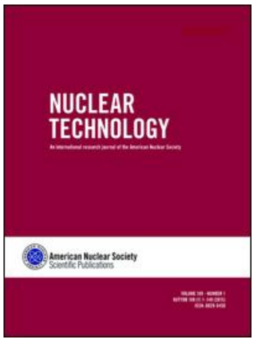

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SEABED DISPOSAL—WHERE TO LOOK

RADIOACTIVE WASTE

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The oceans cover more than 70% of the earth's surface, and while they contain many valuable resources, they also cover some of the most inaccessible and unproductive areas of the planet. With their ability to detoxify and disperse contaminants, the oceans have for many years been used for disposal of biological and chemical wastes, but radioactive wastes present a more complex problem in that the ocean environment cannot detoxify them. Still it appears that certain oceanic areas—the mid-plate/mid-gyre regions—may possibly offer practical and nonpunitive areas for disposal of high-level radioactive wastes.

A program is now under way at Sandia Laboratories to gather the data necessary to an understanding of the features and processes of the mid-plate/mid-gyre regions. This study seeks to identify (a) the knowledge necessary for a judgment concerning their use as a repository, and (b) the areas in which that knowledge is now lacking.

We conclude that the geologic stability and relative uselessness of some mid-plate/mid-gyre ocean basin floors are sufficient justification for an objective investigation of the processes pertinent to their use as an ultimate nuclear waste repository. Far from advocating any immediate decisions to use these regions for disposal, we stress that a systematic study is both prudent and urgent in view of the nuclear waste problem.

INTRODUCTION

Present U.S. Atomic Energy Commission (USAEC) strategy calls for engineered storage of high-level radioactive wastes on land for 30 to 100 years. During that period, "ultimate" disposal schemes are to be developed. Among the alternatives suggested are three generic types: (a) elimination of long-lived radioisotopes by transmutation, (b) disposal outside the earth's atmosphere, and (c) disposal in a terrestrial environment.

The first two—transmutation and space disposal—are conceptually appealing in that the toxic material would thus be permanently removed from potential contact with man. However, the technology for their accomplishment is not developed, and neither concept has been proven technically feasible either in the laboratory or in the construction of prototypical equipment. So, while these two alternatives are attractive, it is possible that we may have to rely on our planet for the disposal of high-level wastes, as we have already relied on it for the disposal of chemical, biological, and some low-level nuclear wastes.

Terrestrial environments may be classed in three categories—land, ice (ice caps or glaciers), and the sea. The first two have been discussed extensively[1] and the sea has been used for the disposal of low-level radioactive wastes.[2] However, there have been no detailed scientific studies of the sub-sea floor—the geological formations below the ocean waters—as a potential disposal ground for high-level wastes.

The oceans' waters have been used for disposal of nonradioactive wastes because of the large potential for dispersal and because such wastes were, in time, detoxified by chemical or biological processes in the sea. Radioactive wastes pose the special problem that they are detoxified by neither biological nor chemical processes. As to dispersal, one recent study[3] could lead to the conclusion that the Iberian basin off Europe could accommodate all radioactive wastes from Europe or the United States for several thousands of years. But a simple comparison of the amounts of waste anticipated by the middle of the next century[4] and the amount of water required to dilute these materials to acceptable levels reveals the fact that if all the wastes were to be *uniformly* diluted in the entire body of the oceans, acceptable levels would be surpassed everywhere by about the year 2060.

Thus, disposal of high-level radioactive wastes into the ocean cannot be a simple matter of relying upon natural processes to handle the wastes. Instead, engineering solutions to prevent their dispersal must be found, and the careful assessment of all possible processes for that dispersal is a prerequisite to the engineering. We treat herein only high-level waste containing traces of transuranics.

One simple fact suggests that the sub-sea floor may be worthy of attention for waste disposal: the seas cover over 70% of the surface of the planet. Thus, in the fact of rising pressures on the land areas and a shrinking global capability of supporting or even housing mankind, the 30% of the earth's surface that is land becomes a scarce resource, and the least accessible and less usable areas of the planet become increasingly attractive candidates for disposal.

There are a number of arguments against using the ocean waters for waste disposal. For example, the ocean (including the sea floor) is within no national domain—it either belongs to all of mankind or to no one, and thus should be protected against unilateral polluting action.[5] We limit our discussion here to the scientific and natural aspects of assessing the sub-sea floor as a repository for high-level nuclear wastes designed in some manner so as to be nonpolluting, i.e., to avoid a release.

A number of resources are available from the ocean and are likely to be even more important in the future. These include hydrocarbons, food, fertilizer, sand, and gravel, and heavy minerals and metals. Around the shores of almost all land masses, and associated with the major surface currents, are divergence zones where nutrients are especially abundant. At these locations, the ocean produces an enormous amount of plant and animal life. This biomass is the foundation for a major food source. Aquaculture, now in developmental stages, promises to increase the productivity of shallow coastal waters.

Hydrocarbon resources are found on the continental shelves and in other areas having great accumulations of sediments.[6] On the abyssal ocean floor in the mid-plate/gyre regions, the only obvious mineral resource is the now famous manganese nodule. These small (golf-ball to orange-sized) concretions are found over much of the very deep (>5 km) ocean floor.[7] But in general, nodules that have immediate commercial interest because of their high cobalt, nickel, and copper content are limited to those fairly restricted biologically productive areas of the deep ocean floor which are covered with watery, siliceous ooze.[8] Figures 1, 2, and 3 show the distribution of some of these resources.

While man is just beginning to exploit the ocean, it is apparent that unless there is massive intervention, the distribution of resources in the sea will continue much as it is today. And, while the science of oceanography is young, and understanding of the seas is far behind that of the continents, enough is known to begin a global understanding of the oceans, and to use this understanding to determine candidate areas for potential waste repositories.

Our knowledge enables us to recognize most of the geological processes that occur on the deep sea floor. We know where earthquakes and volcanoes are likely, where major currents occur, and where violent turbidity currents sweep across the continental margins to the abyssal plains. We know where to expect temporal variations in temperature and some chemical properties of the water. And we have learned where to expect high biological productivity. We know too that mobile water can disperse an unnatural contaminant over great distances at rates as high as tens of centimeters per second. By observing the transport of by-products from atmospheric nuclear tests, and by using natural tracers, we have gained some indication of the routes and rates of this dispersion.

Accepting the need for a scientific assessment of the ocean floors as a nuclear waste repository, we pose several questions that require answers:

1. What parts of the ocean floors are sensible to study, and why?
2. What do we need to know about the natural processes and the effects of waste emplacement on those processes?
3. What technology is necessary for such study and for such disposal?
4. What assurance can we expect that wastes will be isolated from mankind?
5. What will be the cost of such disposal?

In the following discussions we treat the first two questions in some detail on the basis of our present knowledge; we indicate the technological requirements; ignore the costs; and suggest guidelines for answering the questions of assurance. In all the discussions we have limited ourselves to

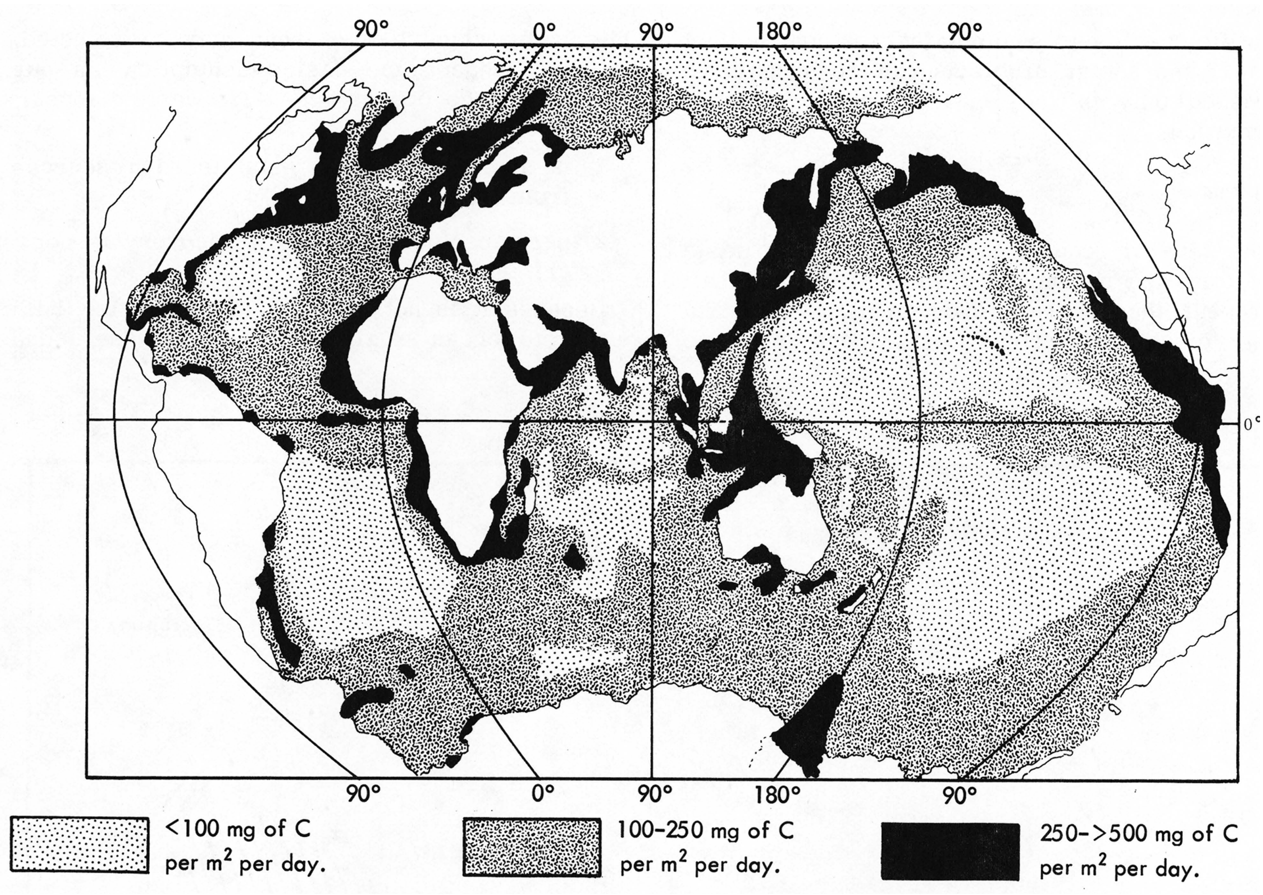

Fig. 1. Distribution of primary production in the World Ocean (adapted from Ref. 9).

