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Why consider subseabed disposal of high-level nuclear waste?

MASTER

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Abstract

Large areas of the deep seabed warrant assessment as potential disposal sites for high-level radioactive waste because: (a) they are far from seismically and tectonically active lithospheric plate boundaries; (b) they are far from active or young volcanos; (c) they contain thick layers of very uniform fine-grained clays; (d) they are devoid of natural resources likely to be exploited in the forseeable future; (e) the geologic and oceanographic processes governing the deposition of sediments in such areas are well understood, and are remarkably insensitive to past oceanographic and climatic changes; and (f) sedimentary records of tens of millions of years of slow, uninterrupted deposition of fine grained clay support predictions of the future stability of such sites. Data accumulated to date on the permeability, ion-retardation properties, and mechanical strength of pelagic clay sediments indicate that they can act as a primary barrier to the escape of buried nuclides. Work in progress should determine within the current decade whether subseabed disposal is environmentally acceptable and technically feasible, as well as address the legal, political and social issues raised by this new concept.

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THE HIGH-LEVEL WASTE PROBLEM

So pervasive is public concern over the safe storage of highly radioactive wastes (both spent nuclear fuel and the residue from reprocessing such fuel) that rarely does a week pass without the appearance of a major newspaper or newsmagazine article on the subject. This concern is fed by and contributes to the complex arguments over the future of nuclear power generation. It also is fed by all-too-frequent press releases announcing yet another problem with an existing low-level disposal site. Regardless of one's view on the future of nuclear power or nuclear weaponry, however, we have been in the nuclear age for more than a third of a century. The debris of this age is already with us. Thus, a sense of responsibility to future generations demands that we find a safe way to dispose of such wastes.

What is "safe"? Like so many of the issues associated with nuclear waste, this one has no generally accepted answer. The range of suggestions extend from "no release ever," to "no release greater than that due to the parent uranium ore from which the waste was generated." The former requirement is unattainable with 100 percent certainty; the latter probably is well within current technology. The degree of difficulty of waste disposal, then, largely depends on where between these two extremes lies an acceptable solution. Thus, the first and toughest issue faced by those of us trying to develop environmentally acceptable disposal options is the need for a societally acceptable performance criterion against which we can test our technical data. Until this criterion is established, we will continue to push for the greatest possible level of safety.

Perhaps an acceptable level of exposure can be related to the natural variability in environmental radioactivity to which we all are continuously exposed. New York and Denver, for example, have different levels of background radiation. Yet how many people take this into account when considering a move between these cities? Very few, we suspect. Thus, if the perturbation of the radiation dose to the population or an individual due to properly disposed-of wastes is small relative to such natural differences, perhaps there should be little cause for public concern. It remains to be seen, however, whether such logic will carry any weight in considerations of this emotion-charged issue!

The companion paper by Anderson and others (1981; this volume) delves further into the nature and magnitude of the waste disposal problem.

WHY EVEN CONSIDER SUBSEABED DISPOSAL?

As with most complex and developing programs, the perception of the Subseabed Disposal Program (S.D.P.) in the eyes of its participants has evolved through time. At present, we perceive the program as a geologic disposal option - our geology simply happens to be covered with water. In this light it seems obvious that an inventory of global geologic disposal options would be woefully inadequate if 70 percent of the earth's surface were arbitrarily excluded. In fact, however, the idea of subseabed disposal grew out of a 1973 conversation between Bill Bishop, then of Sandia Laboratories, now at NASA, and Charley Hollister in which they attempted to identify the least valuable (in the broadest sense of the word) portion of the earth's surface. Their discussion (Bishop and Hollister, 1974) pointed to certain abyssal-clay regions of the sea floor which, as serendipity would have it, also had several other characteristics that are highly desirable in a potential disposal site.

Subsequently, S.D.P. participants have developed rigorous and objective site selection criteria against which the properties of sections of the sea floor can be tested. These criteria and the logic behind their formulation are discussed in a companion paper by Laine and others (1981; this volume), and will not be elaborated here. Suffice it to say that if these criteria can be met by an oceanic site, we will have identified a potential high level waste repository of exceptional technical suitability.

THE "MYTH OF IGNORANCE"

There is a widely held impression among non-oceanographers that we are very ignorant about the ocean in general and the deep-sea floor in particular. Statements like "we know more about the moon's behind than the earth's bottom" (reference mercifully forgotten!) are all too common. Closely allied to this myth is the false impression that we lack the technology to examine or sample the sea floor effectively. It is surprising that such an impression persists, given the well publicized exploits of the <u>Glomar Challenger</u>, <u>Glomar Explorer</u>, and deep submersible <u>Alvin</u>, but it does. While the "myth of ignorance" helps preserve the mystique of the oceans and of the field of oceanography, it is also rather misleading. In reality, we know a great deal about the ocean and the materials beneath it; in some respects much more than we know about the continents over which we clamber and which we can readily examine with all the tools of the modern geologist and geophysicist.

How is this possible? The ocean basins have a number of properties that allow geologic and oceanographic generalizations to be made that are applicable to regions covering millions of square kilometers. Some of these are:

1. The oceanic crustal portions of the lithospheric plates that cover the earth (Fig. 1) are simple relative to continental crust. The oceans basins are geologically young; the sea floor we see today has formed within the last 200 or so million years and continues to form today in a geometrically simple way by sea-floor spreading processes (Fig. 2). In contrast, most continental crust bears the marks of many superimposed cycles of deposition, deformation, uplift, metamorphism, anatexis, and erosion, spanning hundreds of millions to billions of years.

The youth of the oceanic crust and our ability to observe its creation and demise have two important consequences: (a) we can make global predictions of the structure and nature of oceanic igneous rocks on the basis of fairly limited observations; and (b) we can identify tectonically inactive regions with a high degree of confidence.

2. Oceanic volcanism away from very young crust tends to lie above "hot spots" deep in the mantle (Morgan, 1972) which move slowly, if at all, relative to the earth's spin axis. Again, this allows areas of present and future volcanism to be predicted with considerable confidence. The relation of isolated seamounts to plate tectonics or "hot spot" activity is less clear. Limited sampling suggests that such seamounts form when the oceanic lithosphere is young and thin (i.e. close to a mid-ocean ridge). Further work in this area is needed, however.

3. Sedimentation in the deep sea is inherently less complex than in marginal oceanic or terrestrial environments. If areas subject to strong bottom currents, slumps, or turbidity currents (Hollister, Flood and McCave, 1978) are excluded, deposition in the deep sea reflects only:

(a) Biological productivity of the overlying surface waters. Sediments beneath productive areas (Fig. 3) are enriched in the calcareous (calcite) and siliceous (opal) tests of microscopic plants and animals (Fig. 4).

(b) Corrosiveness of the bottom waters. Newly-formed bottom water is depleted in dissolved silica and, as a result, rapidly attacks opal. "Older" water accumulates carbon dioxide by oxidation of falling organic debris, so tends to dissolve calcareous sediments. This corrosiveness increases with increasing depth in the ocean. Because the youngest bottom waters are found in the North Atlantic (they form in the Norwegian Sea), and the oldest in the North Pacific, North Atlantic sediments tend to be carbonate-rich and silica-poor relative to their North Pacific counterparts (Berger, 1970).

(c) Introduction of terrigenous debris via eolian or benthic pathways. Eolian contributions are revealed by the distribution of quartz (a mineral of almost exclusively continental origin) in pelagic sediments (Fig. 5). Benthic boundary layer or nepheloid transport is most evident in the "drift" deposits of the western South and North Atlantic (Fig. 6).

(d) Formation of metalliferous sediments at centers of crustal spreading. These deposits are dominated by iron oxyhydroxides, with lesser amounts of other transition metals and iron-magnesian smectites. Metalliferous sediments form when reduced iron that is leached from newly formed basalt by hot circulating seawater (Fig. 7; Corliss, 1973) reacts with cold, oxygen-bearing bottom water. The bulk of the metalliferous deposits are laid down close to mid-ocean ridges (Bostrom, 1973; Dymond, 1981; Heath and Dymond, 1981), but a small fraction which remains in suspension because of its fine particle size is dispersed widely over the deep-sea floor (Leinen, 1979).

(e) Precipitation of authigenic minerals from seawater. Deep-sea ferromanganese nodules (Glasby, 1977; Heath, 1980) are the most visible authigenic deposits. They have attracted much attention of late because in certain areas (Fig. 8), their Cu and Ni contents of 1-2 percent make them potential ores. In addition, though, dispersed ferromanganese oxyhydroxides, zeolites, smectites, and phosphorite all can form significant authigenic deposits in areas of slow deposition.

Because the great thickness of the overlying water column (5-6 km) and the great distance from sources of detritus tend to filter out high-frequency variations in the supply of sediment to the deep-sea floor, pelagic sediments from any location are remarkably uniform in character (e.g. Heath *et al*., 1970).

4. An understanding of contemporary deep-sea sedimentation patterns combined with the principles of plate tectonics has led to the concept of "plate stratigraphy." The migration of sea floor from a spreading center to a typical abyssal-hill environment and ultimately to the trench of a subduction zone gives rise to a characteristic sequence of sediments. The basal deposits, which are laid down on the shallow (2.5-3 km) rise crest are enriched in metalliferous components and biogenic calcite. As the sea floor cools and subsides (Sclater, Anderson and Bell, 1971), it sinks beneath the calcite compensation depth and begins

to receive fine, carbonate-free pelagic or "red" clay. The character of the clay depends on the relative importance of terrigenous and authigenic inputs, but it is inevitably very fine grained. As the sea floor approaches a subduction zone, it receives more terrigenous detritus which may accumulate under reducing conditions as the enhanced supply and preservation of organic matter consumes the dissolved oxygen in interstitial waters.

Clearly, this idealized sequence will be perturbed if the sea floor drifts beneath a zone of high biological productivity or an abyssal plain, but even in these cases, the paleoenvironmental history of deposition at a site or group of sites has proven to be relatively simple to unravel (van Andel, Heath and Moore, 1975; Heath, Moore and van Andel, 1977; Leinen, 1979; van Andel et al., 1977).

Building on the concept of plate stratigraphy, the relatively young field of paleoceanography has used the sedimentary sequences recovered by the Deep Sea Drilling Project to construct a surprisingly detailed picture of past oceanic conditions. Changes in the calcite compensation depth (van Andel, 1975), in the temperatures of surface and bottom waters (Shackleton and Kennett, 1975), in the distribution of hiatuses in sedimentation (Moore and Heath, 1977; Moore et al., 1979), and in the composition of the siliceous and calcareous microflora and microfauna of the surface ocean waters spanning the past 100 million years are now well known.

WHAT PROPERTIES OF THE DEEP SEABED ARE IMPORTANT TO THE S.D.P?

1. Existence of resources or characteristics valuable to man.

(a) Fisheries. At the present time, only food is extracted from pelagic areas. The distribution of fish catches resembles the pattern of primary productivity, with the most valuable fisheries concentrated along the boundaries of the oceans and regions of upwelling. Even though there would be no interaction between a buried waste cannister and a pelagic fishery the possibility of logistical complications during the emplacement phase would favor a disposal site away from a heavily fished region, other factors being equal.

(b) Potentially exploitable mineral resources. Table 1 summarizes actual and potential economic submarine mineral desposits. Virtually all of these deposits are restricted to the continental margins. The likelihood of future exploration for hydrocarbons in such areas is a major reason for focusing the S.D.P.'s search for possible disposal sites in areas away from thick sediments on continental margins.

The one deep-sea mineral resource that likely will be exploited during this century is manganese (or ferromanganese) nodules. These nodules are ubiquitous in pelagic areas where sediments accumulate at less than about 7 meters per 1 million years (Heath, 1980). However, the nodules are enriched in Cu and Ni (the metals of commercial interest) only in restricted areas of the central and eastern subtropical Pacific (Fig. 8). The nodules low in trace metals are so widespread and face such competition from very low grade deposits on land that they are not a prime factor in our site evaluation activities.

