

RESOURCES OF THE DEEP SEA OTHER THAN MANGANESE NODULES¹

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Introduction

During the Law of the Sea (LOS) negotiations, discussion of deep sea² resources has centered essentially on manganese nodules. This is an appropriate decision since manganese nodules, and their contained elements, have the most immediate potential as a marine mineral resource in the region outside of pending national jurisdiction. The objective of this paper is to describe some of the "other possible resources" of the deep sea--but I wish to emphasize that few of these "other possible resources" are economically meaningful at this time and most may never be.

Before starting, some definitions are appropriate. A resource simply means a supply of something, be it food, minerals or water. Resources such as food or forests are considered to be renewable resources since their supply can be replenished by photosynthesis or other processes. Mineral deposits, on the other hand, are generally considered to be nonrenewable resources since their supply decreases as the material is used. Resources also can be subdivided on the basis of economics. In general, the term "resources" is applied to a supply that can be worked or produced at a price somewhat higher than presently prevailing. A marginal or paramarginal resource is one that is recoverable at one to one and a half times the prevailing price (McKelvey and Wang, 1969), whereas a submarginal resource requires higher costs. A reserve is a known deposit that can be

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²"Deep sea" is used here to define that region beyond the limits of national jurisdiction based on present LOS negotiations or, in other words, the region outside of the exclusive economic zone (EEZ). In this paper it includes both the water and the sea floor although the latter is emphasized. The continental rise is not included in the deep sea as most, if not all, of the continental rise will probably be included within the EEZ.

developed under present technological and economic conditions. These terms are obviously not very precise. What is a resource today may become a reserve tomorrow. However, this is not generally the case for deep sea mineral resources.

One other important point is necessary as an introduction. That is the generally voiced concern that we - the world - are rapidly running out of mineral resources. The earth itself, as well as sea water, contains an immense and essentially inexhaustible supply of minerals. An example often quoted is that one cubic kilometer of average crustal rock contains 200,000,000 tons of aluminum; 100,000,000 tons of iron; 800,000 tons of zinc, etc. (Brooks and Andrews, 1974). Likewise, sea water contains vast amounts of different elements such as over 3 billion tons of uranium and copper, 500 million tons of silver and as much as 10 million tons of gold (or about 2.5 kg for each person on earth). This is not to imply that crustal rocks or sea water will be our future source of these minerals but rather to show that an immense supply exists. For example, considering gold, its average concentration in sea water ranges from 0.000004 to 0.000006 ml/l or about 50 pounds per cubic mile of water. The value of the gold in a ton of sea water, however, is only one thousandth of a penny. The two major mineral resources that are in danger of being exhausted are oil and gas. Oil and gas are chemical compounds formed by biochemical processes requiring time periods in the order of millions of years for formation.

Resources of the Deep Sea Water Column

The deep sea, for the purposes of this paper, can be divided into two regimes, the water column and the sea-bed (including the sediment and rocks below the sea bed). Although the latter is the principal subject of this manuscript, some comment about the resources of the former is appropriate. Three particular types of resources are possible from the deep sea water column. The first is the water itself and, in particular, using glaciers or icebergs as a source of fresh water. This subject has received considerable recent publicity due to interest by the Saudi Arabian Government in such a project. It is possible to move icebergs with existing technology; however, there are big unknowns such as cost, how long it will take, and whether ice can be moved from Antarctica to the Middle East before it melts. Conventional thinking would indicate that the idea is unreasonable, but it should be emphasized that over 80% of the world's fresh water supply is in the form of ice; the volume of the ice is equivalent to more than 200 years of rainfall. Moving icebergs to areas like New Zealand or Australia, where water is also needed (and thus not having to cross the equator) may be more feasible and practical.

The second possible resource from the deep sea water column is biological resources. The biological potential of the open

ocean as shown by Ryther and others is generally very small. This is mainly due to the "unmixed nature" of the surface waters which prevents nutrients at depth from being returned to the surface waters and re-introduced into the biological cycle. Most estimates are that about 99% of the commercial biological resources of the ocean are to be found in coastal and upwelling regions (generally not in deep sea areas). One major exception to this is the Antarctic region where the west-wind drift causes a strong vertical mixing of the water column and the replenishment of the surface nutrient supply. A principal result of this is an apparently large resource of krill, a shrimp-like organism, in this region. The actual amount available of this high protein resource is unknown, but estimates of potential yearly catches of 200 million tons (about three times all other fish caught) have been made. Krill, at this time, should not be considered as a solution to the world's food problem as several problems exist, including the understanding of its ecology within the Antarctic food chain, difficulties in processing the catch, and fishing in the Antarctic including both technological and legal complexities.

