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GUIDELINES FOR THE SELECTION OF SITES FOR DISPOSAL OF RADIOACTIVE WASTE ON OR BENEATH THE OCEAN FLOOR

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CHAPTER 1: INTRODUCTION

The concept of disposal of high-level radioactive wastes into geological formations beneath the ocean floor was first considered seriously by investigators in the U.S.A. in the early 1970s (1), and led to a research programme to investigate the feasibility of the concept in detail (2-4). In the U.K. the Royal Commission on Pollution and the Environment (5) recommended a programme of research into disposal under the ocean bed, and it subsequently became the declared policy of H.M. Government to investigate the disposal of high-level radioactive waste both on and under the seabed (6).

As a preliminary to more detailed investigations this report presents an assessment of factors which will probably need to be taken into account in selecting potential disposal sites. It is based in part on a survey of available published and unpublished literature, especially references 7 to 10. For summaries of the scientific background to high-level radioactive waste disposal in the oceans, and for an assessment of the present state of knowledge, the reader is directed to reference 10.

It should be borne in mind that in many instances present quantitative knowledge concerning the properties and processes of the seabed and oceanic waters is poor (10), and the suggested guidelines may need modification as investigation into seabed disposal progresses. To minimise the need for revision, the guidelines given here have generally been stated in qualitative terms. It will be the aim of future research to determine acceptable quantitative values of the parameters involved.

1.1 The time-scale of waste decay

Inevitably in determining site selection guidelines one must consider the time-scale of waste decay. Unfortunately this cannot be represented by a single parameter, since radioactive waste contains many elements with vastly differing half-lives, and some of these give rise to new radioactive species not present in the original waste (11, 12). Most fission products decay over a time-scale of the order of 10^3 years - after 1000 years the total activity of both the waste as a whole and the fission products in particular will have fallen to about 0.1% of their initial values (11). Virtually all of the heat output occurs during this first thousand years. In addition, some fission products and most actinides decay over longer periods so that the total activity falls off in a way similar to that shown in figure 1. At present it is difficult to define the maximum period over which the integrity of the disposal scheme should be ensured and it will be necessary to consider processes and to model their effects over a sufficiently long period to encompass all significant effects of the waste.

In view of the long half lives of some elements it is not realistic to expect to be able to contain every radionuclide until it decays completely A practical aim is to design a disposal scheme which will restrict the levels of radioactivity in the environment to acceptable levels, although the precise values of these levels may be open to discussion.

1.2 Seabed disposal options

There are two basically different options for seabed disposal of high-level radioactive waste (Figure 2):

i) The waste could be placed on the seafloor where the canister, the wasteform itself, and any additional engineered barriers will provide initial constraints on the rapid release of the waste. After the breakdown of these barriers one would rely on dilution and dispersal of the waste in the ocean waters to restrict the activity to acceptable levels.

ii) The waste could be emplaced within the sediments or rocks of the seafloor. Present evidence suggests these could possibly provide a very substantial barrier to the release of waste.

Different considerations will apply to the selection of disposal sites under the two options, although some will be common to both. The guidelines presented in the following chapters are numbered sequentially, with a prefix A for sub-seabed and B for on-the-seafloor ones. To try to ensure completeness, as many factors as possible have been identified, and it is possible that some of these may turn out eventually not to be strongly site-dependent.

No specific assumptions are made about the waste-form, but for convenience of discussion it is taken to be solidified and contained in a canister.

1.3 Site selection guidelines

The strategy of this report is to identify the mechanisms of containment or dispersion within each disposal option. The ways in which these mechanisms can be enhanced or diminished are then discussed, and finally the individual characteristics of a site which will affect these changes are presented. The optimum values of these characteristics represent site selection guidelines, but it is emphasised that they should not be used blindly as rules of thumb. Ultimately it is the efficacy of the disposal method as a whole which must be assessed, and this will require detailed modelling and radiological assessment.

Not all factors should carry equal weight, although it is difficult at this stage to rank them satisfactorily. The order in which they are given generally follows a logical development of the subject and should not be taken as an indication of priority.

The following two chapters outline the containment and dispersal mechanisms in the two oceanic disposal options and the various processes which may affect them, together with the main characteristics to be considered at each site. Detailed discussion of these characteristics is given in the appendix. Finally, chapter 4 discusses the availability of areas suitable for further investigation on the basis of current knowledge.

CHAPTER 2: EMPLACEMENT BELOW THE SEABED

In this disposal option, the containment philosophy is one of multiple barriers. The canister forms the first barrier to the spread of waste, and may contain it for some 500 years or possibly even longer (13). After failure of the canister, the wasteform would be open to the action of the surrounding pore-water and, in the case of a borosilicate glass, could be completely dissolved within a few thousand years (11).

The next barrier is the sediment or rock medium surrounding the waste. This medium is intended to act as a physical barrier against mass movement of the waste, and as a chemical barrier by adsorbing onto itself nuclides which might be moved by migrating pore-water. Present evidence suggests that under certain conditions this barrier alone might be effective in isolating the radionuclides from the water mass for tens of thousands of years.

Some of the longer-lived radionuclides may eventually pass through the geological barrier. Also, there could be an unforeseen failure of the barrier, or some waste might be deposited on the seafloor as a result of an emplacement accident. In these cases one would have to rely on the ocean water to disperse and dilute the waste to acceptable levels. The factors optimising this dispersion and dilution will be considered as the primary requirements for selection of sites for disposal on the seafloor but for sub-seabed disposal they must rank below the factors defining the efficacy of the geological barrier.

2.1 The geological barrier

Most of the site selection requirements for sub-seabed disposal will apply equally to disposal in soft sediments or in the underlying lithified rocks, so for convenience the term 'disposal medium' will be used where the distinction is unimportant.

2.1.1 Failure modes of the geological barrier

The geological barrier could potentially fail in any of the following ways:

(i) It could be physically disrupted by mass movement or slumping of sediments, erosion, dissolution, faulting, folding, volcanic or seismic activity.

(ii) Thermal convection of soft sediments could be initiated if high temperatures are engendered by the waste itself.

(iii) Radioactive nuclides leached from the wasteform could be carried to the seafloor by active migration of pore water. This would be enhanced if high thermal gradients occur around the wasteform, and would be facilitated by the presence of fissures and other water-conducting strata. The effect could be reduced by adsorption of nuclides onto the sediment particles.

(iv) Even in the absence of pore-water migration, radionuclides could reach the seabed by diffusion through stationary pore-water. This could be slowed by adsorption of nuclides onto sediment particles.

(v) The medium could be physically weakened by the emplacement procedure, or physically or chemically altered by the heat or radioactivity of the waste (for example, remineralisation might occur, so that minerals with desirable properties such as high adsorptivity are replaced by minerals with less desirable properties).

(vi) Naturally occurring gas, or gas released from solid hydrates by radiogenic heat, could disrupt the medium.

(vii) Safe emplacement might be difficult or impossible because of the presence of obstructions such as boulders, or because of other unsuitable geotechnical properties.

Those effects which are consequent on radiogenic heat production could of course be ameliorated by longer pre-disposal storage or by incorporating smaller proportions of waste in the wasteform.

2.1.2 Predictability of stability of the barrier

The geological barrier should be expected to remain intact for as long as is necessary to restrict the release rates of waste materials to acceptable levels. Unfortunately, this time is not easy to determine at present, though it should become clear from the outcome of detailed modelling of disposal schemes.

The shortest time-scale of unpredictability is for catastrophic events such as earthquakes, volcanic erruptions and mass-movements of sediments, although the areas in which these processes occur at present are (or can be) fairly well defined. The next longer time-scale of variability is that of climatic fluctuations, particularly during ice-ages. For such periods, major rearrangements of ocean currents and erosion patterns may occur over thousands to tens of thousands of years. However, the likely extent of such fluctuations can be estimated from the geological record of glacials and interglacials within the last million years. On scales greater than a million years variations in conditions probably take place fairly smoothly with time-scales of a few million to a few tens of millions of years, and will be controlled principally by plate movements and long-term climatic variations. The predictability of the geological barrier for times greater than about one million years is not likely to be good.

The predictability of the physical and chemical properties of the barrier will depend on a thorough understanding of the processes involved, together with in situ testing and experimentation. If the chemistry of the medium and pore-water is well buffered, its predictability will be greater.

2.1.3 Desirable characteristics of the geological barrier

The following is a list of desirable characteristics which can be derived from the considerations of the preceeding two sections. They are discussed fully, with quantitative estimates of the various parameters where known, in the appendix. In this section, 'recent' is to be taken as meaning 'during at least the last one million years'.

a) Geological setting

A.1 The site should avoid areas near steep slopes where sediments may be unstable.

A.2 It should avoid areas of recent erosion, dissolution or mass movement of sediment, or the waste should be buried deep enough to be unaffected by such processes over a suitably long period.

A.3 The site should avoid areas of recent tectonic activity.

A.4 It should avoid areas of recent volcanic activity.

A.5 It should be in a region of low seismic activity.

A.6 It should have adequate sediment thickness.

A.7 The disposal medium should be laterally homogeneous.

b) Physical and chemical properties of the disposal medium

A.8 The disposal medium should have low natural pore-water convection, and low permeability to minimise induced pore water movement.

A.9 It should provide low diffusivity for the waste ions.

A.10 It should have high specific adsorptivity to trap radionuclides.

A.11 It should have a large active grain surface area (and therefore small grain size) to maximise nuclide adsorption.

A.12 It should have low organic carbon content to minimise ion mobility.

A.13 It should be strong enough to resist mass thermal convection.

A.14 A sufficient thickness of the medium should have high plasticity to promote self-sealing, unless engineered sealing can be devised.

A.15 The medium should contain no natural gases or gas hydrates.

A.16 The site should be relatively free of obstructions on the seafloor.

A.17 The thermal conductivity of the medium should be high enough to ensure acceptable *in situ* temperatures.

A.18 The properties of the medium should not be adversely affected by the presence of the waste.

A.19 The pore water chemistry should be such as to minimise corrosion of the canisters and leaching and migration of radionuclides, and preferably to maximise predictability of the system.