(c) Interference with societal activities. Both shipping lanes (Fig. 9) and submarine cables provide some constraints on site selection. There are few enough cables (Fig. 10) that this constraint is not particularly severe. Shipping lanes, like major fisheries, would not be affected by a filled or inactive disposal site, but would be undesirable during the emplacement phase of waste disposal because of possible interference with normal transportation practices.

(d) Intangible resources. The pelagic areas of prime interest for waste disposal have no current or future scenic value or value for recreation, inhabitation or engineering construction that would be impacted by development of waste repositories. In this sense, the mid-plate, mid-gyre regions of the oceans have the lowest intrinsic value per unit area and lowest susceptibility to damage by waste disposal of any region on earth.

2. Geologic and Climatic Stability

As discussed previously, the relatively simple tectonic regime of the ocean basins allows the identification of huge areas away from both lithospheric plate boundaries (the "mid-plate" regions) and hot spots. These areas are demonstrably less susceptible to singular geologic events than any other part of the globe.

In addition, the work of the CLIMAP program (CLIMAP 1976, 1980) has shown that the cores of the great mid-ocean gyres (Fig. 11) are remarkably insensitive to the climatic changes of the past 20,000 years, a period during which the earth's climate has passed from a full glacial to a full interglacial mode. Inasmuch as the climatic change from 18,000 years ago to today is as great as any change in the past 60 million years, this "mid-gyre" climatic stability is unlikely to have changed over the past 10^6-10^7 years.

3. Uniformity

The development of a valid model of waste behavior in a submarine formation will be easiest and the level of confidence in the model will be greatest if the properties of the geologic formation are uniform or vary continuously. A major effort of the S.D.P. over the past several years has been aimed at determining whether deep-sea sediments, particularly in pelagic clay areas, display such uniformity. Results to date from two study areas (MPG-I and II) north of Hawaii (Fig. 12) are encouraging. For example, cores taken from topographic highs and lows several kilometers apart show remarkable correlations of identifiable horizons (Figs. 13-16). Clearly, in both MPG-I and MPG-II, sediment is being deposited more rapidly in lows than on highs (the variation is about a factor of two in each case), but the relative difference has been very uniform through time. In the case of MPG-I, the illustrated correlations cover the past 2.6 million years, whereas in MPG-II, the correlated intervals correspond to about 25 million years of deposition.

At a larger scale, comparison of geochemical data from core GPC-3 in MPG-I and core Y74-58P in MPG-II (Fig. 17) shows excellent correlations over a distance of some 720 km of the relative abundance of sedimentary components in the two cores (Leinen, 1979). For both the local and regional correlations, sedimentation rate changes of an order of magnitude during the past 50 million years have not disturbed the basic consistency of the patterns of sedimentation.

In the cores analyzed to date, lateral variations in properties are minimal, and vertical variations are gradational. Only where thin beds of volcanic ash appear in the sedimentary sequence are there discontinuities in the physical and chemical properties of the cores.

4. Predictability

For a geologic formation to form an acceptable waste repository, we must be able to predict that its integrity as a barrier to nuclide migration will not be impaired by some geologic event in the next 10^4 to

10^7 years (the exact figure will be determined by the containment criteria that are finally chosen and the properties of the entire system of barriers with respect to waste migration). Since we cannot possibly make direct observations of a repository for a long enough period to serve as a basis for predictions of geologic stability, we must base such predictions on the geologic history of the formation of interest and on its response to past environmental perturbations.

In this regard, the barrier properties of the pelagic clay formations of the mid-plate, mid-gyre regions reflect a demonstrable degree of insensitivity to external oceanographic and climatic conditions that probably is unmatched by any other formation on earth. For example, the intensively analyzed core GPC-3 (Doyle and Riedel, 1979; Hollister _et al_., 1980; Leinen, 1979; Prince, Heath and Kominz, 1980; Silva, 1977) from study site MPG-I consists of over 24 meters of undisturbed pelagic clay representing more than 70 million years of deposition. During this period, MPG-I has drifted with the Pacific lithospheric plate from a latitude of about 8°N to its present position at 30°N (Prince and others, 1980). As the site drifted from the northeast trades, through the horse latitudes to the fringes of the westerlies, and as the supply of continental detritus to the North Pacific waxed and waned in response to the topographic evolution of North America and global climatic changes, the core site received fine-grained detritus that changed gradually from terrigenous clays to smectite-ferromanganese clays to terrigenous clays again. Despite variations in sedimentation rate from 0.2 m per 1 million years beneath the horse latitudes to 2 or 3 m per 1 million years beneath the loess-laden Pleistocene westerlies, there are no measureable breaks in sedimentation (Fig. 18; the biostratigraphic resolution is about 4 million years [Doyle and Riedel, 1979] suggesting that no more than about 1 meter of sediment could be missed). Furthermore, the changes in composition of the sediment have little effect on its ability to contain buried wastes.

Thus, given the northwest direction of drift of the Pacific plate and the depositional environment lying ahead of the MPG sites, we can confidently predict that such areas will continue to receive a steady rain of fine sediment for millions of years to come.

The predictable depositional conditions, the insensitivity of sediment properties to glacial-interglacial climatic changes, and the viscoelastic properties of the sediments that render them essentially immune to damage by seismicity make the MPG clays as predictable as any geologic environment anywhere.

CAN DEEP-SEA CLAYS FORM AN ADEQUATE BARRIER TO THE MIGRATION OF BURIED NUCLEAR WASTES?

Assessment of the adequacy of the geologic barrier in the deep sea involves answers to two questions:

1. Are the ion-retardation (sorption) values of the clays high enough and the permeability low enough to prevent significant escape of dissolved nuclides by diffusion or advection?

2. Are the mechanical properties of the clays adequate to prevent vertical movement of a buried waste container?

Partial answers to both questions are given in the companion papers by McVey and others (1981; this volume) and Dawson and others (1981; this volume). Suffice it to say here that results to date support the adequacy of the red clay barrier, but that further laboratory and field experiments are needed to fully test this conclusion.

SOCIETAL FACTORS

The accompanying paper by Anderson and others (1981; this volume) touches on the legal-political-social issues raised by the subseabed disposal concept. Although one would be foolish to ignore such issues at this time (and the S.D.P. is not; e.g. Deese, 1978), it is clear that any action to modify national or international laws or regulations prior to the establishment of the technical and environmental feasibility of the concept would be difficult to justify. It is equally clear, however, that the S.D.P. should make every effort to inform the widest possible audience of our activities to reduce misunderstandings and to allow the assessment of the concept to proceed in a responsible and rational way. Also, it is not too soon to explore possible international modes of operation that could make the most effective use of the subseabed option should it prove environmentally feasible. The U.S. is unlikely to be the first nation to emplace wastes in the seabed, regardless of the progress of the S.D.P., because present U.S. policy strongly favors mined repositories as the initial disposal sites. Thus, it is in our best interest to see that the plans of other countries are exposed to an international forum and to a set of regulations that minimize the possibility of unsafe or premature disposal operations.

In addition, we have to fully consider the environmental impact of possible accidents, whether en route to a disposal site, or during the emplacement process. The paper by Gomez and others (1981; this volume) describes some of the water-column work that forms part of the monitoring and accident assessment efforts of the S.D.P. It is worth noting that such studies have application to the fate and impact of <u>any</u> of man's wastes, radioactive or otherwise, that find their way to the deep sea.

Finally, an aspect of subseabed disposal that should not be overlooked, given the ephemerality of man's social institutions, is the remoteness of prospective deep-sea disposal sites. Even with the full technical resources of a country like the U.S., and an exact knowledge of the locations of buried waste containers within a special acoustic navigation net, it will be expensive and difficult to retrieve such containers. Without the technology or location information, deliberate retrieval by terrorists or by a hostile society will essentially be precluded, as will inadvertent recovery by a future society less technically sophisticated than our own. The natural barrier formed by 5 or 6 kilometers of water in unlikely to be matched by any artificial physical barrier that we can construct!

CONCLUSIONS

The overview presented here and supported by the following papers in this symposium provides clear answer to the question asked by our title; a competent assessment of subseabed geologic formations is part of a responsible global search for an ultimate disposal site for high-level nuclear wastes. However, we still are several years from an answer to the question: "Is the subseabed disposal of high-level wastes technically feasible and environmentally acceptable?" At this stage of the program, however, we have identified no technical factors that argue against the continued assessment of the concept. Our continuing research program is designed to identify such factors, if they exist, as expeditiously as possible.

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Table 1. Marine Mineral Deposits

Deposit	Comment
Oil (Petroleum)	Areas of thick sediments (essentially continental margins)
Natural gas	As for oil
Sulfur	Salt domes on continental margins
Phosphorite	Shallow shelves, bank and seamounts
Sand and gravel	Nearshore and continental shelves
Placers (drowned)	Areas within about 150 m of present sea level (gold, diamonds, "black sands")
Sulfides	Formed at spreading centers. Should be scattered throughout the upper oceanic crust of all ages.
Coal and other terrestrial minerals	Found in submerged continental rocks in nearshore regions
Manganese nodules	Ubiquitous in and on deep-sea clays. Rich in Cu and Ni only in sub-equatorial areas.
Geothermal waters	Seawater hydrothermal systems at spreading centers. Temperatures up to 350°C.

Figure Captions

Fig. 1. Boundaries between the major lithospheric plates. Each plate moves independently as a relatively rigid body.

Fig. 2. Idealized cross section through a lithospheric plate showing the zones of creation (mid-ocean ridge) and destruction (trench).

Fig. 3. Distribution of primary production in the surface waters of the world oceans. Units are gm C/cm^2/1000 yr (multiply by 10 for gm C/m^2/yr).

Fig. 4. Content (carbonate-free) of biogenic opal in surficial deep-sea sediments. Isopleths in weight percent.

Fig. 5. Content (carbonate- and opal-free) of quartz in North Pacific deep-sea sediments. Isopleths in weight percent. The trade-wind and westerly influences are clear.

Fig. 6. Drift deposits of silty clay formed in the North Atlantic by strong, contour-following, bottom currents.

Fig. 7. Circulation pattern and products of an idealized mid-ocean ridge hydrothermal system (Corliss, 1973).

Fig. 8. Copper content of Pacific deep-sea ferromanganese nodules (Heath, 1980, after Skornyakova, 1979). Isopleths enclose locations of nodules containing more than the stated Cu concentrations. Lower grade nodules are found throughout the Cu-rich areas.

Fig. 9. Major shipping routes.

Fig. 10. Trans-oceanic deep-sea cables.

Fig. 11. Sea-surface temperature difference between August 18,000 years ago and August, today (CLIMAP, 1980). Isotherms in °C. Temperatures in unshaded areas differ by less than 2°C.

Fig. 12. Locations of S.D.P. study areas MPG-I and II, relative to major physiographic features and the 5 km isobath in the North Pacific (after Prince _et al_., 1980).

Fig. 13. Location of MPG-I cores (Fig. 14) relative to thickness of underlying sediments.