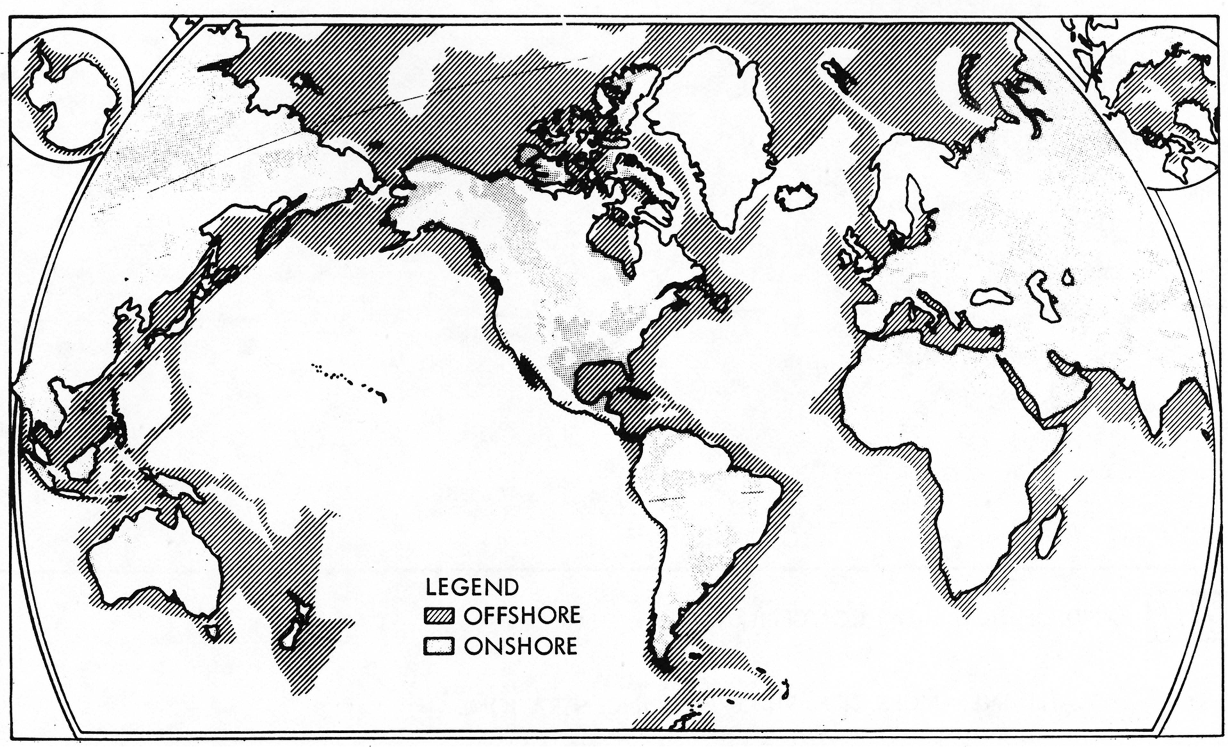

Fig. 2. Possible petroleum-producing areas in the oceans and on land (drawn after McKelvey and Wang, Ref. 6).

scientific questions, assuming that the concomitant political and social problems can reasonably be addressed only in the light of sound scientific information.

Requirements

The general requirements for a nuclear waste repository are outlined elsewhere,[10] and we shall not repeat them here. However, it is useful to base a discussion of the ocean floors on some criteria by which likely areas may be selected. We have made some basic assumptions in our treatment of the oceans *vis-à-vis* waste disposal. These include

1. no interference with established resources from the sea
2. permanent disposal (i.e., recovery is not a criterion).

Because it is not possible to generalize with regard to ocean regimes, there will be found

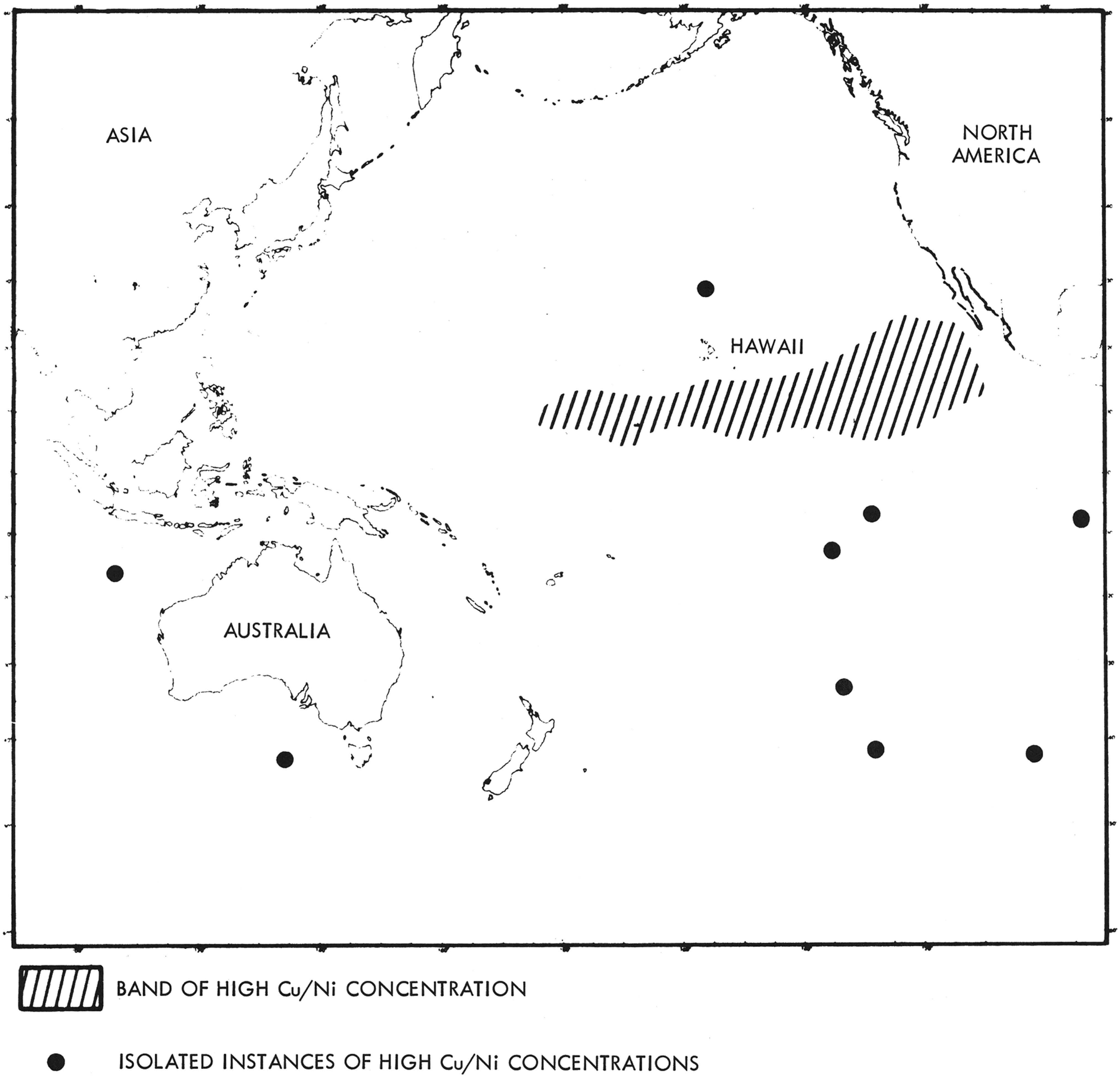

Fig. 3. Heavy metal concentrations in manganese nodules in the Pacific (adapted from Ref. 8).

singular places that might otherwise be suitable as repositories but which do not fit our general categories. We shall not inventory the oceans in enough detail to isolate all the small areas having such characteristics, but will limit ourselves to areas that occur in many parts of the world, or that are in some way typical. Thus, by our approach, one requirement we have applied to the ocean regimes is that a candidate disposal area be extensive. In addition, we assume the worst case—that of wastes containing the long-lived transuranic elements—which eliminates from our consideration areas that might be useful for disposal of shorter lived wastes (say ≤1000 yr).

The logistical and engineering requirements for ocean disposal have recently been summarized[10] (Fig. 4). These are relevant in the discussion of ocean areas that might be candidates, because engineering and logistics will in part determine the accessibility of each area and the kind of information needed for an assessment of its utility.