2.2 Dispersion of the waste if it reaches the seafloor

Any waste which passes through the geological barrier and reaches the seafloor will be subject to dispersal, dilution - and possibly concentration - by the action of the water and biological agents. The selection guidelines for on-the-seafloor disposal are designed to minimise the risks associated with such occurrences, and they are developed in Chapter 3. However, since the intention of sub-seabed disposal is for the geological medium to be the major barrier, these additional requirements should remain subordinate to those given above.

2.3 Operational and general considerations

The site should be suitable for the efficient, economic and safe emplacement of waste. Since conflicts of interest over alternative uses of the site would increase the probability of disturbance, the potential for such conflicts should be minimised. Also, because of the long time-scale of waste decay, there is a possibility that society as we know it may break down, and for this or other reasons the location of a disposal site may be lost. It should therefore require no long-term surveillance, and should be unlikely to be disturbed by accidental interference in the future. Other political and legal constraints may also influence the choice of a site.

The following factors will therefore also need to be considered:

A.20 The effect of geotechnical properties of the disposal medium on ease of emplacement.

A.21 The occurrence of exploitable natural resources.

A.22 The proximity of seabed installations.

A.23 The positions of national boundaries and effects of international agreements.

A.24 Whether the size of the site will allow economical use.

A.25 The proximity of major shipping lanes.

A.26 Climatic suitability.

CHAPTER 3: EMPLACEMENT ON THE SEABED

In this option, one relies on the integrity of the canister and the waste-form to provide initial containment. The advantages of the method are that the canisters are exposed to the efficient cooling effect of the ocean waters, and emplacement is likely to be relatively cheap. The disadvantage is that, once the canister is breached (perhaps after 500 to 1000 years) the waste form may be completely dissovled within a few thousand years. Thereafter a proportion of the radionuclides entering solution may be adsorbed onto sediment particles on the seafloor. The understanding of the processes involved is rudimentary, but it is likely that a sizeable proportion (possibly the majority) of the radionuclides would eventually enter into the general oceanic circulation. The safety of the method will then depend upon an efficient dispersal and dilution of the dissolved waste by the water. It is not yet possible to say whether or not this could be achieved.

3.1 The role of the sediments

It may be desirable that as much as possible of the radioactive material entering the sea water by solution should be rapidly scavenged by sediment particles which either have been or are about to be stably deposited on the seafloor. However, if biological transport and concentration turn out to be significant, one might want to avoid local concentrations of activity in the surface sediments. In any case it is probable that some radioactive material would be carried considerable distances downstream (not necessarily in a constant direction, as bottom currents may be very variable in direction) before being adsorbed or mixed into the general oceanic circulation.

The best conditions for rapid scavenging would be for the site to be in a region where there is a lot of suspended sediment with a high specific adsorptivity for the radionuclides, which is in the process of being permanently deposited. However, it might be very difficult to establish whether such a regime could be expected to continue for a period of thousands of years especially if (as is likely) this includes a glacial period.

3.1.1 Failure modes associated with the seafloor

The following are the failure mechanisms (i.e. those which may lead to unacceptably high release rates) which have been recognised so far, and which have a site-specific element:

i) Physical damage to the canister. This might arise as a result of mechanical abuse due to impact with an obstacle (e.g. a boulder, outcrop or wreck) during emplacement or due to a catastrophic geological event, such as a sediment slump or a volcanic eruption.

ii) Canisters could be buried, possibly leading to overheating. Burial could result from a steady accumulation of sediments (perhaps accentuated by the canister's presence), from sinking of the canister into too-soft sediments (possibly sediments fluidised by earthquakes), or from mass-movements of sediments. In the latter case, several canisters might even be brought close together, exacerbating any overheating.

iii) There could be inadequate adsorption of radionuclides onto the sediments near the disposal site, either because the water carrying the disolved waste is not long in contact with the sediment, or because the sediment has low adsorptivity for the ions involved.

iv) Canisters or radioactive or toxic sediments could be disturbed or recovered by human activities, such as bottom-trawling, mining or cable-work.

3.1.2 Desirable properties of the seafloor environment

All of the below-the-seabed requirements A.1 to A.5, which relate to the stability of the seafloor, should be included here, with the addition of the following:

B.1 The site should be in an area of extensive sediment cover (unless biological transport is likely to be a problem).

B.2 The sediments should have a high specific adsorptivity and low organic carbon content (unless biological transport is likely to be a problem).

B.3 The site should be relatively free of obstructions.

B.4 For wastes with a significant heat output, the sediments should have an adequate strength to support the waste canisters.

B.5 Sedimentation should not result in burial of the canisters during the period of high heat production.

B.6 To prevent accidental disturbance, the site should avoid potentially exploitable minerals, bottom-fisheries, or sites for seabed installations. (This is similar to A.21, but must rank much higher in the case of on-the-seafloor disposal).

B.7 The site should preferably have a high concentration of suspended, high specific adsorptivity sediment in the process of being deposited (unless biological transport is likely to be a problem).

3.2 Biological considerations

With the possible exception of bioturbation, there is no biological activity which is known to be positively helpful in providing safe disposal of high-level radioactive wastes. Bioturbation might be beneficial in removing contaminated sediments from the seafloor and replacing them by fresh ones which could adsorb more waste (if indeed that proves desirable). The ways in which biological activity might be detrimental are:

i) By the concentration of radionuclides or other toxic substances through food chains.

ii) By providing rapid transport of toxic substances from the disposal site (or other areas of high concentration).

iii) By throwing contaminated sediments into suspension so that they can be carried away by currents.

We therefore deduce the following guidelines

B.8 The benthic (bottom dwelling) biomass should be low to minimise the entry of waste into a food chain.

B.9 The mid-water biomass in the vicinity of the site should be low to minimise potential vertical transport.

B.10 Mid-water vertical migrations should be small.

B.11 Bioturbation may be desirable if it does not lead to erosion of the seabed. (This may conflict with B.8).

3.3 Oceanographic considerations

That part of the dissoved waste that is not scavenged by suspended sedimentary particles will be moved away from the disposal site initially by currents near the bottom and perhaps by thermal convection, will become diluted and dispersed by turbulence and entrainment mechanisms, and may eventually be spread world-wide. The effectiveness of these mechanisms in maintaining radioactivity and toxicity levels within acceptable limits depends on the time-scales of the many factors involved - the rate of dissolution of the container and waste-form, the rate of decay of the relatively short-lived fission products, the rate of decay of the long-lived actinides, and the rates of the mixing processes in the oceans. It is not even a priori obvious whether a site should be chosen where the mixing is vigorous and fast enough to lead to rapid dilution to acceptable levels, or where it is slow enough to allow the waste to decay sufficiently before reaching the environment of man.

At present, it is suggested that:-

B.12 Current stresses should be low to assure sediment stability.

B.13 The site should be deep to minimise vertical transport.

B.14 The site should avoid regions in which there is direct, rapid advection to sensitive areas such as fishing grounds.

B.15 The site should avoid high latitudes where the vertical stability of the water column is low.

B.16 The site should avoid regions adjacent to continental slopes, sea-mounts and islands where vertical transfer of water may be rapid.

B.17 To avoid excessive dissolution of the canisters and waste form, the bottom water chemistry should be suitable.

3.4 Operational and general considerations

All the same general considerations and requirements (A.20 to A.26) as stated in section 2.3 will apply, but it is emphasised again that in the case of on-the-seabed disposal the requirement for avoiding accidental disturbance or recovery is much greater (see also B.6).

CHAPTER 4: IDENTIFICATION OF AREAS THAT MIGHT PROVE SUITABLE FOR DISPOSAL OF HIGH-LEVEL RADIOACTIVE WASTES

4.1 Introduction

On the basis of our present knowledge of the oceans, and using the guidelines developed in chapters 2 and 3, it is possible to eliminate fairly large areas as candidates for disposal sites. This can be done with most confidence for the factors regarding geological setting and seafloor stability (A.1-A.5) which apply both to sub-seabed and on-the-seafloor disposal options. The areas which remain turn out to be relatively few, and their suitability will have to be examined by further work to define the physical and chemical properties of the sediments, and the oceanographic, biological and sedimentary/erosional regimes in which they occur.

This discussion is restricted to the North Atlantic, though it should be noted that the Americans and others are studying several areas in the North Pacific in addition to some Atlantic areas.

4.2 Areas which appear unlikely to be suitable

Several considerations indicate that active plate boundaries should be avoided because they are intrinsically unstable or have little sediment cover (A.3 to A.6). Several others require that shallow areas and areas of steep slopes be avoided (A.1, B.8, B.13, B.16). Together, these restraints rule out all of the Mid-Atlantic Ridge, active transform faults such as the Azores-Gibraltar fracture zone, the continental margins, oceanic islands and major seamounts (Figure 3), and exclude most areas of high benthic biomass (Figure 8).

The requirement for reasonably large areas of sediment (A.24, B.1) restricts the selection to sites far from the Mid-Atlantic Ridge. This is because the seafloor on the ridge flanks is characterised by abyssal hills, where basaltic rocks outcrop, restricting sediment occurences to relatively small intermontane basins and valleys. As one goes farther from the ridge axis the seafloor gets older, and the greater accumulations of sediments partially cover the abyssal hills so that sedimentary basins become wider.

However, except on the abyssal plains and in areas of unusually thick sediments, continuous expanses of sediment as wide as 100 km are rare (Figure 4). It is possible that smaller basins could be used for disposal sites, but they would need careful study to be sure there was no danger of disturbance from sediments moving off the surrounding slopes (A.1).

Between the abyssal hills and the continental margins lie the continental rises and abyssal plains - areas of gently sloping to very flat-lying sediments deposited largely by turbidity currents from the continental margins. Much of these areas is thought to be unsuitable for waste disposal because of the possibility of turbidity currents disturbing a site (A.2). If future studies showed that such currents could be predictably avoided, the abyssal plains might merit further investigation for on-the-seabed disposal. The coarse-grained sediments deposited in most of the plains by turbidity currents make these areas unsuitable for under-the-seabed disposal (A.8, A.11, possibly A.14, A.20). However, in the distal parts of the abyssal plains (i.e. the parts farthest from the sediment sources) turbidity currents will have lost most of their momentum and coarse-grained sediment load so that their undesirable effects may be absent there.