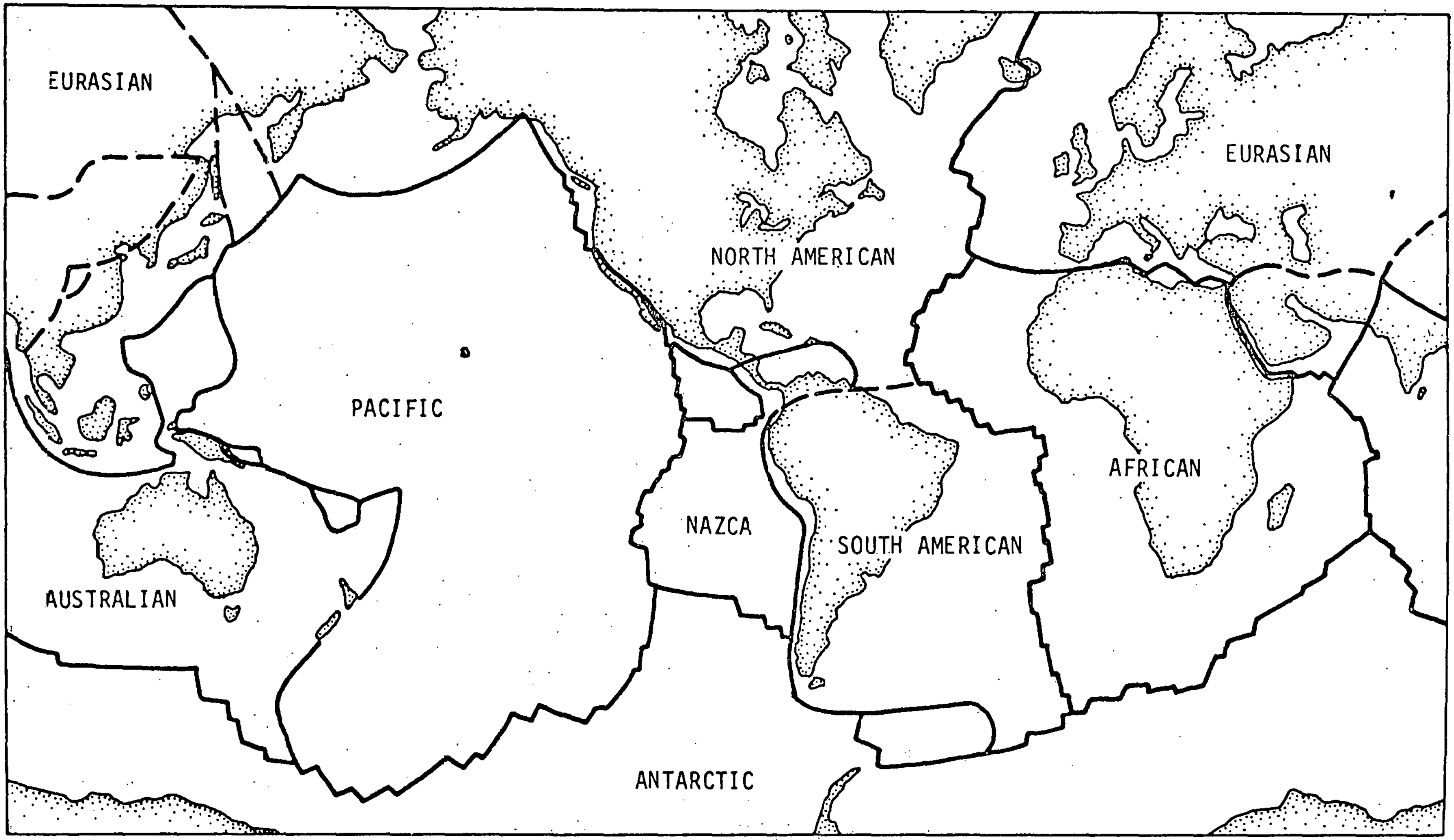
Fig. 14. Relative sedimentation rates of MPG-I cores for the past 2.5 million years. The ratios are constant despite severalfold changes in absolute sedimentation rates (after Prince _et al_., 1980).

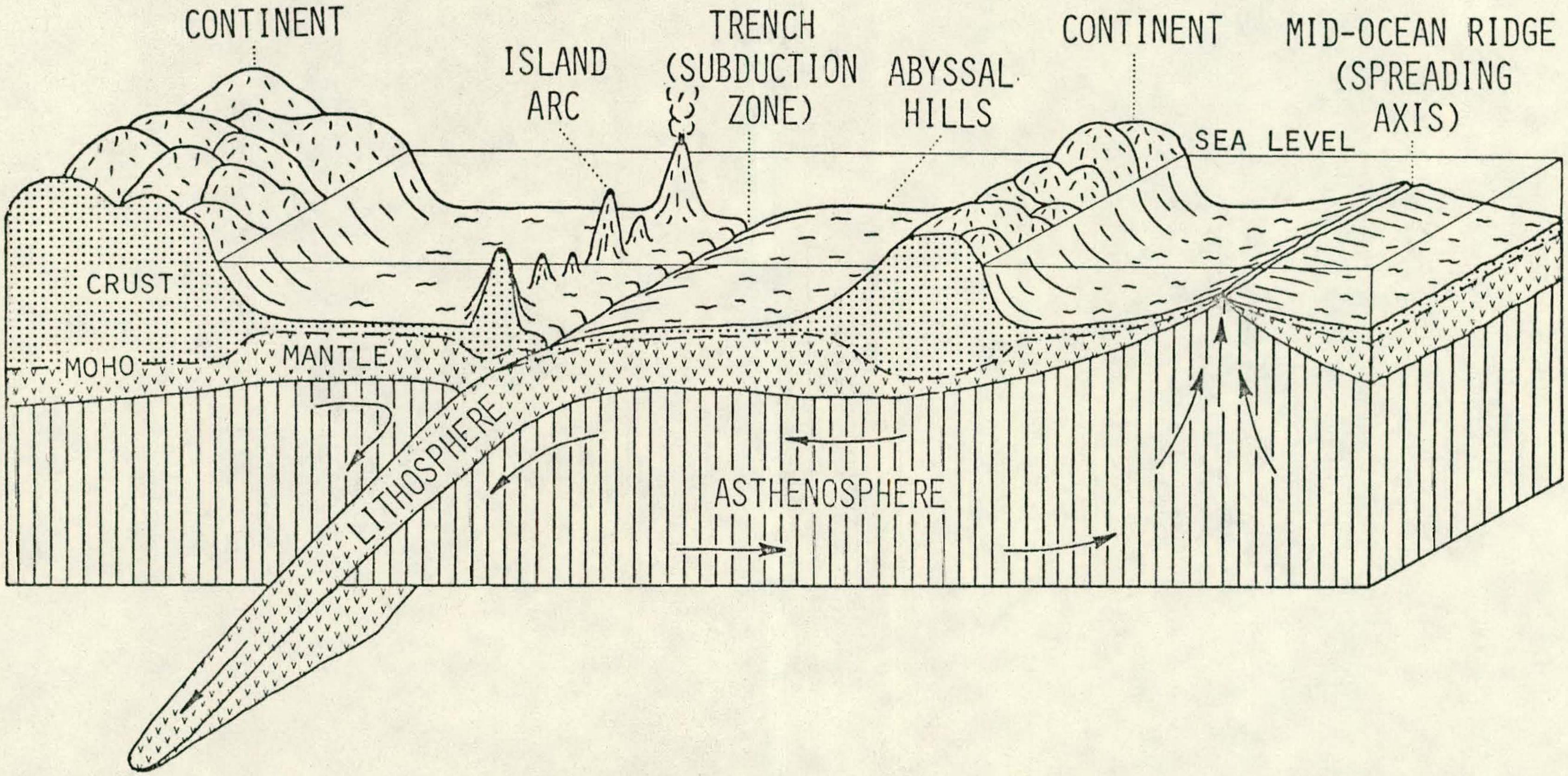
Fig. 15. Topographic settings of MPGII cores 58P (topographic depression) and 62P (ridge top). Isobaths in corrected fathoms.

Fig. 16. Relative sedimentation rates of MPG-II cores Y74-58P and Y74-62P. The top of 58P was lost during the coring operation.

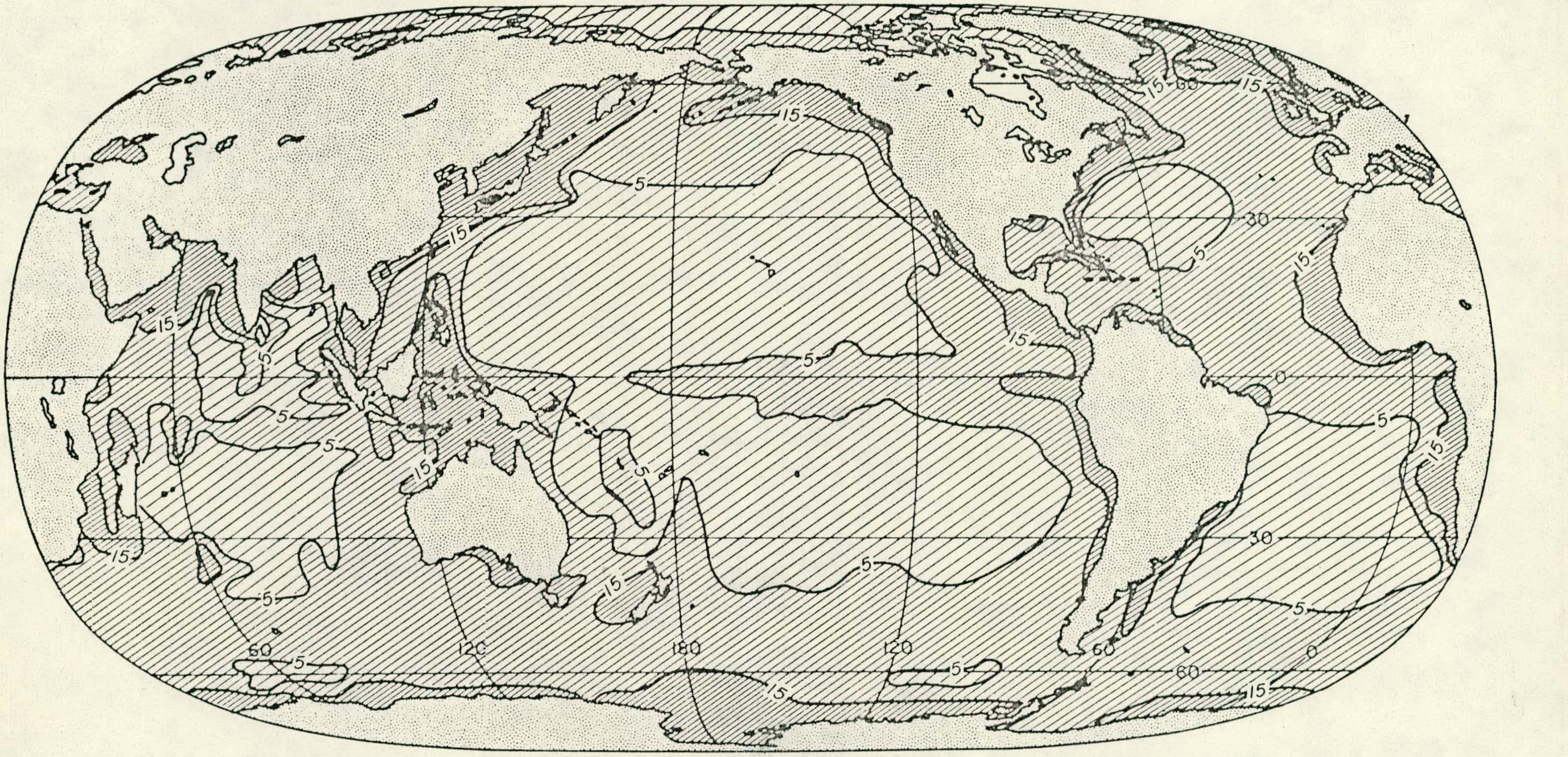
Fig. 17. Comparisons of the contributions (weight percent) of detrital and hydrothermal particles to cores from MPG-I (GPC-3) and MPG-II (Y74-58P). Chemical data partitioned using Dymond's (1981) technique.