In general, engineering requirements for ocean disposal will include a system for transportation of wastes, a system for their emplacement on or in the ocean floor, and a system for containing the wastes once emplaced. Some components of these engineering systems are

Transportation

1. special trucks and casks for land
2. special docks and/or ports
3. special ships
4. casks for shipboard shielding
5. special transfer facilities at the emplacement platform.

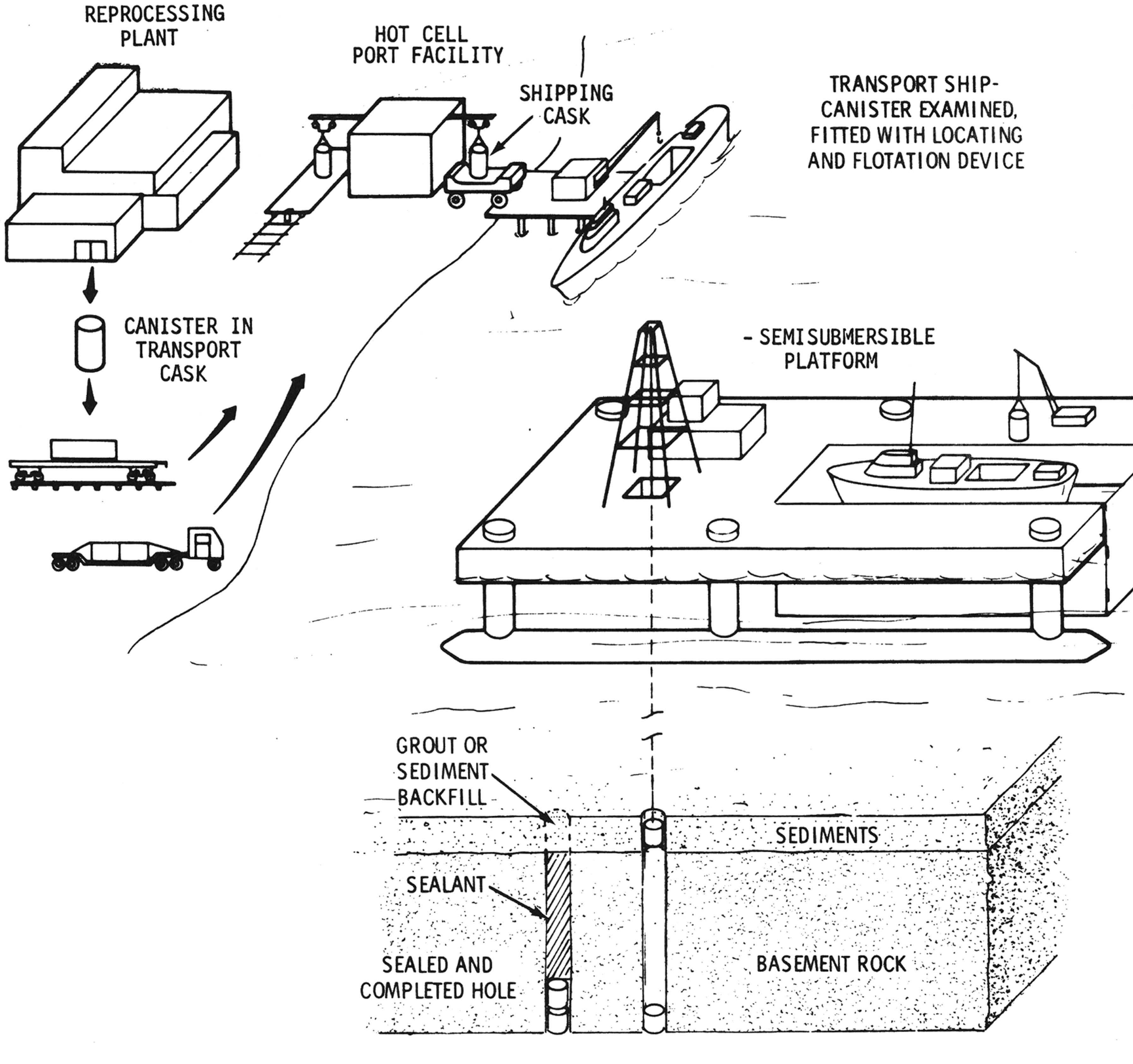

Fig. 4. The major conceptual engineering requirements for disposal in the seabed (from Battelle-Northwest Laboratories, used with permission).

Emplacement

1. drilling equipment
2. special ship or platform (or both if drilling and emplacement require separate facilities)
3. handling equipment both on the platform and in the water column
4. remote manipulating and monitoring equipment on the bottom.

Containment

1. a long-lived canister
2. a sealant for the hole in the sea floor.

While most of the technology for these requirements is either available or within the reach of present know-how, some development will be needed, along with proof of the concepts.

The requirements for the natural system—that is, the ocean environments—that should be applied in the selection of candidate areas may be summarized under two generic headings: stability and isolation. As will be seen, these imply a large number of individual criteria, but some broad definitions are:

Stability

1. lack of cataclysmic events
2. predictability of processes for necessary times ($\geq 10^6$ yr).

Isolation

1. distance from human habitations
2. low rates of all natural processes
3. longevity of the disposal system.

We use these characteristics to limit our discussions to reasonable alternatives.

Within the ocean areas there are a number of cataclysmic events that could adversely affect the performance of any disposal system. Some are indigenous to the ocean environment, and others are characteristic of the earth at large. The major types of these natural events or forces are earthquakes, volcanism, turbidity currents, slumping and liquefaction of sediments, erosion by rapid currents, intrusion by molten igneous rock, and intrusion by man. As we shall see, there are ocean areas that, on the basis of modern oceanographic data, appear stable with respect to these events.

In the following discussion, the predictability and rates of natural processes are included as central concerns. In fact, an understanding of the history of the oceans as they now exist and of global patterns within the ocean system is paramount to a sensible separation of the ocean into a few areas of interest.

THE OCEAN ENVIRONMENT

While there have been seas throughout the history of the earth, the oceans and their floors as they exist today are geologically young; that is, the oldest oceanic rocks recovered from the deep ocean floor are only 155 million years old.[11] Yet we know that the continents are of the order of 3 to 4 billion years in age, and exposed outcrops of ancient oceanic sediment, seen by us as old mountain ranges, are of the order of tens to hundreds of millions of years in age.

During the past decade a revolution has taken place in the concept of sea-floor evolution. Recently acquired oceanographic data demand, for adequate explanation, that the ocean floors be continually built and destroyed by dynamic processes of crustal movement. This concept, once called continental drift, has been reborn as "plate tectonics" or the "new global tectonics." The concept says that the globe is made up of a number of solid rock "plates" composed of oceanic or oceanic-plus-continental crust (Fig. 5). These plates are constantly moving in predictable directions and speeds; they are colliding in regions of seismically active deep-sea trenches and in regions of mountain building. Plate boundaries are either areas of crustal destruction, where the edges of plates are being thrust under (subducted) or over other plates, or they are areas of construction where, if the earth's diameter is to remain constant, new crust must be made at a rate equal to the destruction rate. Such growth takes place at the center, or rift valley, of the mid-oceanic ridge (MOR), which is a globe-circling welt about 40 000 km in length. At this "spreading center," new molten basalt is constantly being injected, causing the seafloor to spread 2 to 4 cm per year.

Volcanism is associated with both the growth and destruction patterns of the plates and perhaps with "hot spots" over which the plates move. Figure 6 shows locations of volcanoes and the seamounts that are their remains in the deep ocean, and one can see that only a few areas appear devoid of past volcanic activity.

It is within this framework of crustal unrest that we describe the principal features of the ocean environment, highlighting the characteristics that may apply to the problem of long-term disposal.

We do not attempt a discussion of the complex biological communities in the several ocean provinces, but merely call attention to the overall biological productivity illustrated in Fig. 1 as an indicator of the location of biological processes that might have an effect on waste disposal. Nor do we discuss the detailed chemical differences between the several areas of the ocean floors.

While we recognize the importance of biological and chemical processes in assessing the oceanic provinces for possible disposal concepts, and while these aspects are included in the larger consideration of one of these areas now under way, the discussion herein will focus on the geological setting, the frequency of geological events, and the rates of geological processes. No attempt is made to review the basics of marine geology; a standard reference[7,12] may be used for background information.

The oceans are divided into three principal physiographic provinces, each occupying about a third of the world ocean area (Figs. 7 and 8):

1. continental margins (continental shelf, inland seas, marginal plateaus, continental slope, continental rises)
2. ocean basin floor (abyssal plains, abyssal hills, oceanic rises, deep sea trenches)
3. mid-oceanic ridge (ridge flank and crest, rift valley and rift mountains, fracture zones).

Any of these major provinces may be interrupted by volcanic seamounts or islands and in the following discussion each province is treated in categorical order. It is helpful to remember that, with few exceptions, geologic processes on the continents are primarily erosional whereas in the oceans they are principally depositional.