The occurrence of ice-rafted material on the seafloor and the danger of rapid vertical mixing in the water column, as well as a desire for a reasonable climate at the disposal site, will restrict disposal sites to moderate or low latitudes (A.8, A.16, A.20, A.26, B.3, B.15). At present, the International Atomic Energy Agency recommendation is for latitudes less than 50° (14) but this may need modification in the light of future research. Figure 5 shows the occurrence of ice-rafted material in the North Atlantic, but the southern limit of the area is poorly defined at present.

The rather simple discussion given above allows a first attempt to be made at identifying unsuitable areas. If we simply reject all areas which either have less than a 100 km extent of continuous sediment or are abyssal plains, the areas remaining are as shown in figure 6. Distal abyssal plains may prove to be suitable, but their limits cannot be accurately mapped at present.

Of the areas shown in figure 6, those in the far north (say north of 50 °N) can be rejected, at least tentatively, for the reasons given above.

4.3 Areas which merit further investigation

Except for the northern ones, few of the areas indicated in figure 6 can be rejected on the basis of current knowledge. Areas of small grain-size (clays) are especially desirable and are shown in figure 7. Detailed geological surveys to investigate stability, and sampling of sediments to determine their physical and chemical properties, are now needed in these areas and the distal abyssal plains. Further studies of biological and oceanographic processes are also needed. It is emphasised that no potential disposal sites have yet been chosen; the studies proposed for these areas have the purpose of determining whether they have the general properties needed for consideration as disposal sites.

Not all potential areas can be investigated immediately, and those which have been identified for study within the next one or two years are briefly described below. The areas are not in any order of preference. Their approximate positions are given below, and indicated in figure 6, but their limits are quite flexible.

Identification of these working areas has been largely carried out in co-operation with the international scientific community, principally through the Nuclear Energy Agency Seabed Working Group. It is intended that this co-operation should continue, both in the identification of study areas and in the execution of surveys and experiments.

a) Area north and east of Bermuda - MPG3 north (29 °-36 °N, 55 °-65 °W)

This is part of the third 'Mid-plate-mid-gyre' (MPG) region chosen by the Seabed Working Group (the other two are in the Pacific). It includes a thick sedimentary plateau, the Bermuda Rise, with sediments some one or two kilometers thick, and some distal parts of the Sohm abyssal plain. Preliminary studies by the Americans and French in 1978 indicate very active erosion over much of the NE Bermuda Rise, though the deeper sediments might be suitable for deep burial of waste.

b) Area south of Bermuda - MPG3 south (22°-29°N, 58°-69°W)

This is the second part of the north Atlantic mid-plate-mid-gyre area. It includes distal parts of the Hatteras and Nares abyssal plains; sediments in the latter may contain a significant proportion of clay particles (Figure 7). Existing data in this area are being compiled by American workers, and cruises will be planned as necessary after evaluating those data.

c) Greater Antilles Outer Ridge (20°-22°N, 64°-68°W)

This is a sedimentary ridge built up to the north of the Greater Antilles. The thickness of nearly one kilometer and extent of the sediment make the area attractive. This area is in a very early stage of evaluation by the workers in the U.S.A.

d) South flanks of King's Trough (41°-43°N, 20°-23½°W)

A thick (half to one kilometer) and moderately extensive sedimentary blanket covers the flank of the southern ridge bounding King's Trough. One short core taken in the area shows that the sediment is a calcareous ooze with a mean grain size of about 0.006 mm. The measured permeability was 10^{-11} cm^2. Several of the area's properties (e.g. depth less than 4000 m, relatively high latitude) make it a marginal choice, but its proximity to the U.K. makes it attractive for generic studies (of sediment stability processes, for example) even if it does not rank high for final site selection.

e) Area west of Gt. Meteor seamount (29°-33½°N, 26°-31°W)

This is one of the few areas where a reasonable extent of sediment can be found within the abyssal hills provinces of the north Atlantic. Sediment thickness is about five hundred meters. The area is covered by Dutch seismic profiling tracks at a density of about one every 30 km. These are being analysed at present. Perhaps the most important unknown is whether the area is far enough from the seamount to avoid disturbance from sediment slumps or turbiditiy currents originating there.

f) Cape Verde Basin (18°-22°N, 30°-34°W, and 22½°-25°N, 26°-29°W)

The southwesterly of these two areas contains another small area of extensive though thin (200 to 300 m) sediments in the abyssal hills west of the Cape Verde Islands. One short core in the area recovered very fine carbonate silt (grain-size 0.006 mm) with permeability 10^{-11} cm². The area merits further surveying to determine the precise extent and nature of the sediment. The northeasterly area is in the distal Cape Verde abyssal plain.

APPENDIX: SITE SELECTION GUIDELINES - DETAILED DISCUSSION

In this appendix the guidelines outlined in chapters 2 and 3 are expanded and discussed more fully. Where possible, indications of quantitative values have been given, but in most cases they are only estimates based on rather poor information. All these factors should be predictable over the relevant time-scales (of the order of 10^3 years for the thermal effects, longer for most of the others). In practice this means that the relevant processes must be fully understood. The final choice of a site will involve the joint optimisation of all factors, rather than optimisation of each individually.

A. EMPLACEMENT BELOW THE SEABED

(The first five requirements also apply for on-the-seafloor disposal).

i) Geological setting

A.1 Stability of the seabed

The disposal site itself should be an area of seafloor gradients low enough to preclude gravity-induced movement of sediments. Some large slides and slumps are known to have started on slopes as low as 0.5° (15). The site should be sufficiently far removed from steep areas to avoid disturbance from sediment slumps, slides, debris flows or turbidity currents travelling from such areas and triggered by either natural or man-made events. Continental margins, fracture zones, large seamounts and scarps (Figure 3) should therefore be avoided. Areas of local scarps or other seabed irregularities, which might accentuate current action or indicate non-uniform sub-seabed conditions, should also be avoided.

This guideline ranks high for disposal on the seafloor or in the uppermost, soft sediments, but may have lower priority for deep burial of waste into lithified rock.

A.2 Absence of erosion

The waste should be buried deep enough to avoid any predicted erosion, or else the site should be in an area where absence of erosion can reasonably be predicted over the time-scale of waste decay. This will require that there be a record of continuous, reasonably uniform sedimentation, with no evidence of erosion, non-deposition or mass-movement of sediment in about the past 10^6 years, and no likelihood of it under present or possible future oceanographic regimes.

Again, this guideline ranks high for on-the-seafloor and soft-sediment disposal. For deep burial into lithified sediments it is less stringent, the requirement then being that any erosion should be predictably low enough not to reduce the effectiveness of the geological barrier to an unacceptable degree.

A.3 Tectonic stability

The site should be one in which recent (younger than at least 10^6 years) tectonic deformation such as folding or faulting is absent and can reasonably be expected to remain absent over the time-scale of waste decay. It should not therefore be located near a mid-ocean ridge axis, active transform fault, subduction zone or other active structure.

A.4 Absence of volcanic activity

The site should not be in an area where there has been active volcanism within at least the last 10^6 years. This includes areas of mid-plate volcanism (e.g. oceanic islands) as well as mid-ocean ridge axes and island arcs. Close to active volcanic areas (say within a distance of the order of 100 km) there is a danger of new eruptions, which could disrupt the seabed or at least cause substantial local heating. Within a somewhat greater area there is the possibility of rapid sedimentation due to tephra or ash falls, which could lead to burial and therefore overheating of waste placed on the seafloor (B.5).

A.5 Seismic stability

The site should have a demonstrably low probability of seismic activity. Since seismic activity tends to be patchy on a time-scale of years to decades, this will require extensive observations in a large area around a potential site to provide adequate statistics on epicentre distributions for the assessment of risks.

The main risk from earthquakes is triggering of sediment mass-movements, or production of fissures facilitating fast pore-water circulation. Earthquakes might also induce pore-water flow by seismic 'pumping' (16), and under certain conditions they can fluidise sediments (17, 18) possibly leading to sinking of canisters (this would be critical for on-the-seafloor disposal) or, in the presence of strong temperature gradients, to convection of the sediment.

Again, this requirement rules out sites near all mid-ocean ridges, transform faults and active trenches or subduction zones.

A.6 Adequate sediment thickness

A sufficient thickness of sediment is required above the canister to restrict to an acceptable level the rate of migration of radionuclides from the emplacement position to the seabed. The actual thickness required will depend on the permeability (A.8), diffusion coefficient (A.9) and adsorptivity (A.10) of the sediment. Based on very preliminary studies, ions might diffuse on the order of 100 m in 10^6 years in the absence of ionic adsorption (19), and be driven at least a few metres in 10^3 years by thermal convection of pore-water (20) (but see A.8). These rates would be lower if there were strong ionic adsorption. There should also be an adequate thickness of sediment below the waste to prevent downward migration by diffusion or convection to possibly more permeable basement rocks which might outcrop eventually on the seafloor, and to facilitate prediction of processes such as pore-water convection.

A.7 Lateral homogeneity of disposal medium

To facilitate prediction of processes such as heat transfer or pore-water movement, and to give confidence in the uniformity of geological processes at the site, it is desirable that the medium should be reasonably homogeneous, and that any departures from homogeneity be known. Sediment properties should be checked at selected intervals by continuous coring to depths well below the intended disposal level, and horizontal continuity between these cores should be demonstrated by geophysical means, principally high-resolution acoustic profiling.

ii) Physical and chemical properties of the disposal medium

A.8 Low permeability

Any natural pore-water convection should be sufficiently slow, and the medium should have sufficiently low permeability (both vertically and horizontally), to ensure that pore-water migration from the waste to the seafloor remains acceptably low. It has been suggested (21) that in some sedimented areas natural pore-water convection may be as fast as 3.4×10^{-6} cms^{-1} ($1.1\ my^{-1}$).