The third resource of the deep sea water column could be its use as an area for innovative thermal energy conversion (OTEC) systems (Figure 1) or for other systems such as capturing wind or wave energy. This subject is treated elsewhere in the symposium and need not be examined further here.

Before considering the resources of the sea bed and underlying rocks of the deep sea, a few words about the state of our knowledge of this region is appropriate. During the last two decades we have learned much about the evolution of the sea floor; these discoveries have come from a collection of routine geophysical and geological observations made over many years. The observations can be incorporated into a single, unifying concept called sea-floor spreading, or plate tectonics. To reach this level of understanding marine scientific research in all parts of the ocean was necessary. Ironically, it is this type of research, having basic scientific goals, that stands a good chance of being most restricted because of the law of the sea negotiations.

Resources of the Deep Sea Bed

The sea-floor spreading concept has shown us that the ocean and the continents are composed of a number of large and small plates that move relative to each other (Figure 2). In general, three types of movement between plates are possible; the effects of the movement are seen mainly at the plate boundaries. In some areas one plate is thrust or collides against another, and in this instance if one plate is composed of heavier oceanic material it will generally be thrust under a lighter continental plate. These areas, called convergence

OCEAN THERMAL ENERGY CONVERSION (OTEC)

Oceans are constantly collecting massive amounts of solar radiation and storing it as heat energy. A gigantic heat engine – such as diagrammed here – uses the warm surface water as the heat source, and the cold water from the depths as a heat sink. The warm water vaporizes a liquid, such as ammonia. Like steam, this gaseous, pressurized ammonia drives turbine-generators. The ammonia then is condensed to its liquid form by the cold ocean water, and this closed cycle continues. When fully developed, an OTEC heat engine is expected to supply significant amounts of electric power at competitive prices.

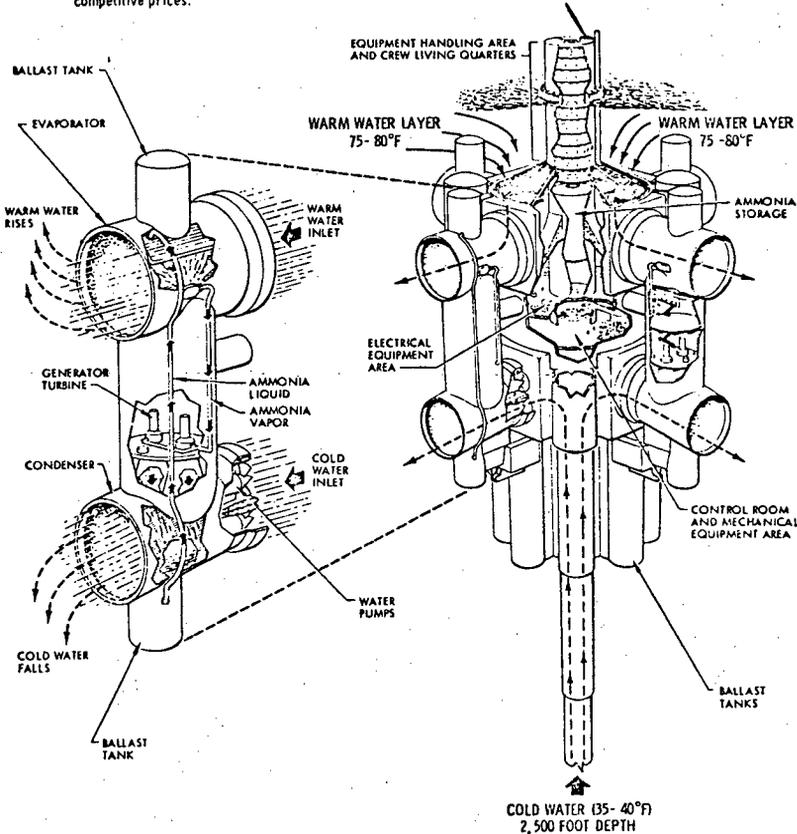


FIGURE 1

A MODEL OF AN OCEAN THERMAL ENERGY CONVERSION SYSTEM.
Figure courtesy Lockheed Missiles and Space Company