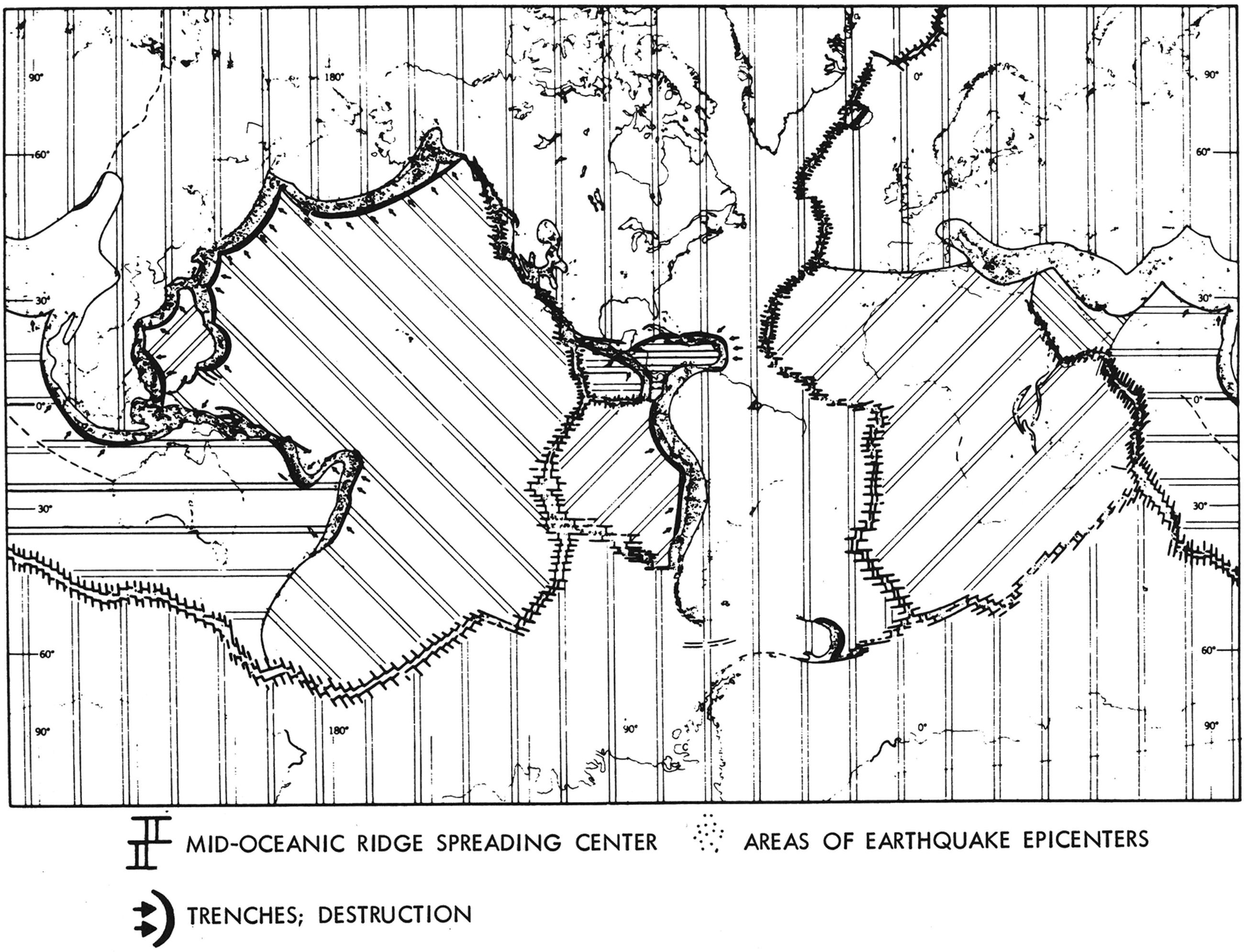

Fig. 5. The crustal plates (drawn after Ref. 7).

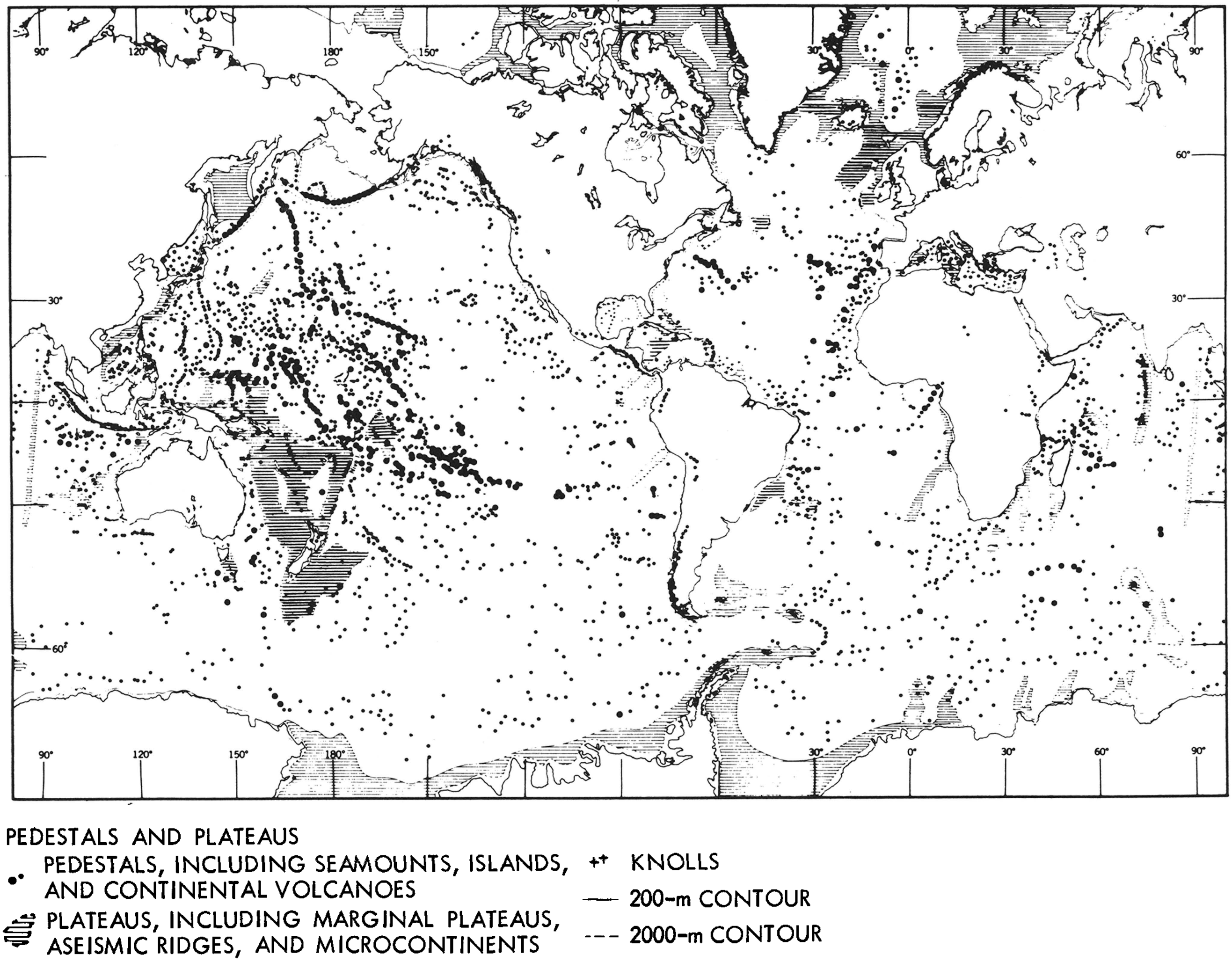

Fig. 6. Locations of major seamounts and plateaus in the world oceans (adapted from Ref. 7).

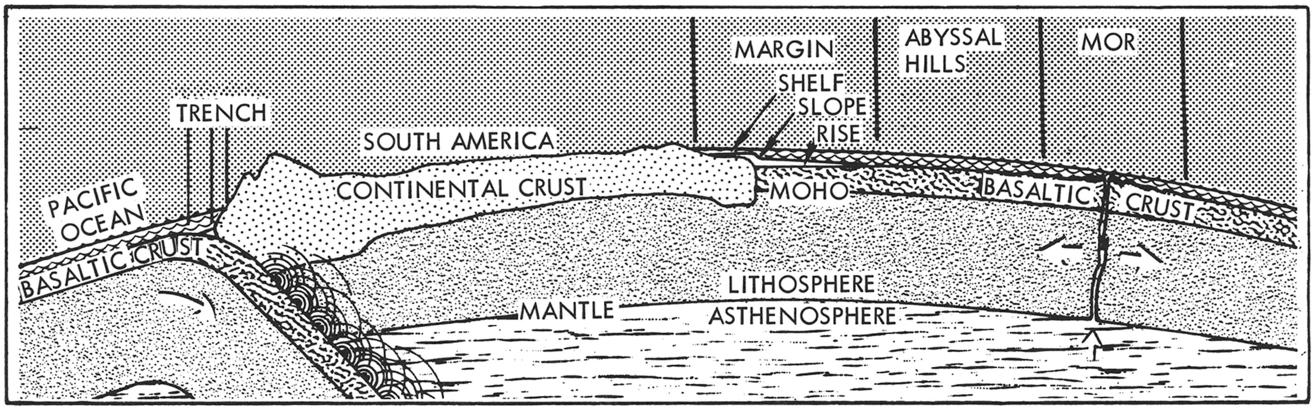

Fig. 7. Schematic diagram of the dynamic ocean regimes.

The Continental Margin (Shelf, Slope, Rise, Fans, Cone, Deltas)

Between the beach and the landward edge of oceanic crustal basalt lies the "wetted perimeter" of the continents—the continental margin (Fig. 9). This is the most dynamic environment of the ocean, where seasonal temperature changes in the water are high, chemical and biological processes are most variable, and geology is most complex and unpredictable. Here lie most of the remaining pools of hydrocarbons, as well as most of the world's great fishing grounds. Surface material of the continental margin changes radically over short distances, ranging from hard rock to gravel to clay within a few miles to tens of miles.