Some pore-water migration will be induced by thermal expansion due to the heat output of the waste, although this effect could be reduced by longer pre-disposal storage. In any case the migration should be slow if the Rayleigh number is much less that one (20). The Rayleigh number depends on the permeability and thermal diffusivity of the medium, the rate of heat input and the expansion coefficient, viscosity and specific heat of the water (20). The most highly variable factor between sites is probably the permeability of the medium, which in general can be expected to decrease with decreasing grain-size of the sediments. The properties of water at high temperatures and pressures are not well known, but assuming they are not too different from those known at lower temperatures or pressures, and taking typical values for the other variables, then the Rayleigh number will be of the order of 3×10^5 QK where Q is the rate of heat input in watts and k is the permeability in cm^2 (20). Thus for a 1 kw heat source, k should be much less than 3×10^{-9} cm^2. Although permeabilities of deep-sea sediments are not extensively known, this value would probably be appropriate to very fine sands or silts (10).

In addition to low bulk permeability, there should be no other potential flow-paths such as unsealed faults or fissures, or beds of coarse sand interbedded with finer material. The latter are characteristic of turbidites (except in their distal regions) so areas with such deposits (e.g. much of the abyssal plains) should be avoided. Other sources of coarse-grained material within sediments are winnowed foram sands (generally found on high-standing areas, or possibly in sediments slumped from such features) and some volcanic ashes.

A.9 Low diffusivity

Even in the absence of pore-water migration (A.8), any dissolved radionuclides would slowly move by diffusion. The coefficient of diffusion, which is a function of sediment type and the ion concerned, should therefore be low. There does not appear to be a great deal of variation between sediments, and typical values are between about 3×10^{-6} and 5×10^{-6} $cm^2\ s^{-1}$ (19, 22). In the absence of any adsorption of ions, such values would allow diffusion through about 100m to 125m in 10^6 years.

A.10 High ionic adsorptivity

Migration of waste radionuclides can be slowed if the sediment solid phase exhibits a high adsorptive capacity for the waste ions. The distribution or sorption coefficient is defined as the ratio of ions locked up on the medium to those in solution and free to move. Values considerably in excess of one are desirable.

It is known that most deep-sea sediments possess this property for most relevant ions (19), though further studies are still needed. The effect is believed conventionally to be associated with the presence of clay minerals, but some observational data suggest that this hypothesis may be oversimplified (19, 23). It is therefore important that the components of the sediments most active with respect to dissolved ions be identified.

A.11 Small grain size

Since adsorption of ions occurs on the surfaces of particles, the disposal medium should have small grain size in order to maximise the active area. Small grain size also tends to correlate with low permeability (A.9). Sediments with moderate grain size (sands) may be more susceptible to liquefaction by earthquakes (17, 18).

The finer-grained sediments occur farthest from the continental margins and generally in the deepest water. The finest grained of all are the deep-sea clays, generally found in water over 4-5 km deep. Reference 24 and Figure 7 give the generalised distribution of sediment types in the Atlantic.

A.12 Low organic carbon

Organic matter in sediments may react with some waste elements to produce soluble complexes which can migrate easily. It may also indicate a reducing environment which could affect canister corrosion (A.19). Organic carbon content should therefore be low, though precise limits are uncertain at present.

A.13 and A.14 Adequate shear strength and plasticity

The disposal medium should have high enough shear strength to prevent thermally induced mass convection. On the other hand, certain emplacement techniques (e.g. free-fall penetration) may require that the sediment should not be too strong, and should be capable of self-closure after emplacement.

There are few reliable measurements of shear-strength in deep-sea sediments, but those which exist suggest values in the region of 10 to 100 kPa in the upper 100m (10).

A.15 Absence of gases and gas hydrates (clathrates)

Sediments with high natural gas content are potentially unstable and should be avoided. Under typical temperature and pressure conditions in the upper few hundred metres of deep ocean sediment, hydrocarbon gases can combine with water to form solid hydrates or clathrates (25). If such hydrates existed at a disposal site, heat from the waste material might dissociate them to produce free gas, leading to enhanced pore-water circulation or even disruption of the sediments.

A.16 Absence of surface obstructions

The site should be relatively free of obstructions such as boulders, wrecks or other artefacts, which could impede emplacement, damage waste containers, or lead to scouring and erosion. In high latitudes, glacial erratics might present an unacceptable obstacle. Such rocks have been found at least as far south as 30 °N in the eastern Atlantic (26), but their precise distribution and density are not well known at present. Obstacles might be permitted at a disposal site if suitable emplacement techniques were employed, but their positions would need to be accurately mapped.

A.17 High thermal conductivity

The thermal conductivity of the medium should be high enough to facilitate adequate conductive heat dissipation from the waste and avoid large in situ temperature increases. High temperatures would increase the risk of pore-water or even whole-sediment convection, would probably accelerate canister corrosion and leaching of the wasteform, and might cause adverse changes in the physical and chemical properties of the disposal medium. They would also make prediciton of the disposal system more difficult.

The conductivity of sediments is largely a function of water content; the finer grained (higher water content) sediments generally have slightly lower conductivities. However, the variations are fairly small and most sediments have conductivities between about 0.8 and 1.0 Wm^{-1} K^{-1}.

A.18 Minimisation of adverse changes to disposal medium

Because deep-sea sediments have relatively low thermal conductivities (A.17), there will be some increases in in situ temperatures, though these could be reduced by longer storage before disposal. These raised temperatures may very well cause changes in the physical and chemcial properties of the disposal medium, and the high levels of radioactivity around the waste may also cause changes. As far as possible, a disposal medium should be chosen in which these effect, especailly adverse changes, are a minimum. Where they do occur, they should be predictable. At present there is virtually no information on this subject.

A.19 Suitable pore-water chemistry

The pore-waters at the disposal site should have the optimum properties for minimising corrosion of waste canisters and leaching and migration of radionuclides, and preferably for producing a relatively stable, predictable system. Several important waste-derived species appear to be less mobile in oxidising conditions. On the other hand, reduced sediments are better buffered against changes of acidity (pH) and oxidation potential (Eh). It is not yet clear what are the optimum pH and Eh conditions for minimising corrosion, and they may well depend on the materials involved. The mechanisms which control pH and Eh balances in sediments are only partly understood at present.

A moderate proportion (~30%) of carbonate in the sediment may be desirable in order to stabilise the pH of the pore-water environment.

iii) Operational and general considerations

A.20 Suitable geotechnical properties for easy emplacement

In addition to the properties given above, which relate to the efficiency of the geological barrier, the disposal medium should possess suitable geotechnical properties to allow reasonably easy, economical emplacement. For free-fall penetration this would require a sediment which was not too stiff (but subject to A.13 and 14). For free-fall or drilled emplacement, significant thicknesses of sand and gravel should be avoided. Substantial deposits of ice-rafted glacial sands may occur as far south as about 40° to 45°N (27). For drilled emplacement into basement the rocks should be competent and not fissured or brecciated; young oceanic basement (near mid-ocean ridge crests) is heavily fissured and difficult to drill (28).

A.21 Avoidance of exploitable resources

To minimise the risk of future disturbance of the site, it should be in a region of low resource potential or else any resource present should be recovered before disposal begins. Resources may include seabed minerals, sand, gravel and fish.

A.22 Avoidance of seabed installations

The site should as far as possible avoid areas of existing or foreseeable installations such as submarine cables, military defence systems, etc.

A.23 Political considerations

Due consideration must be given to the constraints imposed by national boundaries, international agreements (such as the UN Law of the Sea Conference) and other policitcal factors.

A.24 Adequate area for economical disposal

The site or sites should have a large enough area to allow disposal of economically reasonable quantities of waste. (The Nuclear Energy Agency Seabed Working Group currently recommends an area greater than 100 km square, allowing 10^6 canisters at 100m centres. However, the use of several somewhat smaller sites would probably be feasible). The size distribution of sedimentary basins in the north Atlantic is shown in Figure 4.

A.25 Avoidance of shipping lanes

The site should preferably not be directly beneath a major shipping lane to avoid risk of collision and undue inconvenience during operation of the disposal facility. There is some evidence of heavy deposits of clinker (from coal-burning ships) beneath historical shipping lanes, and this might conceivably hamper emplacement.

A.26 Good climatic conditions

To minimise operational difficulties and accident risks, the site should preferably be in a region of good weather and sea conditions.

In addition to the guidelines given above most of those in the next section would apply to under-the-seabed disposal, though less rigorously.

B. EMPLACEMENT ON THE SEAFLOOR

i) Seafloor environment

Points A.1 to A.5 concerning seafloor stability apply, in addition to the following:

B.1 Extensive sediment cover

Unless there is likely to be a problem of biological transport from sediments, there should be suitable seafloor sediments extending down-current (which may effectively be in several or all directions) from the disposal site for as far as signigicant quantities of suspended or dissolved waste may come into contact with the seabed. At present it is impossible to estimate how far this would be. On the other hand, if biological transport does seem to be a problem, one would wish to avoid concentrating waste in surface sediments.

B.2 High adsorptivity

See A.10, A.12 and B.1

B.3 Freedom from obstructions

See A.16

B.4 Adequate shear strength (See also A.13 and A.14)

The seabed should be strong enough to prevent canisters from sinking even a few metres if that would cause them to overheat. Reliable measurements of bearing strengths are rare, but usually indicate very low strengths, rising to about 10 kPa within a metre depth. In some circumstances sedimentary strength can be dramatically reduced by earthquakes (18).

B.5 Avoidance of burial by sedimentation

When an obstacle impedes the flow of sediment-laden water, part of the load may be deposited in much the same way that snow drifts. Clearly a site should be chosen where this effect is small enough that canisters will not be buried during the time-scale of high heat generation (of the order of 10^2 to 10^3 years). This could best be achieved by choosing an area where there is little suspended sediment, but would need to be balanced against B.7. (See also A.4).

