, G.R. and Moore, T.C., J. Marine Res., 36, 161-183 (1978).

(18) Moncrieff, A.G. and Smale-Adams, K.B., Mining Congress J., 46-50. Dec. (1974).

(19) JOIDES, Bull. Amer. Assoc. Petrol. Geol., 51, 1787-1802 (1967).

(20) Wiebe, P.H., Boyd, S.H. and Winget, C.J.Marine Res., 34, 341-354 (1976).

(21) Eittreim, S. and Ewing, M. In: Suspended solids in water (R.J. Gibbs, editor), Plenum Press, N.Y., 213-225 (1974).

(22) Zobell, C.E., In: Advances in Organic Geochemistry (E. Ingerson, editor) Macmillan, N.Y., (1964).

(23) Heath, G.R., In: Studies in Paleo-Oceanography, Spec. Publ. Soc. Econ. Paleont. Miner. Tulsa, 20, 77-93 (1974).

(24) Edmond, J.M. Deep-Sea Res. 21, 455-480 (1974).

(25) Berger, W.H. and Winterer, E.L., In: Pelagic Sediments: on Land and Under the Sea, (Hsü, K.J. and Jenkyns, H.C., editors), 11-48 (1974).

(26) Broecker, W.S., Li, H.-H. and Peng, T.-H, In: The Impingement of Man on the Oceans (D.W. Hood, editor) Wiley-Interscience N.Y. 287-324 (1971).

(27) MacKenzie, F.T. and Garrels, R.M. Amer. J. Sci, 264, 507-525 (1966).

(28) Scheidegger, K.F., Earth Planet. Sci. Letters, 17, 397-407 (1973).

(29) Froelich, R.N. Jr., Klinkhammer, G.P., Bender, M.L., Luedtke, N.A., Heath, G.R., Cullen, D., Dauphin, P., Hammond, D., Hartman, B. and Maynard, V. Geochim. Cosmochim. Acta. (in press).

(30) Manheim, F.T., Narragansett Marine Lab. Occas. Publ. No. 3, 217-276 (1965).

(31) Bender, M.L., Fanning, K.A., Froelich, P.N., Heath, G.R. and Maynard, V. Science 198, 604-609 (1977).

(32) Schink, D.R., Guinasso, N.L. and Fanning, K.A., J. Geophys. Res. 80, 3013-3031.

(33) Manheim, F.T., In: Chemical Oceanography (Riley, J.P. and Chester, R. editors) 115-186. Academic Press N.Y. and Lond. (1975).

(34) Garrels, R.M. and McKenzie, F.T. Evolution of Sedimentary Rocks, W.W. Norton and Co. N.Y., 397pp (1971).

(35) Grim, R.E., Clay Mineralogy, McGraw-Hill, N.Y. 384pp (1953).

(36) Sayles, F.L. and Mangelsdorf, P.C. Jr., Geochim. et. Cosmochim. Acta, 41, 951-960 (1977).

(37) Hower, J., Eslinger, E.V., Hower, M. and Perry, E.A. Geol. Soc. Amer. Bull., 87, 725-737 (1976).

(38) Calvert, S.E. Phil. Trans. Roy. Soc. London, A290, 43-73 (1978).

(39) Jenne, E., Adv. Chem. Ser. 73, 337-387 (1968).

(40) McCrone, A.W., J. Sedim. Petrol., 37, 475-486 (1967).

(41) Robinson, B.P., U.S. Geol. Survey Water-Supply Paper 1616 129pp (1962).

(42) Duursma, E.K., Oceanog. Marine Biol. Ann. Rev. 10, 137-223 (1972).

(43) Means, J.L., Crerar, D.A., Borcsik, M.P. and Fuguid, J.O., Nature, 274, 44-47 (1978).

(44) Bondietti, E.A., Reynolds, S.A. and Shanes, M.H., In: Transuranium Nuclides in the Environment, 273-287 IAEA Vienna (1976).

(45) Hetherington, J.A. and Jefferies, D.F., Neth. J. Sea. Res. 3, 319-338.

(46) Hetherington, J.A. In: Environmental Toxicity of Aquatic Radionuclides, 81-106, Ann Arbor Science, Ann Arbor, (1976).

(47) Hetherington, J.A. and Harvey, B.R., Mar. Pollut. Bull 9, 102-106 (1978).

(48) Pillai, K.C. and Mathew, E., In: Transuranium Nuclides in the Environment, 25-44, IAEA, Vienna, (1976).

(49) Livingston, H.D. and Bowen, V.T., In: Environmental Toxicity of Aquatic Radionuclides, 107-121, Ann Arbor Science, Ann Arbot, (1976).

(50) Koide, M., Griffin, J.J. and Goldberg, E.D., J. Geophys. Res. 80, 4153-4162 (1975).

(51) Volchok, H.L., Bowen, V.T., Folsom, T.R., Broecker, W.S. and Schuert, E.A., In: Radioactivity in the Marine Environment, 42-89, National Academy of Sciences, U.S.A. (1971).

(52) Bowen, V.T. In: Marine Chemical Aspects of Water and Air Pollution, IAPSO Symposium, Genoble, France, September 1975.

(53) Goldberg, E.D. and Bruland, K. In: The Sea, 5, 451-489, Wiley-Interscience, (1974).

(54) Altschuler, Z.S., Clarke, R.S. and Young, E.Y., U.S. Geol. Surv. Prof. Paper 314-D (1958).

(55) Ku, T.-L., Knauss, K.G. and Mathieu, G.G. Deep-Sea Res. 24, 1005-1017 (1977).

(56) Kolodny, Y. and Kaplan, I.R., Geochim. Cosmochim. Acta 34, 3-24 (1970).

(57) Kigoshi, K., Science 173, 47-48 (1971).

(58) Knauss, K.G., Ku, T.-L. and Moore, W.S., Earth Planet. Sci. Lett. 39, 253-249. (1978).

(59) Bernat, M., Bieri, R.H., Koide, M., Griffin, J.J. and Goldberg, E.D., Geochim Cosmochim. Acta 34, 1053-1071 (1971).

(60) Bernat, M. and Allegre, C.J., Earth Planet. Sci. Lett. 21, 310-314 (1974).

(61) Antal, P.S., Limnol. Oceanog. 11, 278-292 (1966).

(62) Li, Y.H., Ku, T.-L. and Mathieu, G.G., Earth Planet Sci. Lett. 19, 352-358 (1973).

(63) Broecker, W.S , Li, Y.H. and Cromwell, J., Science 158, 1307-1210 (1967).

(64) Symp. on Management of Radioactive Wastes from the Nuclear Fuel Cycle (IAEA and NEA (OECD)), Vienna (1976).

(65) Morris, J.B., Boult, K.A., Dalton, J.T., Delve, M.H., Gayler, R., Herring, L., Hough, A. and Marples, J.A.C., Nature 273, 215-216 (1978).

(66) Lewis, J.B. Atom (255), 8-15 (1978) and Taylor, R.F.(personal communication) (June 1978).

(67) McCarthy, G.J., White, W.B., Roy, R., Scheetz, B.E., Komarneni, S., Smith, D.K. and Roy, D.M. Nature, 273, 216-217 (1978).

(68) Nature, 274, 413 (1978).

(69) The Oklo Phenomenon. Proc. Symposium Libreville, Gabon (IAEA, Vienna) 646 pp. (1978).

(70) Seabed Disposal Program, Annual Report, Parts I and II, Jan-Dec 1976, ERDA, Sandia Laboratories, Albuquerque, New Mexico. (1977).

(71) Bischoff, J.L. and Dickson, F.W. Earth Planet. Sci. Lett., 25, 385-397 (1975).

(72) Lerman, A. The Sea: ideas and observations. 6, (E.D. Goldberg editor) 695-738. John Wiley & Sons New York (1977).

Chapter 3

HIGH LEVEL RADIOACTIVE WASTE DISPOSAL IN THE DEEP OCEAN

PROBLEMS OF DISPERSION - PHYSICAL OCEANOGRAPHY

INDEX

SUMMARY

This chapter provides information on the present state of knowledge of the physical processes which cause diffusion of material in solute form from the deep-sea floor, and identifies those areas of research where more work is needed before the safety of disposal on or in the ocean bed can be assessed.

Section 1 emphasises the inadequacy of gross diffusion coefficients in parameterizing the mixing. It is suggested that understanding of possible pathways requires an appreciation of the specific physical processes operating in different parts of the ocean.

Section 2-5 summarise our present understanding of and observational evidence for the operation of specific physical processes in the layer immediately adjacent to the sea floor, in the interior of the deep ocean and at the continental slope. Observations, though sparse, serve to illustrate the spatial and temporal variability.

The importance of the world wide developing interest in the modelling of future climate is emphasised in relation to the long term fate of radioactive waste.

After identification in Section 7 of a number of related but largely unconnected existing programmes it is suggested in Section 8 that due to variability a sustained programme will be required to ensure adequate understanding.

Specifically, in the benthic boundary layer, measurements are needed of heat flux, shear stress and variability of thermal structure. In the deep ocean the existing

knowledge of large scale variability of currents is inadequate to support a programme of waste disposal which relies to any extent on dispersion in the water and a programme of float tracking is proposed.

Numerical models of circulation incorporating the results of field investigations need development to permit them to be adequate for predictive use in site specific studies. The application of the newly developed models of climatic change to studies of long term and large scale variability is recognised.

1. INTRODUCTION

1.1 The objective of this chapter is to describe what is known of the turbulence or of the physical processes leading to dispersal which operate in those parts of the deep ocean into which radio-active waste may be introduced directly by a release from or on the sea floor, or in those parts to which it may subsequently be carried; to state briefly what is at present known and what yet needs to be known if sound estimates are to be made of the possible concentration levels in sensitive parts of the ocean following dumping in, or on, the sea floor. It will be clear from the account which follows that too little is known of the dynamics of the deep ocean to predict with any confidence the route along which radio-active nuclides might be carried once released into the ocean water. More research is needed before the hazards can be assessed. Recommendations on the nature of this research are made in Section 8.

1.2 When a solute is introduced into a large body of water, it is carried, or advected, by the ocean current and spread, or diffused, by the eddying, turbulent motion. In engineering applications, it is usual to describe the effect of the ensemble of mechanisms which cause diffusion by an 'eddy' diffusion coefficient, which may be a function of position and time. The fluid is regarded as a turbulent medium and the dynamics of the individual mechanisms or processes which operate to diffuse the solute are largely ignored, their net action being blanketed in the choice of the coefficient.

The use of gross diffusion coefficients to estimate mean concentrations is, however, only appropriate once the diffusing property has spread to such a size that it exceeds the scales of variation, the turbulent eddies, leading to diffusion. Even in simple flows the errors involved in ignoring this condition are considerable. It is for example inappropriate to use a coefficient describing one-dimensional longitudinal spreading in a flow through a circular pipe until the diffusing material introduced at some point in the pipe cross section and at some position along the pipe has diffused right across the cross section. Such diffusion takes an unexpectedly long time. It is equally inappropriate to use some mean coefficient describing the vertical diffusion to calculate mean concentrations occurring at levels above a point source on the floor of the deep ocean until the diffused solute has spread to cover the ocean floor, and is thus affected by all the components contributing to the calculation of the vertical diffusion coefficient. It will be apparent in later sections that the time for such mixing is so great as to make the use of such a coefficient for releases from small areas invalid if realistic estimates of concentration in particular sensitive areas in the ocean are to be obtained. Indeed the use of a gross coefficient may well lead to results which have no relevance to reality. Instead a model is appropriate which accounts for the physical diffusive processes in limited parts of the ocean where eddy coefficients may be estimated and correctly applied, for example in the benthic boundary layer. We shall therefore discuss diffusion, and the physical processes of diffusion (for we must know their scale in our estimates to ensure the size of the diffusing 'cloud' is greater) in parts of the ocean, rather than treating the ocean as a whole.

The greatest hazard will probably result from an extreme concentration occurring for a relatively short period in a certain locality and not as a result of the mean concentration at some place in the ocean reaching a critical value. The study is thus concerned with the probability of high concentrations and the statistics of extreme values. These may again be more readily estimated through a knowledge of the efficiency and probability of individual processes which, perhaps, acting together, may result in a rapid (relative to the mean rates) spread from a point of release to a region in which the presence of the solute is dangerous. It is however certain that present knowledge of large scale ocean circulation and turbulence is not yet sufficiently developed to allow the prediction of these potential extreme values.

1.3 The emphasis on physical processes is intentionally suggestive of a 'pathways' approach, a certain process being efficient in transferring solute from one part of the ocean to another. The processes operate on different time and space scales; the pathways are of corresponding scales. The ocean is throughout its depth a turbulent medium characterised by 'events', resulting from the operation of the physical processes, which are intermittent and intense for short periods of time and in small volumes. The most energetic events, or those which lead to the most rapid diffusion or advection, may be rare but, even when average conditions are considered, may dominate the longer lasting 'background noise'. In view of the long half-lives of some of the potential radio-active wastes, even climatic changes which may change the circulation pattern of the ocean must be considered to be of importance.

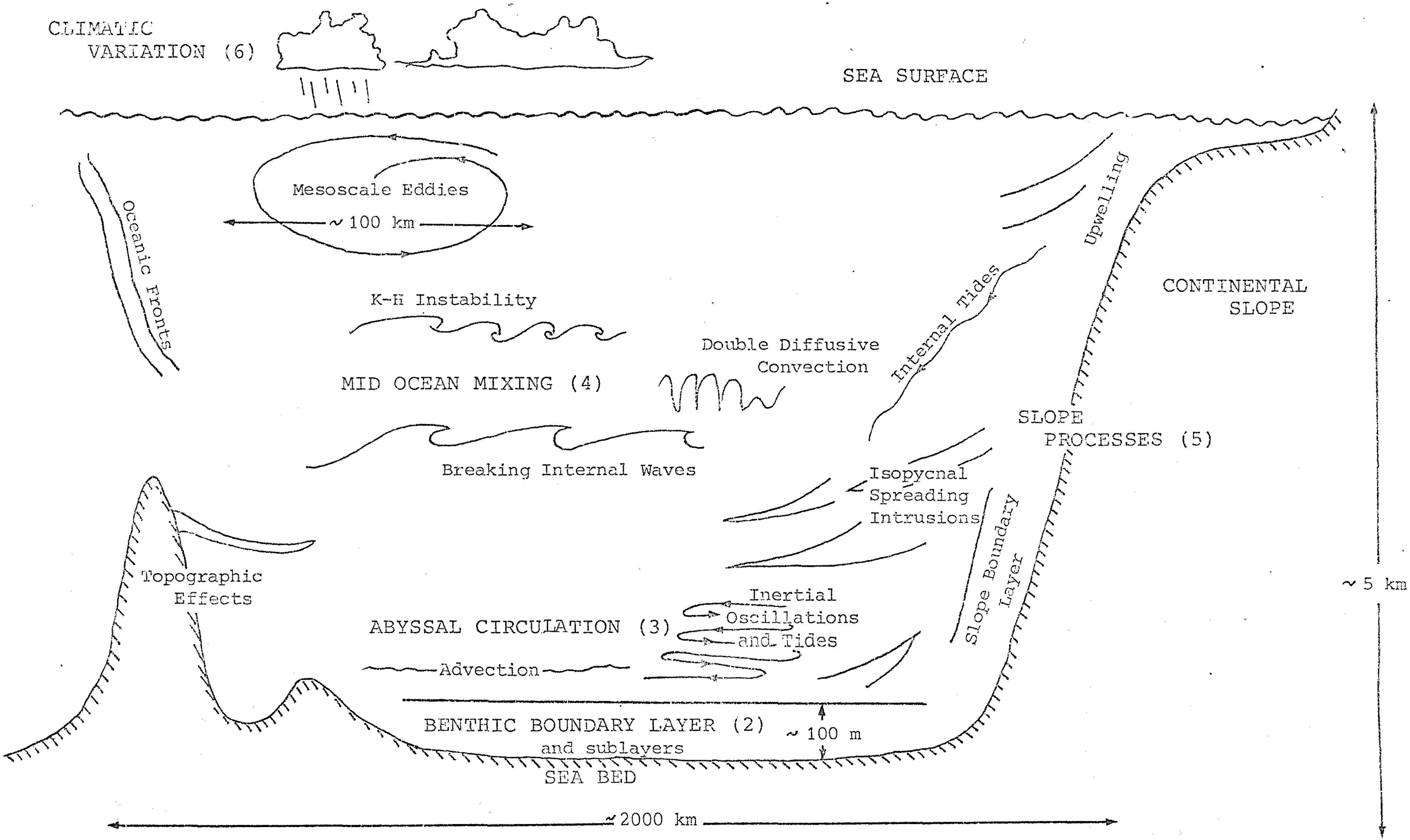


Fig. 1. Overview. Diagram showing the processes of dispersion in the ocean. The scale is grossly exaggerated. Figures in brackets indicate the sections in which processes are

1.4 Figure 1 is a diagram intended to illustrate some of the features and processes which may effect dispersion from the sea floor. The diagram serves as an introduction to the chapters of the report which follow, dealing with our present knowledge of diffusion and advection in the benthic boundary layer, mid-water and around the continental slopes and islands.

1.5 For the purpose of this review it is supposed that the radio-active wastes or dangerous derivatives are released into the sea water in the form of a neutral or passive solute and spread as such. In practice they may diffuse in like manner, or be carried in association with mineral particles lifted (perhaps temporarily) from the sea bed or, near the source, be carried from the sea bed in a thermal plume arising from the decay of the wastes themselves. The mechanism of entry of the radio-active nuclides into the sea water is not discussed in this Chapter, (but see Chapter 2), nor is their eventual passage to man. These aspects, vital to the understanding of the dangers inherent in radio-active waste disposal, are more comprehensively discussed in other chapters of this report.

1.6 Much research has already been carried out on atmospheric diffusion and where appropriate (for example in the benthic boundary layer) results will be applicable to oceanic diffusion. Pasquill's reviews (1 and 2) are valuable sources of details and further references and illustrate the difficulties of accurate prediction of pollution in the natural environment.

1.7. Where possible we shall give examples of measurements which have been made of the various processes in the ocean. These are usually chosen with the North Atlantic in mind but in many cases the best, sometimes only, measurements are from other parts of the ocean. Some topics will be but briefly mentioned, being more appropriate to the chapters in other disciplines. One of these is pore water contained in upper layers of sediment which, being party to the exchange in the regions immediately above and below the sea floor, is intimately involved in the process of transfer of solute from the sediment into the water of the benthic boundary layer (see Chapter 2). We have also omitted discussion of the eventual diffusion of matter to the sea surface itself, being content to confine attention to diffusion in the deep ocean. Diffusion through the thermally stratified ocean layers, the main and seasonal thermoclines, to the surface may be inhibited by the large vertical density gradients, although the concentration of current shear at these levels and consequent reduction in stability, measured by a parameter called the Richardson number, makes this uncertain (see 4.6). No thermocline is, however, present in the Arctic regions (3.6) where vertical exchange is known to be considerable. Once past the seasonal thermocline diffusion to the surface is likely to be very rapid in the near-surface mixing layer anywhere in the ocean.

1.8 The number of recent publications included in the references indicates the vitality of studies in this field and the rapid rate of development (and sometimes change) in our understanding of the important physical processes.

2. THE BENTHIC BOUNDARY LAYER

2.1 Solute released from a source on the deep ocean floor (or, via processes in the sediment, into the sea water from a source buried in the sediment) enters a layer of water which differs in character from the water at higher levels, because of the proximity of the sea bed. This layer is generally called the benthic boundary layer. It is thought to be similar in some respects to the atmospheric boundary layer (the atmosphere immediately above the Earth) but as yet few measurements have been made of its detailed properties, and its mean structure is unknown. It is, however, natural to suppose that diffusion of solute in this layer will be similar to that occurring in the 'near field' of a near-neutral atmosphere from a ground source. It is in this layer that the largest concentrations may be found (unless some biological process is found which may concentrate the waste products later in its diffusion path) and where contamination of local sediment and marine life is most direct.

2.2 Structure of the benthic boundary layer

The boundary layer is conceptually composed of several layers in which different physical balance are important. These layers are summarised in Appendix 1; the structure of the lowest layers is comprehensively reviewed by Wimbush and Munk (3). A velocity boundary layer transfers the stress from the ocean floor to the overlying fluid whilst thermal layers accomodate the geothermal heat flux, about

10^{-6} cals. cm^{-2}. s^{-1} , and perhaps a heat flux produced by radio-active waste. Above and in the upper layers of the benthic boundary layer structure, the temperature gradient is often near the adiabatic lapse rate of about 10^{-6} deg C. cm^{-1} , temperature increasing with depth. The friction velocity, $u_* = \sqrt{\tau/\rho}$, is an essential quantity in determining the structure and properties of the layer. Turbulence in the boundary layer will arise predominently from shear if

$$u_* > K_v \left(\frac{g a H}{c_p \rho f} \right)^{1/2} \qquad (\,)$$

(see Appendix 3 for notation) which will almost always be the case in the natural benthic boundary layer where u_* is typically about 0.1 cm s^{-1}.

There are, at present three methods for measuring u_* and these are described in Appendix 2, together with the methods available for determining the heat flux, H.

Sediment will be moved if the currents are sufficiently large. There is a considerable body of work on this topic, aimed at predicting the critical speed at a certain height, usually 1m, above the sea bed at which grains of a certain size, comprising the sediment, will first be brought into motion. For non-cohesive sediments the best estimate of this threshold speed, u_{100}, appears to be through the 'Shields curve' relating the stress $\tau = \rho u_*^2$ on the sea bed to the Reynolds number $u_* D/\nu$, where D is the diameter of the bed grains. Figure 2 shows a Shields curve (4) incorporating recent data. This has been translated into a curve relating u_* or u_{100} against grain diameter (5), figure 3,

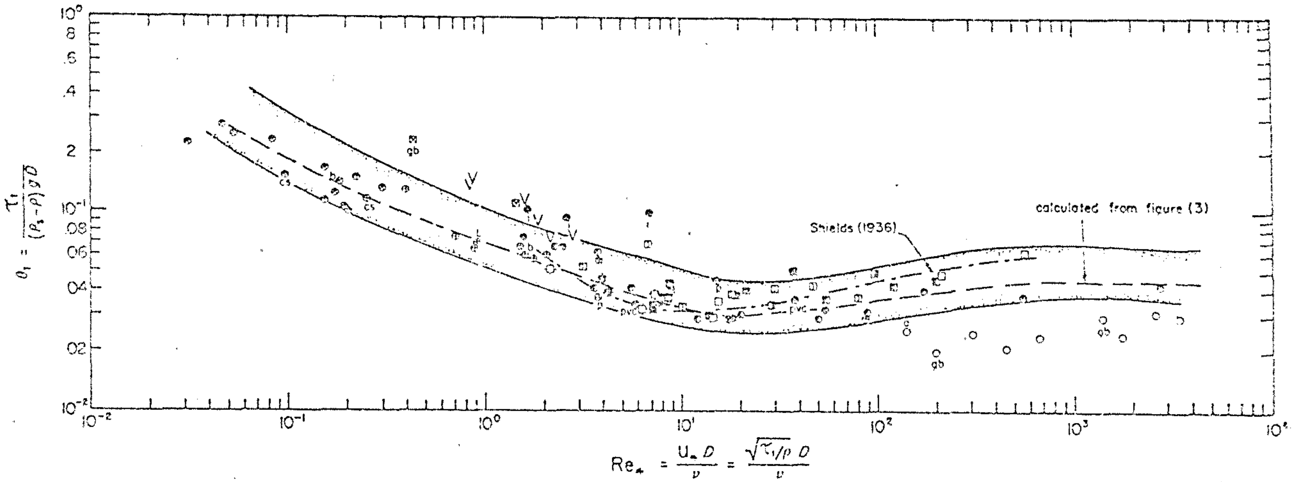


Fig. 2. Shields curve (4) showing the variation of θ_1 at the onset of sediment motion with Re_*, where $\theta_1 = \tau/gD(\rho_s-\rho)$ (τ is the stress, $\tau = \rho u_*^2$; ρ_s is the sediment density; ρ is the water density, D is the sediment particle size) and Re_* is the Reynolds number based on u_*, D and ν, the kinematic viscosity of the water. The shaded area envelopes most of the data points.

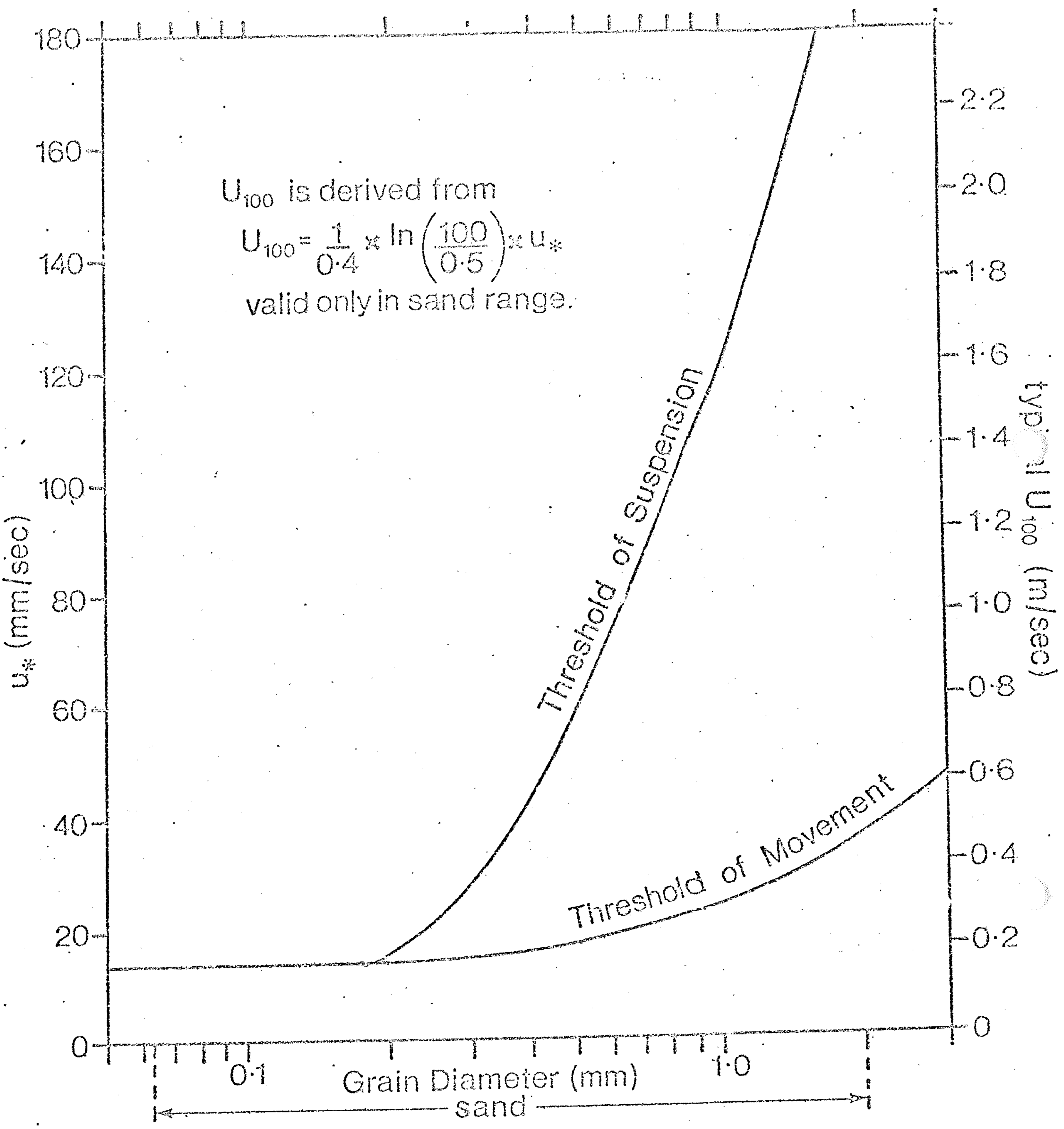


Fig. 3. The variation of u_* (or u_{100}) needed for threshold movement of sediment with grain diameter D (from 5) - see text for explanation.

using values of density and viscosity appropriate to sea water and sand grains, and relating u_* to u_{100} using the logarithmic profile A(1) for a neutral flow with $z_0 = 0.5$ cm, typical of a rippled bed. (There is some inconsistency in this derivation since the Shields curve is strictly valid for a flat bed, being derived empirically in laboratory experiments, and the conclusions are as yet untested in the ocean).

It is found in experiments in shallow water that the particle concentration and integrated transport are highly sensitive to changes in u_*, once the critical threshold speed is sufficiently exceeded, (a factor of about two appears sufficient). It is found that the concentration of particles of size 180 µm measured at a height of 10 cm above the bed, varied as $u_*^{4.66}$ and inferred that the integrated transport would vary approximately as u_*^7.

It is however likely that, should the option of disposal below the sea bed be taken, an area covered by fine grain, and therefore possibly cohesive, sediments would be chosen, since their mechanical and chemical properties are more likely to prevent the subsequent escape of wastes. (If this option were chosen knowledge of the dynamics of the boundary layer may none the less be important in case of accidental discharge during the injection of waste, or to establish the stability of the sediment to erosion). We know of no theoretical understanding which would enable us to predict with confidence the onset of motion of a cohesive sediment on the deep ocean floor.

2.3 Observations in the benthic boundary layer.

2.3.1 Near bottom observations.

Wimbush and Munk (3), report observations of current and temperature measured within 3.5 m of the sea bed in a fairly level and dynamically smooth area off California where the water depth was about 4000 m. Horizontal currents were measured at several levels using a heated thermometer device (6) and this was supplemented by a dye injecting system together with a camera (7) which provide an independent measure of current and an idea of the scales of bottom roughness. The current record was dominated by the semi-diurnal tides, with a maximum amplitude of about 4 cms^{-1}.