Most of the continental shelves (200 to 300 m deep) and marginal plateaus (to 1000 m deep) are covered with silt, sand, and gravel (e.g., the Blake Plateau); most inland seas (e.g., the Japan Sea) are floored with finer material. The continental slope (200 to 3000 m deep) and rise (3000 to 4500 m) are generally covered with silty clay. The thickest deposits of this organic fine-grained sediment, often interbedded with sand layers, are found beneath the deltas, aprons, and cones off the mouths of major rivers. A combination of factors, including the high organic content (potential oil sources) and interbedded sand layers (potential reservoirs) makes these areas particularly suitable for hydrocarbon production. In these regions the rate of sediment accumulation is relatively rapid, and this, combined with relatively steep slopes, provides optimum conditions for sediment failure (slumping, turbidity currents, etc.). Evidence that these processes occur is abundant.

Bottom currents on the continental shelves are strong but variable, with velocities often exceeding 50 cm/sec, and strongly influenced by wind direction, storms, and tides. Currents on the deeper

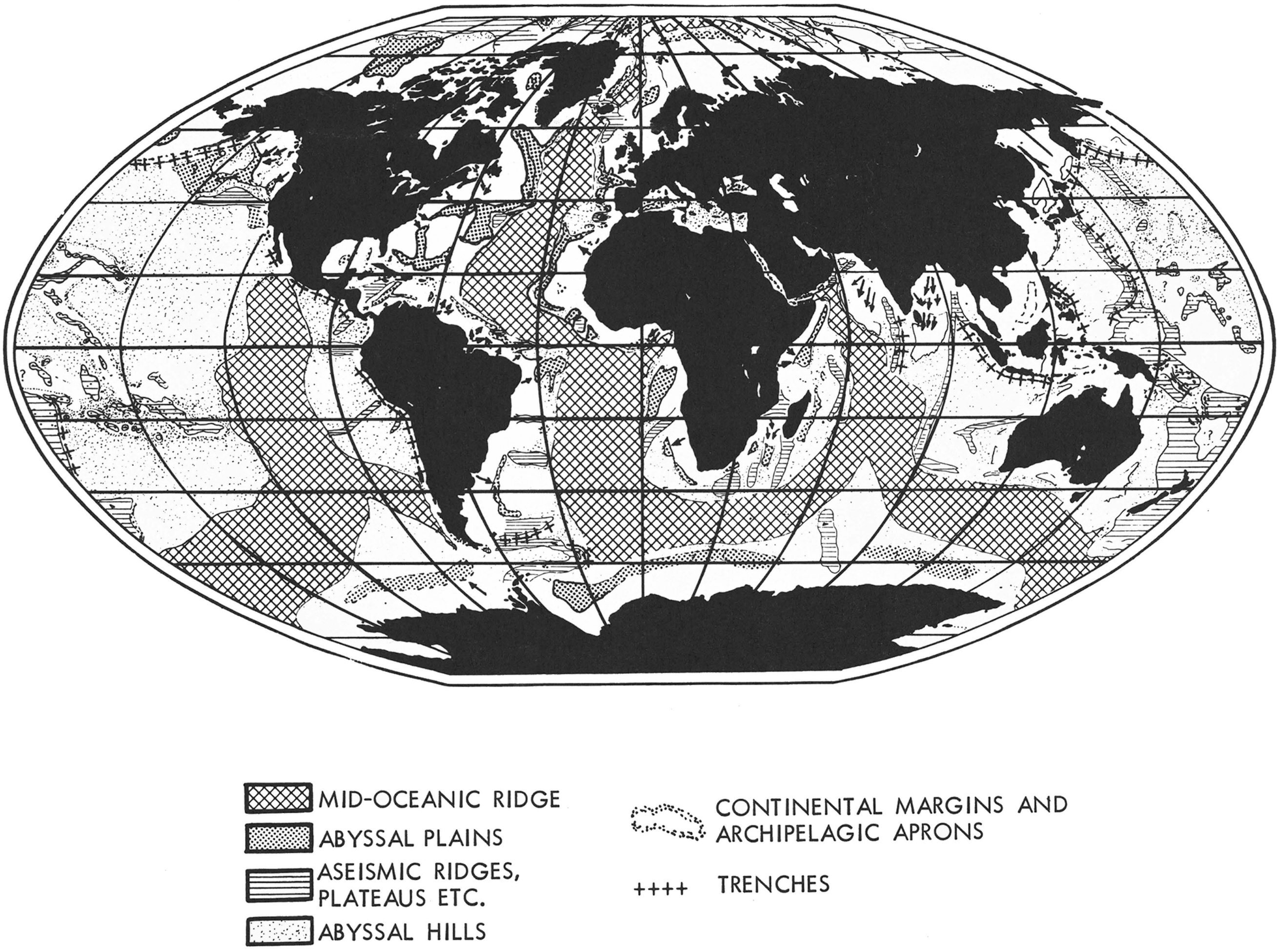

Fig. 8. The major oceanic provinces (drawn after Ref. 8).

marginal plateaus are influenced more by steady-state wind-driven circulation. Velocities of bottom currents here are of the order of 10 to 25 cm/sec. Current velocities on the slope are generally of the same order and are principally driven by differences in salinity or temperature (thermohaline) or are associated with internal waves and tides.

Abyssal bottom currents on continental rises on the western sides of ocean basins generally vary between 10 and 35 cm/sec, are also thermohaline, and tend to be constant in direction. Abyssal currents on eastern sides of the major oceans are generally weak and variable, and are principally tidal.

Also of importance to a discussion of the ocean environment is the position of the continental margins relative to areas of crustal growth or destruction. Because most continents are moving, it is useful to think of their surrounding margins either as being on the "leading" (destructive) or "trailing" (constructive) sides. Leading edges are characterized by very narrow seismically active continental shelves (e.g., the west coast of the Americas), and precipitous, rocky, and faulted continental slopes. Shelves on trailing edges are generally broad, flat, and seismically inactive (e.g., east coast of the Americas). Clearly it would be meaningless to average shelf characteristics of these two very different margin types. These fundamental differences must be kept in mind during the following discussion of the deep ocean floors.

Ocean Basin Floor (Abyssal Plains, Abyssal Hills, Deep Sea Trenches)

This province, occupying another one-third of the ocean area, is the deepest ($4\frac{1}{2}$ to 11 km) of the three provinces and includes the flat abyssal plains, the gently rolling regions of abyssal hills,

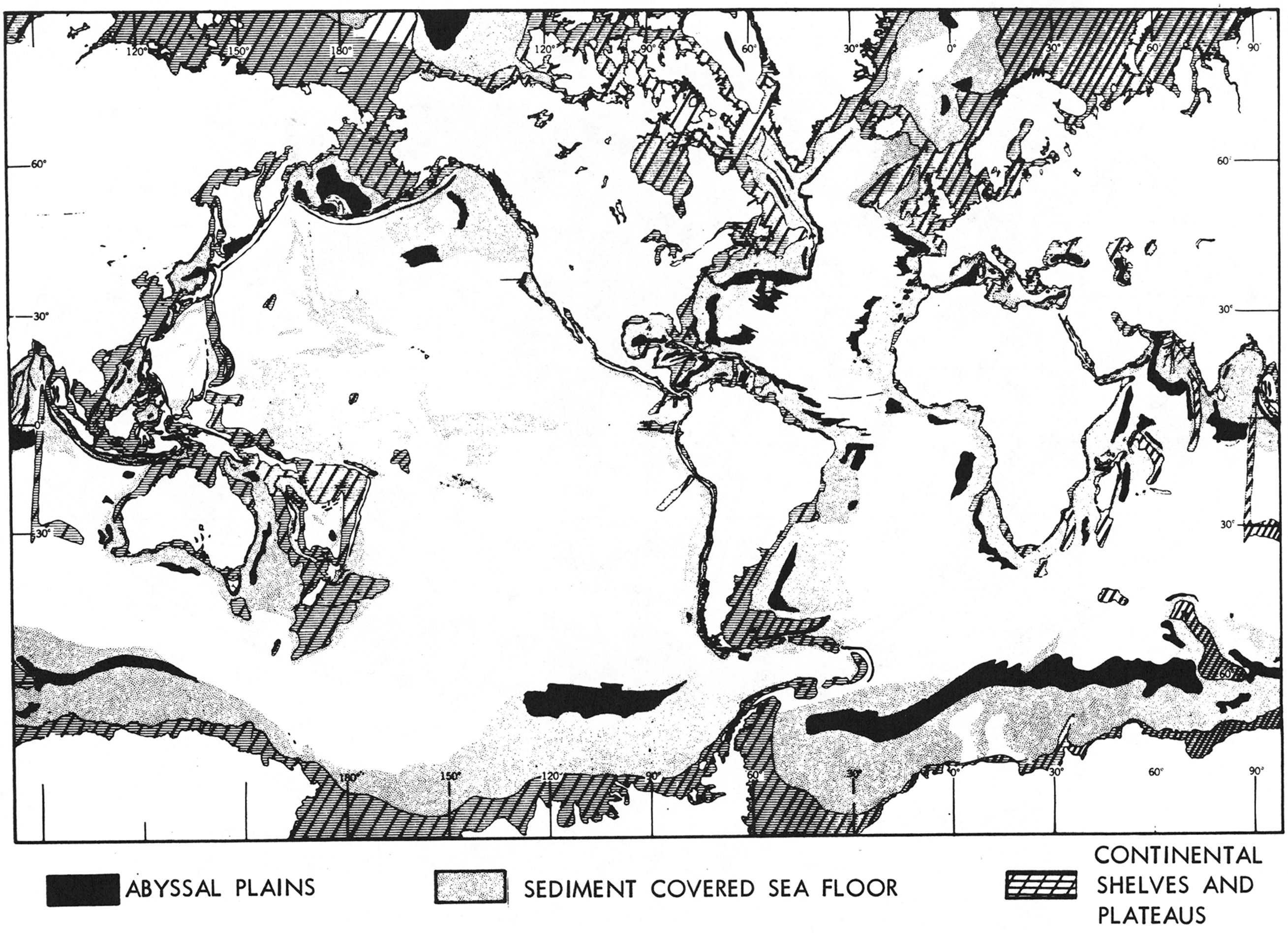

Fig. 9. Continental margins and the abyssal plains of the world's oceans; areas of terrigenous deposits (drawn after Ref. 7).

and the deepest portion of the oceans—the deep-sea trenches (Fig. 5).