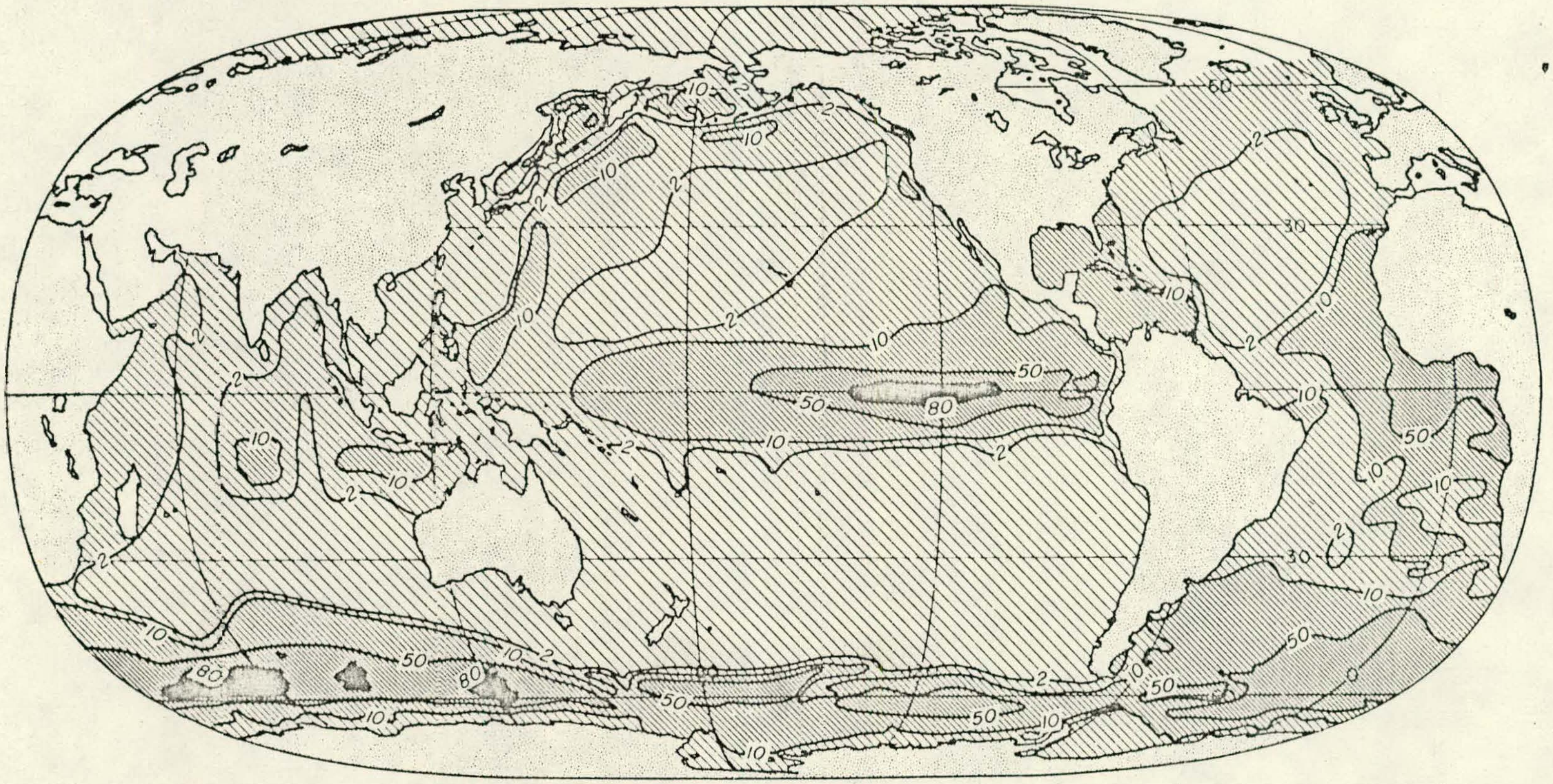
Fig. 18. Age versus depth of sediments in MPG-I core LL44-GPC3 (Fig. 13). The outer lines show the uncertainty of the ichthyolith stratigraphy (Doyle and Riedel, 1979). Sedimentation has been essentially continuous (any gaps must span less than 1 meter or 4 million years) for 70 million years.


EURASIAN
EURASIAN
NORTH AMERICAN
PACIFIC
AFRICAN
NAZCA
SOUTH AMERICAN
AUSTRALIAN
ANTARCTIC


CONTINENT
ISLAND ARC
TRENCH (SUBDUCTION ZONE)
ABYSSAL HILLS
CONTINENT
MID-OCEAN RIDGE (SPREADING AXIS)
SEA LEVEL
CRUST
MOHO
MANTLE
LITHOSPHERE
ASTHENOSPHERE

2


15
5
30
0
60
120
180



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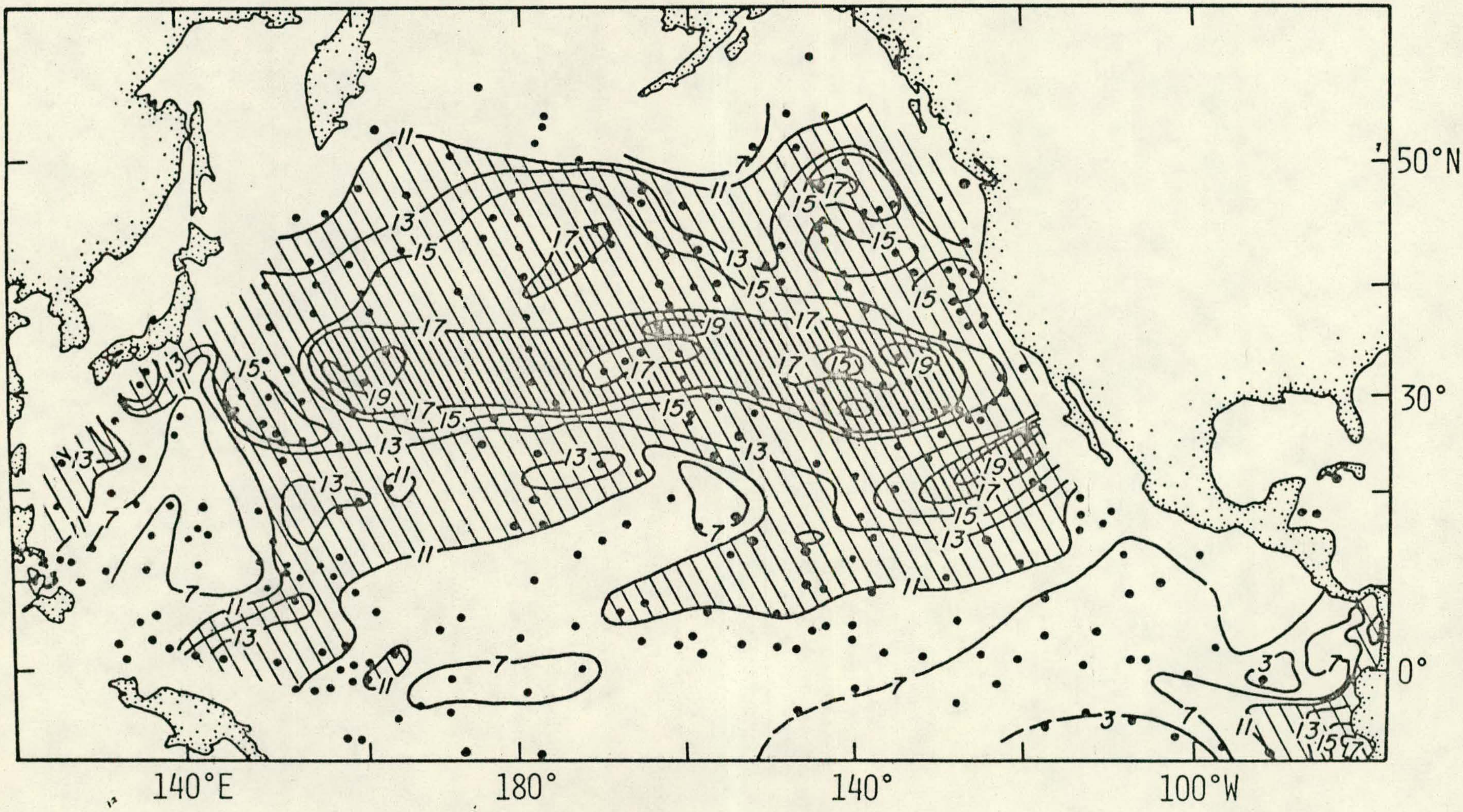