Methods B and C (Appendix 2) were used to determine u_*. These estimates differed somewhat, 0.14 and 0.09 cms^{-1}, in the one case quoted. Estimates of u_* using method B (2.2) ranged between 0.02 and 0.2 cms^{-1} during the tidal cycle. The logarithmic layer extended up to slightly more than 1m, thus giving maximum value of K_M of about 8 cm^2s^{-1}. The mean veering of the current (in the Ekman spiral sense) between observations over three days at 40 cm and 320 cm above the sea bed was 3^o, as compared with an estimated $\psi_o = 13^o$. The small value observed was probably the result of unsteady flow (3, section 6).

The temperatures were measured by quartz crystal sensors (8). Variations of about 2 milli-degrees were recorded. The observed gradients were 1.3Γ which agreed well with theoretical predictions based on equation A3, with an assumed 'global' average value of H. Estimates of the heat flux, using method C (Appendix 2) were in good accord with the heat flow measured by the direct method/in the same area (see also 9) although limited by the slow (1 min) sampling rate.

There was no evidence in the observations that the sediment was disturbed by the currents which were always smaller than those expected to be necessary to initiate sediment motion.

There are numerous observations of turbulence near the sea bed in shallow waters (10, 11, 12; see also 7.1.3) but those of Wimbush and Munk's appear to be the only detailed observations in deep water other than some short term measurements on the continental slope in the Gulf of Cadiz (13). Accurate temperature observations are also scarce. Brown et al (14), however report variations of as much as 40 milli-degrees C in the MODE area SW of Bermuda, much greater than those found in the Pacific, and thought to be related to the presence of Antarctic Bottom Water.

2.3.2 Observations of large scale structure of the benthic boundary layer.

The overall structure of the boundary layer is now known to vary considerably both in position and in time. The first indications that this might be so, came from observations of turbidity and the study of the nephloid layers. A recent survey paper (15), describe observations made in the North Atlantic; (see also Chapter 1). These are sparse in some areas (figure 4) but in general there is an increase in turbidity as the ocean floor is approached. This is undoubtedly sometimes the result of matter being advected into an area from a distant source, but in some areas of relatively large currents there is local re-suspension of material from the sea floor.

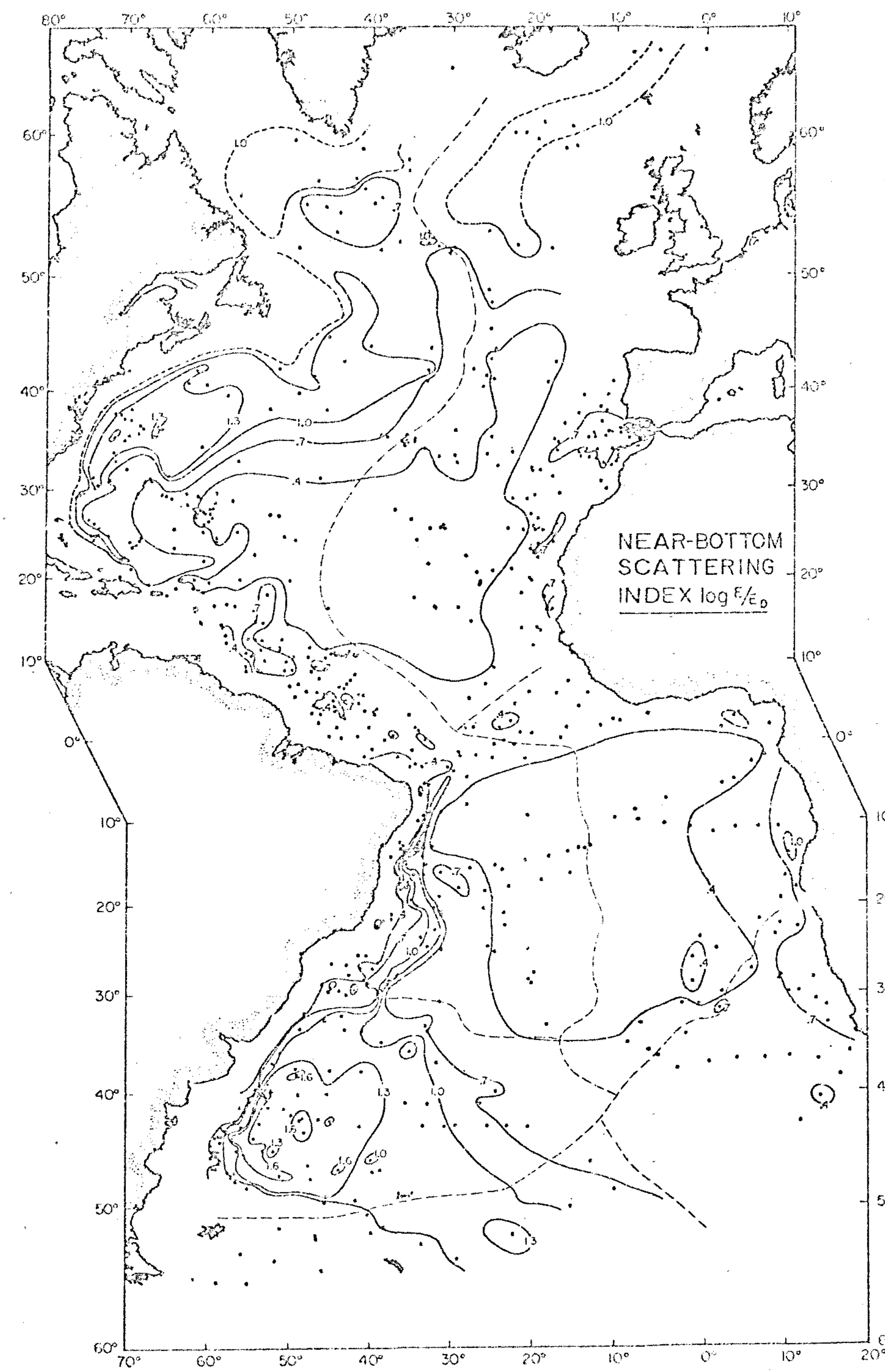


Fig. 4. The turbidity near the sea floor in the Atlantic Ocean (from 15). Observations have been made at the positions marked by dots. The turbidity is generally higher near the Western Boundaries and in the Mediterranean Outflow in the Gulf of Cadiz.

Careful observations of the temperature and salinity structure, show that the lowest 50 - 100 m are sometimes uniform in properties, well mixed, with an adiabatic temperature gradient, the uniform layer frequently being capped by a sharp change in properties (see figure 5a). This structure strongly suggests that in some areas turbulence generated mechanically, or perhaps by convection, at the sea floor is sometimes sufficient to mix the water column up to 100 m or more above the sea bed, although the nepheloid layer is found to be up to 1 Km thick in some areas. The thermal structure is highly variable (e.g. see figure 5b). A series of 130 CTD profiles at 5 min intervals some 30 m apart in a water depth of 5230 m on the Hatteras Plain (17) showed 20% variations in the thickness of the uniform layer (mean thickness 50 m) in periods as short as 40 mins, sometimes accompanied by an increase in the potential temperature of the layer.

Perhaps the most useful work on the benthic boundary layer diffusion has come from the GEOSECS programme and studies, particularly at the Lamont-Doherty Geological Observatory in the U.S.A, of Ra-228 and R_n-222 profiles in the abyssal water column. The Ra-228 and R_n-222 found in the deep sea originate from the sediments. Their half-lives are 6 years and 0.01 years respectively and, there being no known sinks of any significance in the deep ocean, their concentration profiles are a function only of the flux from the sediments, diffusive and advective transport, and radioactive decay. The profiles may thus be used to estimate vertical diffusion (18,19). Figure 6 shows (in the numbers in parenthesis) values of vertical eddy diffusion coefficient estimated from the R_n-222 profile. The coefficient appears to be

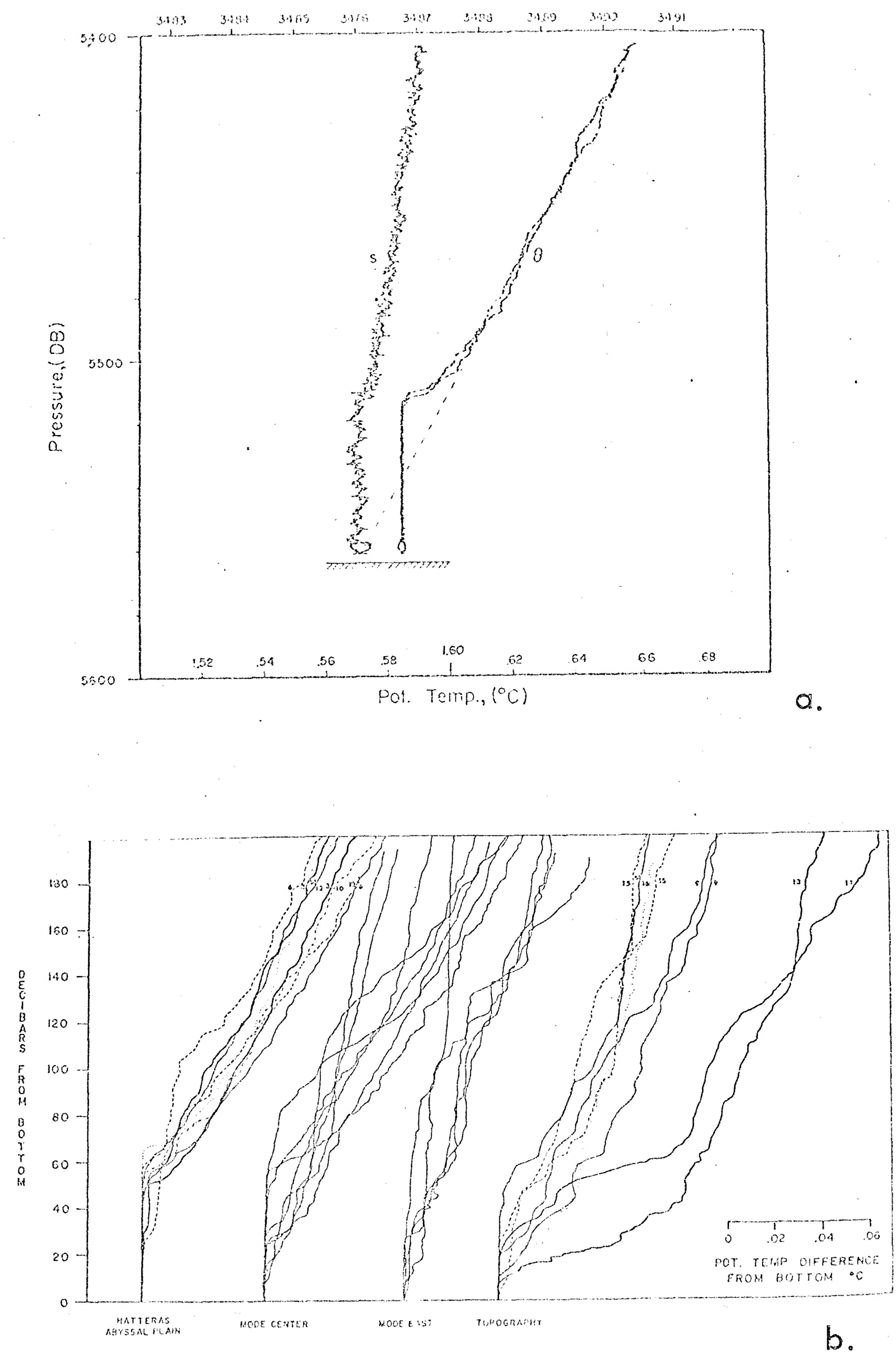


Fig. 5. Profiles near the sea floor (from 16).

(a) Salinity, S , and potential temperature, θ

(b) The variability of profiles of θ in different areas.

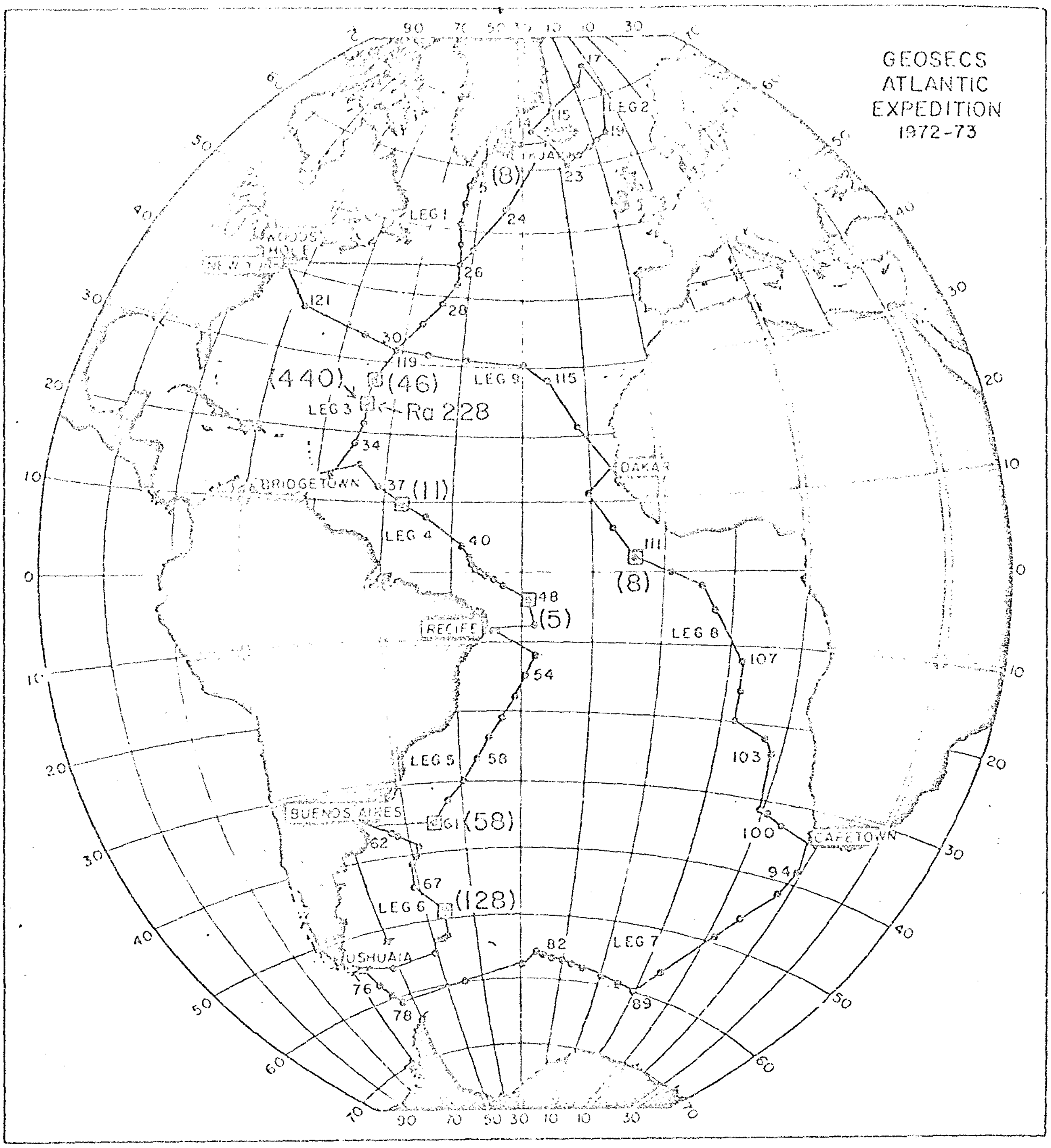


Fig. 6. Estimates (in parentheses) of the vertical eddy diffusion in the lower few hundred metres of the water column using R_n-222 profiles. Units are $cm.^2\ s^{-1}$ (from 19).

inversely proportional to the local buoyancy gradient (i.e. $\sim N^{-2}$). A good correlation is found between the structure of the R_n-222 and Ra-228 profiles and that of the potential temperature (19,20).

It is not yet known what determines the thickness of the benthic layer. If the upper mixing layer of the ocean or the atmospheric boundary layer can be used as analogies, the layer depth will be time-dependent and possibly proportioned to a scale determined by the shear stress and heat flux, the Monin Obukov length scale. It is however, dangerous at this stage to hypothesise since the cause of the structure is as yet unknown. The cause might sometimes, for example, be the breaking of internal gravity waves generated near the ocean surface or locally generated breaking waves (21, 22, see 3.2), in which case the scale imposed by waves (e.g. their vertical wave length) would be appropriate. There is, as yet, no set of observations which can explain the variability of the benthic structure, or which can be used to estimate the rate at which diffusion occurs across its upper boundary.

The variability of the thermal structure of the boundary layer is, in this context, important for two reasons. There is first a clear possibility that layers with uniform properties may be associated with rapid vertical and horizontal diffusion from the sea bed, and this requires further study. There is secondly the question of the fate of water which has become vertically mixed. The collapse and spread of a mixed patch along a constant density (isopycnal) surface will result in water becoming separated from the sea bed, (see figure 7), yet marked with the properties which it attained in its mixed state, and cause steps in the profiles of salinity, temperature, and light scattering corresponding to the

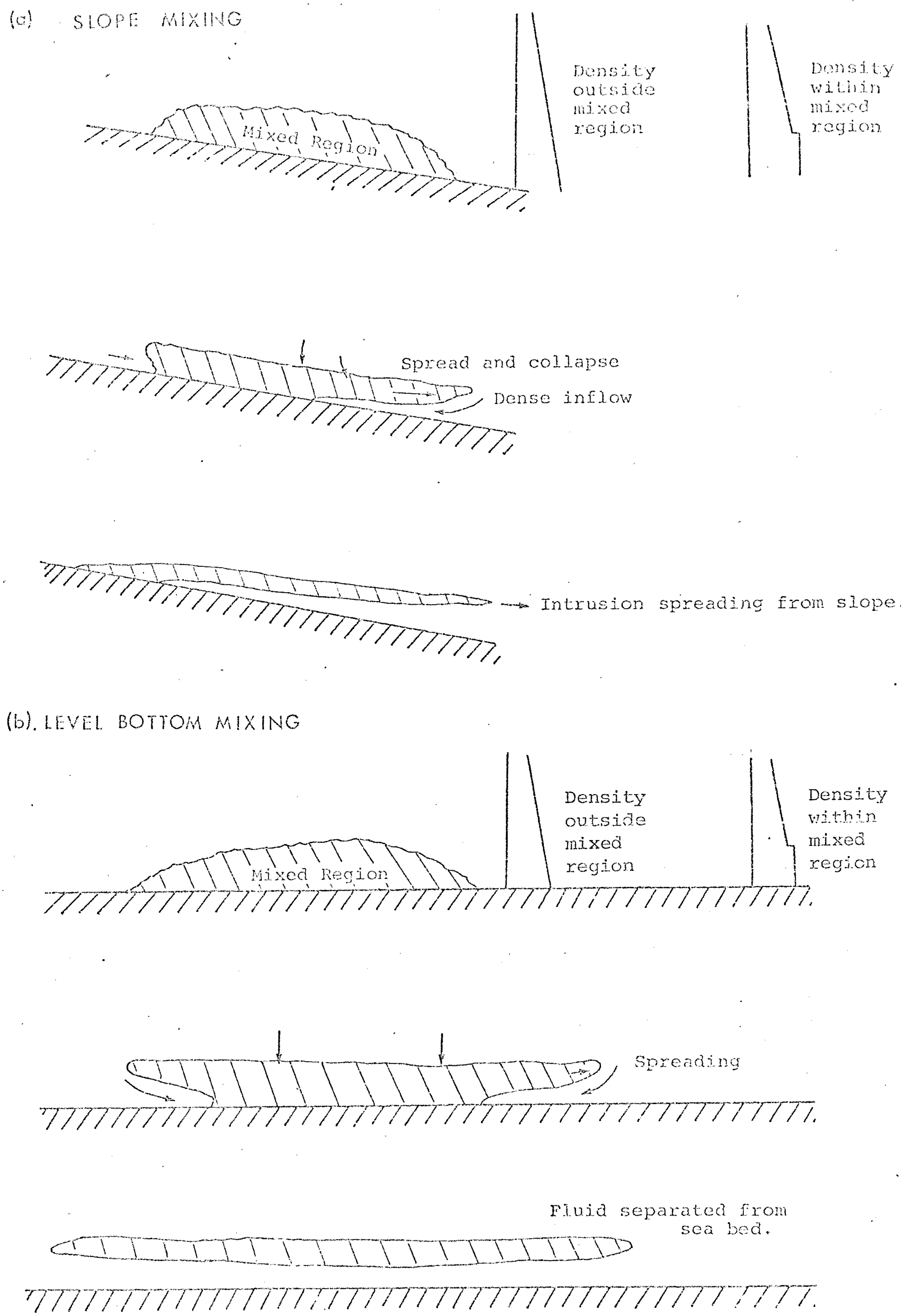


Fig. 7. The spread of a region mixed near the sea floor. (a) on a slope, (b) over a level (i.e. parallel to mean isopycnal surfaces) bottom.

intensive spreading layers - see figure 8. Such 'intrusions' will be discussed later (Section 5).

2.4 The description of the structure of the benthic boundary layer ignores the sublayers which might develop as the result of double diffusive processes (24, and Section 4) following release of the solute through, or on, the sea floor. These processes occur in the presence of two diffusing components (e.g. Salt and heat) when their molecular diffusivities are unequal. It should be noted that even if the rate of solute release were so great that the net resulting stable (heavy) buoyancy flux exceeded the destabilizing buoyancy flux due to heat released by the wastes and the geothermal heat flux together, the effect of double diffusive convection might be to spread the solute vertically (as well as horizontally). In view of the importance of double diffusive effects in other parts of the ocean, their effect in benthic layers should not be disregarded.

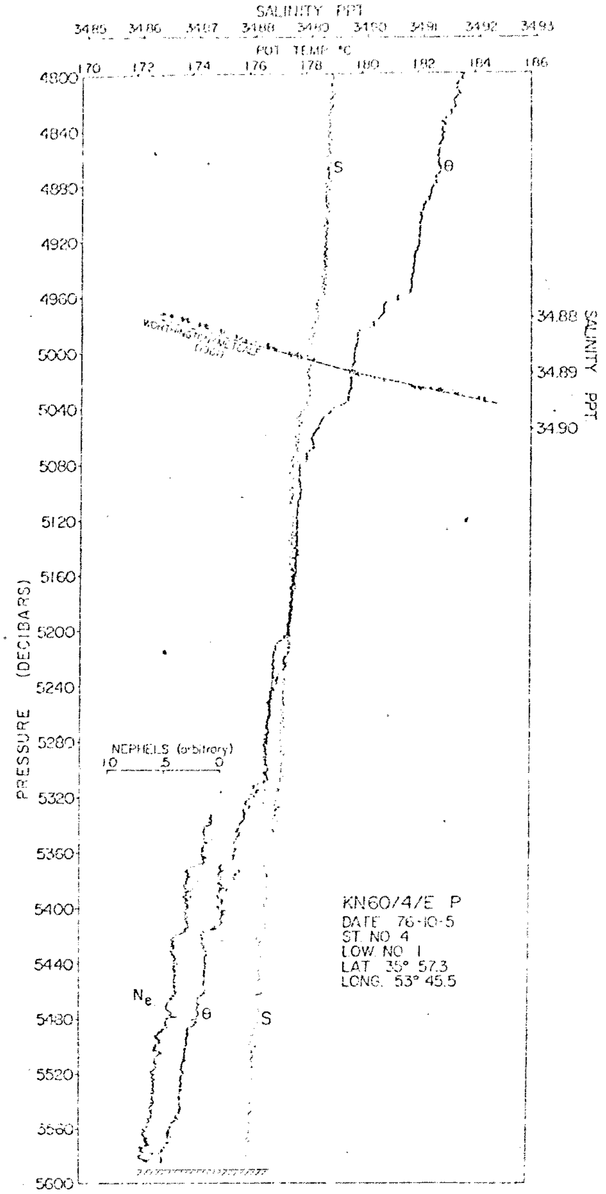


Fig. 8. Profile showing layers defined by their temperature θ, salinity S and nephel N_e content above the sea bed (from 23).

3. ABYSSAL CURRENTS AND CIRCULATION

3.1 Dispersion of material or solute in a plume from a source on the sea bed is, of course, primarily through advection by the mean current and, since the structure of the lower boundary layers is similar, will follow the pattern of short range diffusion already studied in some detail in the atmosphere (1,2). For example, the formula relating the height $\bar{z}$ of the diffused plume to the distance $\bar{x}$ from the source in the logarithmic layer in neutral conditions

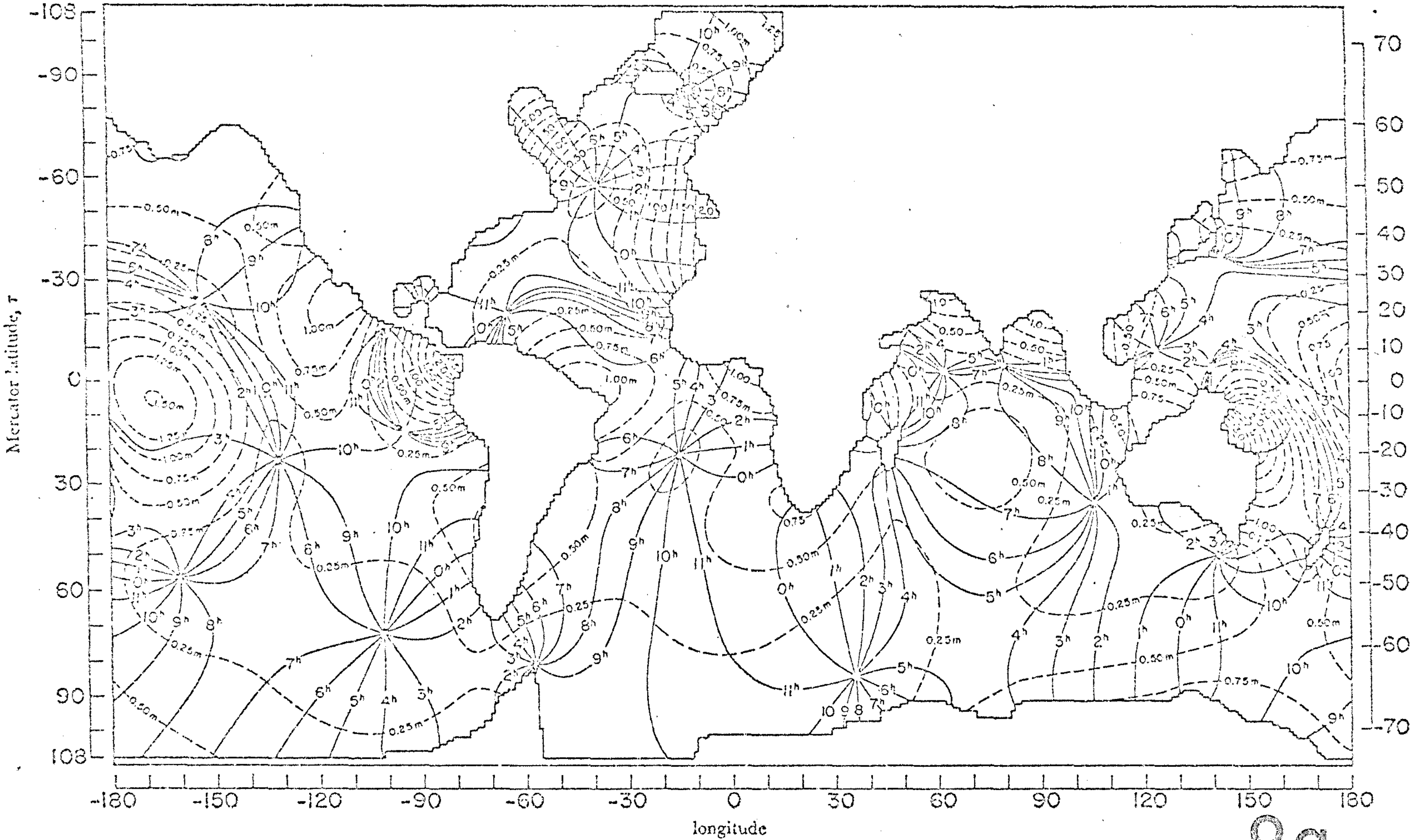
$$\bar{x} = 6.25\,\bar{z}\left[\log \bar{z}/z_0 - 1 + z_0/\bar{z}\right], \text{ (see 2)}, \qquad (2)$$

emphasises the importance of estimates of z_0, the roughness length. It is beyond the scope of this report to discuss in detail the analogies which may be found. These may, however, be used to some advantage, since it is clear that observations made with the same intensity as those which have been made in the atmospheric boundary layer are never likely to be possible in the benthic boundary layer. It is salutary to recognise the considerable problem in sampling even in the atmosphere and to recognise the serious errors possible in estimating atmospheric pollution levels even near the source due to variations in the turbulence and mean properties of the air (1, table 4).

The analogies are limited, because of the highly time-dependent stability of the atmosphere, and the oceanic tides.

3.2 The tides.

As mentioned in 2.3.1 the dominant short-term variability in the benthic boundary layer arises from tidal motions. Figure 9a shows the computed M_2 tidal chart for the world's ocean. In the North Atlantic there are three amphidomic points. The magnitude of the tidal currents is of the order of 5 $cm.s^{-1}$. (figure 9b), corresponding to an oscillatory motion of about 1 km acting in a barotropic mode (i.e. throughout the water depth). This motion will advect water in the upper part of the benthic



Cotidal lines (——) and corange lines (metres) (– – –) for the M_2 tide.