The flat abyssal plains (gradients <1:1000) are built through deposition by the catastrophic and periodic turbidity currents that sweep vast quantities of coarse continental debris from the continental margins to this final resting place by rapid (hundreds of cm/sec) underwater avalanches. The destructive power and speed of these currents have been determined through the failure sequences of submarine communication cables. Sediments recovered from abyssal plains are typically poorly sorted silty clays interbedded with thick coarsely graded layers of sand and gravel. Holes drilled in these regions by the *Glomar Challenger* often collapsed through failure of these incohesive coarse interbedded deposits. The temperature of bottom water on these plains does not vary seasonally, and bottom currents are extremely weak and variable, with tidal velocities of 2 to 5 cm/sec predominating.

The abyssal hills that lie seaward of the abyssal plains are a few kilometers in diameter and a few tens of meters high and are thought to be old ocean crust originally formed as extrusions of pillow basalt from the MOR spreading center. As the crust spreads away from the MOR it cools and sinks, reaching a depth of 5 km in about 50 million years. The vast abyssal-hill province (e.g., most of the North Pacific) is generally covered with 50 to 100 m of brown zeolitic clay overlying a few tens of meters of limestone that was deposited when the hills were part of the much shallower MOR. The mid-plate abyssal hills are seismically passive. These regions are also located in central portions of the wind-driven surface-flowing current gyres that are typically quite stable and relatively unproductive biologically. Bottom currents, although topographically influenced, are weak and variable and their driving forces have not appreciably altered in 50 million years. From the viewpoint of stability, the vast (10^8-km^2) regions of the mid-plate/mid-gyre abyssal hills are unparalleled.

The dynamic deep-sea trenches (7 to 11 km deep) often form the landward boundaries of abyssal hills, especially in the Pacific and Indian Oceans. Here the ocean crust, colliding with and presumably being overridden by lighter crustal rock, is being destroyed at a rate of 2 to 4 cm per year. The arcuate circum-Pacific trenches represent some of the most dynamic regions on the planet (Figs. 5 and 8). Many high-intensity earthquakes occur in or near trenches. This activity triggers massive submarine slides and is associated with extensive volcanism.

The technology does not exist for drilling into these great ocean deeps, so our data come primarily from piston cores tens of meters in length, and from seismic profiles. These data show wide variation in the sedimentary column. Some trenches are nearly filled by flat abyssal plains, some are almost empty, and some show very highly deformed landward edges where sediment has been plastered against the leading front of the advancing continent. Those near major sediment sources are nearly filled with 2 to 3 km of debris; many have at least $\frac{1}{2}$ km of sand, silt, and clay, often containing turbidite sand and gravel beds. The material is deposited at rates from 1 to 100 cm per 1000 years.

Mid-oceanic rises (e.g., the Bermuda Rise) are broad low swells of abyssal hills generally 4 to 5 km below the surface. They may be associated with concentrations of seamounts or islands. Sediment on oceanic rises tends to be thicker than is found on abyssal hills, often exceeding 200 to 500 m. It is a mixture of pelagic ooze and clay and is generally silty clay in texture. The notable increase in sediment thickness results primarily from lack of dissolution of the remains of pelagic plants and animals in water depths shallower than the carbonate compensation depth (the depth at which carbonates falling from the surface are dissolved), which is generally between 4 and 5 km.

Mid-Oceanic Ridge

This 40 000-km-long, globe-circling sea-floor spreading center forms the "constructive" plate-boundary (Figs. 5 and 8). In the center of this symmetrical two-way expanding ridge lies the hot, seismically active rift valley (2 to 3 km deep) where new crust is being continually extruded. Sediment thickness in this shallowest and youngest part of the ocean is generally too small to be detected except as a thin, current-winnowed veneer of pelagic carbonate seen in bottom photographs. Pelagic carbonate ooze may attain 5- to 10-m thickness in low-lying pockets of the rift mountains on either side of the rift valley, and from there, in either direction, sediment thickness increases linearly with distance, age, and depth, from the ridge where, at the carbonate compensation depth, the cold bottom water is able to dissolve the lime faster than it can be deposited, yielding a sedimentation rate of <1 cm/1000 yr.

Water temperatures and currents on the shallowest portions of the rift mountains vary markedly in response to wind-driven currents flowing over and around rugged mountainous relief. Bottom-water velocities may at times exceed 50 cm/sec. The temperature of the central portion of the rift valley may approximate that of molten basalt (1200°C), yet water circulation dissipates this heat so quickly that no water temperature rise can be measured at the sea surface directly above this tremendous (20 000 km^2) heat source.

These three provinces comprise the ocean environment, about which a significant amount of data has been acquired (Table I).

From the data at hand, certain very good first approximations can be made about the rates and kinds of processes that are active in the three provinces. We will now examine these provinces by the criteria of geologic stability and predictability of processes, as we know them today.

TABLE I

Characteristics of the Oceanic Provinces

Physiographic Provinces of the Oceans	Mid-Oceanic Ridge			
	Fracture Zones	Flanks	Crest	Rift Valley
ENVIRONMENT				
Water depth (km)	4 to 6	3 to 5	0.5 to 2	1.5 to 3
Local relief (m)	1000's	100's	1000's	1000's
Regional slope (deg)	10's	2 to 5	10's	<5
Bottom temp (°C)	<3	2 to 4	3 to 5	5 to 15
Texture of bottom sediment	pebbles to sand	sand, silt, clay	boulders to sand	boulders to sand
Sediment thickness above igneous rock (km)	0 to 2	$\frac{1}{2}$ to 2	0 to $\frac{1}{4}$	0
DYNAMIC PROCESSES				
Rate of sediment accumulation (cm/1000 yr)	0 to 10	2 to 4	0 to 5	0 to 1
Currents: Non-tidal currents (cm/sec)	10 to 20	3 to 5	10 to 50	10 to 20
Currents: No. of near-bottom measurements	<10	<10	<10	<10
Erosion or deposition	E	D	E	E
Earthquake frequency	low to high	very low	moderate	very high
Biological activity	low	moderate	moderate	low
Frequency of sediment failure	moderate	low	high	very low
Volcanic activity	moderate	low	high	very high
CHARACTERISTICS GERMANE TO SUB-SEA FLOOR DISPOSAL				
Geologic stability (predictability)	low	moderate	low	very low
Areal extent $(\mathrm{km}^2 \times 10^6)$	← 120 →			
Accessibility by man	low	low	high	moderate
Present Value of Natural Resources, $\times 10^6$ \$ per Annum: Biologic	← 1×10^3			
Present Value of Natural Resources, $\times 10^6$ \$ per Annum: Sand, gravel	← 0			
Present Value of Natural Resources, $\times 10^6$ \$ per Annum: Mineral	← 0			
Present Value of Natural Resources, $\times 10^6$ \$ per Annum: Hydrocarbon	← 0			

THE ENVIRONMENTAL STABILITY AND PREDICTABILITY OF OCEANIC PROVINCES

Assuming that one of the most important criteria for waste disposal is geologic stability and thus predictability over periods of up to a million years, we will now compare the ocean provinces with regard to their frequency of catastrophic events and the rates of natural processes.

Most of our data necessarily come from interpretation of the past record, which is contained in the sediments. The bulk of this information is derived from piston cores 5 to 10 m in length and 6 to 8 cm in diameter, which contain a record that

TABLE I (Continued)

Ocean Basin Floor				Continental Margin			
Seamounts Islands	Trenches	Abyssal Hills (Mid-Plate)	Abyssal Plains	Deltas/Fans	Rise	Slope	Shelf
0 to 3	7 to 11	5 to·6	4 to 6	0.1 to 5	3 to 5	0.2 to 3	0.1 to 0.5
1000's	10 to 100	10 to 100	< 5	10 to 100	5 to 10	100's	5 to 10
10's	2 to 20	<1	$<\frac{1}{10}$	$\frac{1}{2}$ to 5	< 1	4 to 10	< 1
2 to 20	1 to 3	< 2	< 2	3 to 5	1 to 3	3 to 5	2 to 20
gravel and sand	sand, silt, clay	clay	clay, gravel	sand, silt, clay	silt, clay	silt, clay	gravel and sand
0 to $\frac{1}{2}$	1 to 5	$\frac{1}{4}$ to $\frac{1}{2}$	$\frac{1}{2}$ to 2	5 to 10	5 to 10	2 to 10	2 to 20
< 0 to 5	1 to 10	< 1	2 to 5	10 to 500	5 to 50	< 0 to 3	< 0 to 50
5 to 25	2 to 10	2 to 10	< 5	5 to 30	5 to 30	5 to 20	10 to 50
10's	< 5	< 10	10's	10's	100's	100's	1000's
E	D	D	D	D	D	E	D/E
moderate	very high	very low	very low	← very high to low, depending on position of plate boundary →			
very high	moderate	very low	low	high	moderate	high	very high
moderate	high	very low	low	very high	moderate	very high	low
high	high	very low	very low	low	low	low	low
very low	very low	high	moderate	very low	moderate	very low	very low
10	6	130	10 to 20	5 to 10	20	← 50 →	
very high	very low	very low	very low	moderate	low	moderate	very high
—	—	1×10^3 →					9×10^3
—	—	0 →					3×10^2
—	—	0 →					6
—	—	0 →					3×10^4

goes back millions of years. The Deep Sea Drilling Project of the National Science Foundation (NSF) has obtained sediment data from over 300 drill holes that in some instances penetrate the entire sediment column and up to 0.5 km (leg 37) into oceanic basalt. This record encompasses tens to hundreds of millions of years, and often the record indicates change. For example, each change in color, texture, and composition observed in recovered sediment has been caused by some change in depositional conditions. A completely uniform sample, on the other hand, indicates relative uniformity of conditions and material.