B.6 Avoidance of exploitable resources and installations

See A.21 and A.22. However, the risk of accidental disturbance, and possibly even recovery, by activities such as dredging, mining or bottom-trawling, is very much greater for on-the-seafloor disposal. The chosen site should therefore have the minimum of attributes (including, for example, minerals currently uneconomic to recover, deep-sea fisheries, or even areas of unusual scientific interest) which might tempt future investigation, even if knowledge of the site's function is lost.

B.7 High concentration of settling adsorptive sediment

If biological transport from sediments is not a problem, then a high concentration of sediment, highly adsorptive for waste ions, and in the process of being deposited, would perhaps be the surest way of rapidly fixing leached waste ions onto the seafloor. This would have to be weighed against B.5. It might be possible to choose a concentration which was low enough not to bury canisters in 10^3 years, but high enough to scavenge ions effectively at their release rate by leaching. This would require very careful study of the sedimentary processes, and even then the predictability would probably be low. However, it might be undesirable to create a localised concentration of surface activity if biological transport were likely to be a problem.

ii) Biological considerations

B.8 Low benthic biomass

Any disposal site should be in an area where the quantity and biological activity of the benthic organsims are low, to minimise both the chance of transfer back to man and the direct effect of the waste material on the biosphere. While sparsely populated areas are occasionally found in shallow water due to local conditions such as low oxygen levels, this criterion in general restricts possible sites to the deep-sea, that is beyond the continental margins. In such regions, the average benthic biomass is of the order of 0.1 to 1.0 gm^{-2} (Figure 8). There is perhaps a possibility that, given the existence of suitable nutriments, the emplacement of a heat source could itself engender a localised community, analogously to those occurring around hydrothermal vents in the Pacific (29). See also B.17.

B.9 Low mid-water biomass

Like the benthos, the biological community within the water column overlying a disposal site should be relatively sparse. In general these two features will be closely correlated since high surface productivity is usually reflected in the benthos, and the productivity itself tends to decrease with increasing distance from the land.

B.10 Minimum mid-water vertical migration

The most direct, and potentially rapid, biological transport mechanism by which material might be transferred from the seabed to the surface regions is the extensive vertical migration known to be undertaken by many mid-water organisms. Such migrations may have a diurnal, seasonal, or ontogenetic (developmental) periodicity, or may combine all three. These vertical movements are widespread in the upper 1000 m or so of the water column; although deeper vertical movements are thought to be small, there is as yet little evidence to confirm this. However, even if vertical migrations at greater depths are small, they may still be important if they involve organisms which accumulate and concentrate radioactive contaminants.

Where the ocean is less than about 1000m deep, that is over the upper continental slope and on the shelf, the vertical migration patterns provide a direct link between the benthos and the surface layers. A potential disposal site should therefore be remote from such areas, with no major horizontal migration systems linking it with them.

B.11 Bioturbation

The disturbance of the sediment as a result of the activities of animals living in, on, or immediately above the seabed is mainly confined to the upper few centimetres and rarely extends deeper than a metre or so. Bioturbation is therefore unlikely to be significant in the general upward transfer of waste material emplaced deep within the sediment. Nevertheless, once waste material has reached the surface layers of the sediment as a result either of intentional emplacement on the seabed, accident, or the normal physical and chemical processes within the sediments, bioturbation may be significant in its transfer to the sediment/water interface or into suspension. There is also good evidence that bioturbation may increase the rate of surface erosion by near-bottom water currents. A disposal site should not therefore be subject to high levels of such activity if it is also in an area of non-deposition or erosion. On the other hand bioturbation will tend to bury some contaminated surface particles, and bring fresh sediment to the surface which could then adsorb more radionuclides. In a region of continuous sediment deposition, then, bioturbation could be advantageous. Bioturbation is usually indicated by the presence of mounds, pits, grooves and burrows.

iii) Oceanographic considerations

B.12 Low bottom-current stress

The site should be in an area of generally low current stress so that sediment stability can be assured (see A.2). This condition will usually be ensured if the currents are low, and the expected currents during the time-scale of waste decay are low. Regions of known past, present or foreseeable large currents should be avoided. In general this requirement will exclude, among others, areas of rough topography and slope areas where local current enhancement may occur.

B.13 Adequate water depth

Although insufficient is known of the diffusive processes in the water column (B.15), it is likely that the greatest safety will be achieved by placing the waste at the greatest possible depth below the surface of the ocean.

B.14 Avoidance of direct advection to sensitive areas

Areas of known or suspected direct, rapid advection towards sensitive areas (e.g. fishing grounds, mining areas, areas of strong vertical diffusion) should be avoided.

B15 and B.16 Diffusion in the water column

It is certain that no site will be found from which a release of waste products on or through the seabed will be efficiently and rapidly mixed through the entire ocean volume. This being the case, until the most restrictive pathways through the ocean have been established, it is not obvious whether a site of vigorous or weak local mixing is preferable. The former might rapidly reduce the concentration near the release point, possibly (on average) to safe levels but at the cost of spread into a larger volume with a consequent higher probability of transfer to sensitive areas. A weak mixing area (e.g. central oceanic gyre) might lead to longer local containment, but at the cost of high toxic levels building up with the danger of affecting the local environment and the (albeit low) possibility of occasional transfer at high concentration to a sensitive region.

More research is needed to examine the processes of diffusion near the seabed, the routes along which material will be carried in the water, and the probability of extreme concentrations resulting from release of waste on the seabed (see reference 10). Extreme values are important, since fluctuations could produce unacceptably high concentrations of radionuclides at some times and places even if the mean levels are acceptable.

At present it is suggested that a disposal site should avoid:

a) high latitudes where the vertical stability of the water column is low and where mixing to the surface may be relatively rapid;

b) regions adjacent to continental margins, ridges, seamounts and islands, where vertical transfer may be relatively rapid.

B.17 Suitable water chemistry (see also A.19)

It is not yet clear what are the optimum conditions for low canister errosion, and it may be that these will depend on the materials used. In reducing conditions, sulphur-oxidising bacteria may be present and, if a heat source were introduced it is conceivable they might form the basis of a dense, local biological community (see B.8).

iv) Operational and general considerations

Criteria A.20 to A.26 apply here, but it is emphasised that the requirement to avoid accidental disturbance to the site is very much greater for on-the-seafloor option (see B.6).

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FIGURES

Figure 1. The decay of radioactivity in high-level waste resulting from reprocessing of a typical light water reactor fuel. (Drawn from data in reference 8, tables I and II).

Figure 2. Some concepts for oceanic waste disposal: Sub-seabed disposal into soft sediments by free-fall penetrometer (a) or into hard rock by drilling (b); on-the-seabed disposal by free-falling (c) or controlled emplacement (d).

Figure 3. Bathymetry of the North Atlantic after Chase (30). Depth contours at 1 km intervals. Earthquake epicentres are represented by dots.

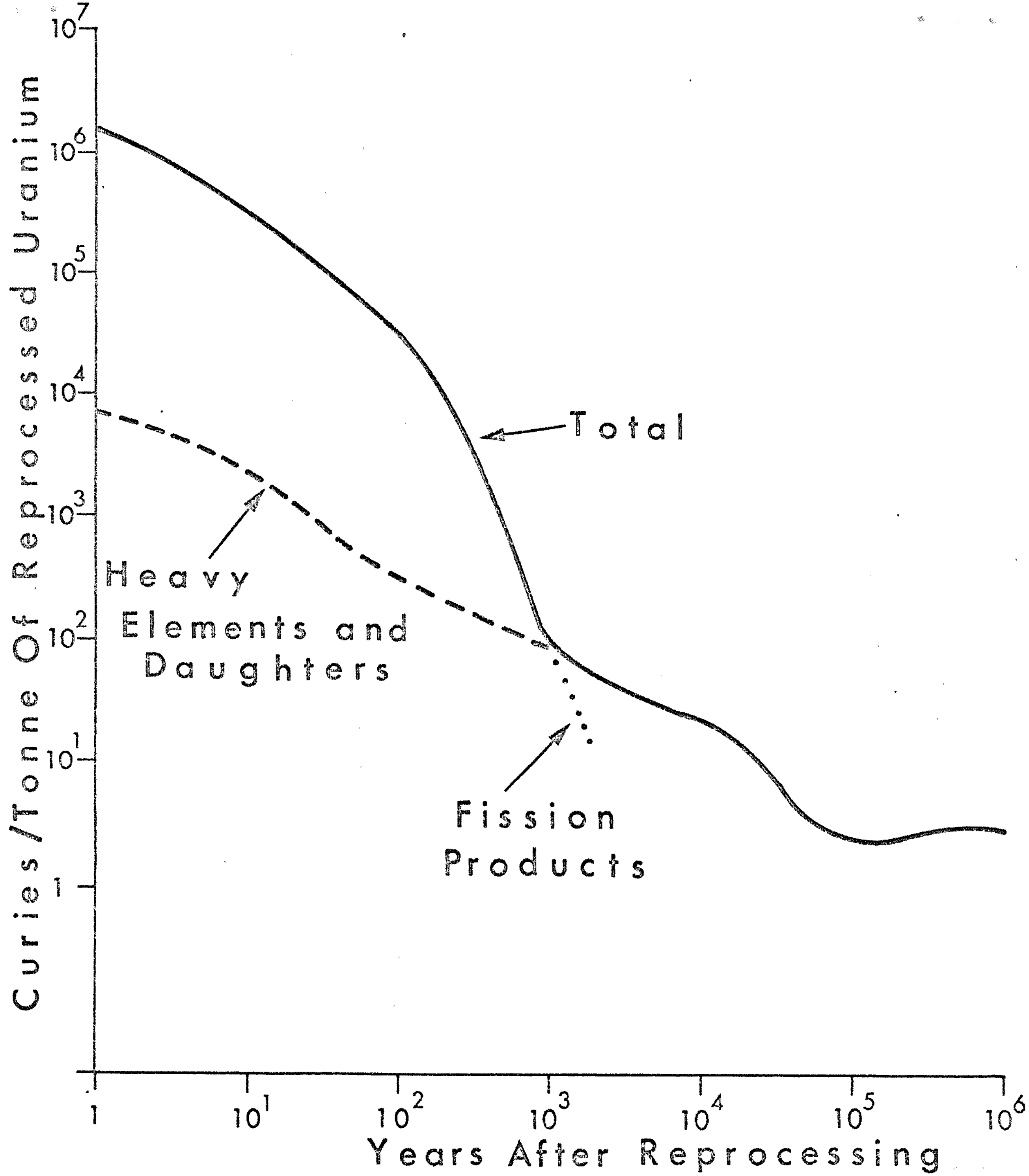
Figure 4. Size distribution of sediment basins in the North Atlantic.