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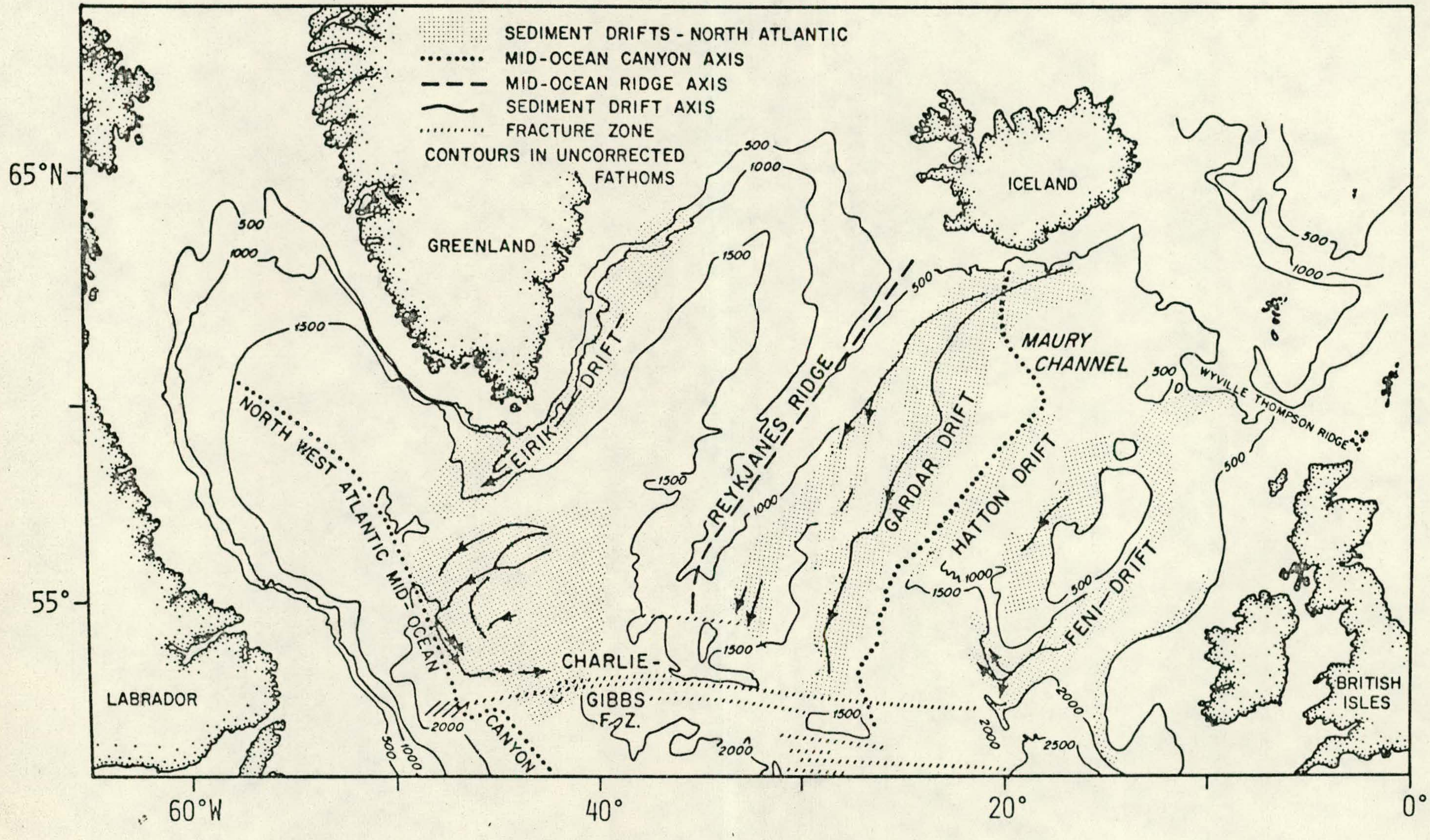
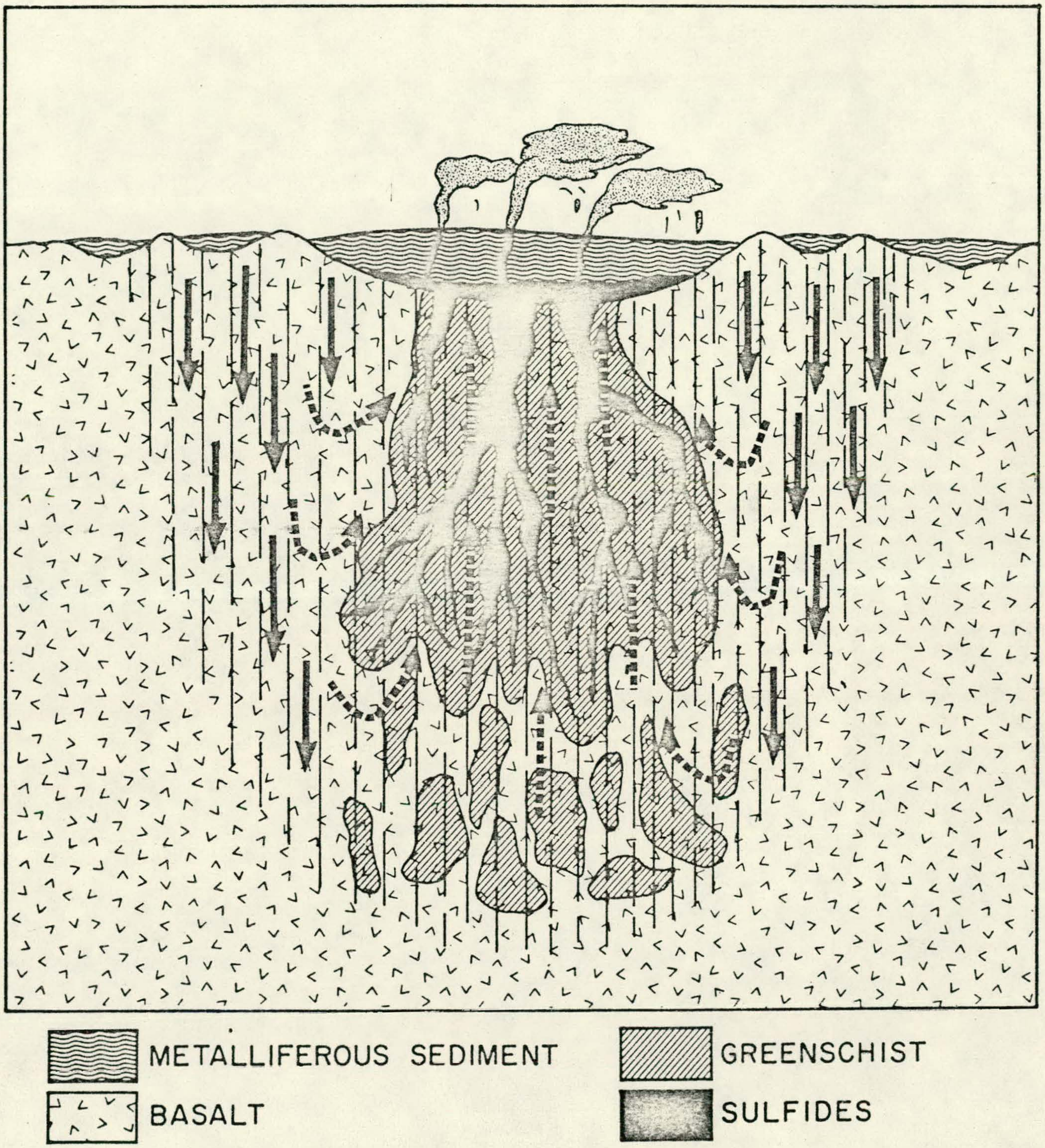
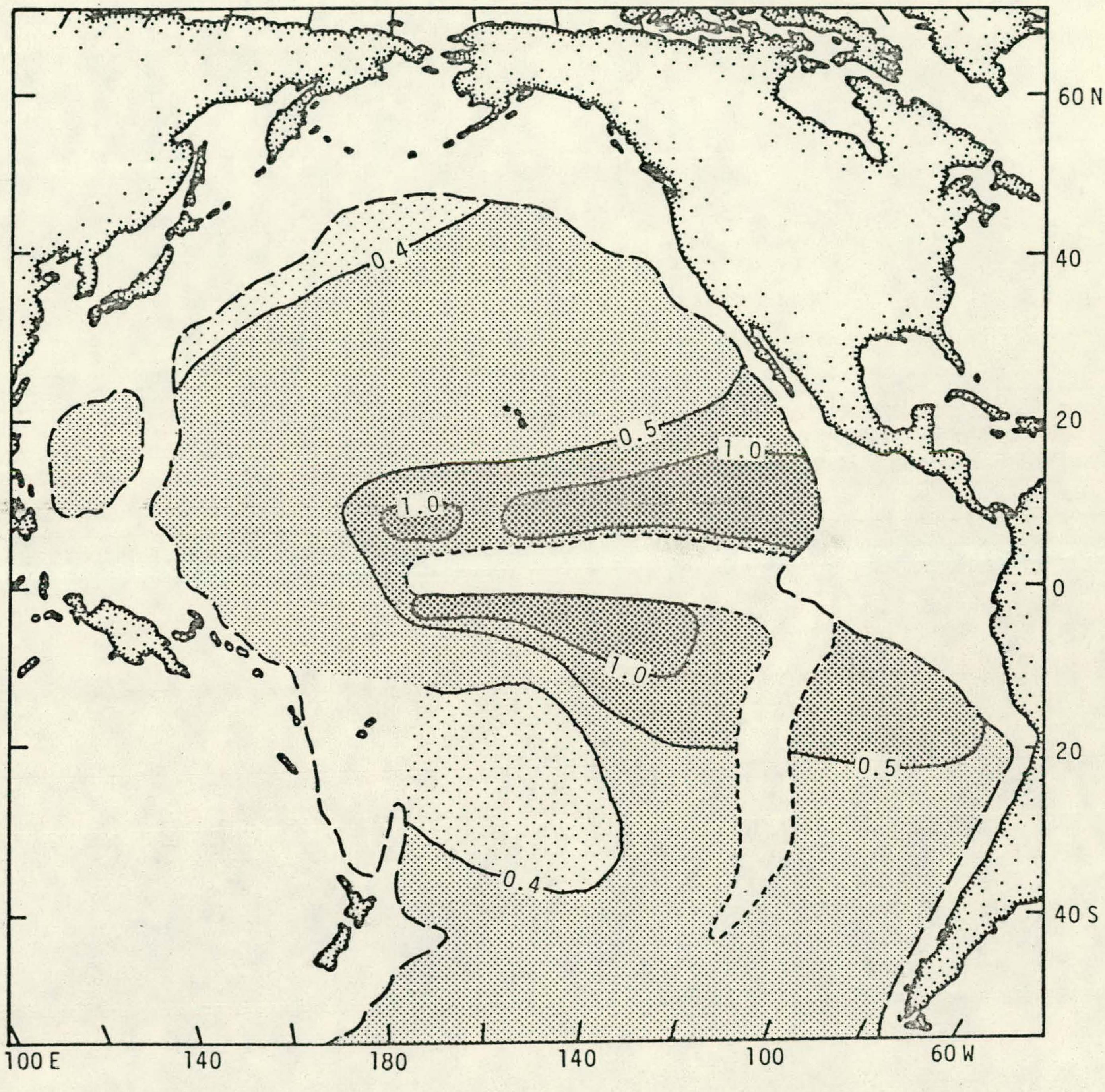
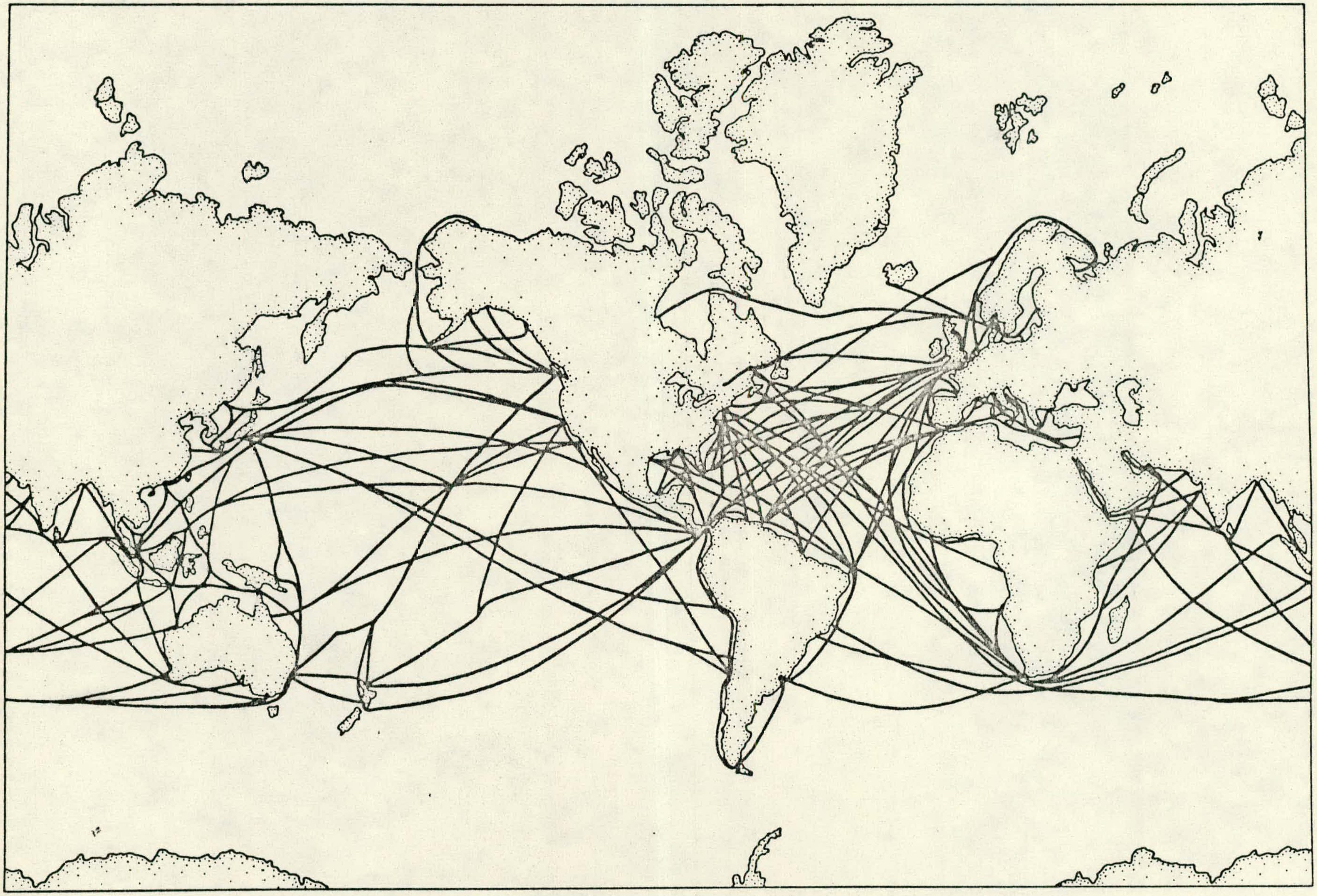
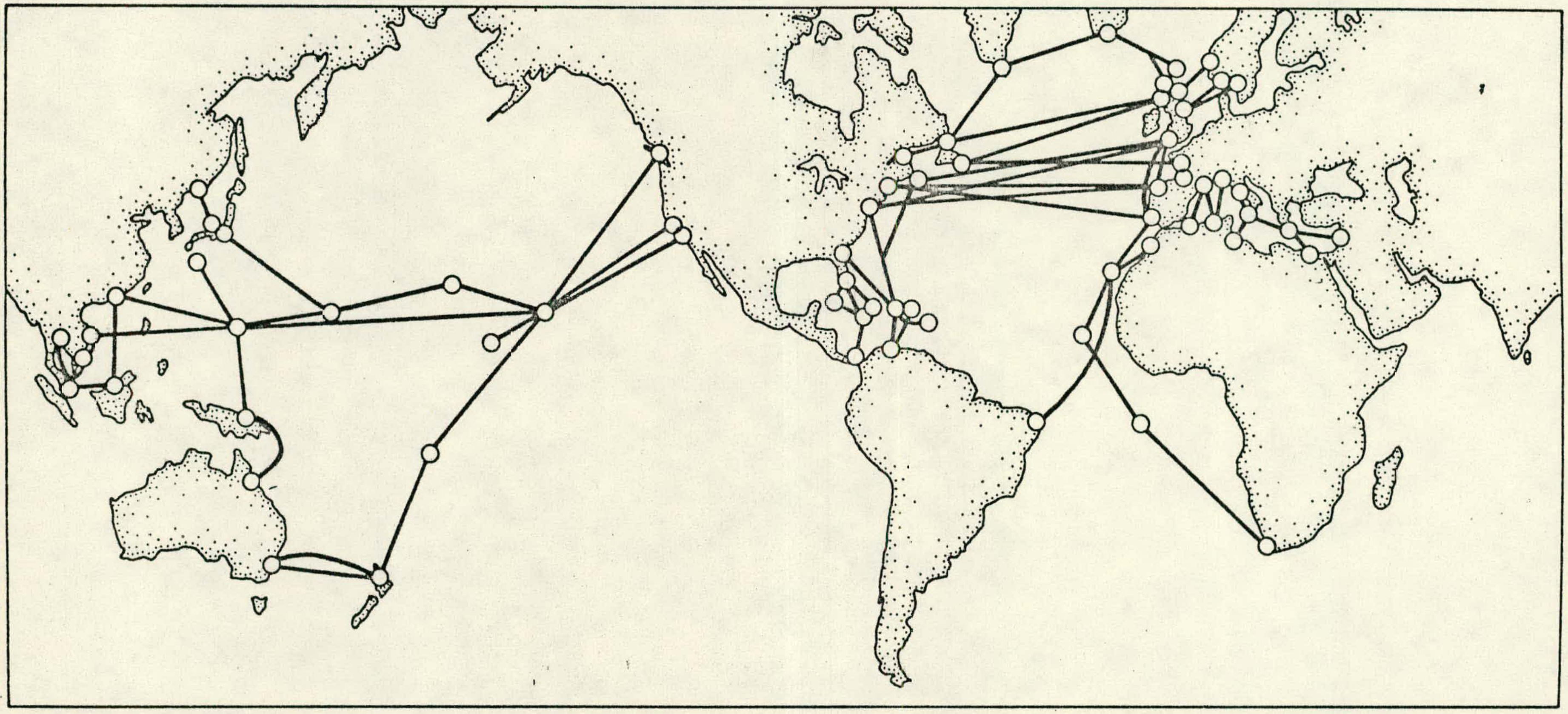