CATACLYSMIC/SPORADIC EVENTS

Earthquakes
Volcanism
Slumping of sediments
Turbidity currents
Rapid currents causing erosion
Ice rafting of boulders
Biological windfalls
Refocusing of tidal circulation
Magnetic reversals
Intrusion by man

Another much shorter time-set of data concerning natural catastrophes comes from seismographs that have been recording earthquake activity for tens of years. Current meters measure velocity and direction for periods of weeks to months, and bottom photographs give us an instantaneous view of the modern sea-floor environment. Occasionally, sedimentary features seen in these photographs indicate "long-term" current effects that may be averaged for periods of months or longer. Seismic profiles show the reflecting horizons of the upper kilometers of unconsolidated sediment. Interpretation of these horizons (whether disturbed, faulted, etc.) yields significant qualitative insight into geologic stability over periods of millions of years.

Samples and seismic profiles taken on the continental margin often reveal conspicuous layering of sedimentary horizons. Cores contain sand interbedded with silt or clay, indicating rapid changes in depositional processes and/or sediment sources. Profiles reveal abundant layering that is often severely contorted. Abrupt color changes suggest variations in source, accumulation rates, or degree of oxidation. Erosional unconformities or hiatuses in the record are also commonly found in margin cores. Thus, we infer that the continental margin has been very unstable over geologic time, and it appears likely that it will continue to be a relatively unstable and unpredictable region.

CONTINENTAL MARGINS

(Shelf, Slope, Rise including Deltas, Cones, Fans)

High resources including

food	recreation
minerals	sand and gravel
hydrocarbons	habitation?

Shallower (<4000 m)
Unstable
Strongest currents
Variable conditions (temporally and geographically)
High sedimentation or erosion
Biologically active

Areas of high sedimentation rates have been cited as desirable disposal sites because of natural burial processes. However, at a sedimentation (burial) rate as high as 1 m per thousand years, which is high for even the most active fans and cones, only 250 to 500 m of sediment will accumulate over a waste container during the time its contents remain dangerous. The technology already exists to penetrate and thus emplace objects 1 to 2 km beneath the sea floor in these regions.

The continental margins off leading edges of moving continents, like the western United States, are seismically very active. Earthquakes on trailing edges like the east coast of the United States are much less frequent. On leading edges the combination of high seismic activity, steep slopes, and high rates of soft sediment accumulation results in optimum conditions for sediment failure, e.g., slumps, slides, turbidity currents, etc.

At the seaward edge of the continental margin are the flat abyssal plains generally best developed off trailing edges, and the deep sea trenches usually found off leading edges. The plains represent the last residing place of seaward-moving continental detritus which becomes entrained in turbidity currents that flow at speeds of tens of meters per second across the continental slope and rise. The frequency of these flows depends on the rate of continental erosion and sediment transport to the top of the continental slope, and the highest frequencies have been recorded from cable ruptures off the Congo Canyon, where approximately 50 occur each century.[7]

Deep-sea trenches are found at the base of most leading edges of continental margins, and here high seismic activity, combined with proximal sediment supply and steep slopes, provides maximum instability.

TRENCHES

- Seismically active
- Volcanic activity
- Unstable sediments
  - slumping
  - sliding
  - turbidity currents
- Adjacent to continents
  - detrital sediments
  - upwelling and biological productivity
  - rich fishing grounds
- Deepest areas
- Subduction might provide permanent disposal
- Severest technological problems

Trenches are thought to be the result of processes of underthrusting or subduction of oceanic crust beneath continental crust. This process cannot be observed directly, but is inferred from the location and magnitude of seismic events, crustal layering, and a tremendous negative gravity anomaly that suggests a significant mass deficiency in the trench region. Here the crust and mantle are being deformed faster than the earth can adjust itself. The bottoms of the trenches are of the order of 10 km across, and if we assume that subduction is occurring at the maximum credible rate, the present floor of the trench will be subducted beneath the continental plate in approximately 250 000 years—a time comparable to that during which nuclear wastes will cease to be dangerous. Little or nothing is known about the piling up of sediments on the leading edge of the continental plate, or about crustal deformations in the trench area. These uncertainties place in doubt the actual subduction of any particular piece of trench floor, and hence whether such a location would be a practical waste depository.

The dynamic processes of the MOR are better understood than are those of the trenches. Here new molten lava flows onto the sea floor, causing crustal growth, and shallow but severe earthquakes occur at rates of up to 10 per day. Currents, strongest on the highest mountains near the ridge crest, are generally weak and variable on the deeper (>3 km) and more subdued flanks of the ridge. Cores from this region show a relatively high degree of variability, with changes in texture, color, and composition, indicating varying conditions of deposition.

MID-OCEANIC RIDGE CREST

- Unstable
  - seismic (almost constant earthquakes)
  - volcanism
- No sediments
- Rough topography
- Shallower (2 to 4 km)
- Hot (molten basalt near surface)
- Strong and variable currents (>50 cm/sec in some areas)

As we progress further from the rift valley to depths of over $4\frac{1}{2}$ km on the lowest flanks of the MOR, we again reach abyssal hills where stability and uniformity become a dominant characteristic, where biologic activity is at its lowest, and where the very cold currents move slowly. Sedimentation is in the form of a rain of fine-grained material from the surface. Manganese nodules that are millions of years in age are found in this province, attesting to a uniformity of condition for at least millions of years.

Cores from abyssal-hill regions tend to be very homogeneous, consisting of abyssal brown clays with an occasional manganese nodule or micronodule. Bottom currents are weak, slopes are gentle (<5 deg local, $<\frac{1}{2}$ deg regional), sediment is uniform, and major earthquakes are unknown or, as yet, unrecorded. All indications from the cores, seismic profiles, and our emerging understanding of global deep circulation attest to the stability of these regions over tens of millions of years.

MID-PLATE/GYRE
(abyssal hills)

- Stable
  - aseismic
  - sediments (no slumping or turbidity currents)
  - $>10^{5-6}$ yr since last major changes
- Invariant conditions (temporally and geographically)
- Slow currents (2 to 5 cm/sec)
- Low bio-productivity (low on surface, very low on bottom)
- Low relief (40 ft/mile)
- Manganese nodules are the only identified resource

The abyssal hills occupy over a third of the total deep ocean floor, or about a quarter of the surface of the planet. These vast areas (10^8 km^2) probably represent the least "useful" part of our planet and will be among its very last habitable regions.

By far the largest expanse of abyssal hills—about the size of the United States—lies in the North Pacific, south of the Aleutian Trench, north of Hawaii, west of the Aleutian Abyssal Plain off Canada, and east of the Emperor seamounts. We are studying this area as a "type-region" that best exemplifies the stable mid-plate/mid-gyre resource-limited real estate.

SEABED DISPOSAL

The earth in general, and the oceans in particular, are dynamic systems. Processes are continually changing the surface and subsurface of the ocean floors, and singular events occur which quickly alter local areas. Thus the problem of disposal of radioactive wastes into the sea floor is one of matching the rates of these processes against the rates of decay of the radionuclides. The time needed for complete decay, including traces of transuranics, is of the order of a million years.

We have compared existing data from the major ocean provinces with an eye toward slow processes, freedom from cataclysmic events, and stability over the time scales of interest. What becomes apparent is that the most stable places in the oceans, and perhaps on the entire planet, are the mid-plate/mid-gyre regions of the major ocean basins. If we accept this tentative conclusion, the next question is, can we conceive of a system that will make use of that great stability for permanent containment of radioactive materials?

While a straightforward answer is not possible with currently available information, one may make suitable assumptions and at least define the questions that must be addressed to determine the feasibility of such disposal. It is probably safe to assume that the technology necessary to transport and emplace materials in the sea floor is possible. In fact, that technology is not a large extrapolation from capabilities that presently exist for offshore oil and mineral exploration and production, or for marine research purposes (e.g., the Deep Sea Drilling Project of the NSF). We can, for example, plug a hole drilled into the sea floor, although the actual effectiveness of those plugs is uncertain. Finally, to place reasonable limits on the present discussion, we assume that the waste material will be solidified, encapsulated, and emplaced well below the sea floor.

The system to be considered, then, includes the encapsulated wastes, the surrounding medium and overlying water column, and the biological community on that bottom and in that water column. In addition, it includes all the natural processes that occur there, plus new processes that may result from the introduction of the wastes and the plug in the hole.

To grasp such a complex system we have found it useful to list the possible barriers to a release of radioactivity. (We consider a release to have occurred when the material reaches man or when some administrative controls must be placed upon an area to prevent exposure.) These barriers are listed below.