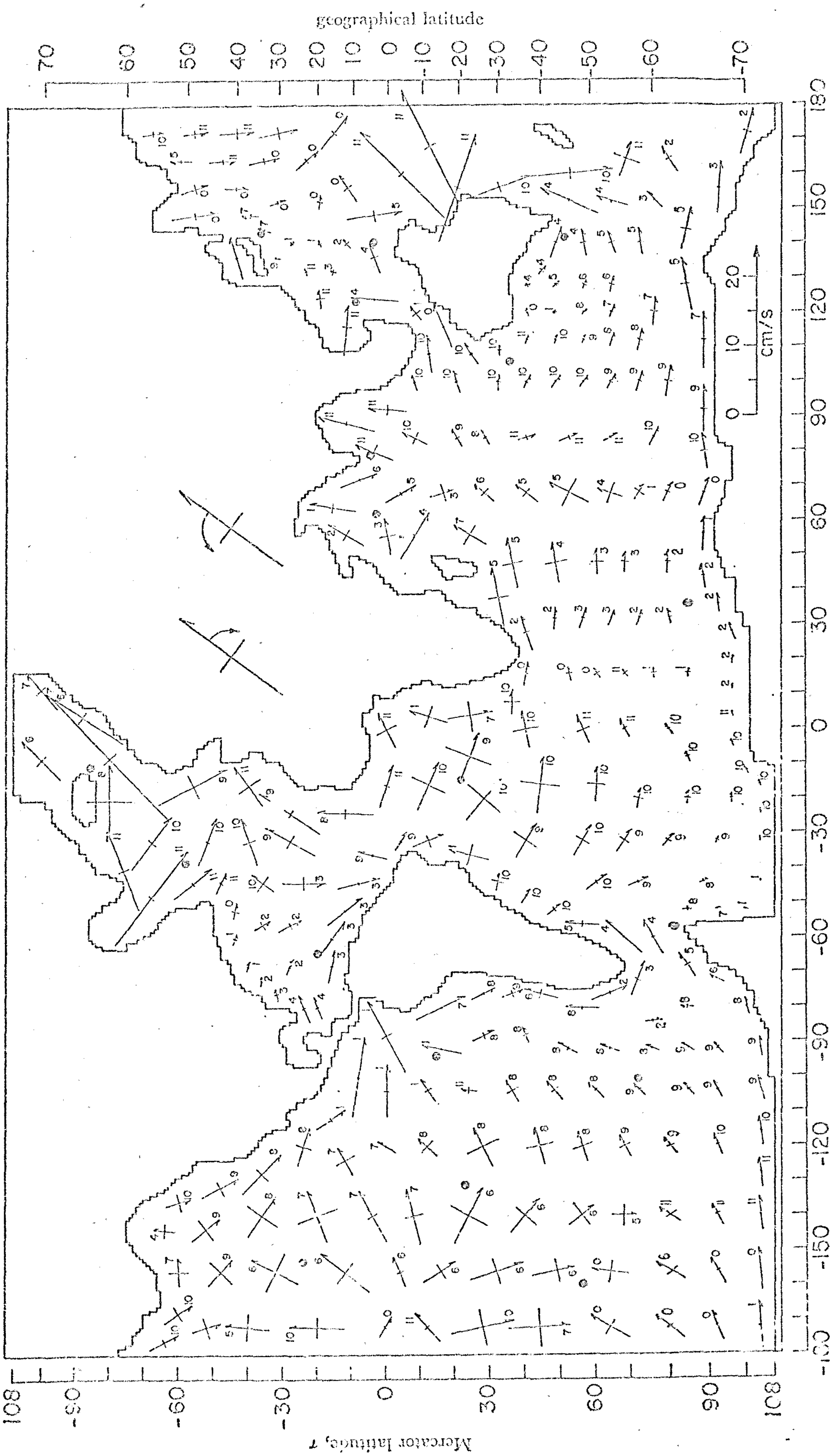
9.a

Fig. 9. The M_2 Tides (from 25).

(a) cotidal and corange lines,

(b) the velocity field.

For details of perimeters and assumptions of the model, refer to the original paper.


geographical latitude
70 60 50 40 30 20 10 0 -10 -20 -30 -40 -50 -60 -70
longitude
180 150 120 90 60 30 0 -30 -60 -90 -120 -150 -180
Mercator latitude, r
108 -90 -60 -30 0 30 60 90 108
0 10 20
cm/s

9.b

boundary layer and serve to disperse material released from the sea bed directly over a comparable distance, some returning back to the sea bed on one tidal cycle, to be spread yet further on subsequent tides. The presence of an oscillatory tidal flow is important in producing enhanced diffusion (26), in the boundary layer itself. Over regions of rough topography it may also generate internal tidal waves which may promote mixing (21,22).

3.3 Inertial oscillations.

These are frequently present in current meter records, often occuring intermittently, perhaps in consequence of their occasional generation at the sea surface by a passing storm (27) and downward radiation through the water column. Drop-sonde records (28) also contain clear evidence of inertial oscillations with a vertical scale of a few hundred metres, and their presence has been reported in the benthic boundary layer (29), where they will produce periodic horizontal advection and effects similar to those of the tides.

3.4 Mesoscale Eddies.

Evidence that the deep ocean is active, rather than almost stagnant, came first from observations by Crease and Swallow (30) who found currents of 5-10 $cm.s^{-1}$ with complete changes in direction over a period of a month or so. The currents are now understood to be caused by large waves or eddies, although much yet needs to be clarified about their dynamics. They are features of some 100 Km scale moving usually westward at a few centimetres per second, and hence have a period of about 100 days. The largest contribution to the variance of temperature measured at a point in the ocean occurs within the frequency band of these eddies (31). No study has yet been made of their effect on the benthic boundary layer.

A comprehensive mid-ocean dynamics experiment (MODE) was made in an area SW of Bermuda in 1973 to examine the eddies. Figure 10 shows the current streamlines at 3000m on six, non-successive days. (These streamlines were constructed from hydrographic data, from which geostrophic currents were estimated, and the currents measured by tracking, neutrally buoyant floats in the SOFAR channel at 1500 m). The non-stationery pattern of eddies is apparent in the figure.

The trajectories of neutrally buoyant floats tracked during MODE by IOS (figure 11) demonstrate further the variability and strength of the currents in the deep ocean. No clear pattern of diffusion can be detected in these short tracks. The floats A, B and C at 3000 m, figure 11a, delineate a triangle (figure 11c) whose area increases after 12th April, at a rate roughly proportional to time and corresponding to a horizontal diffusion coefficient of about 2.10^6 $cm^2. s^{-1}$. This value is fairly typical of mid-ocean, although smaller than the classical estimates of $(1-4) \times 10^8$ $cm^2. s^{-1}$ for the whole ocean (33). Figure 11d shows successive distortion of a quadrilateral of floats at 4000 m. A patch of marked water would soon become highly distorted in the flow field. A far more comprehensive study of floats in the SOFAR

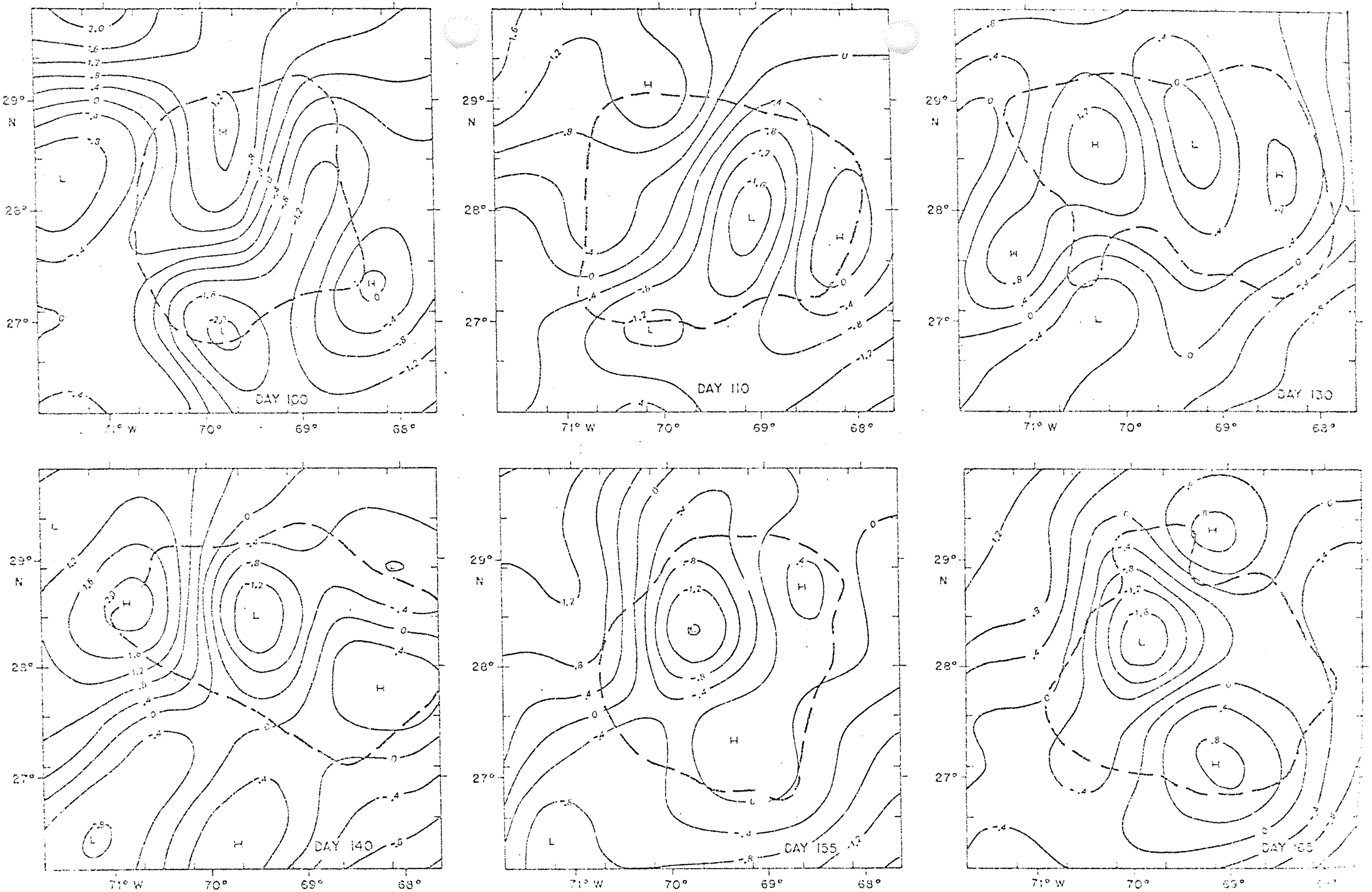


Fig. 10. Streamlines at 3000 m reconstructed from the MODE experiment. The day number is shown on each figure. From Atlas of mid-ocean dynamics experiment (MODE-1) by the MODE-1 Atlas group, 1977.

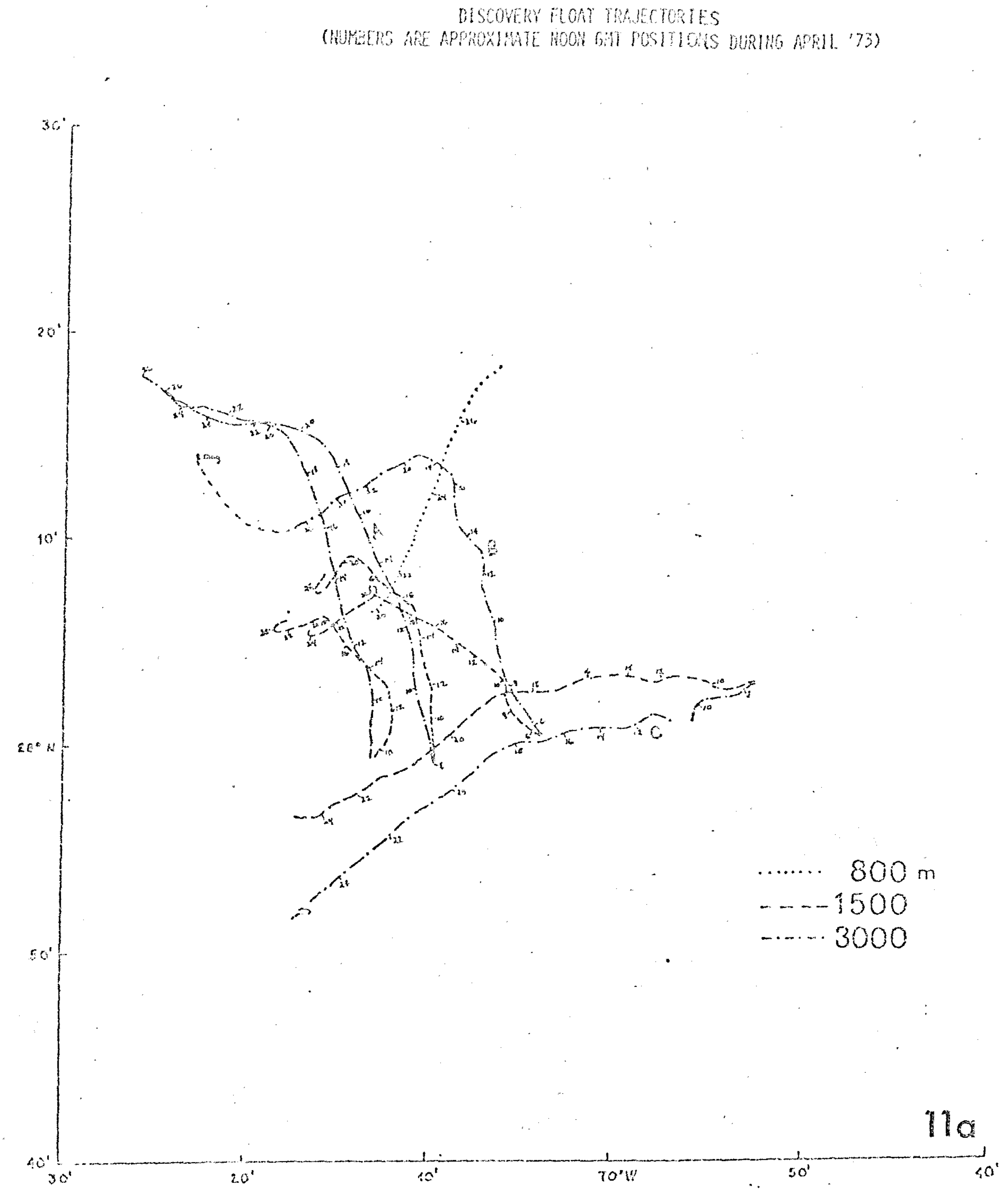


Fig. 11. Float Trajectories at a variety of depths in MODE, (from 32).

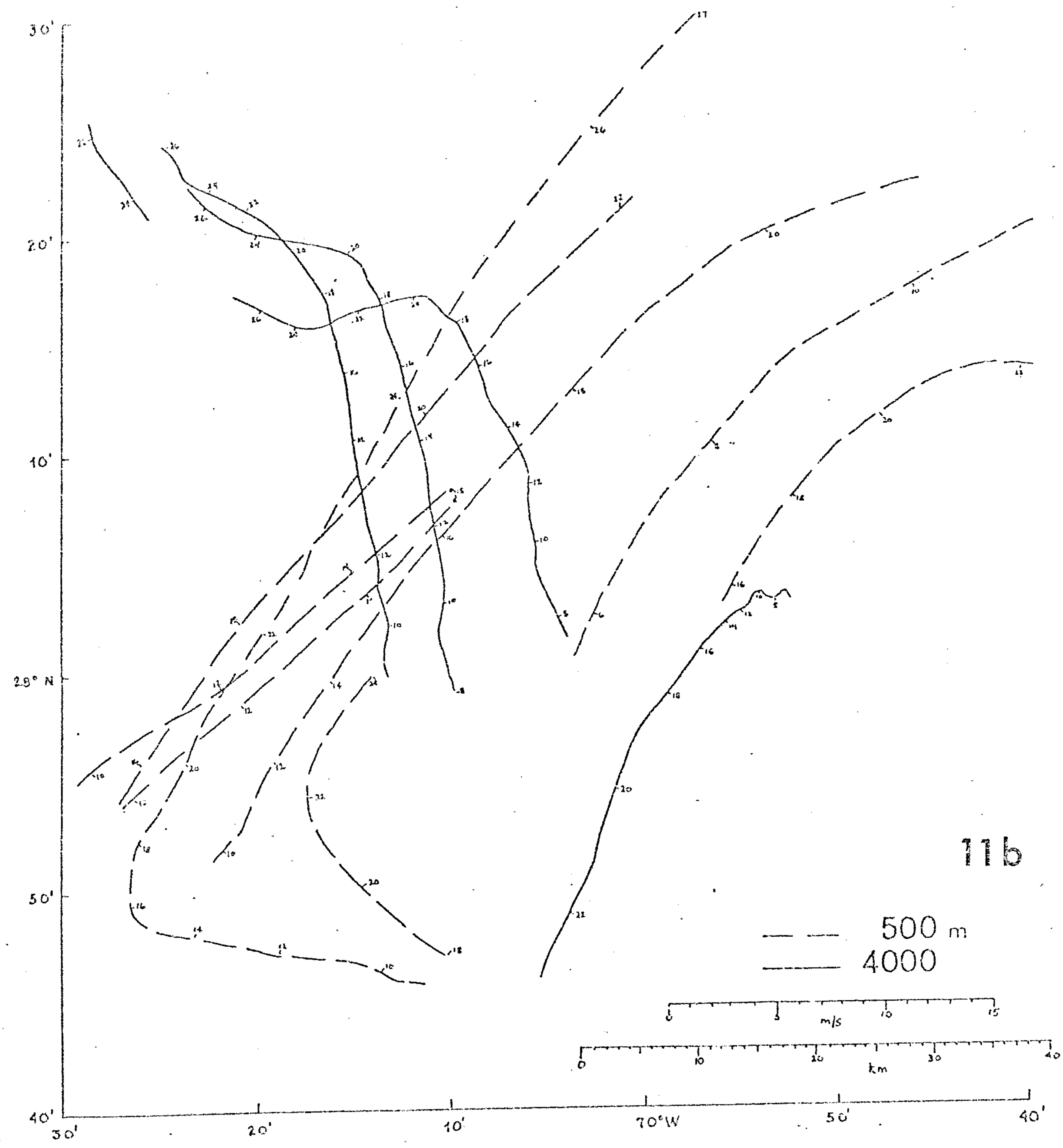
(a) Tracks at 800, 1500, 3000 m. Numbers are the approximate Noon positions during April 1973.

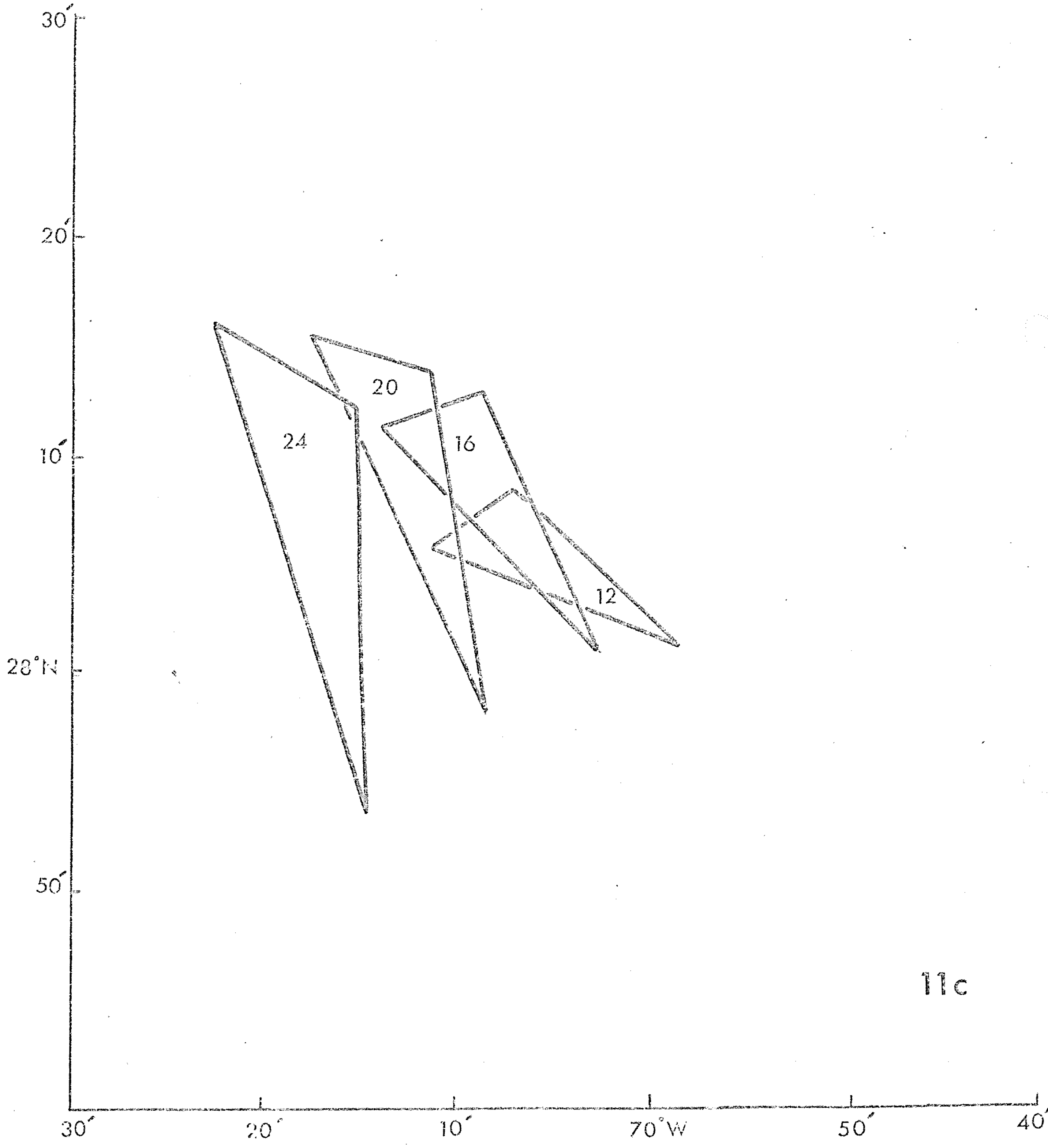
(b) Tracks at 500, 4000 m. Note speeds exceeding 5 cm. s^{-1} at 4000 m.

(c) Distortion of triangle marked by three floats at 3000 m. The position is shown every 4 days.

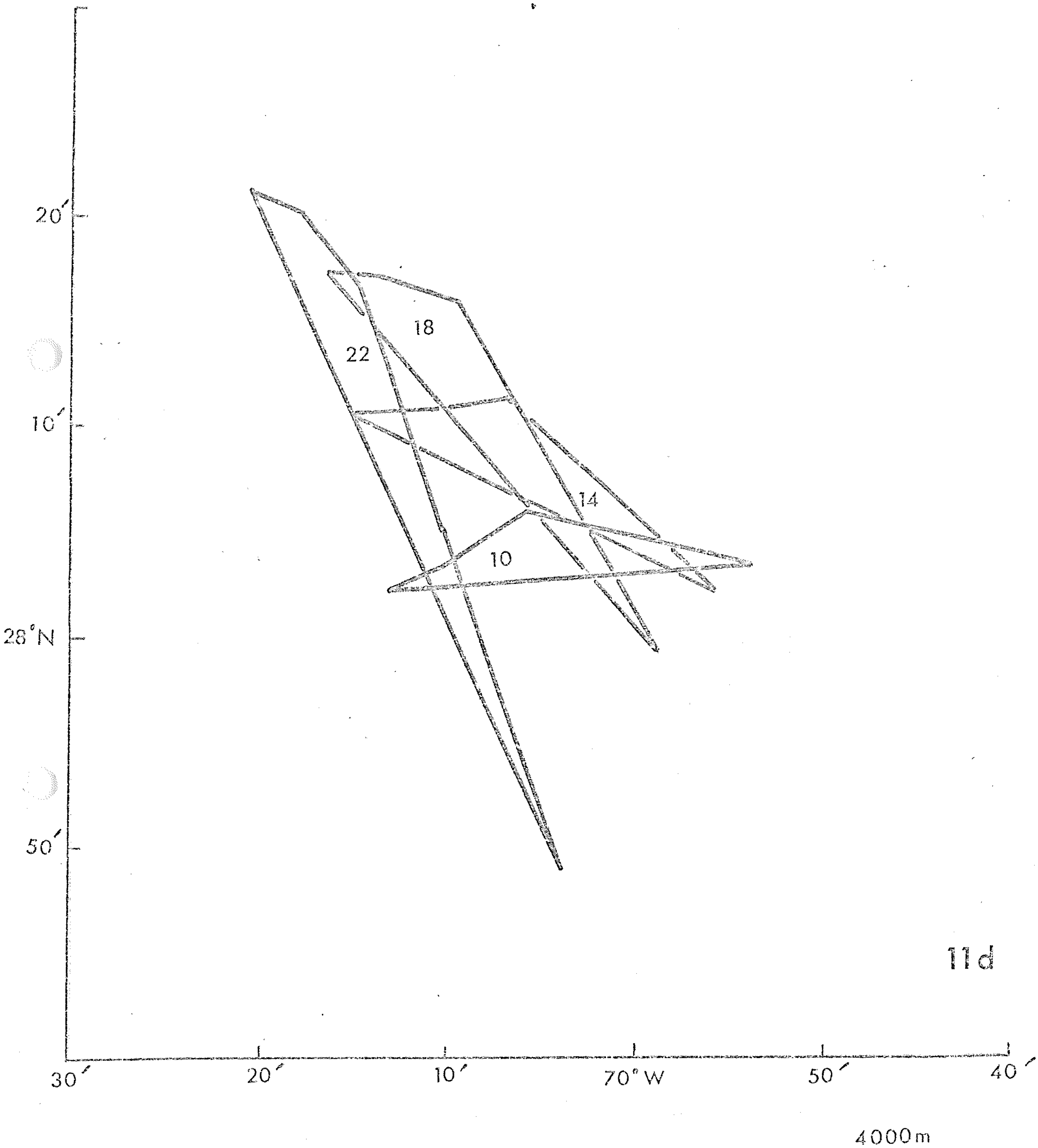
(d) Distortion of a quadrilateral marked by four floats at 4000 m. The position is shown every 4 days.

DISCOVERY FLOAT TRAJECTORIES
(NUMBERS ARE APPROXIMATE NOON GMT POSITIONS DURING APRIL '73)





3000 m



20′
10′
28°N
50′
30′
20′
10′
70°W
50′
40′
18
22
14
10
11d
4000m

sound channel at 1500 m (see figure 12) has been made (34) and the horizontal diffusivities estimated by finding the integral of the Lagrangian covariances (35). The estimated values of the diffusivities were about $7.5.10^6$ $cm.^2$ s^{-1} . Except in the strong western boundary currents it is usual for the eddy currents to completely dominate the mean circulation, and current measurements of duration limited to a fraction of a year may produce erroneous indications of the mean flow. For example figure 13 shows progressive vector diagrams of currents measured 30 m off the bottom in the Pacific over a period of 6 months, indicating a mean westward flow in an area in which the water mass characteristics and theory of the abyssal circulation predict an eastward flow.

The eddies appear to be akin to the cyclonic depressions in the atmosphere and it is possible that, like the atmospheric eddies, fronts form part of their structure. If so, these are regions of relatively rapid vertical transport and mixing of water from the benthic boundary layer.

3.5 Topography

The topography (hills, ridges and valleys) of the ocean floor appears to influence the trajectories of water particles at considerable heights above it, an effect which has been studied by Hogg (36, 37) and which was the subject of a 3 month long experiment by IOS in the abyssal ocean West of Portugal in 1975. This revealed the effect of an isolated hill on the flow pattern and density structure on an otherwise flat abyssal plain. The

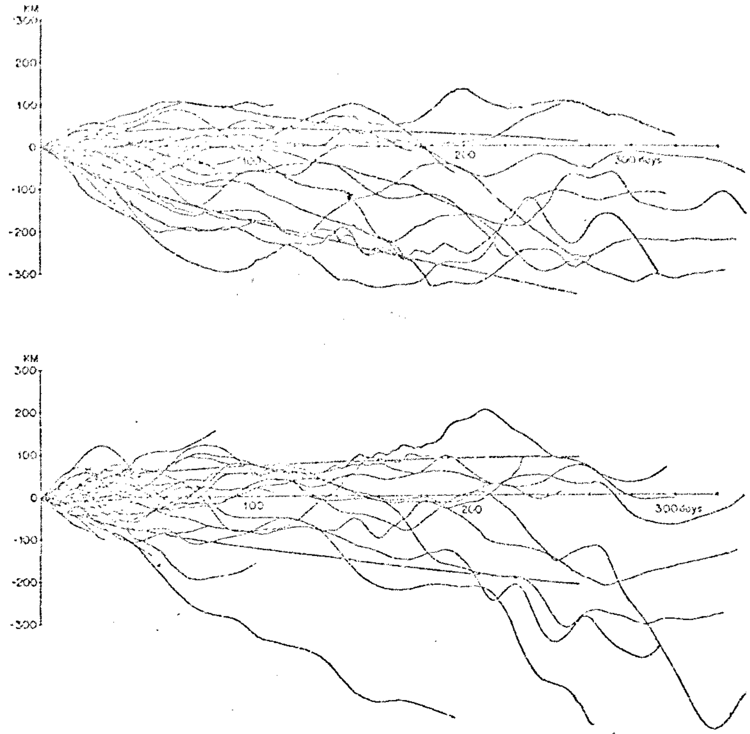


Fig. 12. Displacement of float tracks in the SOFAR channel at 1500 m in (a) E/W and (b) N/S directions (from 34). The bold lines show the mean computed dispersion.