Figure 5. Occurrence of ice-rafted material recovered in dredge-hauls and Deep Sea Drilling Project cores (black dots) together with contours of maximum rate of deposition of glacial sands in milligrams per square centimetre per thousand years, and inferred limits of drift ice, from references 26 and 27.

Figure 6. Areas with horizontally continuous sediments extending at least 100 km (hatched) and probably largely unaffected by turbidity currents, from Figure 4. Lettered areas indicate preliminary study areas identified in section 4.3. Heavy line is seaward limit of abyssal plains.

Figure 7. Distribution of major sediment types in the North Atlantic.

Figure 8. Distribution of benthic biomass in the Atlantic Ocean.



Curies/Tonne Of Reprocessed Uranium
10^7
10^6
10^5
10^4
10^3
10^2
10^1
1
Total
Heavy Elements and Daughters
Fission Products
1
10^1
10^2
10^3
10^4
10^5
10^6
Years After Reprocessing

Fig. 1

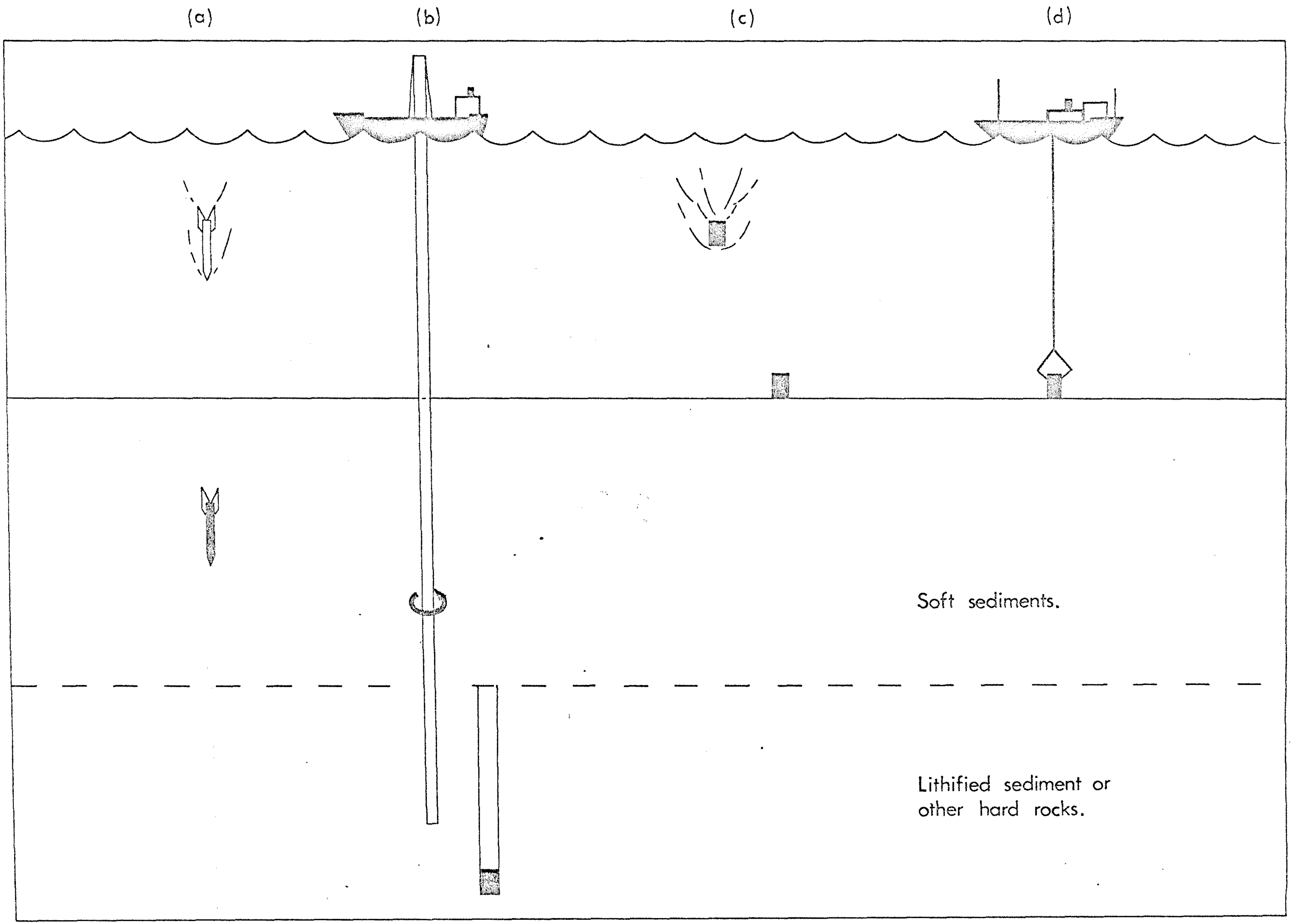

(a)
(b)
(c)
(d)
Soft sediments.
Lithified sediment or
other hard rocks.

Fig. 2

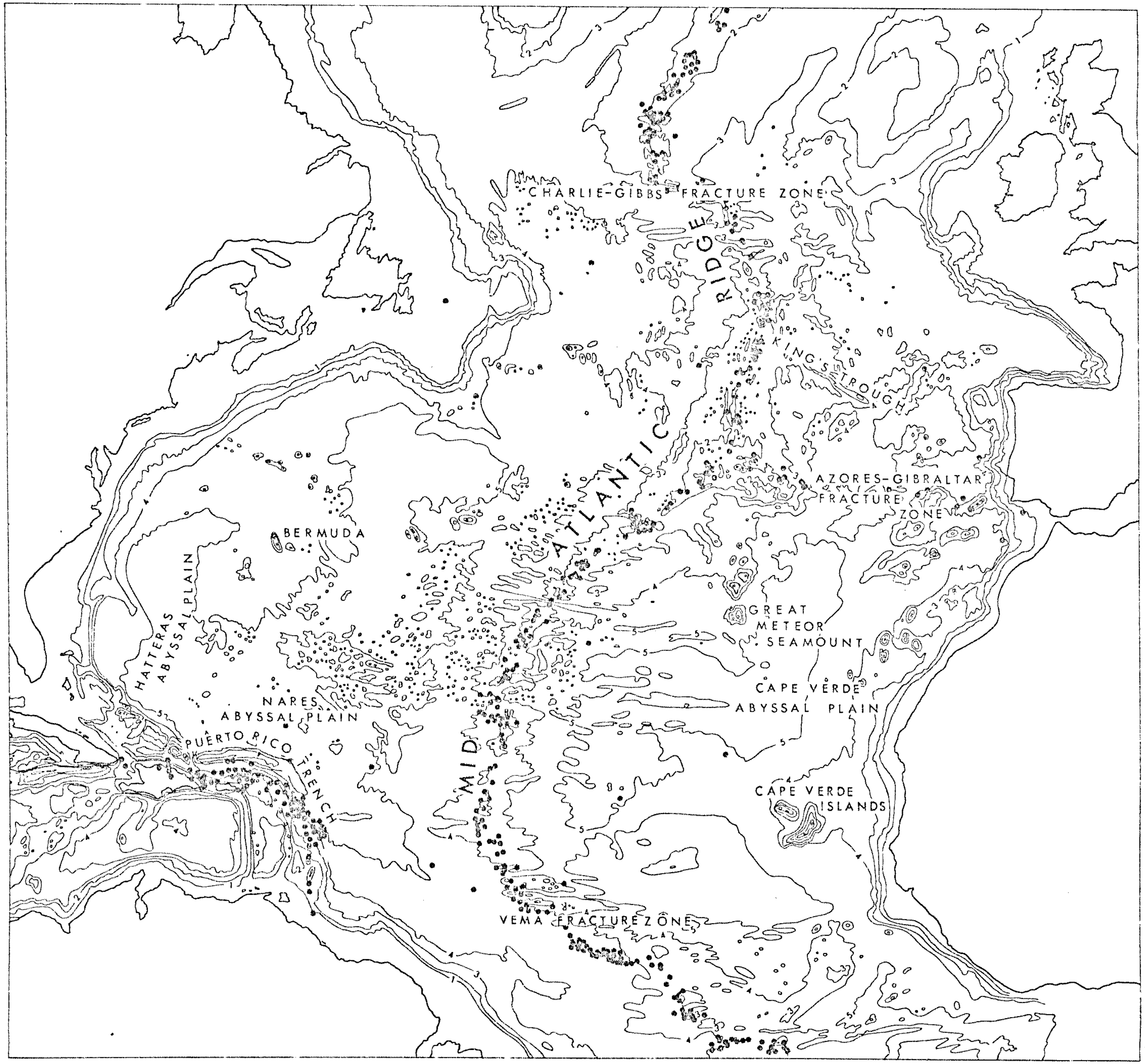

CHARLIE-GIBBS FRACTURE ZONE
MID ATLANTIC RIDGE
KING'S TROUGH
AZORES-GIBRALTAR FRACTURE ZONE
BERMUDA
HATTERAS ABYSSAL PLAIN
GREAT METEOR SEAMOUNT
CAPE VERDE ABYSSAL PLAIN
NARES ABYSSAL PLAIN
PUERTO RICO TRENCH
CAPE VERDE ISLANDS
VEMA FRACTURE ZONE