SEDIMENT DRIFTS - NORTH ATLANTIC
MID-OCEAN CANYON AXIS
MID-OCEAN RIDGE AXIS
SEDIMENT DRIFT AXIS
FRACTURE ZONE
CONTOURS IN UNCORRECTED FATHOMS
GREENLAND
ICELAND
LABRADOR
BRITISH ISLES
EIRIK DRIFT
NORTH WEST ATLANTIC MID-OCEAN CANYON
REYKJANES RIDGE
GARDAR DRIFT
HATTON DRIFT
MAURY CHANNEL
FENI-DRIFT
WYVILLE THOMPSON RIDGE
CHARLIE-GIBBS F.Z.
65°N
55°
60°W
40°
20°
0°
500
1000
1500
2000
2500

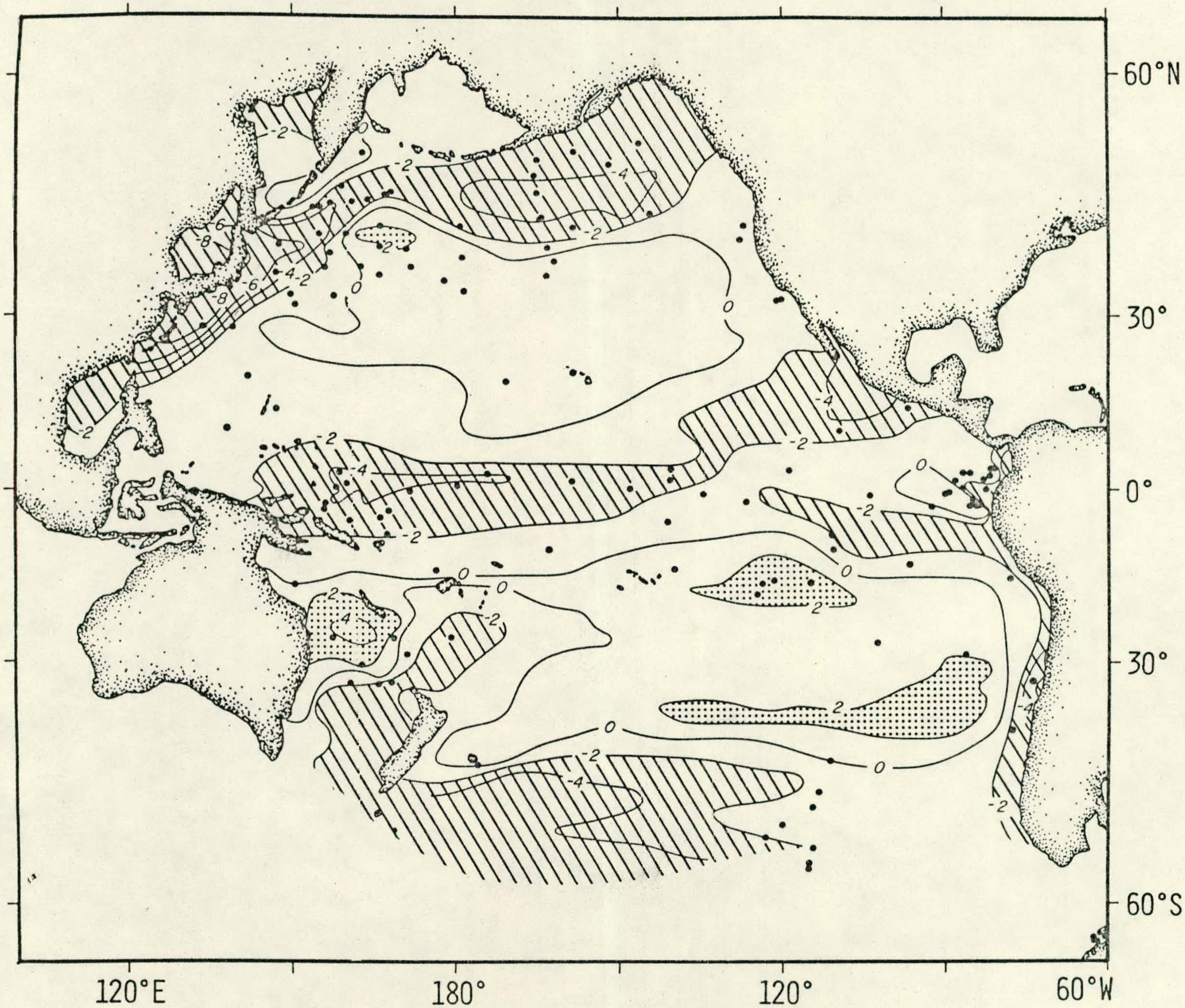

METALLIFEROUS SEDIMENT
GREENSCHIST
BASALT
SULFIDES



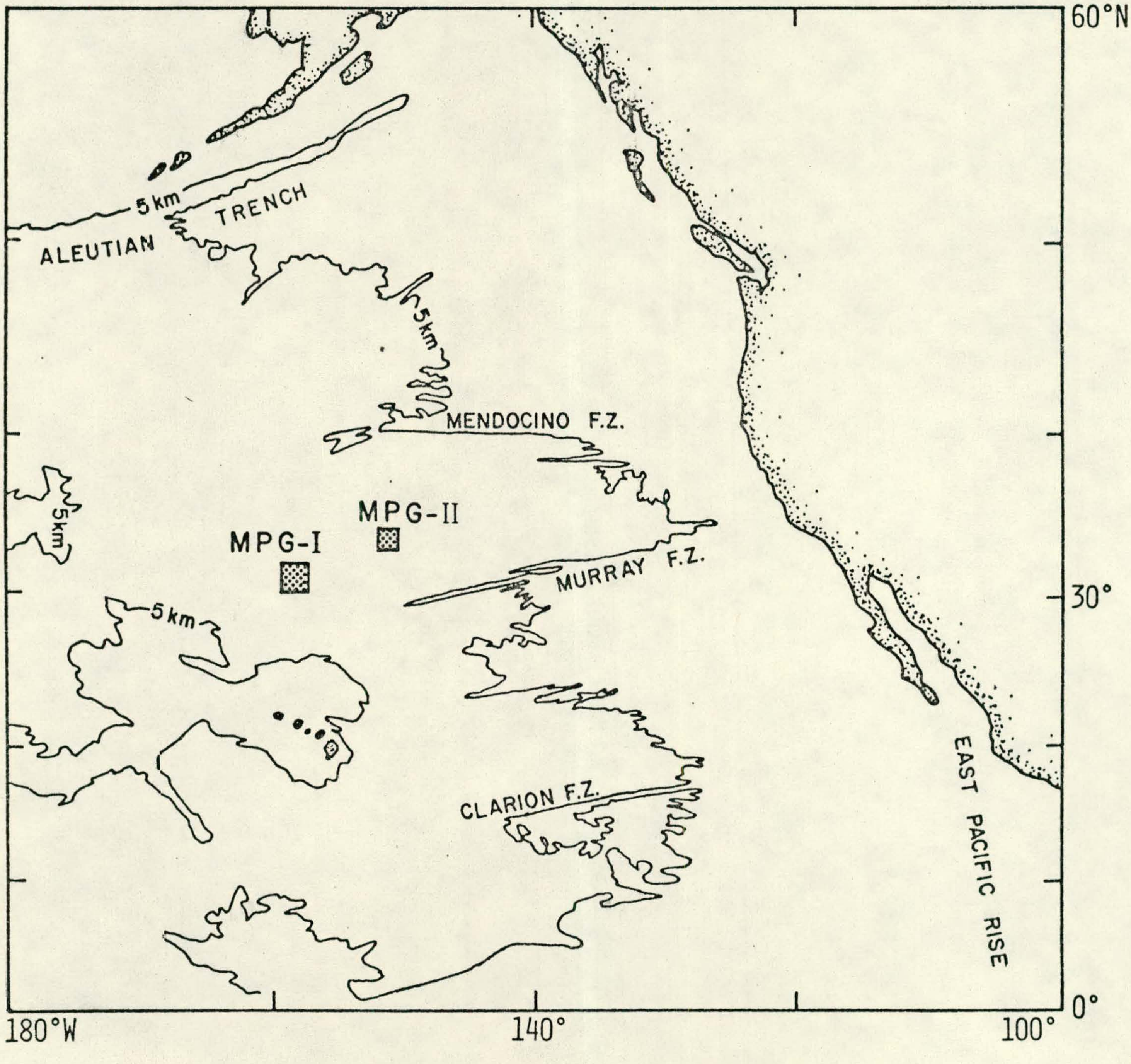
60 N
40
20
0
20
40 S
100 E
140
180
140
100
60 W
0.4
0.5
1.0
1.0
1.0
0.5
0.4