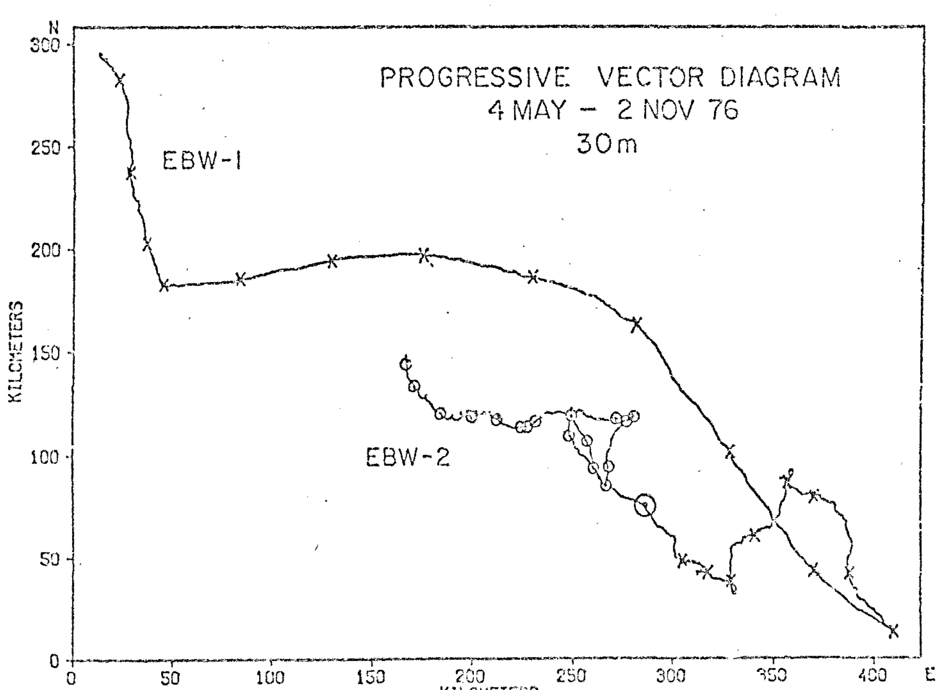


Fig. 13. Progressive vector diagram of currents measured 30 m above the sea floor at A (11°43'N, 138°23'W) and B (8°27'N 150°49'W) (from 29 DOMES experiment).

effect of topography on the isopycnal surfaces can be detected to several times the height of the topographic feature above the plain and radially outwards to the order of twice the diameter of the feature (Gould, Hendry and Huppert - manuscript in preparation for publication).

3.6 Mean Currents

Except in the Western boundary currents, advection by mean currents is generally at speeds much less than those associated with the tides, inertial waves or eddies; as Munk has put it, the ocean is an AC, not a DC, device. Information on the mean currents comes primarily from studies of water masses and, for the North Atlantic, these have recently been summarised by Worthington (38). Figure 14 shows a diagram of the circulation of the deep water, that colder than 4°C. (This diagram differs significantly from Stommel's (39) diagram, based largely on theoretical ideas). Worthington finds no direct pathway for near bottom water to reach the surface within the North Atlantic. The meridional pathways for water exchange are shown in the box model in figure 15, whilst the residence times in years of water at different levels in each of six basins identified by Worthington are shown in the table, figure 16. These times, while imperfect, embody what is presently known from physical measurements about the rate of formation and mixing of the North Atlantic water masses. Figures 15 and 16 makes it clear that solute released into the lower

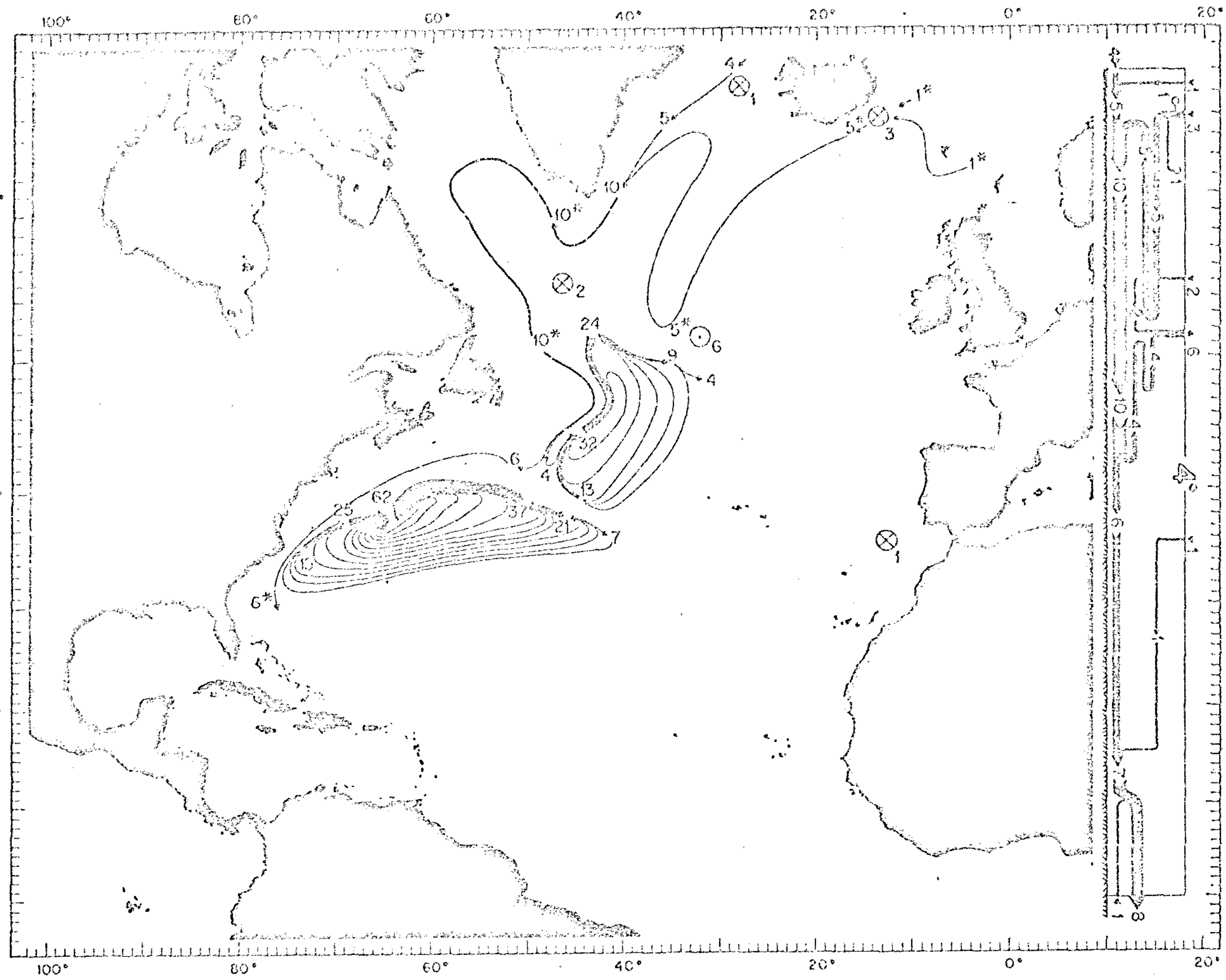


Fig. 14. Circulation of deep water in the N. Atlantic (from 38). The vertical arrow symbols represent vertical upward or downward exchange with overlying water. The numbers show the transport in units of $1 \times 10^6\ m^3\ s^{-1}$. At the right is a box model of the N-S transports, units also in $1 \times 10^6\ m^3\ s^{-1}$. Two main anticyclonic gyres lie in the Western basin with a narrow Southward flow along the continental slope.

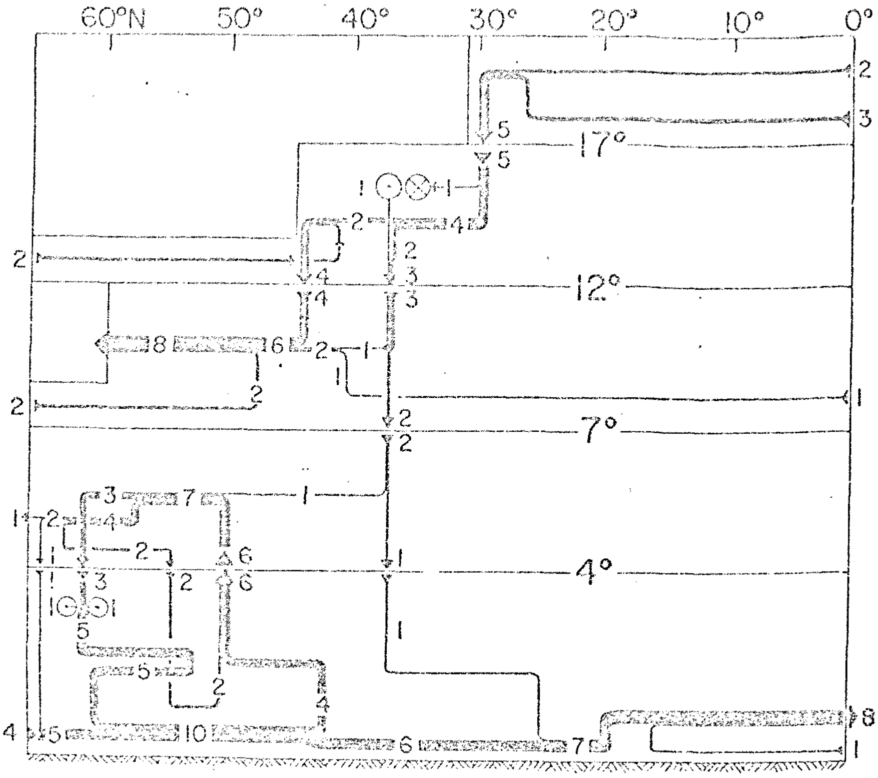


Fig. 15. A box model of circulation in the N. Atlantic (from 38). Five layers are defined by their temperature ranges and exchange between the layers is shown by vertical arrows crossing the horizontal boundaries. Units are $1 \times 10^6\ m^3\ s^{-1}$. No direct flow to the surface layers is found in the N. Atlantic. The main inflows are from the Norwegian Sea through the Denmark Straight and over Iceland Faroe Ridge. There is a net flux of about $7 \times 10^6\ m^3\ s^{-1}$ to the South Atlantic.

T/°C	>17	17–12	12–7	7–4	<4
Labrador Basin	0 0 0	2 0.7 11	2 0.8 13	2 1.9 30	12 10.5 28
European Basin	0 0 0	.4 0.2 2	8 2.1 8	7 1.4 6	11 4.5 13
North American Basin	3 3.2 34	2 2.4 38	1 2.4 76	0 6.1 >387	7 28.1 127
North African Basin	2 1.4 22	8 2.7 11	4 5.7 45	2 6.3 100	1 20.9 662
Guiana Basin	3 0.5 5	0 0.3 >19	1 1.1 35	0 3.3 >209	8 7.9 31
Guinea Basin	2 0.5 8	0 0.8 >51	0 1.8 >114	0 4.8 >304	0 14.8 >938
North Atlantic	5 5.5 35	8 7.1 28	10 13.9 44	8 23.8 94	14 86.7 196

Fig. 16. Residence time in years in each layer and basin in the North Atlantic (from 38) based on estimates of the rate of formation and mixing of the water masses and on the assumption of steady state.

layers of this ocean will not, in the mean, be diffused through the water column to the surface in the vicinity of the release area but will be advected along isopycnal surfaces to another ocean basin, perhaps into another ocean, before it reaches the surface.

3.7 Diffusion along density surfaces: possible direct links between the benthic layers and the ocean surface.

It is possible that, without any trans-isopycnal mixing whatsoever, solute released at the ocean floor could be carried almost to the sea surface. Figure 17 shows a North-South vertical section of constant density surfaces through the Pacific. By mixing or advection along these constant density surfaces, material released from the sea bed between 60°S and 55°N can reach the 300 m level near the Antarctic Convergence at 65°S. (The Atlantic Ocean section is similar in this respect). The section through the Drake Passage shown in figure 18 shows how extreme is the isotherm and isopycnal tilt in this area. Whilst the mean ocean circulation does not favour such a pathway, diffusion along isopycnal surfaces is far more rapid than across the surfaces. The diffusion coefficients are of the order of 10^6 and 10^0 $cm.^2 s^{-1}$ respectively, (see 3.4 and 4.1). The relatively large horizontal diffusion is the consequence of 'quasi-horizontal turbulence' of which the mesoscale eddies form a component. The processes of trans-isopycnal mixing are discussed in section 4. It is known that vertical or (trans-isopycnal) overturning and mixing at scales exceeding a certain size, the

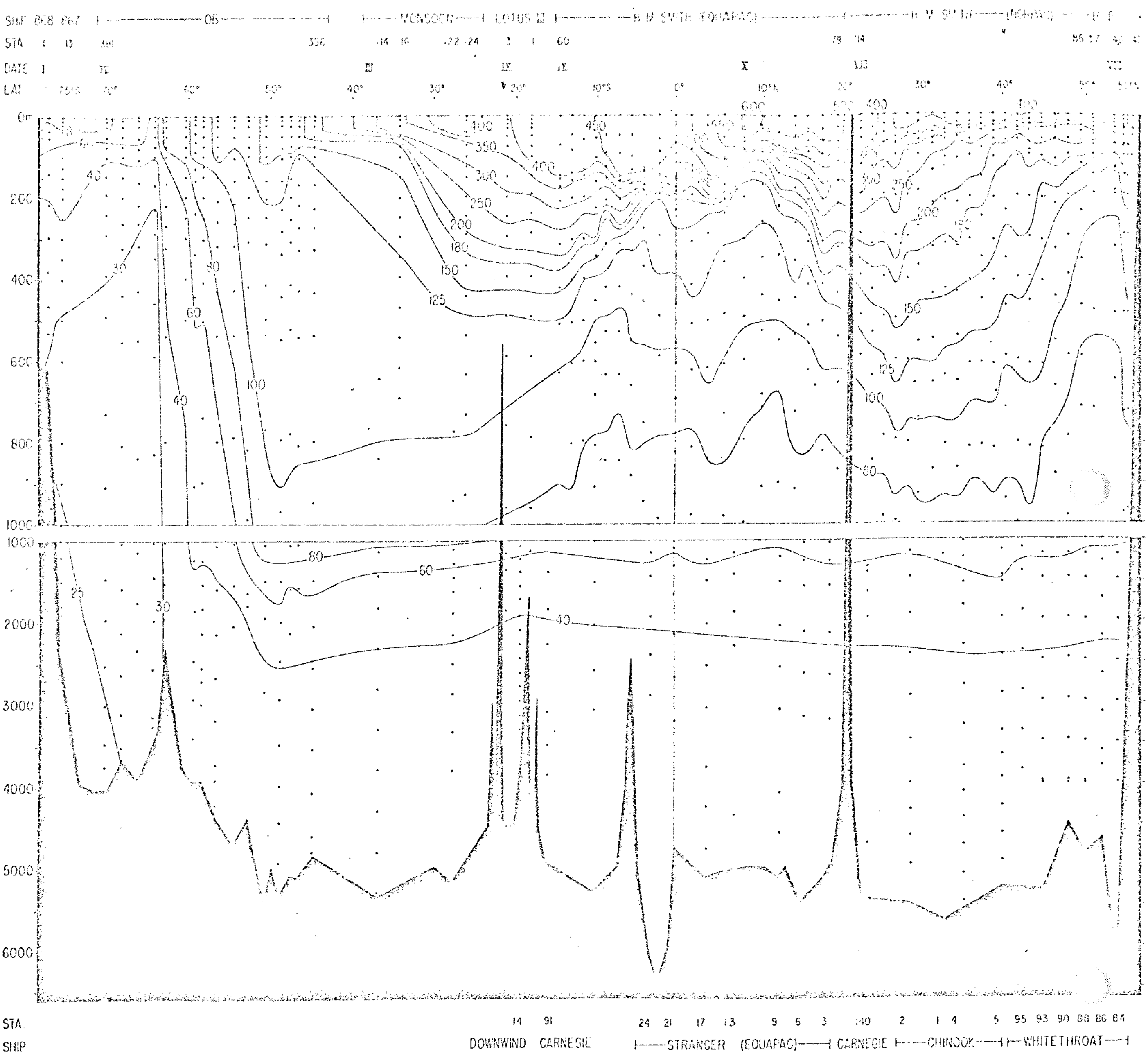


Fig. 17. The observed meridional section of specific volume anomaly of the Pacific Ocean (from 40). Units are centilitres per ton.

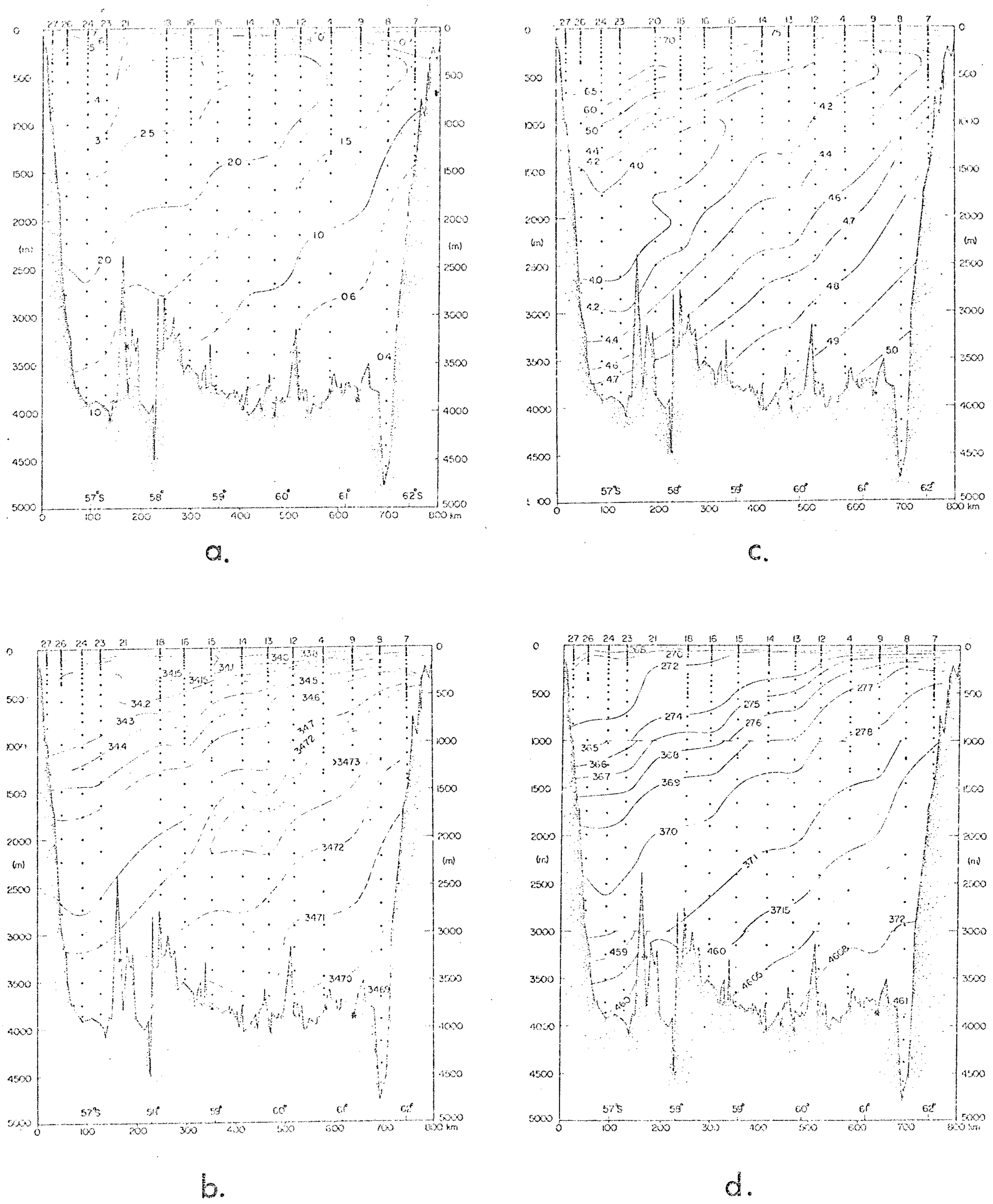


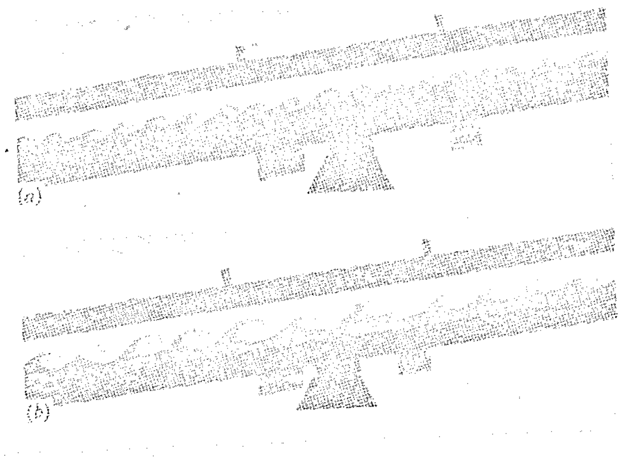
Fig. 18. Sections of (a) temperature(^{o}C) (b) salinity(o/oo) (c) dissolved oxygen (ml.l^{-1}) and (d) density parameter (kg.m^{-3}) across the Drake Passage (from 41) showing especially the large tilt of the isopycnal surfaces.

Osmidov length scale, relating the stability of the stratified water column to the energy dissipated by the turbulent motions, are inhibited because of the presence of the overall stable vertical density gradient. Thus isotropic turbulence occurs only at small scales, probably of the order of 1m and 'horizontal turbulence' dominates at larger scales. Such mixing is the subject of the next section.

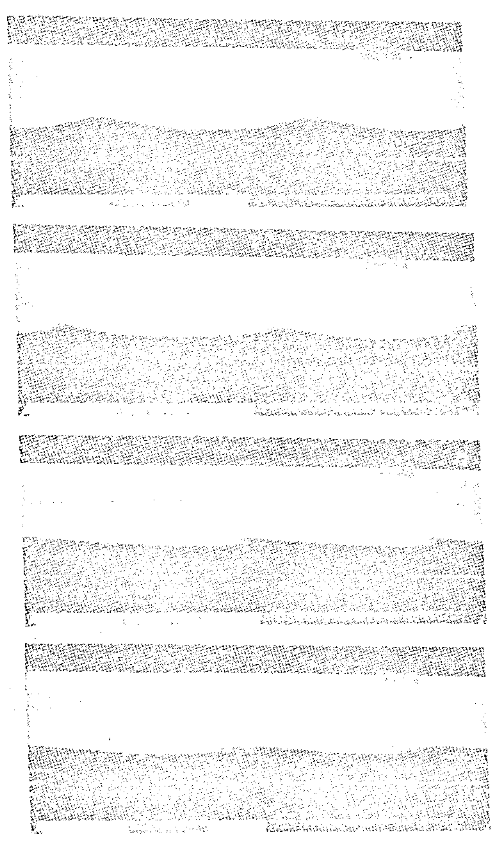
4. TRANS-ISOPYCNAL MIXING IN MID-WATER.

4.1 Munk (42) has surveyed vertical diffusion in the ocean, arriving at a gross figure of about 1.3 $cm.^2 s^{-1}$ for the eddy diffusion coefficient in the Pacific Ocean, corresponding to a vertical flux at a rate of about 4.4 $m.yr^{-1}$. These figures do not lead to the clear identity of an obvious process or location in which the diffusion is most active. In particular it is not certain whether vertical diffusion is dominated by mixing in mid-water or by mixing near ocean boundaries. We, therefore, consider in this section the processes which may occur in mid-water, and in section 5 the processes which occur in special localities where mixing may be most efficient, namely the continental slopes and islands.

4.2 Diffusion in mid-water (the water column above the benthic boundary layer and below the near surface 'mixing' layer) and away from the continental boundaries, is dominated by stratification. Three sources of trans-isopycnal mixing are known: (a) shear induced instability (sometimes called Kelvin-Helmholtz instability) (b) internal wave breaking, when the waves become so large that the horizontal particle speeds exceed the phase speed of the waves and (c) double diffusive instability, (see also 2.4) of which there are two kinds, diffusive convection and 'salt finger' convection. Diffusive convection may occur when warm, but salty, water lies below lighter and relatively cold fresh water, whilst finger convection occurs when the warm and salty water lies above heavier cold, but fresh, water. Photographs of the processes as observed in laboratory experiments are shown in figure 19.



a.



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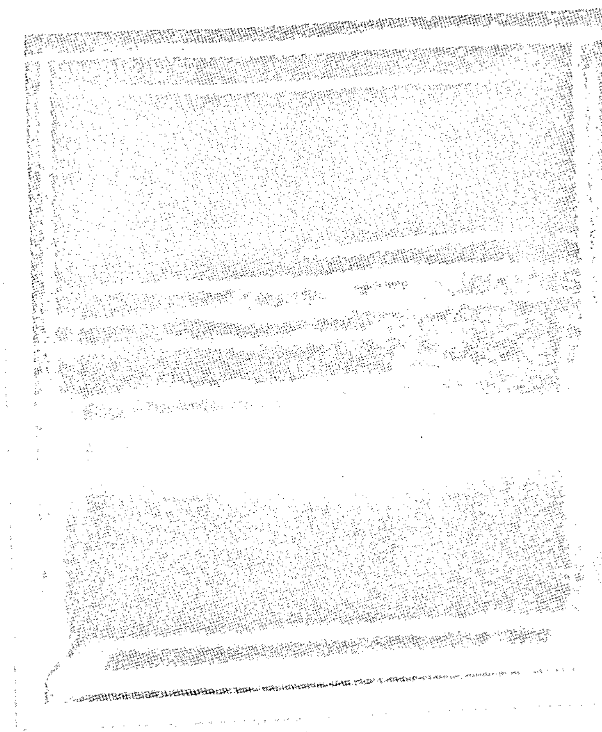
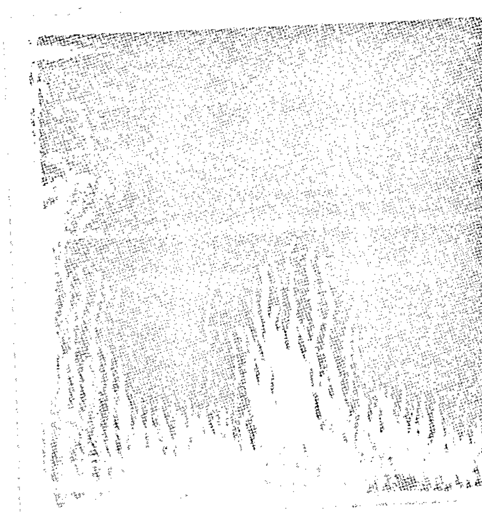


c.



d.

Fig. 19. Processes leading to trans-isopycnal mixing:-

(a) Shear flow instability (from 42),

(b) Internal wave breaking (from 43),

(c) Layers resulting from double diffusive convection,

and (d) Salt fingers resulting from double diffusion (from 24).

4.3 It is not known which of these processes dominate mixing in mid-water, although clear evidence of both (a) and (d) have been obtained.

Direct observations of (a) have been made by divers in the Mediterranean thermocline (44). The overturning patches of fluid, 'billows' were about 10-30 cm high. Gregg (45) using a free fall microstructure probe shows inversions of scales of about 3 m which might however, be caused by breaking internal waves. Cairns (46) interprets some of his observations made from a neutrally buoyant float as billows some 5 m high at a depth of about 750 m. This instability can only occur if a parameter, the Richardson number, measuring the ratio of the stable density gradient to the current shear, is less than one quarter. Observations of velocity and density gradients (28, 47, 48) show that such low values are not uncommon in the deep ocean and thus that shear instability may occur fairly frequently. Attempts have been made (49) to quantify the diffusion which could be attributed to instability caused by the shear induced by internal gravity waves, but this, at present, rests on tenuous assumptions and the uncertainty of the estimates is considerable. The occurence of breaking internal waves (b) is also enhanced in regions of low Richardson number.

Evidence of double diffusive instability is reviewed by Turner (24) and comes largely from observations of layered structures in regions in which the vertical gradients of temperature and salinity are such as to promote the instability. Firm evidence of 'salt fingers' in the Mediterranean outflow have been obtained by photographic studies (50) and further supporting evidence comes from work (51) using a towed body, and free fall probes (45).

4.4 Measurements using very sensitive fast response free fall probes have been used to estimate the vertical diffusivity of heat, K_H, using a relationship proposed by Cox and Osborne,

$$K_H = \kappa \overline{(\theta')^2} / (\overline{\theta'})^2, \qquad (3)$$

where κ is the molecular diffusivity (about 1.5. 10^{-3} cm.^{2} s^{-1}), of heat and θ' is the vertical temperature gradient. The assumptions implicit in this relationship are summarized by Gregg (45 § 8) and involve horizontal isotropy and the absence of mean local upward currents. It is thus assumed that the mean isopycnal surfaces are horizontal so that K_H is the trans-isopycnal diffusion coefficient. Measurements (45,52,53,54) in the Pacific give estimates as high as 5 cm.^{2} s^{-1} in the high shear region of the Equatorial undercurrent, 2 - 60 cm.^{2} s^{-1} in an "active" shallow intrusive feature off California, and 0.03 cm.^{2} s^{-1}. at depths of 200 - 2000 m in the centre of the subtropical gyre of the North Pacific in calm weather. These compare with values of 10 - 10^3cm.^{2} s^{-1} in the surface mixing layer during the passage of a mild storm. Gregg suggests that values of about 0.15 cm.^{2} s^{-1} are typical background levels in mid-ocean.

4.5 Gregg's observations serve to illustrate the great spatial and temporal variability in K_H and its control by physical processes. No measurements are yet available which relate the microscale observations of K_H to the presence or internal structure of mesoscale eddies. In these eddies shear instability and internal wave breaking are likely to be important since the eddies appear to produce vertically extensive regions of low dynamical stability (that is of low Richardson number) and hence may lead to rapid vertical diffusion.

4.6 Modelling diffusion in mid-water

The most commonly used semi-empirical relation between Richardson number and vertical diffusion coefficient of heat is (55)

$$K_H = A_o \left(1 + 3{\cdot}33 \, R_i \right)^{-3/2}, \qquad (4)$$

where R_i is the local Richardson number and A_o is the value if K_H in neutral conditions. This relation is moderately successful in determining mixing rates in quasi-steady conditions, where R_i is well determined.

The variation of ratio K_H / K_M , where K_M is the vertical eddy diffusivity of momentum, has also been extensively studied (see 24 , figure 5.13 and 56 , figure 2) and is found to decrease rapidly with R_i , indicating the relatively rapid mixing of momentum but slow mixing of heat (or solute) at large R_i .