POSSIBLE BARRIERS

Generic

- Distance from habitation
- Depth of water
- Constant conditions (temporally and geographically)
- Geologic stability (seismic and sediments)
- Predictability (lack of cataclysmic events)
- Sparse biology
- Large dispersal medium (as last resort)

Stepwise (repository to man)

- Waste form (solid nonleachable)
- Cask (noncorrodible)
- Accretion of chert or manganese oxide on cask
- Melted medium may solidify into a secondary container
- Impervious medium (basalt or sediments)
- Heat drives off water preventing transport
- Slow advection through sediments
- Ion exchange or concentration in sediments
- Sediment surface (special chemistry)
- Slow currents (tidal only, very small throughout)

These barriers fall into two loose categories that we have termed "generic" and "stepwise." Those falling in the former class, such as distance from humanity and relative freedom from cataclysmic events, merely describe the setting—the conditions to which the engineer can design the system.

The stepwise barriers, listed in more or less the sequence in which they would be encountered, are possible effective preventions for dispersal of radioactive material. For example, several solids have been made from simulated high-level radioactive wastes that have very low solubilities and leaching rates ($<10^{-5}$ g/cm^2 per day) and there are a number of cask materials (e.g., nickel, zirconium, titanium) that might have considerable lifetimes in contact with either water or the solid material of the rock and sediments.

Several natural accretionary processes occur in or on the sediments. Manganese and iron oxides precipitate from the water to form manganese nodules on the sediment surface, and amorphous silicates form beds and nodules of chert within the sediments. There is an intriguing possibility that these processes and the melting of the rock itself by heat from the waste could provide added protection by the *in situ* formation of an additional barrier to movement of the radionuclides. Of course, at or near the sediment surface, erosional processes (including biological) could have the opposite effect.

Both the basaltic crust of the ocean floor and the overlying sedimentary layers are relatively impervious to the movement of water or materials through them. Beds of amorphous chert could act as a cap to upward migration of pore water containing radionuclides, and furthermore, heat from the wastes may dry the area around them, thus keeping away mobile water. Water movement upward through the sediments is slow, with rates comparable to those of sediment deposition above it, and the sediments can retard the movement of some elements by ion-exchange processes. The manganese nodules, biological activity on the surface of the sediments, and some early indications from studies of artificial radioisotopes deposited by nuclear testing, all attest to some unknown but interesting processes at or near the sediment/water interface which might immobilize some isotopes.

The final barrier to the isotopes reaching man is, of course, the water column itself. Time scales of thousands of years for transport by the slow bottom currents of a particle of water across the Pacific basin may not be impossible. However, water-current data do not now exist that would allow a suitable calculation, and transport by internal motions of the water (e.g., eddies) or by biological mechanisms could be orders of magnitude more rapid.

In short, the rate at which any one of the barriers might be breached could be sufficiently slow as to assure isolation. It is these rates, taken together, which must be assessed for each of the important isotopes in the radioactive wastes.

ASSESSMENT OF THE SYSTEM

It is beyond the scope of this paper to even briefly indicate the amount of information available about many of the processes stated and implied in the list of barriers given above. It is even less possible to describe herein the greater amount of information required to understand the entire ocean/sediment/rock/waste system that would be involved in the containment of emplaced wastes.

An assessment of the efficacy of that containment, which is in effect an assessment of the technical feasibility of seabed disposal, requires the synthesis of the results of a number of investigations in diverse disciplines. We offer here an abbreviated list of the studies (many ongoing) that are required to determine technical feasibility.

NEED TO KNOW

- Leaching and corrosion rates (at pressure and temperature with radiation)
- Thermal processes (e.g., conduction and convection)
- Transport processes in rock and sediments
  - structural properties
  - chemical properties
  - driving forces (e.g., heat, compaction)
  - plug competency
- Transport processes in water column
  - diffusion and microstructure
  - currents (tidal and throughout)
  - upwelling/advection
  - biological (food web or mobile species)
  - thermal plume
- Geologic/geographic distributions of properties and processes
- Biological effects (both on and by the canister)
- Technological capability
  - transportation
  - emplacement
  - manipulation
  - monitoring

The investment required to develop the necessary baseline information regarding the environment and its interactions with emplaced wastes will be significant, but modest relative to the investment in the engineering system necessary for this or any other disposal concept. Present laboratory and oceanographic research capabilities are nearly adequate for the needed inquiries into the great mid-plate/mid-gyre regions. The present paucity of detailed data about these areas results from the same fact that makes them possibly attractive for disposal purposes; they are relatively devoid of activity, either geologic or biological, and have thus been of little interest to oceanographers.

CONCLUSIONS

If mankind must deal with radioactive wastes, it is incumbent upon us to search all of the earth's surface for areas that might be useful in this regard. About 70% of the earth's surface is covered by the oceans, and from our brief survey of that 70%, we have reached several conclusions:

1. The mid-plate/mid-gyre regions of the major oceanic basins are the most stable and perhaps most otherwise useless regions on earth.

2. Emplacement of waste canisters well below the surface of the sediments, likely deep into the basalt, seems possible and appears to provide a set of barriers to the release of radionuclides.

3. While there are not sufficient data now to assess rates and kinds of sea-floor processes, or the technical feasibility of seabed disposal of radioactive wastes, enough is known to define the questions and the systematic interdisciplinary effort required to answer them.

4. The central North Pacific—the largest mid-plate/mid-gyre region in the world—is one suitable and convenient area for the initiation of such studies.

Thus, while far from advocating seabed disposal, and almost as far from a conclusion that it is technically feasible, we have identified a type of area on the planet that we feel deserves careful study as a possible repository, and we cannot presently define any insurmountable technical barriers to such a disposal concept.

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REFERENCES

1. See, for example: *Proc. Symp. Management of Radioactive Wastes from Fuel Reprocessing,* Nov. 27 to Dec. 1, 1972, Organization for Economic Cooperation and Development, Paris (1973); A. S. KUBO and D. J. ROSE, "Disposal of Nuclear Wastes," *Science,* 183 (4118), 1205 (Dec. 21, 1973); E. J. ZELLER, D. F. SAUNDERS, and E. E. ANGINO, "Putting Radioactive Wastes on Ice," *Bull. Atomic Scientists,* p. 4 (Jan. 1973).

2. See, for example: "Radioactivity in the Marine Environment," Panel on Radioactivity in the Marine Environment, Committee on Oceanography, National Academy of Sciences, Washington (1971); *Proc. Symp. Disposal of Radioactive Wastes into Seas, Oceans and Surface Waters,* May 16-20, 1966, International Atomic Energy Agency, Vienna (1966); *Radioactive Waste Management Practices in Western Europe,* Organization for Economic Cooperation and Development, Paris (1972); *Radioactive Waste Disposal Operations into the Atlantic, 1967,* International Nuclear Energy Agency, Organization for Economic Cooperation and Development, Paris (1968); *A Closed System of Radioactivity,* Japan Atomic Industrial Forum, Tokyo (Aug. 1973).

3. G. A. M. WEBB and F. MORLEY, "A Model for the Evaluation of the Deep Ocean Disposal of Radioactive Wastes," NRPB-R14, National Radiological Protection Board (June 1973).

4. J. O. BLOMEKE, J. P. NICHOLS, and W. C. McCLAIN, "Managing Radioactive Wastes," *Phys. Today,* **26**, *8*, 36 (Aug. 1973).

5. Several recent laws and conventions are designed to prevent pollution of the world's oceans. See, for example: The Marine Protection, Research, and Sanctuaries Act of 1972, Public Law 92-532, enacted Oct. 23, 1972; "Convention on the Prevention of Marine Pollution," A Message from the President to the 93rd Congress of the U.S.A., Feb. 28, 1973, U.S. Government Printing Office, Washington (1973).

6. See, for example: K. O. EMERY, "Continental Rises and Their Oil Potential," *Oil and Gas. J.*, **67**, 231 (1969); V. E. McKELVEY and F. F. H. WANG, "World Sub-Sea Mineral Resources," *Miscellaneous Geologic Investigations,* U.S. Geologic Survey, Map #I-632 (1969).

7. B. C. HEEZEN and C. D. HOLLISTER, *The Face of the Deep,* Oxford University Press, New York (1971).

8. D. R. HORN, B. HORN, and M. N. DELACH, "Worldwide Distribution and Metal Content of Deep-Sea Manganese Deposits," *Proc. Symp./Workshop Manganese Nodule Deposits in the Pacific,* Oct. 16-17, 1972, Department of Planning and Economic Development, Honolulu, Hawaii (1972).

9. O. J. KOBLENTZ-MISHKE, V. V. VOLKOVINSKY, and J. G. KABANOVA, "Plankton Primary Production of the World Ocean," in *Scientific Exploration of the South Pacific,* p. 183, Standard Books No. 309-01755-6, National Academy of Science, Washington, D.C. (1970).

10. "High-Level Radioactive Waste Management Alternatives," WASH-1297, U.S. Atomic Energy Commission, Washington (May 1974).

11. C. D. HOLLISTER and J. I. EWING, *Initial Reports of the Deep Sea Drilling Projects—Cruise 11,* Washington, D.C., U.S. Government Printing Office (1972).

12. See, for example, F. P. SHEPARD, *Submarine Geology*, 2nd ed., Harper & Row, New York (1963).

13. M. N. HILL, *The Sea; Ideas and Observations on Progress in the Study of the Seas*, Vol. III, *The Earth Beneath the Sea*, John Wiley, New York (1963).

Contribution No. 3033, Woods Hole Oceanographic Institution.