Fig. 3

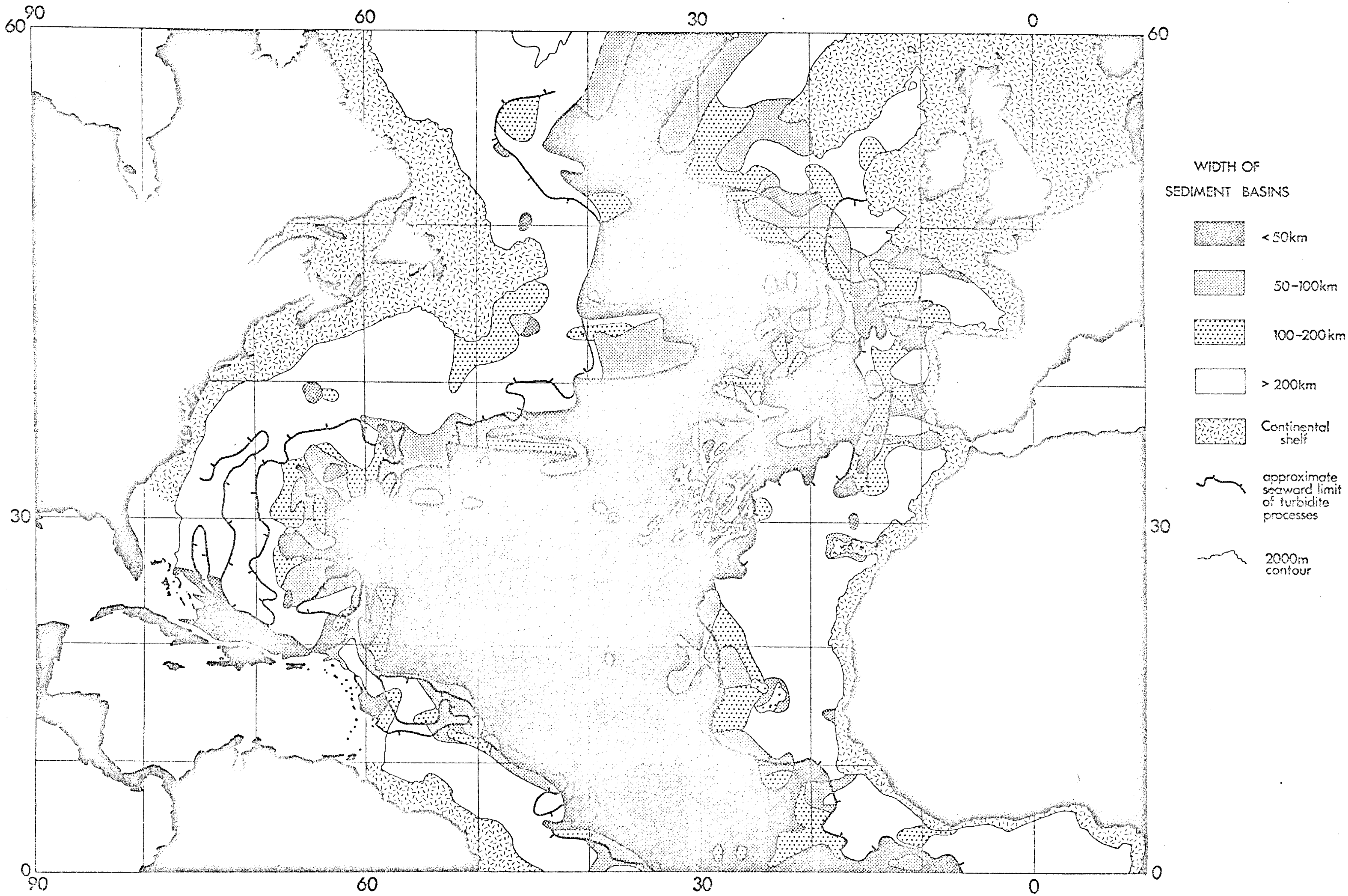

WIDTH OF SEDIMENT BASINS
< 50km
50–100km
100–200km
> 200km
Continental shelf
approximate seaward limit of turbidite processes
2000m contour
90
60
30
0
60
30
0

Fig. 4

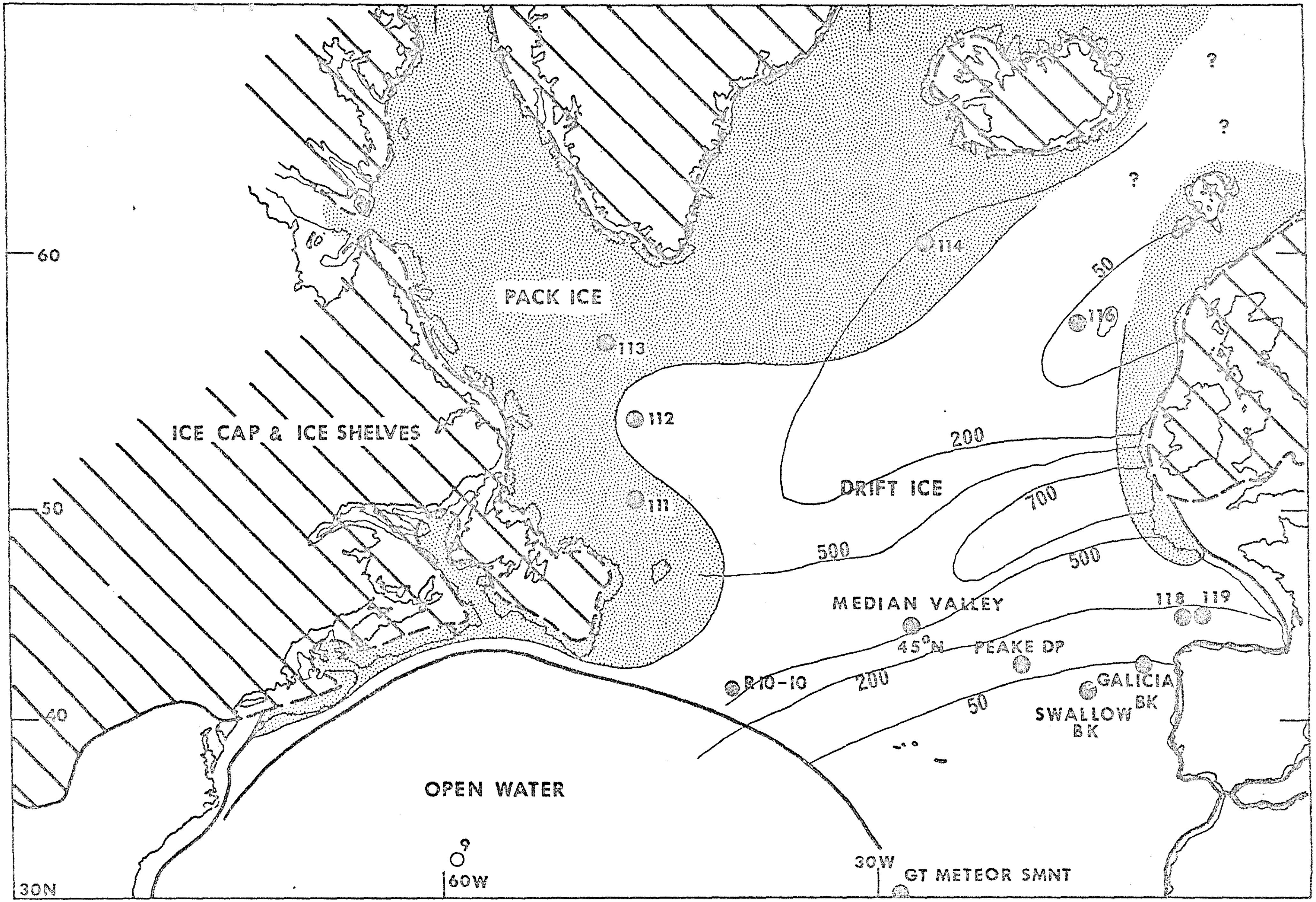


Fig.5

Suggested ice limits at maximum extent of glaciation.