4.7 Near surface diffusion

Diffusion in the upper layer of the ocean (which in some ways is similar in character to the benthic boundary layer), although relatively well studied, is yet poorly understood. It has been reviewed by Bowden (57). The majority of data comes from studies of dye diffusion experiments, either from continuous point source releases or instantaneous sources, and range in scales from 100 m to 100 Km and 1 hr to 1 month. The apparent horizontal diffusivity of the dye is a function of horizontal scale. Obuko (58) finds $K = 0.0103\ l^{1.15}$ (K measured in cm.^{2} s^{-1} and l in cm.), the exponent lying between that of unity, proposed by Joseph and Sendner (59), and 4/3 proposed by Ozmidov (60). (It is clear that other dimensional quantities must influence this relationship but they are at present unknown.) Kullenberg (61) has recently studied mixing in the thermocline and finds horizontal spreading at rates which are much lower than in the mixed layer. Vertical profiles of dye patches show clear evidence of strong isopycnal spreading in thin vertical layers.

5. SLOPE PROCESSES

5.1 The continental slopes, separating the deep ocean from the continental shelves, have gradients of around 10°. They are often incised with canyons and gullies. Steep slopes may be sources of mud slides and turbidity currents which, fanning out from the base of the slope, may effect the benthic boundary layer and sediments some distance from the slope itself (see Chapter 1). Near the sea bed processes similar to those described in Section 2 operate, but now stratification of the water column may play a different role. In this chapter we discuss some of the processes which cause diffusion near continental and mid-ocean island slopes. Their importance is such that Armi (23) has claimed that vertical mixing near the ocean boundaries can account for almost all the vertical diffusion in the deep ocean without any significant vertical diffusion in the interior.

5.2 The boundary layer and internal waves

Close to a sloping boundary a logarithmic layer similar to that described in Section 2 may be expected. The theory of an Ekman boundary layer has been given by Wunsch and Hendry (62). The overall thickness is found to be

$$\eta_c = \frac{K_v u_*}{P_r^{1/2} N \omega_c} \qquad (5)$$

and the momentum eddy coefficient

$$K_m = 0.5 K_v u_* \eta_c ;$$

where $\qquad \omega_0 = \left(\frac{f^2}{N^2} \cos^2 \gamma + \sin^2 \gamma \right)^{1/2}$

and K_v is Von-Kármán constant, about 0.4, u_* is the friction velocity, P_r is the Prandtl number, N is the local Brunt-Väisälä frequency, f is the Coriolis parameter and γ the slope angle.

Rattray (63) has shown that the interaction of the surface tides with a continental slope will generate an internal tide. The theory of internal tides was developed by Wunsch (64) . The internal waves propagate off-shore as rays with tangent slopes

$$\frac{n^2 - f^2}{N^2 - n^2} \qquad (6)$$

where n is the wave frequency (2π /period, where period is about 12.5hrs for the semi-diurnal tide). For typical values of f and N this slope is not far from that of the continental slope itself and internal tidal waves are probably generated in regions where the two are equal. In these regions intensified currents and mixing are expected.

Observations have been made by Wunsch and Hendry (62) on the NE American slope south of Cape Cod. They estimated the thickness of the boundary layer

$$\eta_c \sim 3\text{m}$$

and inferred that

$$K_m \sim 3\text{cm}^2 .\ \text{s}^{-1}$$

in the layer. There was evidence of the enhancement of the baroclinic (internal) tide as the slope was approached and a veering of the current with height of about 10° between 3 and 10 m off the bottom.

5.3 The effect of widespread mixing in the sloping stratified boundary layer is to generate currents up the slope near the bottom and down the slope at the top of the mixed layer. The mixing causes the water near the bottom (top) to become lighter (heavier) and it therefore rises (sinks). A theory of the vertical transfer deriving from this mixing is given by Wunsch (65) but the net flux, given $K_H \sim 3\ cm^2.\ s^{-1}$ as observed, is too small to explain a significant proportion of the totals estimated for the Pacific by Munk (42).

5.4 Intrusions

Figure 20 shows a succession of temperature profiles made near Bermuda. These demonstrate an apparent increase in the 'steppyness' of the profiles as the island slope is approached. It is thought (65) that the steps represent regions of fluid which have been mixed on the slope and which are spreading at their own density level along isopycnal surfaces (see fig. 7) diffusing and hence loosing their 'signature' the further away they are from the island. (Mid-ocean islands thus act as 'oceanic stirring rods'.). Armi (23) has described observations of similar structures in the deep ocean (see figure 8). The sources of mixing may be internal waves breaking on the slope or regions of enhanced slope mixing due to extreme bottom roughness or large currents.

A good example of such slope mixing between the Mediterranean

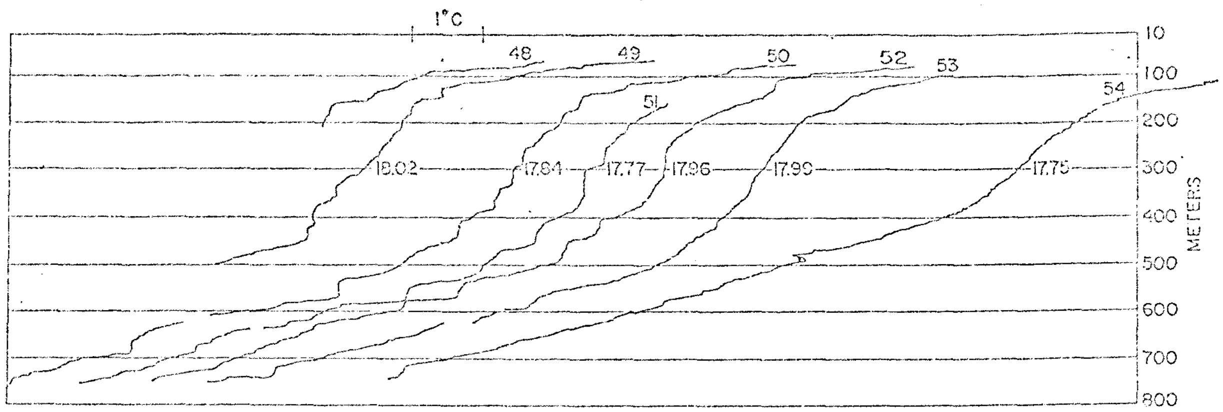


Fig. 20. Profiles of temperature v. depth along a section towards Bermuda, on the left, (from 65), showing an increase in fine structure as the island is approached.

water and North Atlantic water is found in the Gulf of Cadiz with subsequent intrusive mixing along isopycnal surfaces (66). Laboratory experiments have been made by (67, 68) to investigate the spreading of mixed layers in stratified surroundings.

An alternative cause of the near-slope layers is, however, possible where the temperature and salinity stratification of the water column are such as to permit double diffusive convection, see Section 4. Studies (69, 70) in the laboratory have demonstrated how layers develop and rapidly intrude from the slope onto the interior of the fluid.

5.5 Upwelling

Upwelling is a term given to the ascent of water from the thermocline, or below, to the surface on western continental slopes. The water is often nutrient enriched and the process is thus of great importance to local fisheries. Major sites off Peru, the Oregon coast and NW Africa have now been quite extensively studied. Although originally recognised as resulting from the Ekman layer pumping of surface water off-shore when the wind stress has a long-shore component, it is now known that it can be forced by internal Kelvin and shelf waves (71), perhaps propagating from a distant source. The region of upwelling is confined to about one Rossby radius of deformation from shore ($a_1 = c_1 f^{-1}$, where c_1 is the speed of the first mode long internal wave and f is the local Coriolis perimeter) typically 30 Km, and is greatest near the thermocline, being predominantly a first internal mode-like response. Vertical displacements of over 100 m are not uncommon. Associated with upwelling are longshore currents, coastal jets and counter currents (72, 73, 74) where horizontal and vertical shear and hence mixing, will be enhanced. Such longshore currents will also cause geostropic tilts of isopycnal surfaces and hence effective vertical diffusion by trans-current mixing along isopycnal surfaces. Recent theoretical studies (75) have demonstrated that ridges and canyons running down a continental slope can be important in locally enhancing upwelling.

Although primarily concentrated near the thermocline and transient (when following a parcel of water moving along the coast through regions of upwelling), upwelling will locally be important in enhancing vertical diffusion near certain western continental slopes.

6. CLIMATIC VARIATION AND MODELLING OF CIRCULATION AND OCEAN TURBULENCE

6.1 It was mentioned in Section 1 that the half-life of some potential radio-active waste products is very great, as much as 24,000 yrs. Over such a great period of time significant changes in the ocean and atmospheric circulation may occur. Figure 21 shows migrations of the North Atlantic Polar Front in the last 65,000 yrs and an even longer time span is covered by figure 22 , showing episodic advances and retreats of the polar and subtropical fronts. Similar changes may occur in equal periods of time in the future, and removal of the thermocline over a large area of the North Atlantic would lead to greatly enhanced vertical diffusion over a considerable area.

6.2 At present the most promising approach to understanding future changes of ocean circulation under climatic variation comes from sophisticated linked ocean-atmospheric numerical models, like that of Bryan, Manabe and Pacanowski (78) . These models reproduce satisfactorily many features of the present circulation. Detailed studies of parts of the ocean in which special processes are important, or studies the processes themselves, have been made. For example the Weddell Sea (79) , the Circumpolar current (80) and upwelling (75) have been studied, although these models have primarily focussed on explaining the currents and density fields, rather than attempting to examine diffusion.

6.3 Studies of large scale ocean waves and turbulence have also been made using analytical approaches and numerical models. Rossby waves and their interaction with topography have been studied

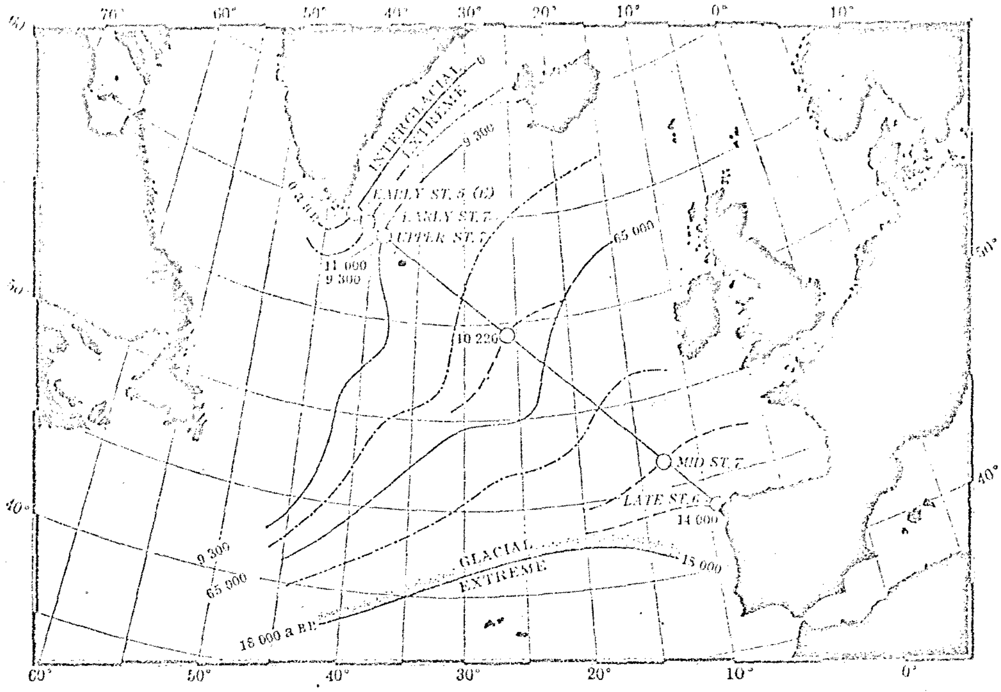


Fig. 21. Migrations of the North Atlantic Polar Front (76).

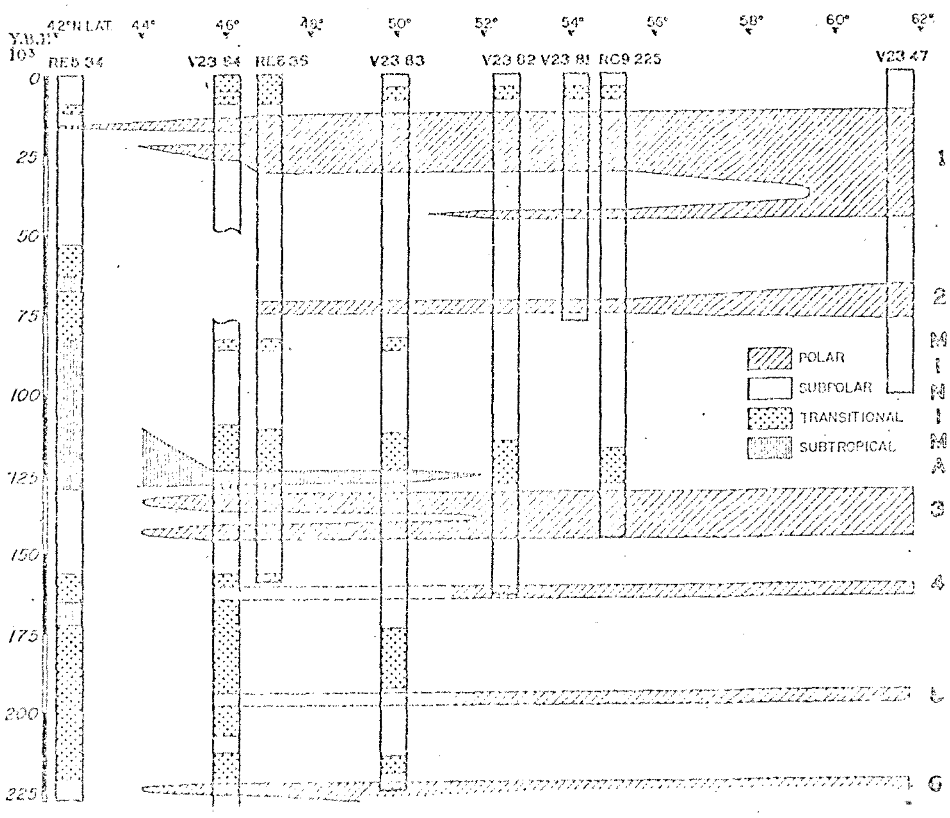


Fig. 22. Migration of the North Atlantic Polar Front for the last 225,000 years. (from 77).

(81) whilst the response of a stratified model of the North Atlantic, including topography, to changes in wind forcing have recently been reported (82) . The development of waves and mesoscale eddies and their interaction on a β-plane has been studied (83) using a numerical box-model. This has demonstrated that the upward migration in size of the largest turbulent scale nearly ceases at a wavenumber $(\beta/2\sigma_u)^{\frac{1}{2}}$ where σ_u is the r.m.s. particle speed and β the northward gradient of the Coriolis perimeter, the turbulent flow initiated at small scales passing through a state of propagating waves with properties and size similar to the observed, mesoscale eddies, and tending towards a flow of alternating zonal jets. Topography can act in a way similar to the β- effect if slopes extend over scales greater than the eddies or waves, although roughness will generally induce a cascade of energy to smaller size (81) .

A numerical study of mid-ocean mesoscale eddies, has been made (84) , using a six-layer model. It is found (figure 23) that the scale of the eddies is smaller in the water below the thermocline than above it, a result in accordance with observations. The overall statistics - eddy advection speeds, length and time scales and horizontal diffusivity - are also consistent with observations, and the models thus appear to be realistic.

6.4 Two existing models of dispersion in the ocean from radio-active wastes dumped on the sea bed, those of Grimwood and Webb (86, 87) and Shepherd (88) provide estimates of probable mean concentration levels. However they fail to include details of the real ocean dynamics by their use of gross diffusion coefficients (see 1.2). The former neglects horizontal advection which, in

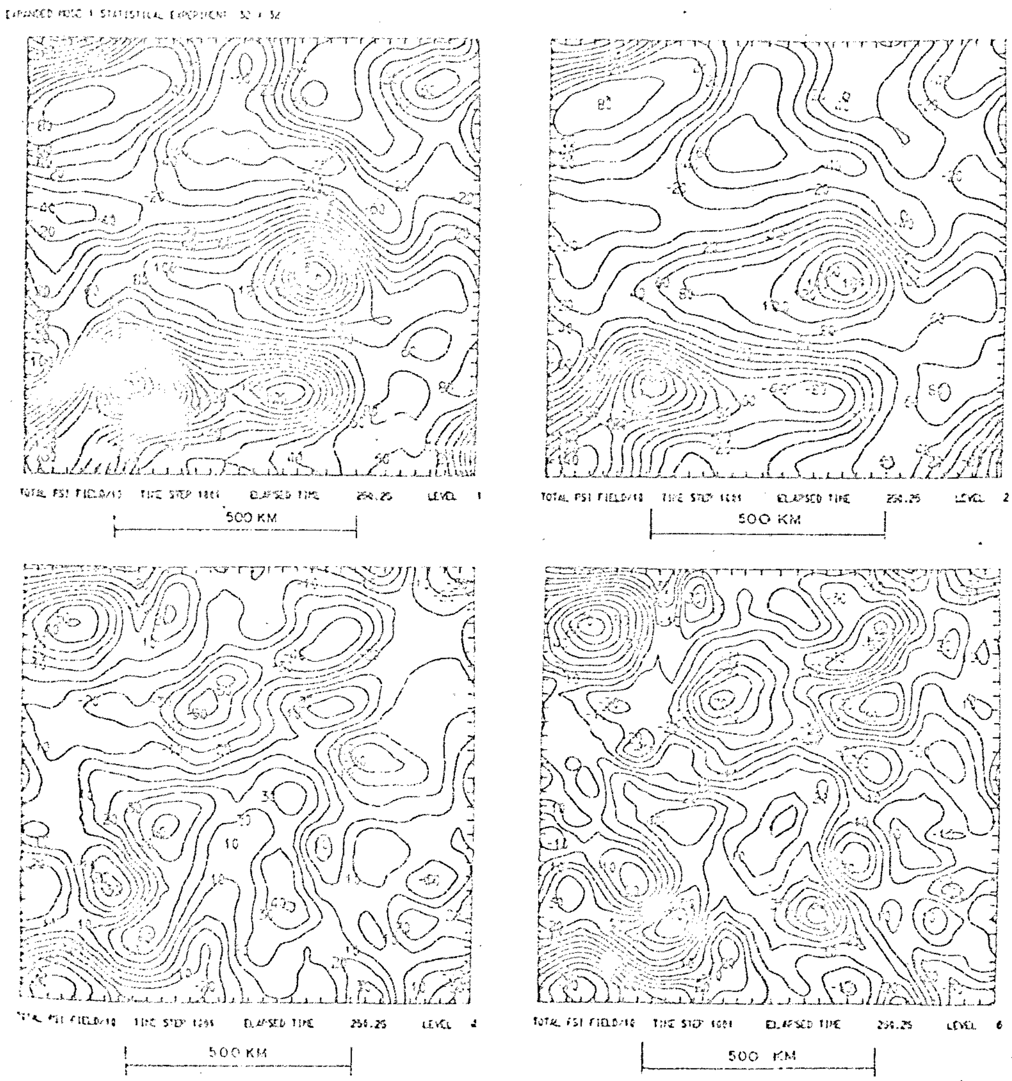


Fig. 23. The stream function fields occurring simultaneously at four of the six levels (1 is the upper level at top left, 6 is the bottom layer at bottom right) of the Owens-Bretherton model (from 85). The initial values of thermocline displacement are taken to match observed values, until zero current below the thermocline. Notice that the scale of the eddies is less below the thermocline than above.

the mean, will carry waste far from the disposal site before it reaches the surface (see 3.6). The latter model of diffusion in a closed ocean basin is concerned with average concentrations and not with estimating the possible variability which, in the model, is blanketed in a safety factor. Neither is specific to a particular ocean or area of ocean.

7 PRESENT AND PLANNED RESEARCH

This is not intended to be a complete list but rather some notes about relevant work, and expertise, mainly in the U.K, of which we are aware. This supplements the information in the earlier chapters and draws attention to some relevant work at present in progress.

7.1 Benthic Boundary Layer

7.1.1 LEBBLE - Low Energy Benthic Boundary Layer Experiment. American programme to study chemical and particulate flux in areas of low currents (low stress): includes use of deep ocean submersibles; beginning soon, probably in the Panama Basin.

7.1.2 HEBBLE - High Energy Benthic Boundary Layer Experiment. American programme developing over next 5 years to study areas of large bottom currents, including bottom currents, temperature, salinity, turbidity, photography, structure of the boundary layer at 300 m above sea bed, and collection of bottom samples to test the stability to erosion by currents.

7.1.3. Experiments on the Continental Shelf.

Experiments have been made by several groups to examine turbulence and sediment motion in the relatively shallow waters of the continental shelf, aimed mainly at assessing diffusion and sediment motion and in providing realistic data for use in numerical predictive models of tidal flow and sediment transport. In general the tidal flows in shallow seas are far greater than those expected near the floor of the deep ocean. Moreover the stratification is weak, especially during the winter months, allowing mixing to occur fairly rapidly and uniformly through the water column, unlike the situation in the deep ocean. The majority of studies (e.g. those at University of East Anglia; MAFF, Lowestoft, F.B.A., and Bristol University), have used the profile method (method B, Appendix 2) to determine the roughness length and shear stress, but others (at Liverpool University, University College of N. Wales, and IOS) have used electromagnetic current meters to estimate the shear stress directly(Method A, Appendix 2). Sediment motion has been studied, for example by H.R.S.Wallingford and IOS. There is thus considerable expertise in the U.K. in making observations and interpreting boundary layer structure in tidal flows. A good understanding of the physics (especially turbulent bursts), of the spectra of velocity fluctuations and of the threshold speeds, has been developed. The technology and engineering involved in making observations close to the deep ocean floor however, introduce a degree of complexity not encountered in these shallow water observations (for example the recovery of instruments from the sea floor and the accurate measurement of weak currents) and at present expertise is available in the U.K. only in Government Laboratories.

7.1.4 Laboratory Studies

Although directed towards an understanding of diffusion of warm water released into a tidal current, there are experiments in progress at DAMTP, Cambridge University, designed to clarify the effect of periodic variations in the mean stream flow on the turbulent flow field, which will be useful in assessing the effect of tidal fluctuation on diffusion in the boundary layer.

7.2 Abyssal currents and circulation

7.2.1 Tides.

Recent observations in the NE Atlantic and theoretical work at IOS are expected to provide greatly improved charts of the mid-ocean tides and hence of the strength of the related barotropic currents.

7.2.2 NEADS

The impetus for the North East Atlantic Dynamics Study (NEADS) came via SCOR WG 34 in an attempt to co-ordinate the resources of European laboratories having the capability to deploy recording current meters on fixed moorings in the deep ocean for periods of several months.

Six sites between latitudes of 30° and 53°N and East of 25°W have now been occupied for almost two years (the planned duration of the experiment). Two are the responsibility of IfM, Kiel, one maintained jointly by the French COB and Musee d'Histoire Naturelle, and three have been deployed by IOS. Shorter records are also available from an additional site maintained by IOS and from a site maintained by MAFF, Lowestoft.

It is hoped that analysis of the records will give a measure of the energies in the mean and fluctuating components of currents at depths ranging from 600 to 4000m and will also reveal the vertical structure of these currents, together with the variation over the NE Atlantic of the energetics of the currents.

7.2.3 POLYMODE

-An experiment developing from MODE and POLYGON (a U.S.S.R. experiment in 1970) to study large scale fluctuating currents with the objective of providing information for the construction of valid physical models of oceanic circulation. This experiment is a collaborative experiment in the N. Atlantic between the USA and the USSR in 1976-1979.

7.2.4 Theoretical Studies

(i) Diffusion

The effect of stratification on turbulent flow over and around topography is being studied at DAMTP, Cambridge University.

The study of variance of concentration on a plume and random walk techniques to study diffusion in tidal estuaries, are being developed at Liverpool University.

(ii) Ocean Circulation (also refers to sections on slope processes, especially upwelling and numerical modelling)

A group at DAMTP, Cambridge University, is internationally recognised for its expertise in the theoretical and numerical modelling of ocean currents (see, for example, 75, 79, 80, 82). Recent work has been on the spreading of cold water in, and from the Arctic Ocean.

MAFF have recently acquired the Bryan et al ocean numerical model (78) for studies of deep water circulation and diffusion.

7.3 Trans-isopycnal mixing in mid water.

7.3.1 Results of a sea-going experiment to study fine-scale structures between Woods Hole and Bermuda in 1976 are not yet available. This joint experiment included the use of a variety of instruments to measure fine structure from vertical scales of about 50 m to 1 mm. to depths of about 2000 m. The University College of N. Wales was involved in this experiment.

7.3.2 Laboratory experiments.

There is expertise in double diffusive convection at DAMTP, Cambridge University and in studying shear flow and internal wave mixing at IOS

7.4 Slope Processes

Laboratory experiments on intrusive flows are being made at DAMTP, Cambridge University.

8. RECOMMENDATIONS FOR FURTHER RESEARCH

8.1 The objective should be the ability to predict the probability of a given concentration arising in any part of the ocean after release from a source on the ocean floor. It is not sufficient simply to obtain estimates of the average probable concentration or its variance. Knowledge of extreme concentrations and their persistence, may be of greater importance. The objective is, however, unlikely to be attained within the next decade or so but it should be possible to identify and quantify the most important processes, to show that there is a reasonable chance that levels will not exceed a certain amount (which may or may not be acceptable) and to improve our knowledge of the routes along which diffusion occurs.

The objectives of research should thus be to gain an understanding or the abyssal circulation and the variability of the ocean, particularly of the deep layers: to develop knowledge of the causes of this variability and of the inter-actions and inter-relation between the mean statistical state of the ocean and the individual processes which operate in it, all of which need to be better defined, with a view to modelling and assessing diffusion. It is essential, in view of the intermittent nature of turbulence and diffusion (see 1.3, 3.4), that any observational programme should be sufficient, in duration and extent, to sample adequately the processes and consequences of diffusion (i.e. be correctly matched to the space-time 'windows' of the processes involved). They should be linked to developments in mathamatical/numerical modelling and to the observations in other disciplines, chemistry, geophysics and marine biology, where appropriate.

The following three related areas of research are basic and may, once more is know, evolve into investigations of other yet-to-be-discovered processes and areas of importance.

8.2 Benthic boundary layer

(a) Long term observations are needed at a few sites of differing bottom topography of:-

the friction velocity

u_* - (see 2.2, hence K_M, see A2);

the vertical heat flux

H - (see 2.2),

the thermal structure of the benthic boundary layer 2.3.2; the turbidity and its change with currents and thermal structure 2.3.2; tidal and other oscillatory flows (3.2.4); so that an adequate model of the layer can be evolved. These physical observations in the water column should be linked to simultaneous geophysical observations (e.g. heat flux in sediment, sediment roughness and composition, porosity, cohesive properties and movement), chemical observations (e.g. suspended particle composition, R_n - 222 and R_a - 228 profiles - see 2.3.2, pore water properties and convection, ion flux) and biological observations (e.g. sediment dispersed by marine organisms) discussed in other Chapters.

(b) Eventually these studies might become site specific (at potential sites for waste disposal) but in the initial stages a proper understanding of the dynamics of the boundary layer could best be gained from studies in different areas and thus in different parameter ranges. It is emphasised that a purely site-specific study may permit the development of a forecast model appropriate to that site, but will not be useful when extrapolation is needed to other areas to which a diffusing contaminent may be carried. Nor may it be valid as the conditions in the ocean change during the decay period of the long-lived radio-isotopes.

(c) Fundamental studies of the erosion and properties of fine grain cohesive sediments, and in situ methods for determining their stability, are needed.

8.3 Abyssal currents and circulations

(a) Except in a few special areas, insufficient is known at present of the abyssal circulation to predict with confidence even the mean direction of advection of a plume from a source on the sea bed. A facility should be developed to remotely track the long term (at least one year) advection and dispersal of clusters of neutrally buoyant instrumented floats near the ocean floor, thus to define the mean circulation and diffusion in ocean basins within which radio-active wastes may be dumped (see 3.4, 3.5 and 3.6).

A long term programme of research using these floats should be complimented by observations with current meters on fixed moorings and integrated with a theoretical programme of dispersal using numerical models (see 8.4). This programme could usefully be linked to that of 8.2 with float releases near areas of detailed boundary study. It is expected that this programme will lead to the identification of areas (e.g. continental slopes) where the presence of energetic processes indicate that mixing may be of great importance and which will subsequently be the subject of further study.

The application of dye (or other passive introduced marker) tracking methods used in the surface layers (see 4.7) to the study of diffusion in the depths of the ocean is fraught with difficulties of instrumentation and adequate sampling, both of the dye and of the possibly rare processes which lead to the most rapid diffusion. Nevertheless, it may untimately be necessary to resort to the tracking of a passive solute to assess vertical (or trans-isopycnal) diffusion rates in mid-water, and techniques should be kept under review.

8.4 Modelling

Several numerical models of ocean circulation and mesoscale eddies already exist (see 6.2.3) but have not been used to trace diffusion of a plume from a sea bed release. The introduction of 'marked particles' into the Rhines or Owens-Bretherton type models of mesoscale eddies and other numerical models of parts of the ocean would be a useful starting point for studying release and dispersion from near bottom in mid-ocean in a realistic manner. Such modelling, including some features of the topography and parameters appropriate to the area, should be made in close co-ordination with the float programme 8.3. Once the numerical techniques have been tested and proved adequate to model dispersion, such modelling could usefully become site specific when a set of possible disposal sites have been selected. It might then be used to predict concentration levels near the site following accidental release of radio-active waste, perhaps using as input a range of measurements from moorings, in much the same way as forecast charts of the weather are constructed. Such a facility might be particularly useful in assessing pilot studies of sites and in determining sensitive regions for monitoring. The random walk methods now being developed at Liverpool University (7.2.4) to provide estimates of diffusion seem most appropriate to oceanic diffusion and are worth particular attention.

Modelling climatic changes and consequent changes in oceanic circulation (see 6.1) is one of the objectives of CARP and is a long term multidisciplinary study which, having relevance to radioactive waste disposal, should be kept under review and encouraged where possible.

Appendix 1. Structure of the Benthic Boundary Layer

The viscous conductive layer, very near the sea bed.

The thickness is the smaller of

(a) velocity layer $\delta \sim 12\nu/u_*$ typically 2 cm

and (b) thermal layer $h \sim \left(\frac{R_{ac} c_p \rho \nu K^2}{\alpha g H} \right)^{1/4}$, typically 3.5 cm.