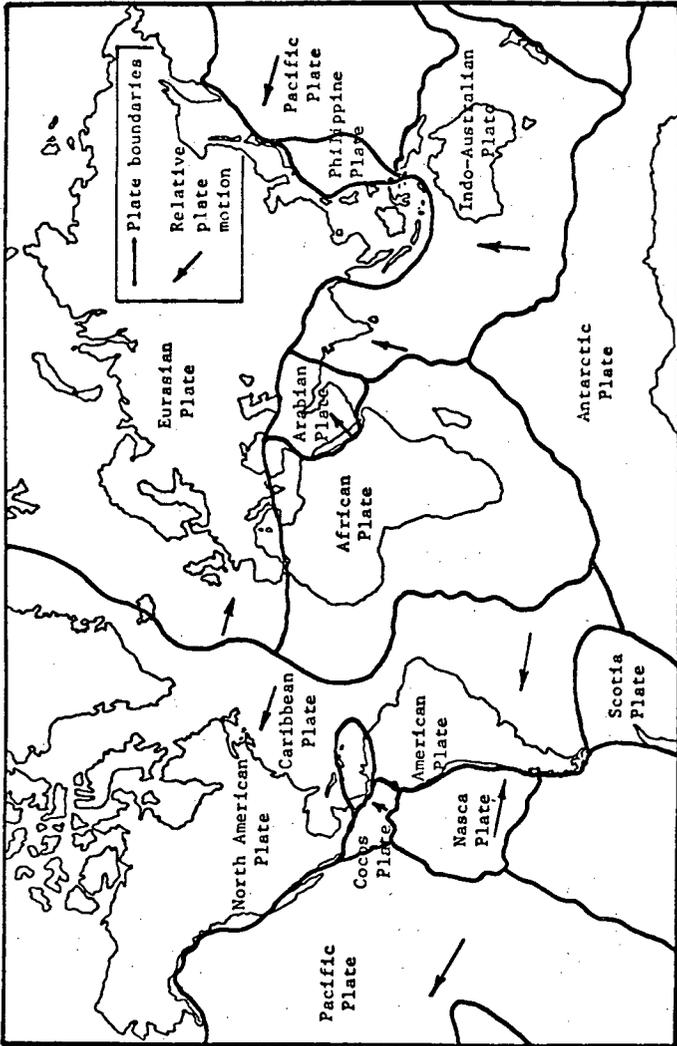


FIGURE 2

The major plates of the world. Some of the larger ones can be subdivided into smaller plates and in some classifications as many as twenty-six plates are possible. The plates have thicknesses in the order of 100-200 km. From Ross, 1979.

zones, often result in deep sea trenches (Figure 3). When plates of the same composition (i.e., two oceanic or two continental plates) collide, a mountain range may result (if the plates are continental) as when the Indian plate collided with the Asian forming the Himalayas. If both plates are oceanic an island arc system may form.

In some regions plates may be moving away from each other (called divergence zones or spreading centers) and new sea floor (volcanic rock) forms in the resulting gap. With time the initial volcanic rock moves away from the spreading center and is covered by a veneer of sediment; but new volcanic rock will continue to form on the spreading center. An example of a divergence zone is the Mid-Atlantic Ridge or the central part of the Red Sea. The third possible type of movement occurs when two plates slide by each other creating a shear zone or a zone of translation. An example of this is the San Andreas Fault in California or the Jordan Rift Valley in Israel. These three types of movement--convergence, divergence and translation--occur at plate boundaries (one plate can have all three types), while within the plate seismic and tectonic activity is usually minimal and the sea floor may have quietly existed and evolved for literally hundreds of millions of years. Plate boundaries, as well as the interior portions of the plates, may have economic potential although the mechanisms and resulting deposits are considerably different for each region. As a plate evolves certain geological events may occur and control the resulting mineral deposits. The one we have heard most about is manganese deposits. These deposits form in the interior portions of plates, isolated from sources of other sediment. Nodules grow extremely slowly, at a rate of about one atomic layer a day, and can easily be buried or diluted by other sediments.

On portions of a plate that are near land and have a large sediment supply, a thick continental rise may form that could have oil or gas potential. This will not occur if a trench or convergence zone is present along the coast since it will trap the sediments and eventually move them under the continent (see Figure 3). Nevertheless, continental rises are outside of the geographic area of discussion for this paper.