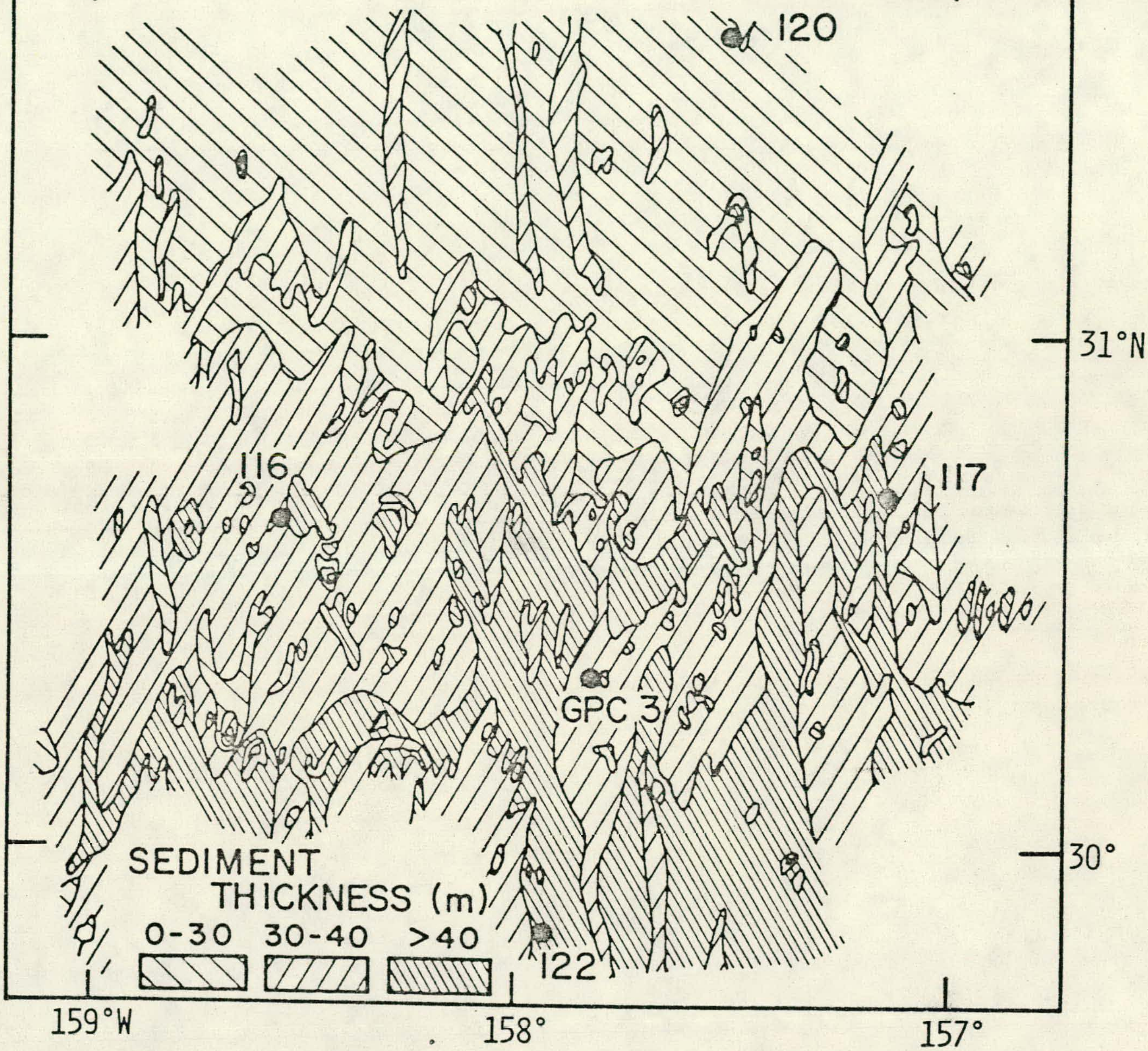


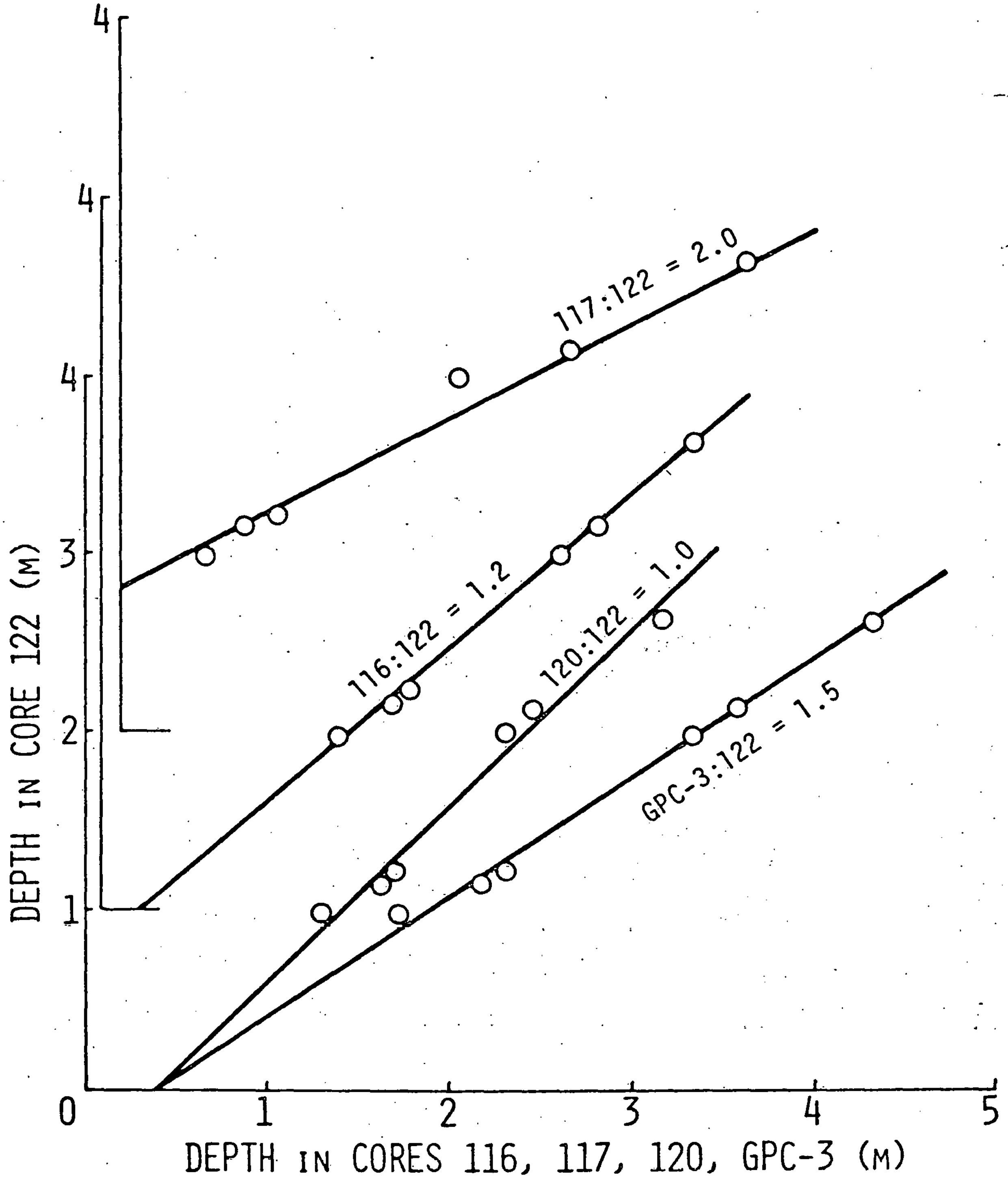




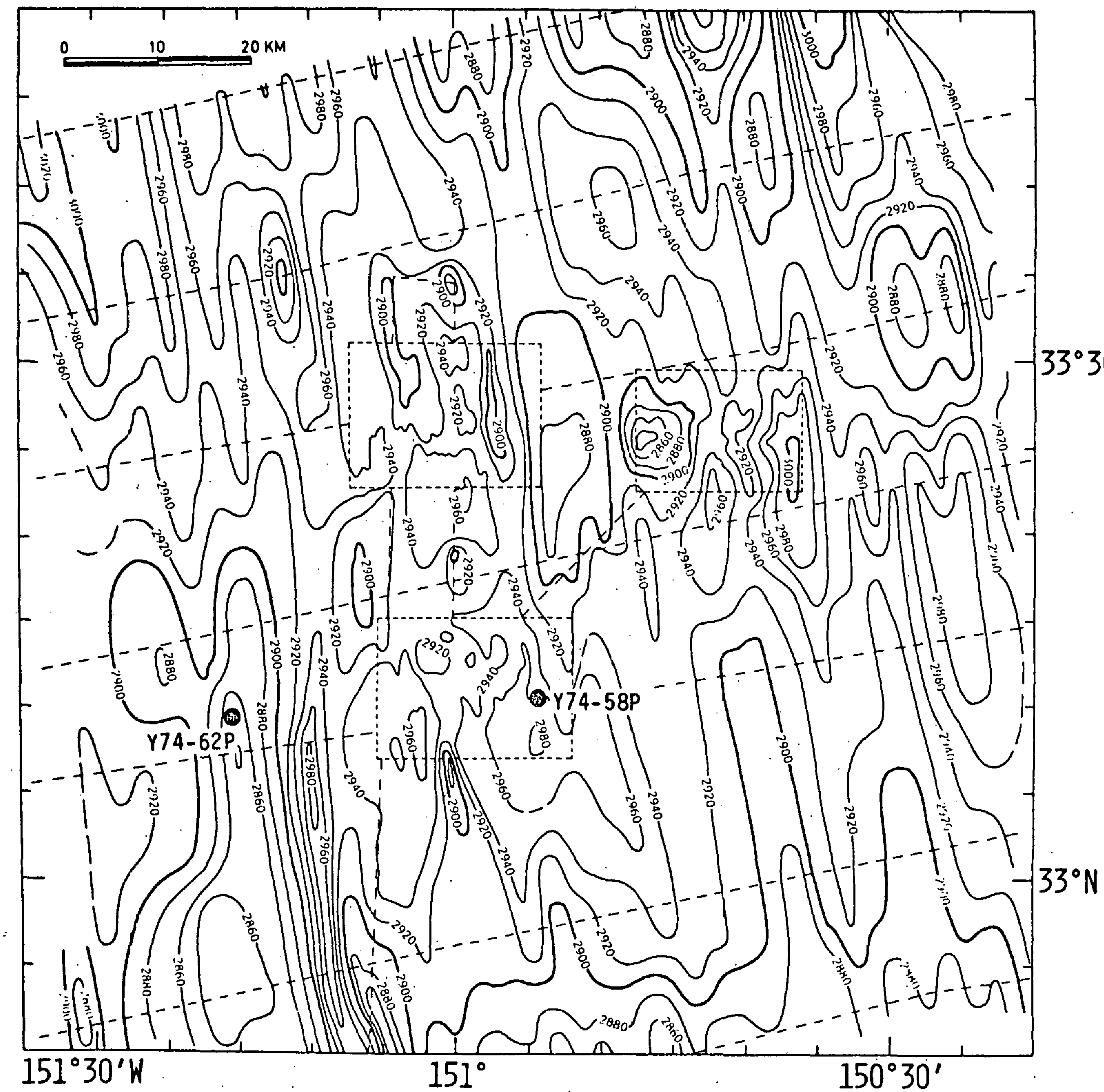
11

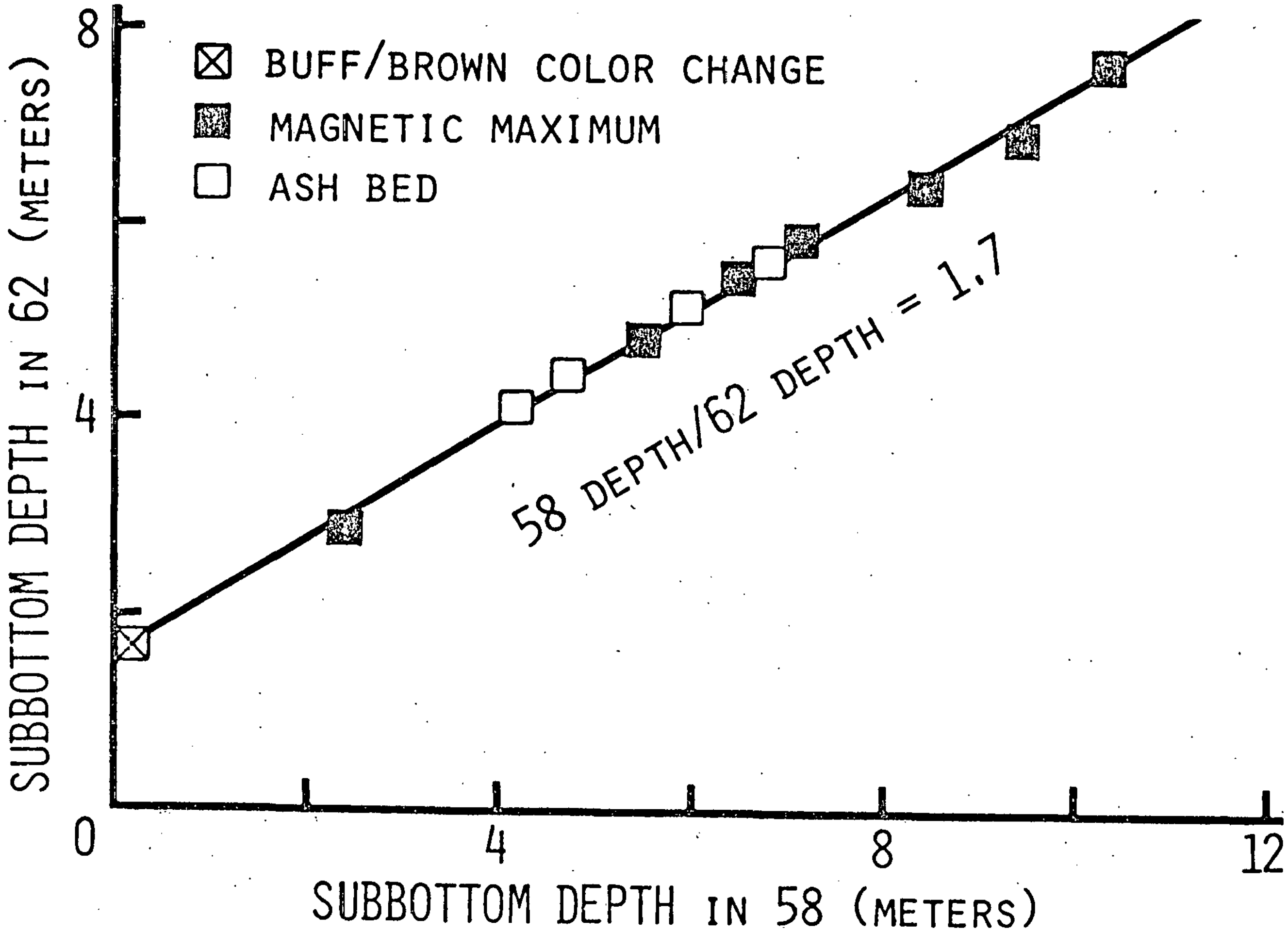

60°N
30°
0°
180°W
140°
100°
ALEUTIAN
TRENCH
5 km
5km
5km
5 km
MENDOCINO F.Z.
MPG-II
MPG-I
MURRAY F.Z.
CLARION F.Z.
EAST PACIFIC RISE

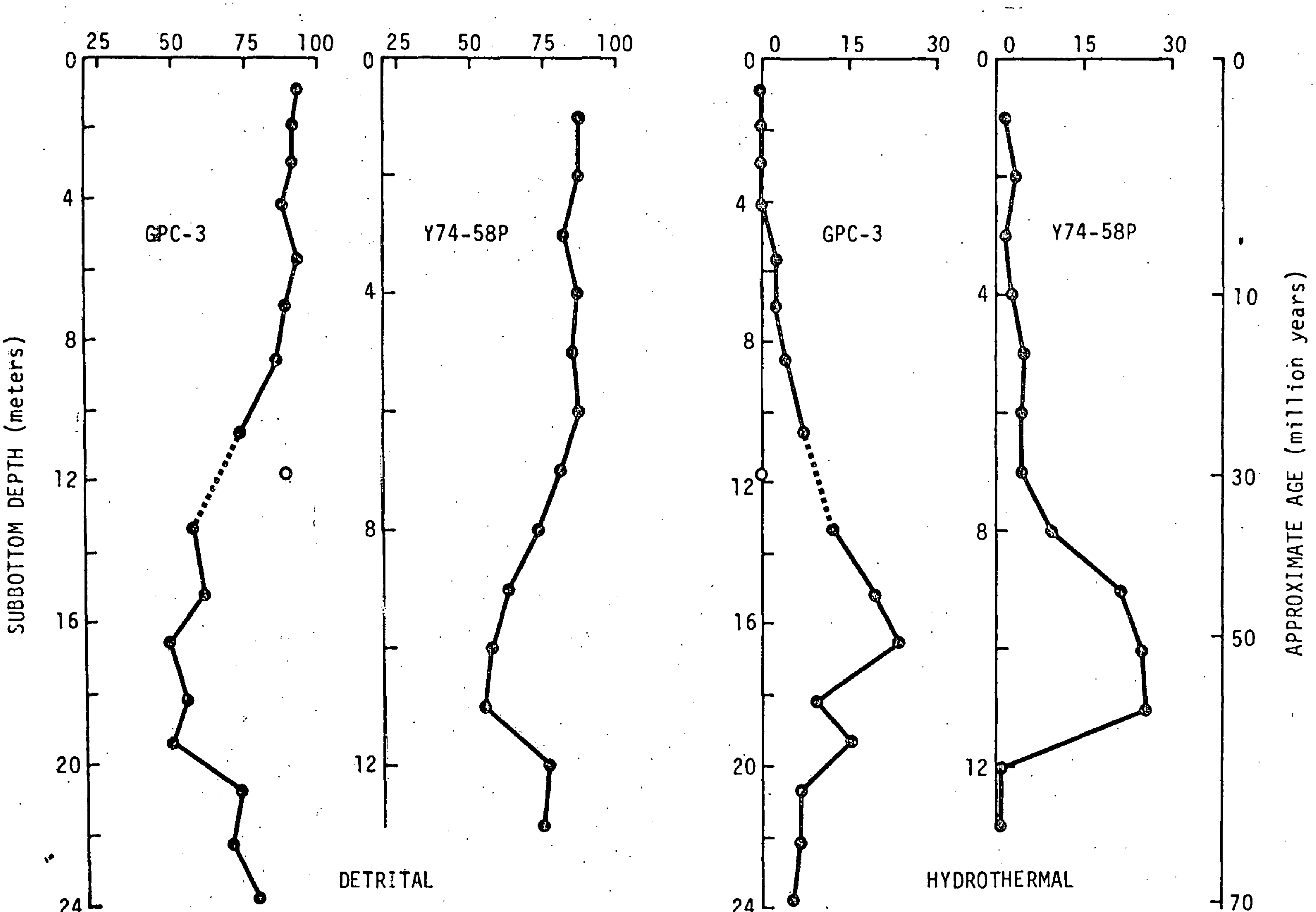

120
31°N
116
117
GPC 3
30°
SEDIMENT
THICKNESS (m)
0-30
30-40
>40
122
159°W
158°
157°



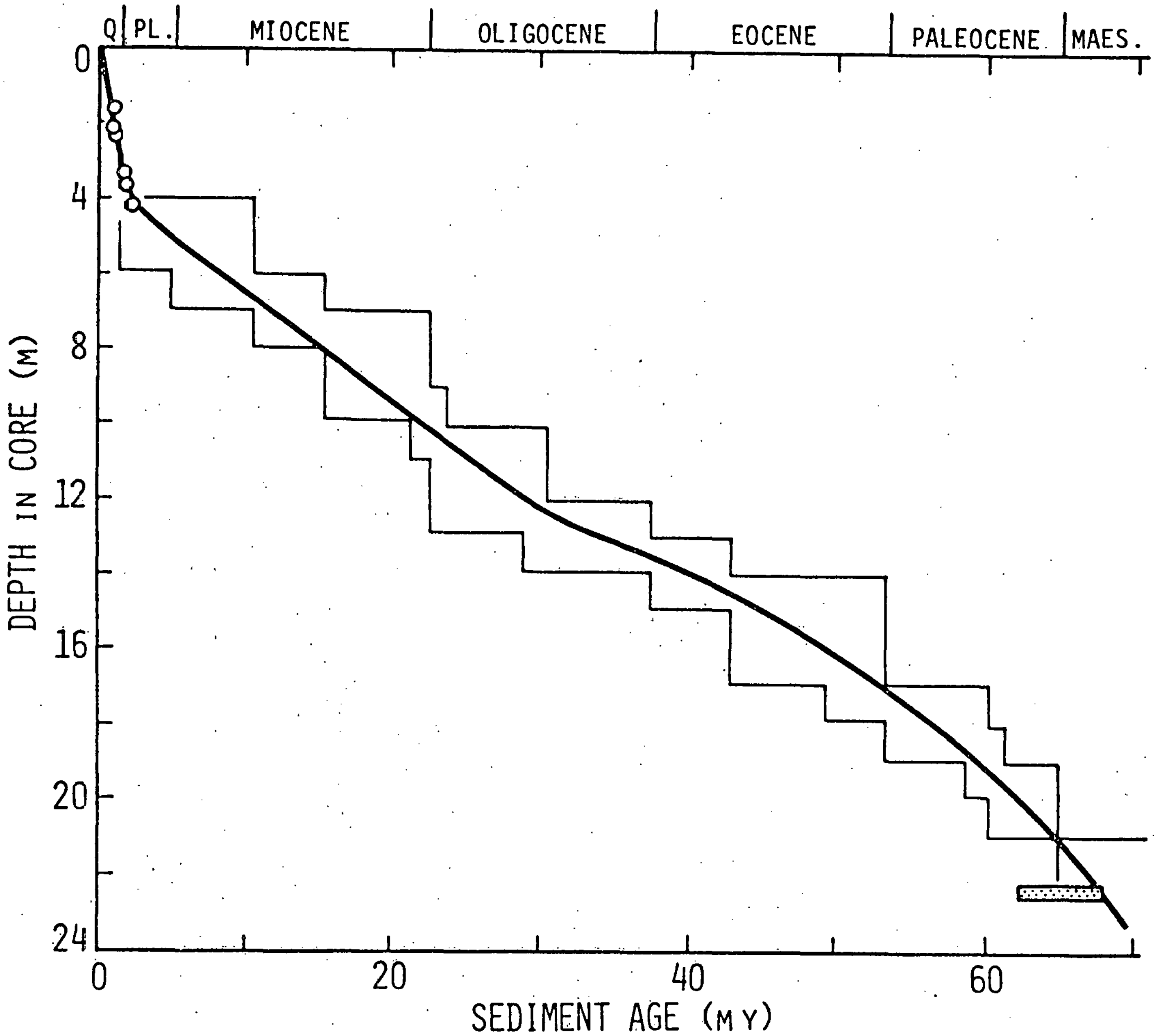
117:122 = 2.0
116:122 = 1.2
120:122 = 1.0
GPC-3:122 = 1.5
DEPTH IN CORE 122 (M)
DEPTH IN CORES 116, 117, 120, GPC-3 (M)
0
1
2
3
4
5


0 10 20 KM
Y74-62P
Y74-58P
33°30′
33°N
151°30′W
151°
150°30′


BUFF/BROWN COLOR CHANGE
MAGNETIC MAXIMUM
ASH BED
58 DEPTH/62 DEPTH = 1.7
SUBBOTTOM DEPTH IN 62 (METERS)
SUBBOTTOM DEPTH IN 58 (METERS)
0
4
8
12
4
8



SUBBOTTOM DEPTH (meters)
GPC-3
Y74-58P
GPC-3
Y74-58P
DETRITAL
HYDROTHERMAL
APPROXIMATE AGE (million years)


Q
PL.
MIOCENE
OLIGOCENE
EOCENE
PALEOCENE
MAES.
0
4
8
12
16
20
24
DEPTH IN CORE (M)
0
20
40
60
SEDIMENT AGE (MY)