Velocity Profile : $\frac{u}{u_*} = \frac{u_* z}{\nu}$

Temperature Profile : $\frac{\theta(0) - \theta(z)}{\theta_*} = \frac{u_* z}{K}$

The boundary layer is smooth if $d < \frac{3\nu}{u_*}$

and rough if $d > \frac{3\nu}{u_*}$.

Velocity Layers

The logarithmic sub-layer of the constant stress layer

The thickness of this velocity layer is about $0.2\, c_f^{1/2} u_*/f$, typically 10 cm.

Velocity Profile $\frac{u}{u_*} = \frac{1}{K_v} \left(\ln \frac{z}{z_0} + \frac{bz}{L_M} \right)$, A(1)

where $z_0 \sim 0.1 \frac{\nu}{u_*}$, if surface is smooth,

$z_0 \sim d/30$, if surface is rough,
and b is about 5. Usually $z \ll L_M$ and the second term in the bracket can be ignored.

$$K_M = k_v u_* z \qquad A(2)$$

The logarithmic sub-layer

The velocity profile (1) is observed to extend heights above the bottom which exceed the limits of the constant stress layer, about 1 m being typical, and A(2), continues to be approximately valid.

The Ekman Layer

Thickness $k_v u_*/f$, typically extending up to 1-10 m above the sea floor and including the logarithmic layer in its structure. Csanady's (90) formulae for the veering, ψ_0, in the Ekman Layer:

$$\left(c_f^{-1} - A\right)^{1/2} = \frac{1}{k_v} \ln \frac{u_*}{f z_0} + B$$

$$\sin^2 \psi_0 = A c_f$$

where $A \sim 25$, $B \sim -5$ in neutral conditions of stratification.

Thermal layers, according to (89).

Forced convective layer

In $h < z < 0.03 L_m$:

Temperature gradient $-\frac{d\theta}{dz} = \frac{\theta_*}{K_v z} = (K_v u_*)^{-1} \frac{H}{c_p \rho z}$ (logarithmic profile
A(3)

K_H has values close to those of K_m.

Mixed convective layer

In $0.03 |L_m| < z < |L_m|$:

Temperature gradient $-\frac{d\theta}{dz} = 1.05 \left(\frac{H}{c_p \rho}\right)^{2/3} (ga)^{-1/3} z^{-4/3}$.

Natural convective layer

$|L_m| < z$:

Temperature gradient $-\frac{d\theta}{dz} = 2.6 K_v^{-2/3} u_*^2 (ga)^{-1} z^{-2}$.

In practice it is frequently observed that the layer of the ocean above the sea bed is fairly isothermal, with a sharp change in temperature at the top separating it from the overlying stratified water some 50 – 100 m above the sea bed. This is discussed in section 2.3.2.

Appendix 2

Measurement of u_* and H in the benthic boundary layer

1. Measurement of friction velocity, u_*

Method A. The horizontal, u and vertical, w, components of current are measured simultaneously in the constant stress layer and the mean product($\sim$the Reynolds Stress) is found:

$$u_*^2 = \overline{uw}. \qquad A(4)$$

Method B. Observations of u at at least two levels in the logarithmic sub-layer are used to determine u_* from A(1), assuming $z \ll L_M$ (near neutral conditions).

Method C. The frequency spectrum of velocity, $S(n)$, is determined from measurements of u in the logarithmic layer. Then,

$$u_* = (K_v z)^{1/3} \left[\alpha^{-1} \bar{u}^{-2/3} n^{5/3} S(n) \right]^{1/2} \qquad A(5)$$

for $z^{-1} \ll n\bar{u}^{-1} \ll L_k^{-1}$,

where $\bar{u}$ is the mean current, L_k is the Batchelor fine scale, $(K^2\nu/\epsilon)^{1/4}$, typically 1 cm, and α is a constant, about 0.135 (3, equation 8). This formula derives from Kolmogorov theory of the inertial subrange, and the Taylor hypothesis. No direct method of determining the stress on the sea bed and then u_*, (for example by drag plates) is as yet available.

2. Measurement of heat flux, H

Four methods are available:-

Method a. (The direct classical method). The temperature gradient $\bar{\theta}'$, in the sediment is measured using a sediment penetrating probe, and a sample of sediment taken to obtain its thermal conductivity, c.

Then $H = -\bar{\theta}' c$.

Method b. The temperature, θ, and vertical velocity component, w, are measured simultaneously in the logarithmic layer and the mean product given the heat flux

$$H = c_p \rho \overline{\theta w}. \qquad A(6)$$

Method c. The frequency spectrum of the temperature, $\Phi(n)$, is determined from measurement of temperature in the logarithmic layer. Then

$$H = c_p \rho u_* (K_v z)^{1/3} \left[\beta^{-1} \bar{u}^{-2/3} n^{5/3} \Phi(n)\right]^{1/2}, \qquad A(7)$$

where β is about 0.09. This equation, from (3 , equation 9) holds in the same conditions as that for A(5).

Method d. The temperature gradient in the forced convective layer may be determined and H found from A(3).

It should be noted in assessing the usefulness of the various methods, that since $\sigma_w \equiv (\overline{w^2})^{1/2} \doteqdot 1.25 u_*$ in neutral conditions (9); 2—; in observations in shallow water Bowden, (10), , finds

$\sigma_w \doteqdot 1.16 u_*$) it is necessary to measure w to high accuracy when the expected values of u_* are small. Simularily, in using method d great care is needed to measure the temperature gradient in the sea, since it is expected to be only slightly larger than adiabatic.

In the logarithmic layer the eddy diffusion coefficient of momentum, K_M, may be determined from A(2) once u_* is known. The eddy coefficient for heat is likely to have similar values. At higher levels K_m may be determined using the equation

$$K_m \doteqdot \beta_i \, \sigma_w \lambda_m , \qquad A(8)$$

where β_i is about 0.44 and λ_m is the equivalent wavelength for the peak (if one exists) in the product of the u- frequency spectrum $S(n)$ and frequency n (found from the Taylor Hypothesis, $n/k = \bar{u}$, see 1) .

Appendix 3

Notation

Symbol	Meaning	Typical Values near deep ocean floor.
A	a constant, about 25.	
A_0	value of K_H in neutral conditions	
a	thermal coefficient of volume expansion	$1.9.10^{-4}$ $^{o}C^{-1}$
a_1	Rossby radius of deformation	
B	a constant, about -5	
b	a constant, about 5	
c	thermal conductivity of sediment	
c_1	wave speed	
c_p	specific heat at constant pressure	0.92 cal.gm.$^{-1}$ $^{o}C^{-1}$
D	sediment particle size	
d	characteristic size of surface roughness	
f	Coriolis parameter (frequency)	$7.7.10^{-5}$ rad s^{-1} at 32^{o}.
g	acceleration due to gravity, about 981cm.^{2}s^{-1}	
H	upward vertical heat flux through the ocean floor	$1.5.10^{-6}$ cal cm^{-2} s^{-1}
h	thickness of conductive layer	3.5 cm.
K	horizontal eddy diffusion coefficient of dye patch	
K_H	vertical eddy diffusion coefficient of heat	
K_M	vertical eddy diffusion coefficient of momentum	
k	wave number	
L_m	Monin-Obukov length	100 m.
L_B	Batchelor fine scale	0.5 cm.

Symbol	Meaning	Typical Values near deep ocean floor
L	horizontal length scale	
N	Brunt-Väisälä frequency, $N^2 = -\frac{g}{\rho}\frac{d\rho}{dz}$.	6.10^{-4} rad.s^{-1}
n	frequency	
P_r	Prandtl Number	
R_e	Reynolds number, $u_* D/\nu$.	
R_i	Richardson number, $N^2/\left(\frac{du}{dz}\right)^2$.	
R_{ac}	critical Rayleigh number	
$S(n)$	frequency spectrum	
S	salinity	
u	horizontal velocity component	
u_*	friction velocity , $\sqrt{\tau/\rho}$.	0.1 cm s^{-1}
u_{100}	horizontal speed at 100 cm above sea level.	
w	vertical velocity component	
x	horizontal co-ordinate	
z	vertical co-ordinate	
z_0	roughness length	
α	constant	
β	northward gradient of the Coriolis perimeter	
β_1	constant, approximately 0.44	
γ	angle of continental slope	
δ	thickness of viscous layer	2 cm.
Γ	adiabatic lapse rate	
ϵ	rate of turbulent dissipation of energy	dissipation of
h_s	thickness of boundary layer on slope	3 m.
θ	temperature	
θ'	vertical derivative of temperature	

Symbol	Meaning	Typical Values near deep ocean floor
θ_*	$= H / c_p \rho u_*$	
θ_1	see caption of figure 2	
κ_v	Von-Kármán constant, about 0.4	
κ	molecular thermal diffusivity	$1.4 \cdot 10^{-3}\ cm^2 \cdot s^{-1}$
ν	Kinematic viscosity	$1.8 \cdot 10^{-2}\ cm^2 . s^{-1}$
ρ	density of sea water	$1.05\ gm.cm^{-3}$
ρ_s	sediment density	
σ_w	r.m.s. vertical velocity	
τ	shear stress, $\tau = \rho u_*^2$.	
ψ_0	angle between direction of flow at base of logarithmic layer and in flow above the boundary layer.	10 deg.
ω_0	see equation 11.	

REFERENCES

1. Pasquill F. Quart. J. Roy. Met. Soc. 97, 369 (1971).

2. Pasquill F. 'Atmospheric Diffusion', Halsted Press, New York, London, Sydney, Toronto. (1974).

3. Wimbush M. & Munk W. in 'The Sea', 4 (1) 731 Ed. Maxwell, John Wiley & Sons.(1971).

4. Miller, M.C. McCave I.N. & Komar P.D. Sedimentology 24 507 (1977).

5. Soulsby R.L. I.O.S. Report, 27. (1977).

6. Caldwell D.R. Rev. Sci. Instr. 39, 1865 (1968)

7. Sternberg R.W. Deep-Sea Res. 16, 549 (1969)

8. Wimbush M. Nature 227 (5262) 1041 (1970).

9. Wimbush M. & Sclatter, J. J. Geophys. Res. 76 529 (1971).

10. Bowden K. J. Geophys. Res. 67 3181 (1962).

11. Heathershaw A.D. Nature 248 394 (1974).

12. Soulsby R.L. J. Phys. Oceanog 7 934 (1977).

13. Thorpe S.A., Collins E.P. & Gaunt D.I. Deep-Sea Res. 20, 933 (1973).

14. Brown W. Munk W. Snodgrass F. Mofjeld F. & Zelter B. J. Phy. Oceanog. 5, 75 (1975).

15. Eittreim S., Thorndike E.M. & Sullivan L. 1976. Deep-Sea Res 23, 1115 (1976).

16. Armi L. & Millard R.C. J. Geophys. Res. 81, 4983 (1976).

17. Greenwalt D. E.O.S. 58 (12) 1163 (1977).

18. Broecker W.S, Feely H.W. & Sarmiento J. Proc. Verb 14, 99 (1975)

19. Sarmiento J.L., Feely H.W., Moore W.S., Bainbridge A.E. and Broecker W.S. Earth and Planetary Science Letters 32, 357 (1976).

20. Broecker W.S. & Bainbridge A. J. Geophys Res. 83 (14) 1963-1966 (1978).

21. Bell T.H. Nature 251, 43 (1974)

22. Bell T.H. J. Geophys. Res 80, 320 (1974)

23. Armi L. J. Geophys. Res. 83, 1971-1979 (1978)

24. Turner J.S. 'Buoyancy Effects in Fluids', Cambridge Univ. Press. (1973).

25. Pekeris C.L. & Accad Y. Phil Trans Roy. Soc. 265, 413 (1969).

26. Bowden K.F. J. Fluid Mech. 21, 83 (1965)

27. Pollard R.T. & Millard R.C. Deep-Sea Res. 17, 813 (1970).

28. Sanford T.B. J. Geophys. Res. 80, 3861 (1975).

29. Hayes, S.P. DOMES Bottom Water Physical Oceanography Component, DOMES Unpub. Ms. No. 4, NOAA, Seattle, Wa. (1977).

30. Crease J. J. Geophys. Res. 67, 3173 (1962).

31. Wunsch C. Deep-Sea Res. 19, 577 (1972).

32. Swallow J.C. MODE Hot Line News 2 (33) (1973)

33. Sverdrup H.U, Johnson M.W. and Fleming R.H. 'The Oceans, their physics, Chemistry and general biology'. New York, Prentice Hall (1942).

34. Freeland H.J., Rhines P.B. & Rossby J. J. Mar. Res. 23, 383 (1975).

35. Taylor G.I. Proc. Lond. Math. Soc. A. 20 196 (1921).

36. Hogg N.G. J. Fluid Mech. 58, 517 (1973).

37. Hogg N.G. Deep-Sea Res. 20, 449 (1973).

38. Worthington L.V. 'On the North Atlantic Circulation' Johns Hopkins Univ. Press, Baltimore. (1976).

39. Stommel H. Deep-Sea Res. 5, 80 (1958).

40. Reid J.L. 'Intermediate waters of the Pacific Ocean', Johns Hopkins Oceanog. Series Vol. 2. (1965)

41. Nowlin W.D., Whitworth T. & Pillsberg R.D. J. Phys. Oceanog 788 (1977).

42. Munk W. Deep-Sea Res. 13, 707 (1966).

42[1] Thorpe S.A. J. Fluid Mech. 32, 694 (1968)

43. Thorpe S.A. J. Fluid Mech. 85, 7 (1978).

44. Woods J.B. J. Fluid Mech. 32, 791 (1968).

45. Gregg M.C. J. Phys. Oceanog. 5, 253 (1975).

46. Cairns, J.L. J. Geophys. Res. 80 299 (1975).

47. Simpson J.H. Deep-Sea Res. 22, 619 (1975).

48. Erikson C.C. WHOI. Tech. Rep. WHOI-77-16, 166pp. (WHOI/MIT Ph.D. thesis) (1976).

49. Garrett C. & Munk W. Deep-Sea Res. 19, 823 (1972).

50. Williams A.J. Science 185, 941 (1974).

51. Gargett A.E. J. Phys. Oceanog 6, 139 (1976).

52. Gregg M.C. J. Geophys Res. 81, 1180 (1976).

53. Gregg M.C. J. Phys. Oceanog. 6, 528 (1976).

54. Gregg M.C., Cox C.J. & Hacker P.W. J. Phys. Oceanog 3, 458 (1973).

55. Munk W.H. & Anderson J. Mar. Res. I, 276 (1948).

56. Kullenberg G.E.B. Estuarine & Coastal Mer. Sci. 5, 329 (1977).

57. Bowden K.F. Mem. Soc. Roy des Sci de Liege 6e ser. 2, 67 (1971).

58. Obuko A. Deep-Sea Res. 18, 789 (1971).

59. Joseph J. & Sendner H. Dtsch Hydrog. Z. 17, 57 (1958).

60. Ozmidov R.V. Bull. Acad, Sci. USSR. At. & Ocean Phy. Ser 1. 439 (1965).

61. Kullenberg G.E.B. Tellus 29, 572 (1977).

62. Wunsch C. & Hendry R. Geophys. Fluid Dyn. 4, 101 (1972).

63. Rattray M. Tellus 12, 54 (1960).

64. Wunsch C. J. Fluid Mech. 35, 131 (1969).

65. Wunsch C. Deep-Sea Res, 17, 293 (1970).

66. Pingree R. Deep-Sea Res. 19, 549 (1972).

67. Wu J. J. Fluid Mech. 35, 531 (1969).

68. Manins P.C. J. Fluid Mech. 74, 547 (1976).

69. Turner J.S. & Chen C.F. J. Fluid Mech. 81, 757 (1974).

70. Linden P.F. & Weber J.E. J. Fluid Mech. 81, 757 (1977)

71. Gill A.E. & Clarke A.J. Deep-Sea Res. 21, 325 (1974).

72. Allen J.S. J. Phys. Oceanog. 3, 245 (1973).

73. Mooers C.N.K., Collins, C.A. & Smith R.L. J. Phys. Oceanog 6, 3 (1976).

74. Pedlosky J. J. Phys. Oceanog. 8, 171 (1978).

75. Killworth P.D. J. Phys. Oceanog. 8, 188 (1978).

76. Ruddiman W.F., Sancetta C.D. & McIntyre A. Phil Trans. Roy. Soc. B. 280, 119 (1977).

77. McIntyre A., Rudderman W.F. & Jantzen R. Deep-Sea Res. 19, 61 (1972).

78. Bryan K. Manabe S. & Pacanowski R.C. J. Phys. Oceanog. 5, 30 (1975).

79. Killworth P.D. Deep-Sea Res. 24 427 (1977).

80. Gill A.E. J. Fluid Mech. 32, 462 (1968).

81. Rhines, P. & Bretherton, F.P. J. Fluid Mech. 61, 583 (1973).

82. Anderson D.L.T. Bryan K. Gill A.E. & Pacanowski Ocean modelling 6, 6.8 (1977).

83. Rhines P.B. J. Fluid Mech. 69, 417 (1975).

84. Owens W.B. & Bretherton F.P. Deep-Sea Res. 25 1 (1978).

85. Bretherton F.P. Quart. J. Roy. Met. Soc. 101 705 (1975).

86. Grimwood P.D. & Webb G.A.M. Nat. Radiol, Protection Board. Tech. Rep. NRPB-R48 (1976).

87. Grimwood P.D. & Webb G.A.M. Nat. Radiol, Protection Board. Tech Rep. NRPB-R58. (1976).

88. Shepherd J.G. MAFF Fisheries Research Tech. Rep. No. 29 (1976)

89. Townsend A.A. Quart. J. Roy. Met. Soc. 88, 51 (1962).

90. Csanady G.T. J. Atms. Sci. 24, 467 (1967).

CHAPTER 4

High level Radioactive Waste Disposal in the Ocean

Marine Biological Research Requirements

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High Level Radioactive Waste Disposal in the Ocean

Marine Biological Research Requirements

Summary

1. The paper attempts to identify the research requirements for exploring the relationship between a sea bed disposal programme, the deep sea ecosystem, and man.

2. A brief account is provided of the main features of the oceanic ecosystem from the sea surface to the benthic boundary layer.

3. The paucity of the available quantitative data is emphasized and the importance of a knowledge of rate processes in understanding the energetics of the ecosystem is also stressed.

4. Possible biological mechanisms by which material might be transported from one part of the ecosystem to another are outlined. These include diurnal, seasonal and less regular vertical and horizontal migrations intimately associated with feeding and reproductive strategies.

5. The available knowledge of the likely direct effects of radioactive waste disposal on the oceanic ecosystem is summarised and some consequential indirect effects on man are identified.

6. In identifying future research requirements the key question is considered to be whether or not any biological processes exist which might transport significant quantities of biomass from the abyssal sea bed back to the sea surface. While it is acknowledged that the available information indicates that such transport is unlikely to be very significant, it is emphasized that the available data are inadequate.

7. In order to supplement these data so that the key question can be answered with more confidence a case is made for research in the

following main areas:

(a) Identification and taxonomy

(b) Spatial patchiness

(c) Community analysis and zoogeography

(d) Improved biomass estimations

(e) Feeding strategies

(f) Reproductive strategies

(g) Diurnal migrations

(h) Ontogenetic migrations

(j) Feeding migrations

(k) Migration up the continental slope

(l) Mathematical modelling of the oceanic ecosystem

8. Finally, an attempt is made to identify which parts of this suggested research programme could and should be undertaken by U.K. laboratories, which parts might be left to non-U.K. organisations, and which parts will require international collaboration.

1. Introduction

The existing models of the dispersal of radioactive isotopes after their disposal in the deep sea either on the sea bed or within the sea bed are entirely physical (1) and have ignored possible mechanisms whereby biological processes may accelerate the movement of isotopes. Furthermore the underlying aim of these models has been to estimate the potential maximum direct dosage to man, so indirect effects have been ignored. Also the degree of spread of any deleterious effects on deep sea communities needs to be examined from a conservationist viewpoint to ensure the public acceptability of any dumping programme. This paper seeks to identify the research requirements for exploring the relationship between a sea bed disposal programme, the deep sea ecosystem, and man.

2. The Oceanic Ecosystem

2.1 The water column is divided for convenience into three main zones, the epipelagic, the mesopelagic and the bathypelagic. Although the boundaries between these zones are not always clearly defined, there are differences in ecological processes between each zone which are important.

2.1.1 The epipelagic zone

The epipelagic zone stretches from the surface to the bottom of the seasonal thermocline which is usually around about 200-250m depth. Wind driven vertical mixing occurs in the stratum above the top of the thermocline and it is within this layer that all the primary productivity in the ocean occurs. Primary production is the term given to the growth of plants (phytoplankton) through the utilisation of the sun's energy by the process of photosynthesis to convert the simple molecules of carbon dioxide and water in to high energy complex organic molecules such as sugars and proteins. This is the prime food source for all animals in the oceans from the surface to the greatest depths. Oceanic plants are nearly all microscopic. Although the quantity or standing crop of plants within the surface layers at any one time is small, the turnover rate is high so that the amount of plant material grown per year (i.e. the productivity) is equivalent to plant production on land (where the standing crop, i.e. the amount of grass, trees and shrubs one can see around, is much higher).

The microscopic plant cells are grazed by small animals which filter them out of the water. These herbivorous animals which are usually small (ranging in size from around 100µm to about 10-20mm in length) constitute part of the plankton. Other planktonic animals include carnivores and detritivores (animals that feed on detritus). The larger animals or nekton are mostly carnivores feeding on the plankton or other nektonic animals.

At the top end of the size range of nektonic animals are the fishes and whales that are commercially exploited by man.

From all these organisms in the epipelagic zone falls a rain of detritus consisting of faecal pellets and dead bodies. This rain of material is an important food supply to deep-living communities. Corpses of many of the larger animals have sinking rates that ensure they reach the bottom before either bacterial degradation can occur to any extent or midwater scavengers can locate and consume them. These are possibly particularly important to sea bed communities.

In figure 4.1 the main pathways of movement of biomass are indicated. However, these do not necessarily indicate all the pathways of energy flow. Assimilation rates are seldom greater than 50% - this is the percentage of organic material that is absorbed by a consumer, the remainder being passed out in the faeces. Metabolic efficiencies are seldom greater than 20%, i.e. only a fifth of what is consumed is converted into new biomass, the remainder is either excreted or else is 'burnt up' by the consumer's metabolism.

2.1.2 The mesopelagic zone

This zone extends from about 200m to 1000m, either the depth of the oxygen minimum, or else the deepest depth to which detectable daylight penetrates. No primary production is possible in this zone because it is below the maximum depth to which sufficient sunlight can penetrate to allow plant growth to occur. The animals within this zone are either a) detritivores feeding on the rain of faecal pellets and other organic debris from the epipelagic zone or b) grazers which inhabit this zone by day and migrate up into the surface layers at night, or c) carnivores

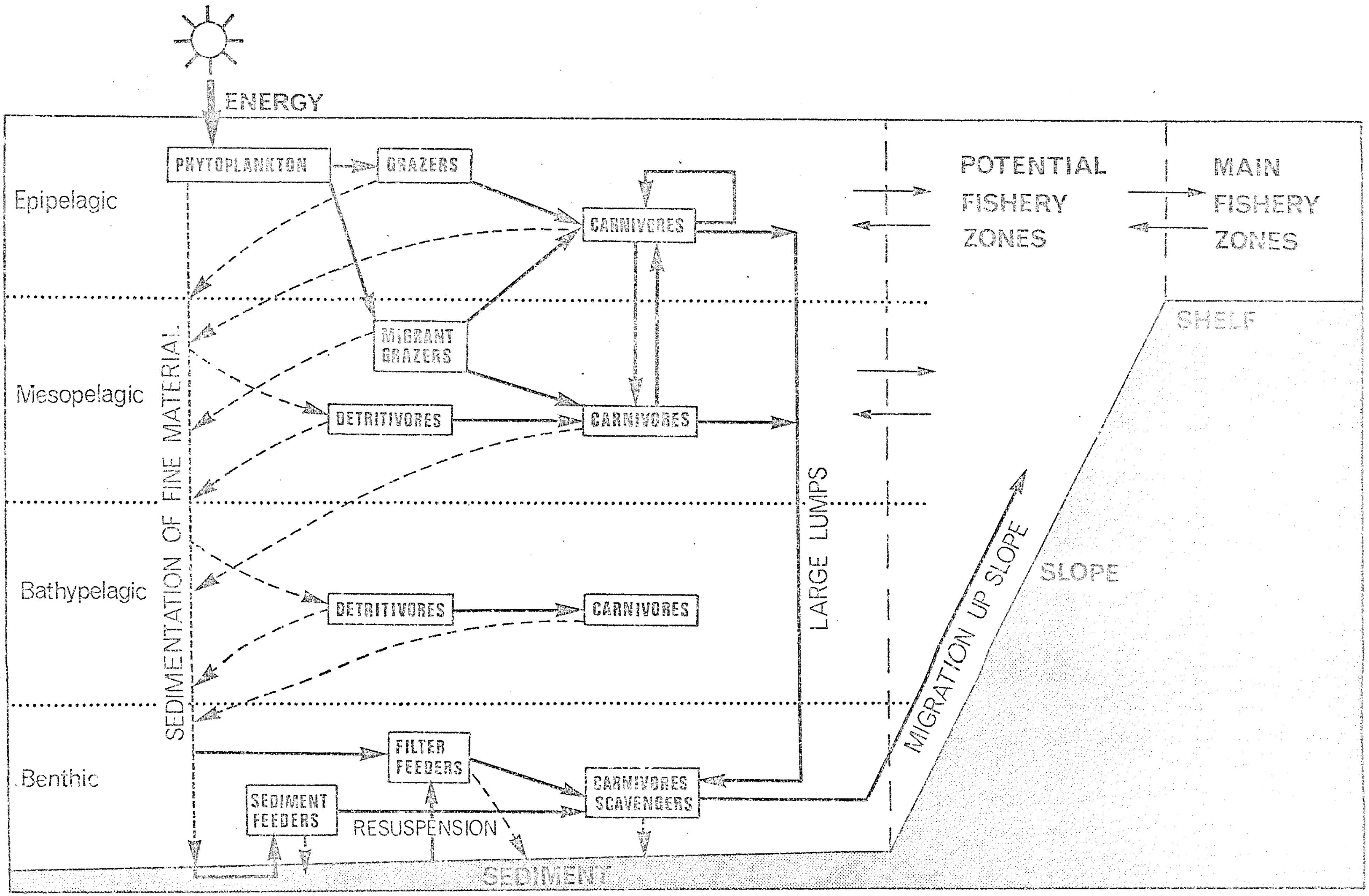


Fig.4·1 Schematic diagram of bentho – pelagic ecosystem.

that either reside within the zone or migrate into the surface layers at night. Hence in figure 4.1 the grazers and carnivores are linked with the epipelagic zone. This zone is the maximum depth to which commercial fisheries are likely to operate economically (e.g. the Espada fishery off Madeira).

2.1.3 The bathypelagic zone

For the subject of this report, the bathypelagic zone is considered to extend from 1000m to the sea bed. Other authors subdivide this zone, but the ecological significance of these subdivisions has yet to be established. The ceiling of the zone is possibly the maximum depth from which significant diurnal migration occurs to shallower depths (but see 4.3.1), certainly for planktonic species if not nektonic ones. Thus of necessity all organisms living at bathypelagic depths will either be detritivores, scavengers or carnivores. The volume of available biomass and the turnover rates of organic material at these depths are unlikely to be high enough to support the larger organisms that may make a significant contribution to the large lump supply to benthic communities; these large lumps are thus most likely to originate from the two shallower zones.

2.1.4 The benthic zone

The benthic community consists of all those organisms intimately associated with the sea bed and therefore living within, on or in the immediate vicinity of the bottom.

Like the phytoplankton benthic marine plants, mainly algae, are limited to regions where the light intensity permits photosynthesis, that is to areas where the sea bed is no more than a few tens of metres beneath the surface. Some animals groups, such as the fishes, are extremely rare or even absent from the very deepest parts of the ocean trenches, but otherwise, and certainly down to abyssal depths (to 6000m), all the major taxa are represented in the benthic community though their relative importance changes dramatically. The benthos therefore ranges from the relatively simple protozoan groups, through the sessile sponges and coelenterates (corals and anemones), the errant or sedantary polychaete worms, the molluscs and crustaceans, to the echinoderms, protochordates and fish.

For convenience the benthos is usually divided into two main size categories, though the distinctions between these are obviously not clear-cut. The meiofauna are those organisms which pass through screens with a mesh size of 300-500μm but are retained on screens of about 60μm mesh, while the macrofauna are retained on the coarser screens. A third, less well defined category, the megafauna, consists of those animals which are too large to be adequately sampled by grabs and corers but would appear on photographic surveys.

A more significant, though practically less useful, classification is that between suspension feeders, collecting small dead or living food particles from the water overlying the sea bed, and deposit feeders, living on organic material in and on the sediment surface. While suspension feeding is mainly typical of the sessile forms such as sponges, corals, the sedentary worms and mussel-like molluscs, deposit feeders tend to be mobile, though they may be very slow-moving or have a very limited foraging range. Predat species feeding on other benthic organisms may be considered as employing a special type of deposit feeding, but highly mobile benthopelagic predators feeding in mid water as well as on the bottom clearly do not fit easily into such a classification.

Suspension feeding is common in shallow areas where the water carries a high load of suspended organic material, or where currents continually replenish the food supply. It has been argued (2) that this feeding strategy also predominates in the very food-poor, deep, central parts of the oceans. However, the available data indicate that deposit feeding, including predation and scavenging (see below), is the dominant strategy throughout the deep sea benthos (3).

Except in very shallow regions, the benthic community is ultimately dependent upon food descending into the system from the surface regions of primary production. Until very recently this was believed to arrive almost entirely in the form of a "rain" of small particles. Because of the depredations of the mid water communities on this material during its descent less and less of it reaches the sea bed with increasing depth and this seemed to be reflected in the observed depth related decrease both in numbers of individuals and numbers of species taken in trawls and dredges. Improved sampling techniques during the 1950s and 1960s have tended to confirm the decreasing benthic biomass in the deep sea (see Section 2.1.5), but at the same time have revealed a previously unsuspected high diversity, with several animals groups being represented by many more species in the deep benthos than in shallower regions (4).