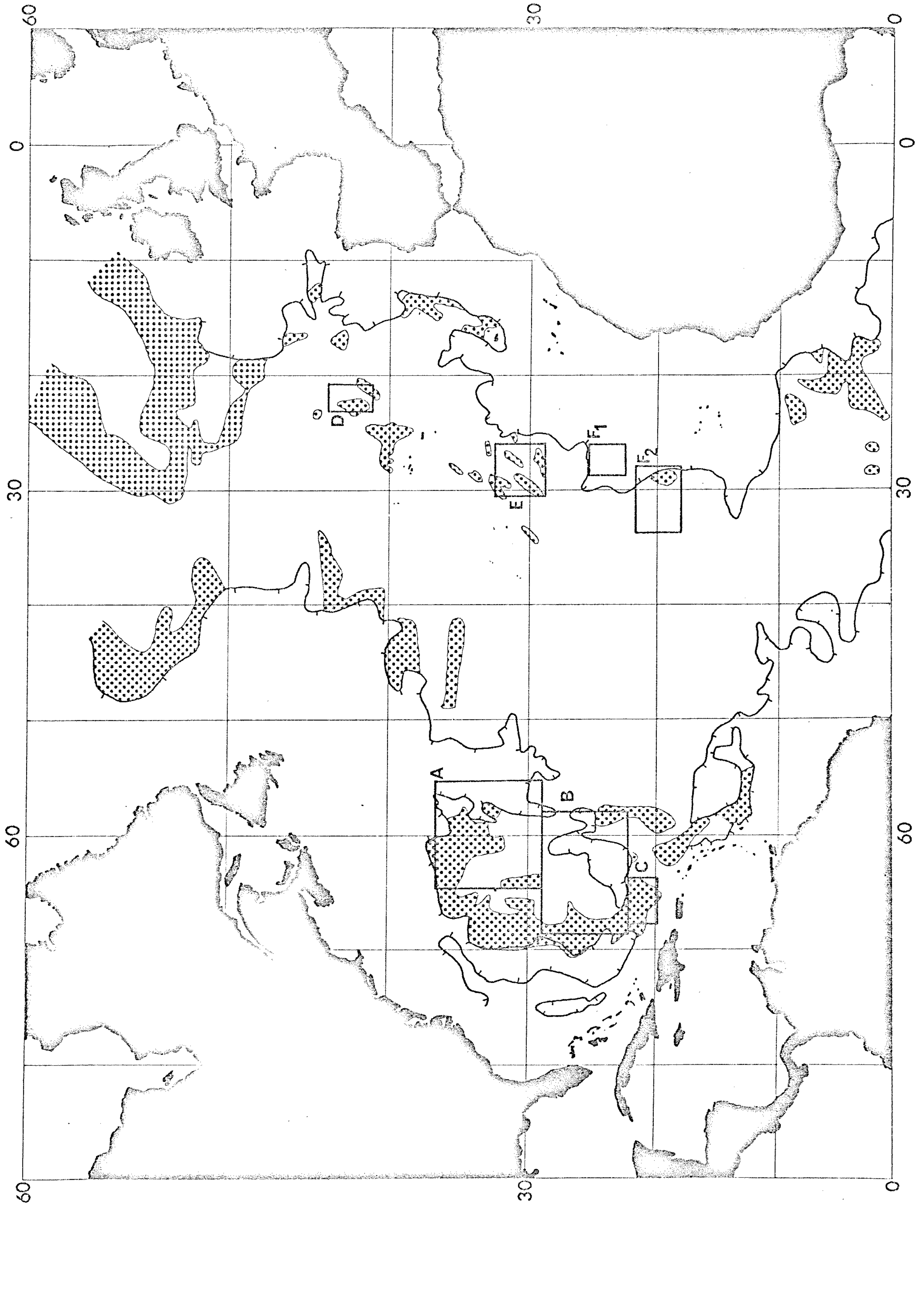
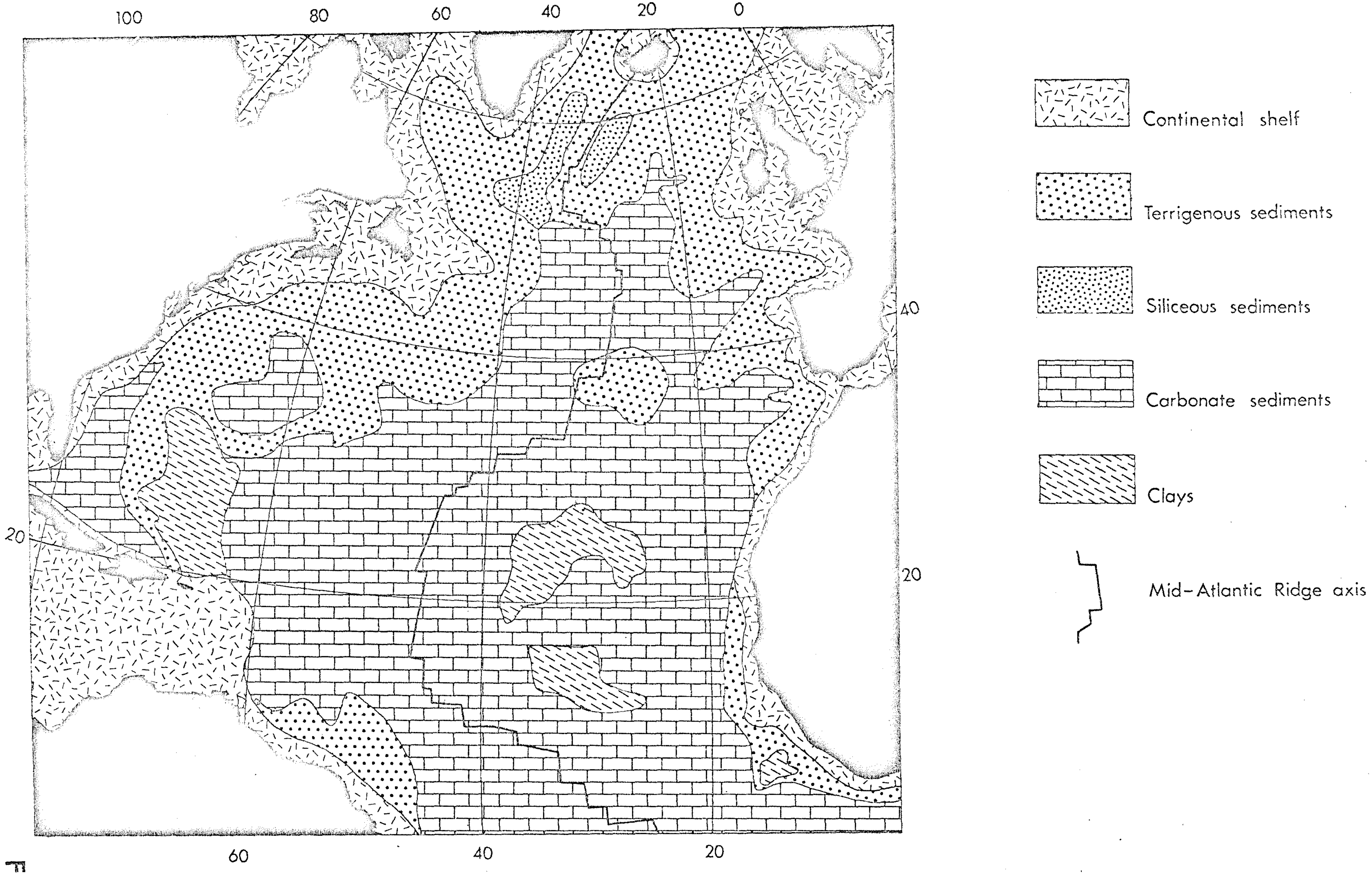


Fig.6



100
80
60
40
20
0
40
20
20
60
40
20
Continental shelf
Terrigenous sediments
Siliceous sediments
Carbonate sediments
Clays
Mid-Atlantic Ridge axis

Fig.7

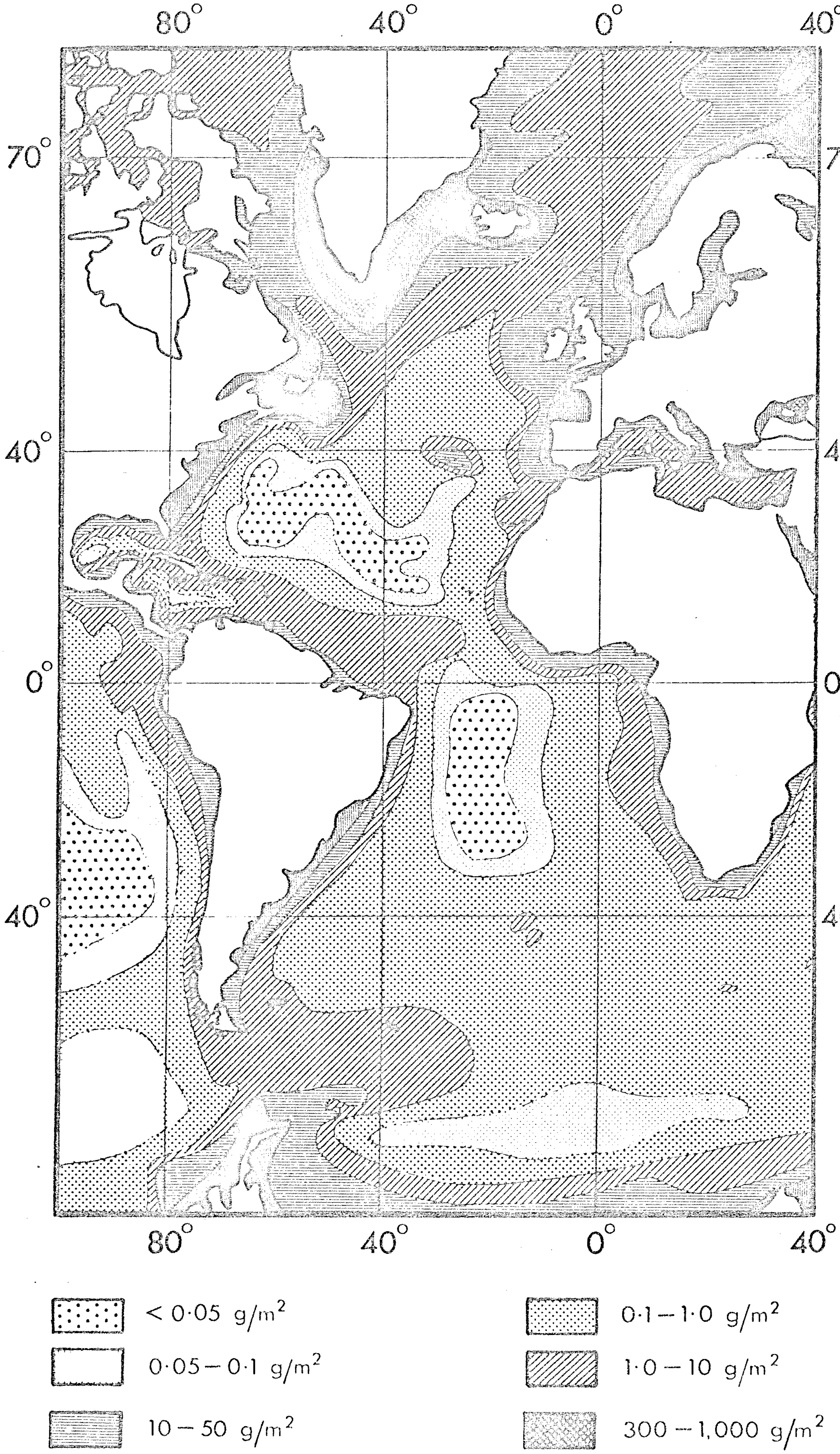

80°
40°
0°
40°
70°
70°
40°
40°
0°
0°
40°
40°
80°
40°
0°
40°
< 0·05 g/m²
0·05 – 0·1 g/m²
10 – 50 g/m²
50 – 300 g/m²
0·1 – 1·0 g/m²
1·0 – 10 g/m²
300 – 1,000 g/m²
> 1,000 g/m²

Fig. 8