Two main hypotheses have been advanced to explain this high species diversity. According to the first (5), the so-called time-stability hypothesis, the long-term stability of the physical conditions in the deep sea has allowed high specific diversity by extreme niche specialisation. Since there is little environmental heterogeneity in the deep ocean it is assumed that this specialisation is in relation to feeding. The second explanation (3) suggests that far from being specialist feeders, since food is in such short supply in the deep sea, most benthic organisms are, of necessity, food generalists within the physical limitations set by size and morphology. The high species diversity is made possible according to this theory by high predation pressures keeping the populations of the smaller organisms so low that they are not in competition with one another either for space or food. A corollary of this theory is that specific diversity should be lower amongst the larger predators and, in general, this seems to be true.

Apart from the inherent academic interest of these concepts, they have considerable general significance. For while the time-stability hypothesis sees the deep sea benthic environment as extremely stable and homogeneous, advocates of the predation theory, while accepting its long-term overall stability, suggest that the benthic community is prone to small-scale disturbances both spatially and temporally. One source of such disturbance is assumed to be the activities of the predators or croppers, but another suggested source is the supply of food to the system. Because of the great depths involved and the low sinking rates it is suggested that the smaller particles may have little directly utilizable food value when they arrive at the deep sea floor. In this case the faster falling, larger parcels such as the bodies of dead euphausiids (krill), fish, squid, whales and so on may be a much more important source of food to the deep sea benthos. The arrival of such large lumps on any particular small area of sea bed would probably be more unpredictable than anywhere on the planet and this could be a potent source of biological oscillation.

Indirect evidence of the possible importance of such large food parcel has been provided by the results of baited camera and trap work which has demonstrated the existence of a considerable population of highly mobile scavengers in all areas of the deep ocean where such observations have been made (3,6,7,8,9). This scavenging community contains representatives of many animal groups, but seems to be dominated by fish and amphipod shrimps which are quickly attracted to the bait, and presumably to any naturally occurring large food parcel, and disperse after it has been consumed.

Apart from their obvious ability to locate and reach a large food parcel quickly, several of the scavenging animals seem to be highly adapted to making use of such an unpredicatable and irregular source of food.

Some of the amphipods, for instance, are able to gorge themselves to such an extent that the body becomes deformed and many of the limbs temporarily useless. Similarly, there is some evidence that they may be able to maintain a high level of "reproductive readiness" for long periods and then, perhaps complete the process rapidly after a single adequate feeding period.

Little is known of the food webs within the deep sea benthos (see section 4.2.1), but those organisms of which the gut contents have been examined seem to be fairly catholic in their tastes within the confines of their broad trophic strategies such as deposit or suspension feeding. The bentho-pelagic fish are perhaps something of an exception since, at least at mid-slope depths, they appear to feed largely on mesopelagic organisms (10). Little is known of the feeding strategy of abysso-bentho-pelagic fish, but from the available information it seems that large lumps would be an important source of food for them.

The major seasonal variations in temperature, light and food supply in the sea are restricted to the near surface zone. In the absence of such variations in the deep sea, seasonal reproduction is not to be expected. Although there is some indication of seasonality at mid-slope depths, the available data for the abyss indicate continuous reproduction in those organisms for which such information has been obtained.

Similarly, because of the remoteness from regions of primary production, the common practice amongst shallow water benthic organisms of producing large numbers of small, pelagic, planktotrophic larvae seems inappropriate for the deep sea benthos on theoretical grounds. In support of this view the deep sea representatives of several groups seem to produce fewer, larger eggs than their shallow-water counterparts indicating either totally abbreviated development or at least the production of large, lecithotrophic (yolk sustained) larvae. Some deep sea groups, such as the rat-tail fishes and some molluscs, nevertheless apparently produce pelagic eggs and larvae which move up to the surface layers but the extent of this strategy is still largely unknown (11,12,13,14).

The importance of a knowledge of the rates of such processes as metabolism, growth and reproduction in understanding the energetics of any biological system is emphasised in section 2.1.5. Because of the technological problems, direct measurements of such rates for the deep sea have so far been very rare. Those in situ experiments on the respiration rates of slope and abyssal benthic organisms which have been conducted indicate that metabolic rates in the abyss may be two orders of magnitude lower than on the continental shelves (15,16), though the metabolic activity of the intestinal microflora from trap-caught amphipods from the Aleution Trench was not significantly lower at in situ pressures than in atmospheric controls (17). Similarly, the single attempt so far made to age a deep benthic animal, a small bivalve mollusc, suggest a longevity of 100 years or so and an age at first maturity of 50-60 years, again an order of magnitude greater than is normal on the continental shelf (18). Finally, recolonisation experiments of defaunated sediment at almost 2000m (19) indicate that this process is much slower at this depth, both in terms of numbers of individuals and species, than on the continental shelf.

On the other hand, recent photographic studies (20) indicate that bioturbation in the deep sea, that is the disturbance of the sediment by organisms living within and on it, may be much faster than has previously been supposed.

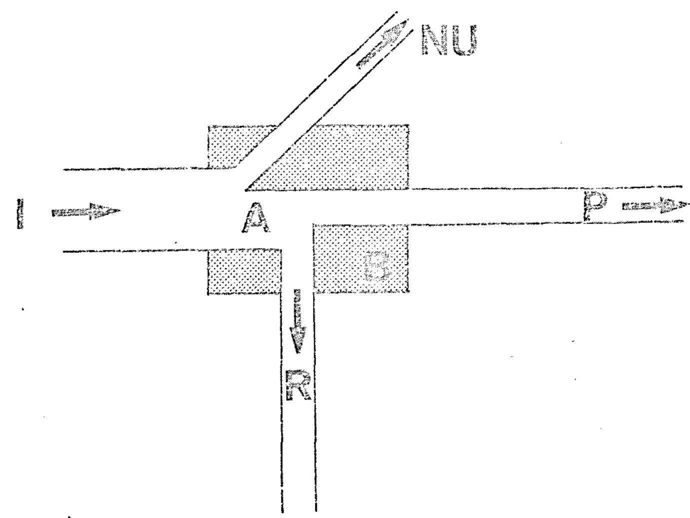
2.1.5 Biomass and energy flow

A quantitative understanding of any ecosystem requires the knowledge of three components, (i) the structure of the food web (ii) the biomass within the various components of the food web and (iii) the energy flow through the components. The latter point is often neglected but in fact is the most important. For instance a grazed field can have a low standing crop but a very high energy flow (in the form of organic compounds with a high energy content passing into the grazing cows. The relationship between the flow of organic material (or production) and standing crop (or biomass) is given by the following formula,

Production = biomass/turn over time

When describing a food web an attempt is usually made to split the biomass into 'trophic' levels with each level representing a stage in the food chain. Fig. 4.2 shows a generalised energy diagram for one trophic level (21). The first point to emphasise is that not all the input energy is useable. The ratio of the useable energy (A) to the input (I) is called the assimilation efficiency and usually is of the order 10 to 50%. Part of this assimilated matter goes towards maintaining the organism and is eventually lost as heat during respiration. The remainder can be transformed into new or different organic matter and results in growth and reproduction. This production (P) is, in turn, available as food for the next trophic level. The net transfer of energy through a trophic level is called the ecological growth efficiency (= P/I) and is usually around 20%. Thus, in a structured food pyramid the biomass of the top carnivores is often less than 1% of the plant biomass.

When an attempt is made to apply these techniques to the deep ocean ecosystem the extent of our present ignorance swiftly becomes apparent. The available biomass estimates are very few and measurements of efficiency are virtually non-existent. Also, as already discussed, benthic biomass is usually classified in terms of size rather than trophic position, as at present the benthic food web is poorly understood. Table 4.1 represents an attempt to produce a production budget for a 4000m water colum in the



I Input or ingested energy
NU Not used
A Assimilated energy
P Production
R Respiration
B Biomass

Fig. 4·2 Generalized energy flow model for a trophic level.

Iberian abyssal plain using the presently available knowledge. It must be emphasised that the figures should be treated with great caution as some of them have been extrapolated from work done in other areas, while others are no more than guesses which can only be estimated within an order of magnitude. The total secondary production is about 20% of the primary production and 90% of this secondary production takes place in the midwater, the remainder being available to the benthic system.

Fig. 4.3 is a very hypothetical diagram of the productive flow within the benthic ecosystem. The input to the system consists of the sediment rain, dead organic midwater organisms ("large lumps") and live midwater organisms which may perhaps be predated by the larger benthic macrofauna and megafauna. The existing data suggest that the sediment rain is the most important although this conclusion rests on the results of one experiment (24).

The available biomass estimates of the meio- macro- and megafauna all show a large statistical variation, even within a given small sampling area (25). It has been suggested (23) that the meiofauna become progressively more important in the deeper ocean, while at 2000m the megafauna and macrofauna have a similar biomass (26). This latter observation prompted the speculation that, as the megafaunal biomass could not be supported by the macrofauna (assuming a normal trophic pyramid), the megafauna must be largely dependent on 'large lumps' for their food supply. This interpretation has been challenged by Merrett (pers. comm.) who states that, at least at 2000m, observational evidence of stomach contents suggests the megafauna are predating on midwater organisms. However, at 4000m, large lumps may still be important and new evidence is needed to resolve this question.

Table 4.1 suggests that bacteria, although having a small biomass, can produce a high proportion of the benthic community production due

Table 4.1 Estimated production in a 4000m water column

Component	Standing Crop gC/m²	Turnover Time (yrs.)	Production gC/m²/yr	Percentage of Primary Production	Source
Primary Production	-	-	85	-	(22)
Plankton/nekton (0-1000m)	6	$\frac{1}{2}$	12	14	Unpublished IOS data
" (1000-2000m)	1.5	$\frac{1}{2}$	3	3.5	"
" (2000-4000m)	0.5	1-10	0.05-0.5	0.06-0.6	"
Benthic megafauna	0.004	1-10	0.0004-0.004	0.0005-0.005	"
Benthic macrofauna	0.08	1-10	0.008-0.08	0.01-0.1	(23)
Benthic meiofauna	0.08	1	0.08	0.1	(23)
Bacteria	0.002	20 hrs	0.9	1	(23)
Large lumps			0.001-0.01	0.0012-0.01	*
Particle sedimentation			1	1.2	(24)
			TOTAL	20%	

N.B. in estimating this total the larger values of a range have been used.

*This was calculated by assuming 50% of the world production of pelagic top carnivores sink to the sea bottom with no significant decomposition during sinking.

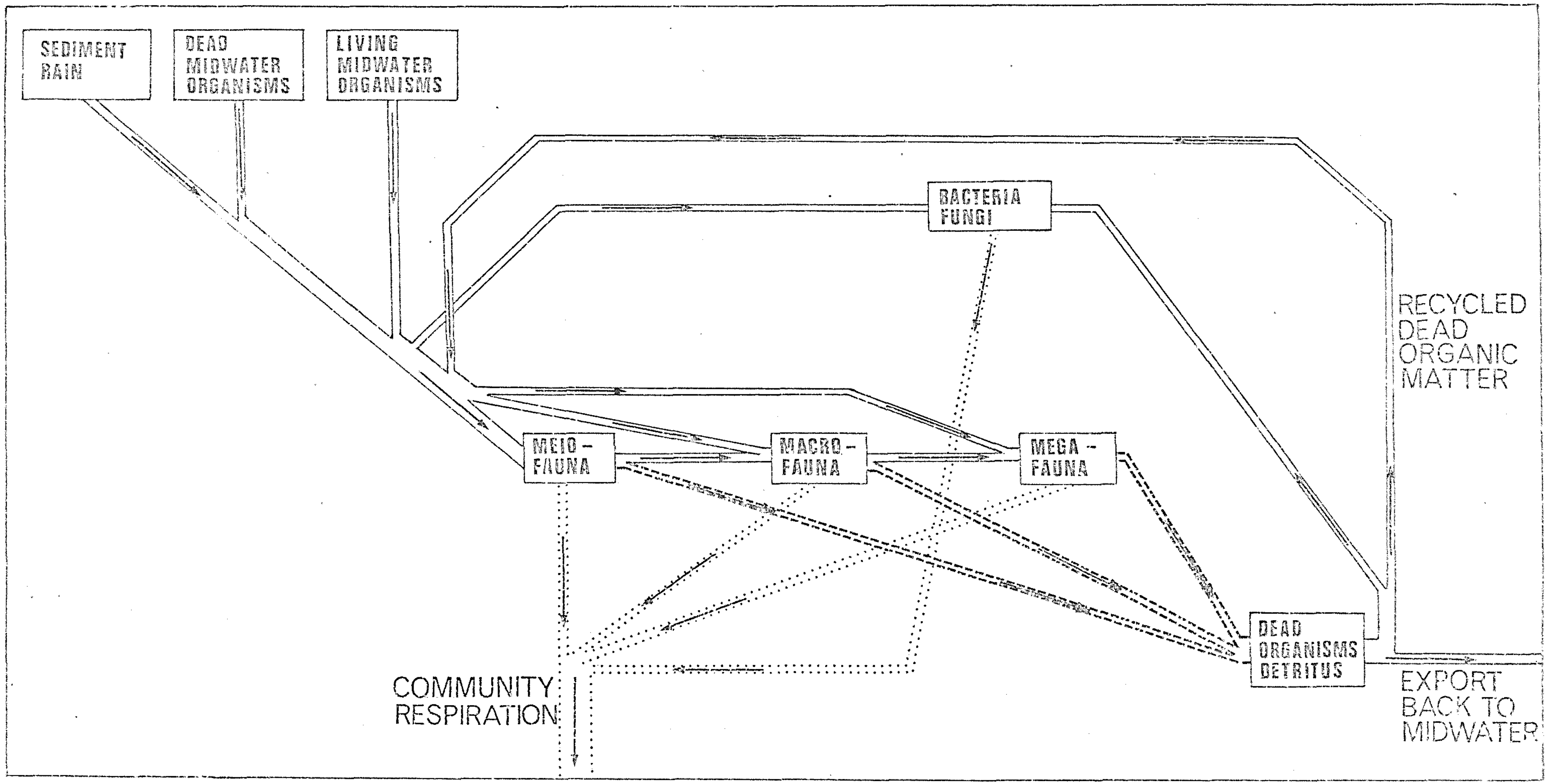


Fig.4·3 Flow of organic matter in the benthopelagic ecosystem.

to their high turnover rate. However, the significance of bacteria in the deep ocean benthos is still a matter of dispute due to a number of contradictory experimental results (23). This is yet another controversy that has to be resolved before the energy flow in the benthic ecosystem can be studied in any meaningful way.

There is some evidence (16) that suggests there is very little accumulation of dead organic matter on the sea floor. Most is probably recycled fairly quickly, although there is the possibility that some returns to the midwater which is obviously important for the waste disposal problem. The methods by which this might occur are discussed in the next two section. The biomass involved in this return flow cannot at present be estimated with confidence although it is unlikely to be a large percentage of the total benthic biomass. If we assume a conservative figure of 10% then, using the figures in table 4.1, this would represent 0.3% of the biomass found in the top 1000m. This level could still be important if the turnover time for this return flow was short (i.e. hours or months). At present we have no information on the turnover time, but a consideration of the likely pathways would suggest years rather than months. The tentative conclusion is therefore that this return flow is unlikely to be important relative to the total production in the top 1000m. However, it is always possible that effects such as selective predation by carnivores might produce a concentration of radioactivity in a similar manner to the concentration of DDT by hawks.

2.2 Special effects associated with continental slope

Continental slopes make up approximately 8-12% of the oceanic area. At the top of the slope, the shelf break is recognisable by a relatively sharp change in the planktonic fauna. This is partly produced by the change in the physical environment and partly by the rapidly diminishing influence of the benthic fauna on the midwater organisms, as the depth of the ocean falls away.

However there is evidence of the benthic slope fishes feeding on midwater organisms (27,28). Migration of deep-living fishes up the slope will bring them in contact with midwater fauna which they would otherwise always be too deep to encounter. Once they connected with the mesopelagic fauna, movement of material upwards would be accelerated through the diurnal behaviour of this fauna. Similarly the higher up the slope they move the more likely they are to come in contact with benthic organisms with planktonic larval stages. This contact would be in areas close to commercially exploited fish stocks and even closer to the potential deep-fishing grounds in which experimental fishing trials have already been attempted.

At present there is very little known about the way in which midwater organisms respond to the shoaling of the sea-bed. Vertical ranges may be pushed up particularly if light is an important environmental factor in controlling vertical range as the turbidity of the surface layers is greater on the shelf than in 'blue water'. Alternatively the range may be depressed, because of the higher availability of food resources close to the sea bed in the nephloid layer.

2.3 Biological transport processes that transfer biomass between the various zones

Knowledge of the transport of biological material is important in estimating the potential contribution of biological processes to the movement of radioactive isotopes in the ocean. To be able to estimate the upward vertical flux of material the dominant downward rates need to be accurately assessed.

2.3.1 Bioturbation

Bioturbation is the general term used to describe the disturbance of sediments by animals living in, on or immediately above them. The activities of those animals result in surface furrows, mounds, craters and burrows and generally cause a mixing of the upper layers of the sediment.

This disturbance rarely extends deeper than 20-30cm beneath the sediment/water interface and never more than a metre or so.

Often in shallow water bioturbation is a relatively rapid process, burrows and craters having a life measured in days or weeks (29,30). In the deep sea, where the biological activity is much lower and the physical environment much more stable, bioturbation is usually considered to be much slower and the resulting features to have a much longer life. In general this must be true, but recent photographic results indicate that bioturbation features may be hardly less ephemeral than in continental shelf regions (20).

Bioturbation may affect the mobilisation of waste material in three main ways. First the disturbance of the near surface layer will rapidly bring shallowly buried material to the water/sediment interface and, of course, vice versa. Second suspension of sediment may be caused by the active ejection of material into the water column during burrowing and feeding activities. Finally, water current erosion may be enhanced by bioturbation as a result both of unevenness of the sediment surface and by a change in the physical characters of the reworked material (31, 32).

However, direct effects of bioturbation on dumped waste material should not be overstated. It could have little effect on the mobilisation of material intentionally or accidentally dumped on the sea bed unless the waste in some way became incorporated into the upper layers of the sediment. For material embedded deeply in the sea bed, on the other hand, vertical transport resulting from bioturbation, affecting as it does only a few tens of centimetres at most, must represent only a very small fraction of the total transport system needed to move material to the sediment/water interface from the embedding site.

The disturbance of the surface sediment by bioturbation may, however, have important indirect effects on waste disposal strategy. Firstly, the interpretation of sediment geochemistry may be complicated by the destruction of the near surface stratification which would be established in undisturbed conditions. Secondly, the sediment geochemistry itself may be altered as a result of such disturbance. Thirdly, bioturbations may have an important effect on the resistance to erosion of muddy sediments.

2.3.2 Diurnal migration

Each night at low latitudes there is movement of plankton and nekton up towards the surface (33). These migrations can be extensive, (up to 500m), larger migrators tending to move greater vertical distances. The timing of the migrations tends to be associated with the change in the light regime, animals either following isolumes or being stimulated to migrate up by the rate of change of light intensity. Downward movement at dawn is possibly by passive sinking in certain species (34). Young juvenile stages are often non-migrants and the migratory habit progressively develops as the animal matures. At latitudes higher than about 40-45° little if any migration occurs during the winter, for example at 44°N 13°W in 1974 there was relatively little migration by planktonic organisms in April, although nektonic species like prawns were migrating extensively. Later in the year the planktonic organisms migrated extensively (Discovery Collections, unpublished data).

The function of these migrations is not established; theories include escape from predation, search for food, more efficient utilisation of metabolic energy, improved reproductive performance, etc. There is some evidence on the pattern of feeding in relation to these migrations (35,36) which is important to the understanding of the vertical fluxes of biomass. But there is surprisingly little quantification of the movement of biomass involved in these migrations. Most of the present data is restricted to the near surface 600-800m of the water column. The evidence of migration occurring from below 1000m is sketchy and unconvincing (37).

2.3.3 Ontogenetic migration

Ontogenetic migration is the result of different stages of the life history of organisms living at different depths in the water column. Many mesopelagic organisms have larval stages that occur in the epipelagic zone where there is an abundance of small food particles for the tiny larvae to feed on. A number of bathypelagic species like the angler fishes also have epipelagic larvae. Some benthic fishes such as the rattails (Macrourids) have midwater larval stages (38). The movement down into deep water may either be a gradual descent with the animals' gradual development, or a sudden downward migration at some critical stage of development. Benthic organisms in shallow water have planktonic larvae that act as a dispersive phase. With increasing depth a greater proportion of benthic organisms change their reproductive strategy away from the shot-gun approach of producing thousands or even millions of tiny eggs hatching into minute larvae that have to feed and grow in the epipelagic zone, to producing a few large eggs hatching into larvae with a very limited planktonic existence, or which may even be brooded by the adult. Even at abyssal depths there may be some species which have an extensive planktonic larval phase (13,14) and these are the species whose eggs and larvae could play a role in transporting radioactive isotopes. It is worth noting that the larvae of shelf species of benthic organisms, which have persistent planktonic larvae have been caught right across the Atlantic (39). There are no data available to quantify this movement.

In addition there are extensive seasonal migrations by midwater organisms that result in considerable upward fluxes of biomass at certain times of the year, particularly at latitudes higher than 40°. Discovery Collections at 44°N 13°W during 1974 showed both planktonic and nektonic species occurred considerably shallower in April than during the summer months. The deep-living mysid Eucopia (a shrimp-like crustacean) was caught at 450m where it was a diurnal migrant in April, but later in the year it was rare above 1000m and probably no longer migrated diurnally. The copepod Calanus finmarchicus which is an extremely important food organism of commercial fish species and is very abundant north of 50°N in the N.E. Atlantic, overwinters in deep water as a stage V copepodite larva (possibly in a non-feeding state) and migrates up to the surface to mature and breed during the Spring bloom. There are insufficient data available to quantify the movement of biomass involved in these migrations.

2.3.4 Deposition of small and large particles

The most important flux of biomass down into the deep sea is by the sinking of particles both large and small down through the water column. The larger a particle, the faster it tends to sink, and the shorter the time that micro-organisms have to degrade the utilisable organic material. Very large particles such as the carcasses of large whales, sharks, and fishes such as tuna probably sink to abyssal depth in a day or two and may provide an important food source to benthic organisms (see 2.1.5). Fine particles tend to clump into aggregates especially in regions where midwater organisms are using mucus extensively for feeding (40).

The sinking of faecal pellets is especially important as a mechanism of accelerating the descent of organic material into the deep ocean. Salps, (pelagic tunicates) for example, are continuous feeders and in bloom conditions consume far more than they can assimilate. The salp faeces are wrapped in a mucus membrane which tends to distintegrate after a couple of days by which time the pellet will have sunk to a depth of 1000m. These are thought to be the source of living phytoplankton sampled at depths of around 1000m. Faecal pellets are found down to depths of 5000m but quantitiative measurements of the deposition rates are only just becoming available. These rates are important in quantifying the flux of biomass in the open ocean, as well as in the study of geochemistry and other geological processes in the region of dump sites (see Chapter 2, section).

2.3.5 Feeding migrations

Extensive vertical migrations are associated with feeding in some species. In sperm whales, which specialise in feeding on squid but will also take fish, 5% of dives off S. Africa were to deeper than 800m (41), and a sperm whale was caught, after a 1 hour 52 minute dive off Durban over a sounding of 3200m, with a fresh bottom living shark in its stomach (42). Weddell seals are known to dive to 600m (43). In the reverse mode, McGowan (44) recorded the capture of a deep-living amphipod at 800m with sand in its stomach where the sounding was over 5000m over a wide surrounding area. The amphipod Eurythenes gryllus are notable in being caught in midwater with stomachs full of mineral particles (45). Discovery Collections include midwater captures of sea cucumbers (Holothurians) at depths of 4000-3500m over soundings of 5000m. Holothurians are likely to be particularly important, as sediment feeders, in the mobilisation of radioactive isotopes from surface sediments. Fishes which are usually considered to be benthic e.g. the rattail Coryphaenoides rupestris have been caught 270-1440m above the sea bed over depths of 1000-2100m (11) in the Denmark Strait, where they formed 45% of the total fishes caught.

2.3.6 Migration up the continental slope

The pelagic feeding of normally epibenthic fishes (27, 28, 46) highlights the potential problem associated with the continental slope region. The range of these fishes stretches from abyssal regions to well up the continental slope. This implies that quite extensive horizontal migrations by these fishes may occur which could take them from areas on the abyssal plain to high up the continental shelf. There they would come in contact with a progressively richer midwater fauna and be stimulated into migrating up off the sea bed to feed. Radionuclides, released by the excretion of these fishes in midwater, might then be linked with midwater organisms that diurnally vertically migrate into the surface layers, or the fish containing the isotopes may be eaten by large predators such as sperm whales.

Also, nothing is known of the influence of the slope on the vertical ranges of midwater species. If, as seems the case, the availability of food is greater close to and on the bottom as compared with the overlying water, then midwater organisms may well extend their vertical ranges deeper down the slope than in the open ocean. If midwater animals living deep near the slope are advected offshore then their movement back up to their normal vertical range could move significant quantities of biomass up the water column.

3. Présent knowledge of the interactions between a waste disposal scheme and the ecosystem

3.1 Benthic organisms

While there is an extensive literature on the biological effects of organic and heavy metal pollutants on shallow water organisms (47), little is known of the effects of radioactive materials on these animals and there is no information available on the effects of any pollutants on the deep sea benthos. In this situation any forecast of the possible effects of radio-active waste must be highly conjectural and based on indirect evidence.

Assuming that any waste dumping would be restricted to a small number of sites and that lateral transport in highly toxic concentrations would be small, any really dramatic effects, such as the total annihilation of the animal community, should be quite localised. In the highly variable environments typical of many shallow water and land areas even such localised damage might be very serious, since populations of rare species whose distribution happened to coincide with the affected region might be considerably reduced or even become totally extinct. The observed relative constancy of the deep sea environment would appear to minimise such effects since, in general, abyssal species tend to be very widely distributed so that devastation would have to be extremely extensive to cause such extinction.

On the other hand, this constancy of the abyssal environment probably means that the local effects of disturbance would be particularly severe. Indirect evidence for this is furnished by the high species diversity encountered in the deep sea for although, as indicated in section 2.1.4, there are differences of opinion about how this diversity has arisen, there is general agreement that the long-term stability of the environment has been a key factor. The inevitable corollary is that the abyssal benthos is likely to be very sensitive to any sudden changes, and there is good evidence from the observed slow growth and recolonisation rates that it would carry the scars for a very long time.

3.2 Midwater organisms

Little is known of possible effects of waste disposal on the midwater ecosystem. Grimwood and Webb (1) reviewed the known literature on accumulation rates of radionuclides and assumed concentration factors of 10^4 for all elements other than Cs and Sr. Although there is no reason to expect deep living organisms to differ in this respect, the evidence to hand so far is all for surface organisms; it is important to confirm these results particularly for organisms that are likely to be highly mobile between depth zones. Effort, too might be best focussed on organisms that are known to process large volumes of water, and to have an exceptional ability to concentrate ions. For example salps have been shown to migrate vertically at least 1000m (48), they continually filter water and they concentrate Vanadium by a factor of 2.5×10^5 (49). Furthermore, they filter large volumes of water (e.g. each animal of Pegea confederata filters 100 mls per minute (50).

The toxic effects of radioactive isotopes do not appear to have been much studied. The accumulation of insecticide residues, Polychlorinated Biphenols (PCB) and heavy metal ions in some organisms is well documented, but as yet no clear evidence of deleterious effects have been recorded. However, effects do not have to be lethal to have important and far reaching effects. Oceanic communities, particularly the deeper-living communities are extremely fragile i.e. any minute perturbation of the environment is likely to cause drastic and irreversible effects. If pathways of significance do exist between the deep-living communities and the epipelagic zone, changes in these communities could have an influence on the organisms of the epipelagic zone with potentially serious indirect effects on man. For example important fisheries may be effected - not directly by contamination with radioactive isotopes, but by an upset of the ecological balance. The oceanic ecosystem plays an important role in the regeneration of atmospheric oxygen and in the removal of carbon dioxide; subtle effects of radioactive pollution could interfere with this role. It is therefore extremely important not only to consider the potential direct dose to man, but also the effects of sublethal doses on the marine ecosystem.

3.3. Whales

Special attention should be focussed on whales as

a) They form a rapid and direct route to man. Sperm whales are known to be able to feed on the bottom at depths in excess of 1000m. Rorqual whales feed at shallow depths but consume vast quantities of zooplankton.

b) They perform long distance migrations so they could carry contaminants over wide areas of ocean.

c) They are subject to extreme public interest and conservationist concern. Commercial exploitation of seals may also restart as a food resource; some species like the Weddell Seal are capable of diving to considerable depths.

3.4 Pelagic birds

There is considerable documentation of the effects of organochloride residues, and the accumulation of PCBs and heavy metals in sea birds, but little is known about the effects of radioactive isotopes on them. They are potentially important in linking the epipelagic oceanic areas with terrestrial environments. They are also of considerable interest to public opinion. Initial observations on mallard ducks feeding on a freshwater pond contaminated with Pn and Am indicate that only 5% of the isotopes consumed was assimilated into the body tissues (51).

4. Future research requirements

The initial question to be answered before any deep sea disposal programme should be begun even as a pilot scheme is whether or not any biological processes exist that may result in the movement of significant quantities of biomass from the abyssal sea bed (i.e. 5000m depth) back to the sea surface, as radio-isotopes are likely to be transported with the organic material. Present knowledge suggests that any such transport is unlikely to be very significant, but present knowledge is based on inadequate data. Research is needed that will identify and roughly quantify potential transport mechanisms, particularly as any such biological processes should be taken into account in site selection.

The necessary precision in the estimation of the rates of the fluxes of organic material will be greater should it prove necessary to attempt accurately to model the deep sea ecosystem. The building of such a model will require a large expenditure of scientific effort and research funds. Furthermore the time required to construct such a model, could well result in a setting back of the time table for the start of disposal. The research requirements would also be well beyond the resources of any one nation or small group of nations.

In drawing up the research requirements in the various fields of interest there has been a noticeable marked variation in the confidence with which the requirements could be described. This reflects a patchiness in the research capability (both in personnel and technology) at present available in this country and internationally for tackling such problems.

Finally it should be emphasised that even if the full ecosystem model does not prove necessary, a continued research effort will be needed to establish that any disposal programme will not result in unacceptable changes in the benthic ecosystem (an esoteric judgement) and to monitor the deep sea communities in the vicinity of dump sites to confirm the correctness of previous conclusions as to the safeness of dumping.

Much of the detailed biological information relevant to the problems of radioactive waste disposal will be site specific. Thus, while the general characteristics and extent of any possible biological transport mechanisms may be established by work in almost any deep ocean locality, it will be possible to identify the consequences of dumping at any particular site only by studies carried out at that site. The criteria for site selection will be mainly non-biological and the selection procedure will inevitably take some time. In the meantime, however, research into the biological problems should proceed for the following reasons.

1. Knowledge of deep sea biology is still so incomplete that in order to understand processes occurring at dump sites it is essential that more information is gathered from other areas. Such information will also be necessary for the long-term monitoring programme which must be undertaken even if the biological results indicate that deep sea dumping would be completely safe.

2. If the present impression of low biomass and therefore of little upward biological transport in the water column below about 2000m is confirmed, the most likely biological route to the surface from a dump site might be across the sea bed and up the slope to depths where the mesopelagic community impinges on the bottom (see sections 2.3.2 and 2.3.6). In such circumstances a knowledge of mid-slope phenomena, particularly in midwater, may be even more important than that at abyssal depths.

3. Any biological transport mechanisms identified are unlikely to be completely site-specific. Horizontal transport, for instance, will immediately tend to remove material from a dump site so that knowledge of the likely vertical transport mechanisms in other regions will be important.

4. Many of the biological questions posed by the problem of radioactive waste disposal will inevitably require considerable development of gear and analytical techniques. There is already too little time available to answer all the questions before some of the crucial decisions are likely

to be taken.

This section attempts to identify the major research studies which should ultimately be undertaken at potential dump sites and some which could, or should, be pursued in other areas even after possible sites have been selected. Before site selection the region where these studies might begin will depend to some extent on the specific questions involved but for logistic reasons a general study area should be one in which abyssal depths are reasonably close to topographically fairly simple slope conditions.

4.1.1 Identification and taxonomy

With the growth and sophistication during this century of disciplines such as physiology, genetics and molecular biology, the study of zoological taxonomy, that is the identification, description and classification of animal species, has become less and less fashionable amongst both potential workers and potential sponsoring bodies. In recent years, however, concern has been expressed that taxonomy has not kept abreast of the needs of these other disciplines and particularly with the requirements of ecologists (52). Nowhere is this short-fall more serious than in the deep sea environment where almost every haul contains previously unknown species.

Ideally, perhaps, all of the necessary taxonomy should be undertaken by institutions, such as museums, which are specifically suited to this type of work. Unfortunately, there are insufficient specialists in such institutions to deal with all of the problems so that the field scientists must themselves inevitably become involved in taxonomy to some extent. While it is essential that taxonomy does not become the prime activity of such institutions, it is equally important that the necessity of such basic research is recognised. Furthermore, it may even be necessary to sponsor specific taxonomic research to answer questions posed by the problems of radioactive waste disposal. This is because a) without an adequate basis of taxonomy, intercomparisons between different programmes carried out at different institutions and by different nations will be impossible b) incompatible data may be generated within a programme that may be used in modelling the deep sea ecosystem, c) a knowledge of the zoogeography of a species is an important indicator of the potential horizontal movement of isotopes and zoogeographic studies are impossible without taxonomy. This is important both for benthic and midwater organisms.

4.1.2 Spatial patchiness

Patchiness of animal distribution presents one of the major problems in the estimation of biomass and studies of diversity. Most animals and plants in the ocean are non-randomly or patchily distributed in space and the reasons for this have interested marine biologists for many years. If animals are randomly distributed then a sample of any size will give a good estimate of animal density. However if the animals are patchily distributed it is necessary to have a sample size greater than the predominant patch size (or sizes) present in the animal community. If this is not achieved any density estimates will be highly variable. This may explain the high variability of benthic macrofaunal biomass estimates referred to earlier. Experiments to estimate the spectrum of patchiness for benthic and pelagic communities are often time-consuming and may require the development of special gear. However it is essential to carry out these experiments in order to obtain reliable estimates of biomass in the bentho-pelagic region.

4.1.3 Community analysis and zoogeography

One of the first steps in the unravelling of food webs in an ecosystem is the description and classification of communities. A community is defined as "a collection of animals often found in each others company" and many multivariate statistical methods have been developed to remove as much subjectivity as possible from the process, using observed species abundance data to define communities. As information becomes available from a wider geographic range, similar statistical methods can be used to delineate zoogeographic areas. This information will obviously be useful in any selection of a possible dumping site and in quantifying the possible range of horizontal migrations.

4.1.4 Improved methods for estimating biomass

Reliable figures for standing stocks both in midwater and on the sea bed are essential for an understanding of the energetics of the deep sea ecosystem (see section 2.1.5). Reasonably reliable techniques have been developed for quantitatively sampling the smaller organisms, both midwater and benthic, but quantiative samples of the larger organisms are much more difficult to obtain. This is particularly true in the benthic zone where towed gears are notoriously non-quantitative. Several possible techniques to overcome this difficulty require further study. These include photography, either alone or in conjunction with towed sampling gears, and the use of manned or unmanned submersibles and traps.

Once such quantitative samples are obtained it is also essential to make the resulting data comparable with those obtained by other workers. This involves all aspects of sample treatment from sorting or sieving techniques to the ultimate measurement of wet weights, dry weights, calorific values, organic carbon equivalents and so on.

Because the turnover rates of micro-organisms, including bacteria, are likely to be so much faster than those of the larger constituents of the deep sea fauna it is also important that accurate measurements of the standing stocks of these smaller organisms should be obtained even though they may seem to be very low indeed (see section 2.1.5).

4.2 Trophic relationships and rate processes

4.2.1 Feeding strategies

The transfer of organic substances through an ecosystem is almost entirely dependent upon feeding strategies. For instance, material dumped on the deep sea floor might become concentrated in the bodies of deposit feeding benthic organisms which never leave the sea bed. If, however, such organisms are then eaten by a vertically migrating midwater animal the dumped material could rapidly approach the surface layers via the pelagic trophic ladder. On the other hand an extensively migrating midwater organisms might contribute nothing to such upward transport mechanisms if it fails to feed during its deeper living periods. A knowledge of the trophic relationships, not only of migrating animals but also of their prey, is essential if the possible transport mechanisms are to be understood.

Three main approaches can be used to obtain such data:

1. The study of comparative morphology to establish general feeding strategies.

2. The analysis of intestinal contents.

3. The use of in situ experiments (remotely controlled experiments on the sea floor).

Given an adequate overall sampling programme, no special samples are necessary for the first two of these approaches, though special preservation techniques may be needed. The third approach is clearly a special case and might involve the use of manned submersibles, free vehicles, and pop-up or moored systems.

As pointed out in 2.1.5 above, for a quantitative understanding of an ecosystem the complete structure of the food web should ideally be known. Such studies are extremely time consuming and may require the attention of taxonomic experts in many different groups so that a selective approach is essential. The priorities for the radioactive waste disposal programme are on the one hand the feeding strategies of the mobile organisms, both midwater and benthic, which are likely to migrate horizontally or vertically, and on the other of the deposit feeding benthic animals which are likely to be the first link in any biological chain tending to return waste material towards the surface layers.

4.2.2 Reproductive strategies; birth and death rates

A knowledge of these parameters is necessary for an understanding of populations and community metabolism. It is also essential if ontogenetic migrations as possible transport mechanisms are to be identified.

Much information on reproductive strategies can be gleaned from occasional samples, for example by the examination of gonads or egg masses for fecundity data or the presence of larval or juvenile forms in regions not occupied by the adults. For detailed information, however, repeated quantitative samples of the benthic and midwater communities obtained over a considerable period and certainly at different seasons, would be necessary. Such a sampling programme could be combined with those discussed in section 4.3.

The estimation of birth and death rates is likely to be quite difficult since the established methods used in shallow water, including tagging experiments, are clearly difficult if not impossible in the deep sea. The alternative technique of the statistical analysis of population structure demands larger samples than those normally obtained and will therefore probably require a specific sampling programme.

4.3 Transport mechanisms

In addition to the need of quantifying the rate processes within the various zones, it is necessary to describe and quantify the transport of biomass, and hence the potential movement of radioactive isotopes, between zones. These have been described in section 2.3.

4.3.1 Diurnal migration

The following information is required to fully quantify the biomass fluxes associated with diurnal vertical migration in the vicinity of a dump site.

a) Perhaps the most immediate relevant problem is whether or not organisms living deeper than 1000m undertake diurnal migrations. Physical processes below 1000m are not so rapid as above that depth, so any movement of biomass could significantly increase the diffusion of isotopes towards the surface.

b) A full inventory of species undertaking migrations.

c) How these migrations vary with each species' development.

d) The seasonal variations in vertical migration.

e) The vertical extent of movement by each species.

f) The timing of the migration and its relationship to the feeding cycle of the component species.

g) The dry weight/calorific value - size relationships of the major components of the community.

4.3.2 Ontogentic migrations

Description and quantification of the fluxes involved in ontogenetic migrations at a dump site will require

a) Repeated observations throughout different seasons on the vertical distribution of plantkon and nekton in the water column.

b) Estimates of the expenditure in reproductive effort of the species involved.

c) Establishment of the life histories of the important contributors to the overall biomass in the water column.

d) Establishment of dry weight/calorific value - size relationships of the major components of the community.

e) A knowledge of the zoogeography of the species involved.

4.3.3 Deposition

The requirements for data on the flux of suspended material through the water column is largely met by the programme outlined in the paper on sediment geochemistry.

Data on the deposition of large 'particles' requires a knowledge of the population statistics of large pelagic fish, squid and marine mammals. Commercial fishery statistics could provide some of this information but a programme of fishing large commercial trawls in oceanic regions would be needed to explore the populations of organisms not commercially exploited. Even this sort of programme would not answer questions on the population statistics of large highly motile fishes (e.g. those caught by long-lining and sports fishing), smaller whale populations (e.g. pilot whales and dolphins), and the large squid populations. Any of these data would be invaluable in improving the precision of biomass budgets (see 2.1.5).

4.3.4 Feeding migrations

Information on feeding migrations will be partly incidental and will be derived from other sampling programmes, and partly dependent on the availability of commercial catches of sperm whales. A special effort should be made to try to quantify sperm whale feeding rates while commercial whaling still exists. They could provide an extremely important short-circuiting mechanisms for the movement of radio-isotopes vertically through the water column. Their main diet is large squid. The biology of these large squid is almost completely unknown, basically because no adequate method of sampling them is yet available other than collecting them from sperm whale stomachs.

4.3.5 Migration up the continental slope

The effects of the impingement of the continental margins on deep sea communities needs special study. Any such movement would provide an important short circuit route for radio-isotopes to be circulated into the near-surface layers and into commercially utilised populations. There is thus a need for a sampling programme on the continental slope to complement any programme at a dump site. This programme need not be site specific and could be initiated before the final dump site has been selected.

4.4 Mathematical modelling of the oceanic ecosystem

It was shown in section 2.1.5 that, with the present state of knowledge, it is not possible to reliably quantify a simple energy flow model as shown in Fig. 4.3. Until this can be done with some confidence it is premature to discuss here any more sophisticated mathematical models. However it is suggested that simple mathematical models should form part of a biological research programme from the very beginning for the often stated reason that only by defining the model do all the lacunae in our knowledge become apparent.

5. Detailed research specifications

In this section the research requirements discussed above are expanded and specific recommendations for sponsored research in the United Kingdom are made. Mention is also made of research institutes abroad where the research in question is being, or could be, undertaken. It should be emphasised that, while an attempt has been made to mention all the U.K. research organisations working in this field, an exhaustive survey of relevant research in all universities and institutes has not been made.

5.1.1 Identification and taxonomy

No single institution, or even nation, can hope to cover all deep sea groups amongst its taxonomic specialists, so that international collaboration to make the most efficient use of the available expertise is essential and must be encouraged.

Beyond this, it is important that taxonomic work in specific groups, either because of their numerical dominance or because of peculiar taxonomic difficulties, should be actively supported by financial sponsorship. This is particularly true in the U.K. where, despite a well-established tradition in taxonomy, there are very few deep sea specialists. Nevertheless, the facilities available at U.K. institutions such as the British Museum (Natural History) and the Royal Scottish Museum are certainly capable of supporting such specialists if adequate funds were available.

5.1.2 Spatial patchiness

To obtain robust statistical estimates of patchiness a large number (100) of, preferably contiguous, samples will be required.

For the study of benthos these samples should ideally be distributed equally in two dimensions, while for the midwater animals a three-dimensional coverage should be aimed for. In practice it is usually impossible to obtain this ideal coverage and some compromises must be made. Sampling methods that can provide partial estimates of patchiness are

(i) Use of a sequential series of photographs obtained from a platform a few feet above the bottom. These could be used to quantify the spatial pattern of the megafauna. Sequential sets of bottom photographs have already been obtained by IOS and are at present being analysed. Some parallel development of statistical analysis techniques will be required to obtain the maximum information from these photographs.

(ii) Repeated sampling of a given area with sledges or grabs or trawls. This could give useful information on the variability caused by patchiness but the spatial scales of this patchiness can only be estimated if the relative position of the samples on the bottom is known. This is only just becoming possible with new techniques (53). In the U.K. this research can be carried out as a routine part of any benthic sampling programme by IOS or SMBA, although the number of samples required will obviously put a strain on the present sorting capacity.

Some work on the variability of biomass estimates obtained from grab samples has been done at SMBA (54) and also in the U.S.A. (25, 53, 55).

(iii) Patchiness of midwater animals can be studied using the Longhurst-Hardy net (LHPR) which allows contiguous samples to be obtained. This net has been used by a number of workers to study horizontal patchiness (56, 57) and vertical distribution (33, 58) at depths between 0 and 1000m.

In the U.K. both IOS and SMBA have had experience in the use of Longhurst nets down to 600m but the existing gear will probably need modification to sample adequately the low density fauna found at greater depths. IOS also have some experience in the development of appropriate statistical analysis methods (59).

5.1.3 Community analysis and zoogeography

Apart from an ability to obtain and classify the raw data, research of this nature requires access to a medium size computer with good data base software and statistical packages. This is available on the IOS Honeywell computer and the biology department have also developed experience in the writing and use of advanced multivariate statistical methods (60,61,62,63).

In the case of the zoogeographic research there is an obvious case to be made for international cooperation. This could take the form of an agreement to pool data into a common data base under the auspices of one of the international oceanographic data centres.

5.1.4 Methods and techniques for biomass estimations

Studies of the standing stocks and turnover rates of deep sea micro-organisms are being actively pursued in other countries, particularly the U.S.A. This is a very specialised field which IOS could certainly not enter without considerable expense and difficulty. This is probably true of other British laboratories also so that the U.K. should leave this research area to the existing teams overseas.

Quantitative studies of the benthic meiofauna and macrofauna are also particularly well-established in the U.S.A., in Germany and in France. In the U.K. there is a good basis for this type of work at SMBA.

The most pressing problem in benthic biomass estimations is in the larger macrofauna and megafauna and a number of groups in the U.S.A. and France are working on this problem. For the relatively immobile megafauna the most reliable method of obtaining quantitative estimates is probably direct observation from manned submersibles. However, this is an extremely costly technique and, in any case is in most cases restricted to depths shallower than the abyssal floor. A more practical approach is the use of towed collecting gears: the IOS has already begun to make such gears more quantitative and to develop simultaneous photographic techniques. The possibility of using tagging and recapture techniques in conjunction with traps fitted with camera systems should also be investigated.

The IOS has also developed what is probably the most efficient quantitative midwater net currently available.

5.2.1 Feeding strategies

Almost any institution involved in general deep sea biology should be capable of carrying out at least some studies of this type, particularly the analysis of gut contents. IOS is already doing so and will continue studies of the feeding of selected groups such as the fish and echinoderms.

If detailed identifications of gut contents are required the assistance of many taxonomic specialists will be needed; this will inevitably involve collaboration both nationally and internationally with the relevant taxonomic institutions.

5.2.2 Reproductive strategies

Information on reproductive strategies is being gathered already by a number of groups in the U.S.A. and Europe, including IOS. However, since the techniques employed vary from one taxonomic group to another and often require considerable expertise, for example in the recognition of gonad developmental stages, there is a strong case for collaboration between institutes to make the most efficient use of specialists in each taxon. At IOS, for instance, our work on reproductive strategies of the echinoderms is being carried out in collaboration with specialists in these groups from the Copenhagen Museum.

5.3.1 Diurnal migration

In order to determine whether organisms below 1000m migrate diurnally (item (a) in 4.3.1), a one off sampling programme of 3 days per depth, each requiring 1 x 2 man years to work up will be required. Depths required are ideally 1200, 1400, 1600, 1800, 2000m, but a compromise of 1250, 1500, 2000m would be realistic. Samples from 1000m are already available but not worked up at IOS Wormley.

The IOS RMT 1+8 net system is probably the only system with the depth capability. The Woods Hole Oceanographic Institution MOCHNESS system is depth-limited by the length of the conducting cable. IOS is one of the few Instituteswhere sufficient expertise in deep oceanic fauna is accumulated under one roof to work up results within a sensible time scale.

If this programme suggested that significant migration occurred at these depths then a more comprehensive experiment (items b-f in 4.3.1) would be necessary. This would take at least 18 months involving approximately 6 cruises with 10 days sampling in the selected area. Working up the material would take about 3-4 years depending on the precision required and the staff available.

5.3.2 Ontogenetic migration

Much of the material needed for this study would be catered for by the 18 month sampling programme needed for the diurnal migration study. For the zoogeographic information there is already a large collection of material at IOS from along 20°W in the N.E. Atlantic, with supplementary collections along 13°W and 17°W between 42°-50°N. Similarly for item (a) some seasonal coverage of the fauna at 44°N 13°W is available. The effort required for working up this material would be approximately 2 x 1 man years per taxonomic group, so long as trained specialists were available. The effort required would be at least 50% greater if new staff have to be recruited; difficult groups e.g. copepods would need significantly greater effort.

For items (b) to (e), if the programme was run in parallel with 5.3.1 then the additional analysis of the results could require a further 1 x 4 man years. If the programme was conducted separately then analysis of the samples would take about 3 x 4 man years.

Probably only the IOS RMT 1+8 multiple net system is suitable for this programme as it samples plankton and nekton simultaneously. The Longhurst net could be used for the plankton studies alone but this would miss the adults of most of the important species involved. Similarly the MOCHNESS system does not sample a wide enough size spectrum of organisms. The standard RMT 1+8 net is suitable but without using a multiple sampling system the increase in ship's time required will add significantly to the cost.

5.3.3 Deposition

a) Immediate use should be made of the commercial whaling operations still extant in the North Atlantic to provide whale population statistics.

b) A programme of study on the populations of small whales should be funded.

c) A deep sea commercial fishing project should be initiated for accumulating statistics on the larger species not caught by conventional research techniques.

This type of sampling has been carried out by the German Research Ship Walther Herwig in the Atlantic on an exploratory basis. M.A.F.F. Lowestoft fishery research vessels have the capability of working such gear down to about 1200m. As IOS is experienced in the likely fish groups to be encountered cooperation between the two groups is recommended.

d) A review of catch statistics for pelagic fisheries should be made to try and establish the required population data, and some experimental fishing should be carried out in areas where no data is available particularly in the region of any dump site.

5.3.4 Feeding migrations

It is to be hoped that information on feeding migrations will be obtained from the sampling programmes already suggested.

5.3.5 Migration up the continental slope

Samplers presently available are limited operationally to areas with relatively gently inclined slope regions (e.g. in the N.E. Atlantic - the Porcupine Sea Bight area and off the Straits of Gibraltar and the Moroccan Coast). For midwater organisms the only opening/closing sampler that has been operated within a few metres of the sea bed is the IOS RMT 1+8 system.

For sampling on the sea bed a great variety of samplers are available which range from traps and grabs, to opening/closing sledge trawls and commercial trawls. The more effective such samplers are in catching the larger organisms, the organisms most likely to be significant in this context, the less quantitative are the samples they collect. Some bottom and near-bottom sampling has already been done by IOS in the Porcupine Bight. However further samples will be needed which, used in conjunction with similar samples in the abyssal plain, could be used to identify any species that are candidates for slope migrations.

Ideally mark and recapture experiments should be used to study migrations, but at present it is not possible to capture deep sea organisms alive, let alone mark them and release them. Furthermore the effort required to provide adequate recapture data will be too expensive to countenance unless deeptrawling does become a commercial operation. A more feasible alternative is to mark individual fish <u>in situ</u> from submersibles with transponders or other devices that would allow them to be tracked. Such a technique has been used for trout within the confines of a small lake at the University of Stirling and also by the M.A.F.F. Lowestoft laboratory (using their sector scanning sonar) for commercial fishes in the sea. At depths greater than 1500m within the 'SOFAR channel' the attenuation of sound is much reduced and tracking acoustically could be more feasible. By the time initial exploratory observations have identified which species have wide enough distributions to be potential horizontal migrators, developments in undersea tracking devices may have advanced for the techniques to be scaled up sufficiently for use in the deep ocean.

5.4 Mathematical modelling

There does not appear to be anyone in the U.K. or the U.S.A. with any experience of modelling a deep benthic ecosystem although a proposal for such a model has been made (64).

In the U.K. considerable experience in the development of large ecosystem models has been obtained at I.M.E.R. in the development of their GEMBASE model of the Severn Estuary ecosystem. At IOS and also the fisheries laboratories at Lowestoft and Aberdeen modelling has been used to study small isolated aspects of the ecosystem rather than the ecosystem as a whole.

Any development of a model of the benthic/pelagic ecosystem would necessitate a large amount of international cooperation as the necessary expertise is not available at any one institute.

References

1 Grimwood, P.D. and Webb, G.A.M. Assessment of the radiological protection aspects of disposal of high level waste on the ocean floor. (National Radiological Protection Board, Harwell, NRPB 48 1976).

2 Sokolova, M.N. In Marine Biology (edited by B.N. Nikitin) Trudy Okeanol. Akad. Nauk SSSR, 20, 227-244 (1959).

3 Dayton, P.K. and Hessler, R.R. Deep-Sea Research, 19, 199-208 (1972).

4 Hessler, R.R. and Sanders, H.L. Deep-Sea Research, 14, 65-78 (1966).

5 Sanders, H.L. Am. Nat., 102, 243-282 (1968).

6 Isaacs, J.D. Scient. Am., 221, 146-162 (1969).

7 Isaacs, J.D. Scient. Am., 233, 85-91 (1974).

8 Schulenberger, R. and Hessler, R.R. Mar. Biol. 28, 185-187 (1974).

9 Thurston, M.H. Mar. Biol. (in press).

10 Marshall, N.B. and Merrett, N.R. In A Voyage of Discovery (edited by M.V. Angel) 483-497 (Pergamon Press, Oxford, 1977).

11 Haedrich, R.L. Deep-Sea Research, 21, 997-999 (1974).

12 Pearcy, W.G. Deep-Sea Research, 23, 1065-1066 (1976).

13 Bouchet, P. C.R. Acad. Sci. Paris, 283, 821-824 (1976).

14 Bouchet, P. Bull. Mus. Nat. d'Hist. Nat. 3rd Ser. 400, 947-971 (1976).

15 Jannasch, H.W. and Wirsen, C.O. Science, 180, 641-643 (1973).

16 Smith, K.L. and Teal, J.M. Science, 179, 282-283 (1973).

17 Schwarz, J.R., Yayanos, A.A. and Colwell, R.R. Appl. and Environmental Microbiol., 46-48 (1976).

18 Turekian, K.K., Cochran, J.K., Kharkar, D.P., Cerrato, R.M., Rimas Vaisnys, J., Sanders, H.L., Grassle, J.F. and Allen, J.R. Proc. Nat. Acad. Sci., U.S.A., 72, 2829-2832 (1975).

19 Grassle, J.F. Nature, Lond., 265, (5595), 618-619 (1977).

20 Paul, A., Thorndike, E.M., Sullivan, L.G., Heezen, B.C. and Gerard, R.D. Nature, Lond., 272 (5656), 812-814 (1978).

21 Odum, E.P. Fundamentals of Ecology. (W.B. Saunders & Co., Pa. U.S.A. 1971).

22 Currie, R.I. Rapp. et Proc.-Verb. Cons. Internat. Explor de la Mer, 144, 96-102 (1958).

23 Thiel, H., Int. Rev. Ges. Hydrobiol., 60, 575-606 (1975).

24 Wiebe, P.H., Boyd, S.H. and Winget, C., J. Mar. Res., 34, 341-354 (1976).

25 Rowe, G.T., Polloni, P.T. and Horner, S.G. Deep-Sea Research, 21, 641-650 (1974).

26 Haedrich, R.L. and Rowe, G.T. Nature, Lond., 269, 141-142 (1977).

27 Haedrich, R.L. and Henderson, N.R. Deep-Sea Research, 21, 739-744 (1974).

28 Pearcy, W.G. and Ambler, J.W. Deep-Sea Research, 21, 745-759 (1974).

29 Chapman, C.J. and Rice, A.L. Mar. Biol., 10, 321-329 (1971).

30 Rice, A.L. and Chapman, C.J. Mar. Biol. 10, 330-342 (1971).

31 Rhoads, D.C. In Trace Fossils (edited by J.P. Crimes and J.C. Harper) 391-406 (1970).

32 Joyce, J.B. Est. and Coastal Mar. Sci. (in press).

33 Longhurst, A.R. In The Ecology of the Sea (edited by D.H. Cushing and J.J. Walsh) 116-137 (Blackwell Scientific Publications, Oxford, 1976).

34 Rudjakov, J.A. Oceanology, 12, 886-889 (1972).

35 Roger, C., Cahiers O.R.S.T.O.M., 12, 221-240 (1974).

36 Merrett, N.R. and Roe, H.S.J. Mar. Biol., 28, 115-126 (1974).

37 Waterman, T.H., Nunnemacher, R.F., Chace, R.A. and Clarke, G.L. Biological Bulletin, Woods Hole, 76, 256-279 (1939).

38 Merrett, N.R. Deep-Sea Research, 25, 147-160 (1978).

39 Scheltema, R.S. In Fourth European Marine Biology Symposium (edited by D.J. Crisp) 7-28 (Cambridge University Press, 1971).

40 Gilmer, R.W. Science, 176, 1239-1240 (1972).

41 Lockyer, C. In A Voyage of Discovery (edited by M.V. Angel) 591-609 (Pergamon Press, Oxford, 1977).

42 Wood, G.L. The Guiness Book and Animal Facts and Feats. (Guiness Superlatives Ltd. Enfield, 1972).

43 Kooyman, G.L. and Andersen, H.T. In The Biology of Marine Mammals (edited by H.T. Andersen) 65-94 (Academic Press, New York and London, 1969).

44 McGowan, J.A. In Seabed Disposal Programe:A first-year report (edited by W.P. Bishop) 305-392 (Sandia Laboratories Albuquerque, New Mexico, 1974).

45 Barnard, J.L. Galathea Report, 5, 23-128 (1961).

46 Okamura, O. Reports of the Usa Marine Biological Station, Kochi University, 17, 1-179 (1970).

47 Bernard, F.R. Environment Canada, Fisheries and Marine Service, Tech. Rep. No. 268 (1976).

48 Wiebe, P.H., Madin, L.P., Haury, L.R., Harbison, G.R. and Philbin, L.M. Science, (in press).

49 Goldberg, E.D. In Treatise on Marine Ecology and Palaeoecology, 1, (edited by J.W. Hedgpeth) Chapter 12, (1957).

50 Harbison, G.R. and Gilmer, R.W. Limnology and Oceanography, 21, 517-528 (1976).

51 Emery, R.M., Klopfer, D.C., Garland, T.R., and Weimer, W.C. In Radio ecology and energy resources (Edited by C.E. Cushing, Jr.) 74-85 (Dowden, Hutchinson and Ross, Inc., Stroudsburg, PA. U.S.A. 1976)

52 ESRC Taxonomy in Europe. Interim report of a study by an European Science Research Council ad hoc group. Review, 13. (European Science Foundation, Strasbourg, 1977).

53 Jumars, P.A. Deep-Sea Research, (in press).

54 Gage, J. and Geekie, A.D. Mar. Biol., 19, 41-53 (1973).

55 Jumars, P.A. J. Mar. Res., 30, 253-266 (1976).

56 Wiebe, P.H. Limnol. Oceanogr. 15, 205-217 (1970).

57 Fasham, M.J.R., Angel, M.V. and Roe, H.S.J. J. Exp. mar. Biol. Ecol., 16, 93-112 (1974).

58 Williams, R., and Hart, P.J.B. In The Early Life History of Fish (edited by J.H.S. Blaxter) 233-243 (Springer-Verlag, Berlin, 1974).

59 Fasham, M.J.R. Oceanogr. Mar. Biol. Ann. Rev., 16, 43-79 (1978).

60 Angel, M.V. and Fasham, M.J.R. J. mar. biol. Ass. U.K., 54, 879-894 (1974).

61 Angel, M.V. and Fasham, M.J.R. J. mar. biol. Ass. U.K., 55, 707-737 (1975).

62 Fasham, M.J.R. and Angel, M.V. J. mar. biol. Ass. U.K., 55, 739-759 (1975).

63 Fasham, M.J.R. Ecology, 58 (3), 551-561 (1977).

64 Wishner, K. In Seabed disposal program annual report, part II, Jan.-Dec. 1976. (Edited by D.M. Talbert) Appendix M, (Sandia Laboratories, Albuquerque, New Mexico, U.S.A., 1977).