The resources of the deep sea bed and below, exclusive of manganese nodules, can be categorized into two major groups: first, the sediments themselves, and second, zones of mineralization occurring at areas of divergence and certain unique heavy-metal rich muds. The deep sea does not have significant oil and gas potential for two major reasons. First, the total sediment accumulation is too thin and second, the actual rate of deposition is too slow. The slow rate of sedimentation (a few cm or less per thousand years) ensures that organic material from settling plant and animal material will remain on

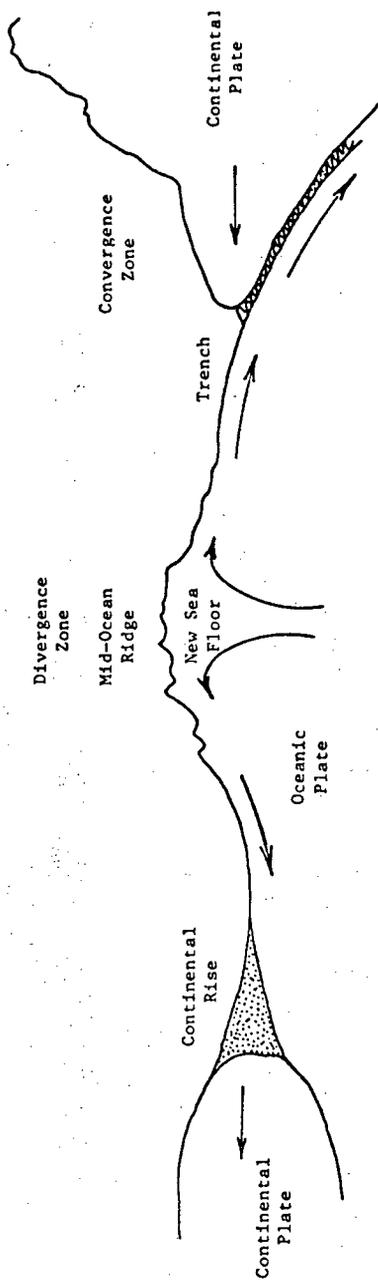


FIGURE 3

Schematic view of an oceanic and two continental plates. Note the convergence zone on the right of the figure where the oceanic plate is being thrust under a continental plate, whereas on the left side of the figure both the oceanic and continental plates are moving (arrows indicate direction of movement) in the same direction and a continental rise has formed rather than a trench.

the sea floor surface long enough to be oxidized and thus will not be converted into petroleum. If the sedimentation rate were high, the organic matter could be preserved by burial. The sediments themselves generally are microscopic particles and shells that usually do not produce sufficient reservoir or source beds for petroleum accumulation. In addition, the resulting thin sediment layer (a few hundred meters or so), because of the low deposition rate, will not be adequate to produce the heat necessary for the important geochemical reactions that form oil and gas.

Deep Sea Sediments

Deep sea sediments can be divided into two basic groups: red or brown clay and oozes (mainly shells of planktonic organisms). The dominance of one or another is a function of their sedimentation rate. Brown clays have extremely low sedimentation rates on the order of a few millimeters per thousand years; whereas oozes accumulate at the rate of a few centimeters per thousand years or an order of magnitude faster than the brown clays. Under areas of high biological activity, the settling shells (oozes) will generally dilute any brown clay deposit.

Brown clay deposits cover an area of about 100 million square kilometers of the sea floor. Assuming an average thickness of 200 meters, they have a volume of about 20 million cubic kilometers. Their weight would be about 10^{16} tons with about 5×10^8 tons being deposited yearly. Chemical analyses of the brown clays show as much as 9% aluminum, 6% iron, and smaller amounts of copper, nickel, cobalt and titanium. Some of these metals are more enriched in brown clay than in rocks mined on land, and thus it is logical to think that brown clays on the sea floor might eventually also be mined. Mero (1969) has estimated that brown clays contain enough aluminum and copper that, if they could be economically mined, there would be a supply that would last over one million years at present rate of consumption. The "if" is a big one, for among the major problems are recovery from depths of 5,000m or more far from land and considerable difficulties in refining the fine-grained material.

The oozes are of two main types, calcareous oozes or siliceous oozes, determined by whether they are composed mainly of shells made of calcium carbonate or shells made of siliceous material. Collectively, oozes exceed brown clays in areal extent, although the two are not mutually exclusive. It is a question of which dominates; this is influenced by near-surface oceanographic conditions that determine the growth of the organisms and the depth of water, since calcium carbonate tends to dissolve below depths of 5,000 meters.

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Calcareous oozes may cover as much as 50% of the ocean floor and can contain carbonate contents as high as 95%. At these concentrations they could be used as a source of lime for cement. As in the case of brown clays, the volume of this material is awesome and if ever mined, could supply lime at an amount equal to several million years of consumption. On a carbonate-free basis, carbonate oozes are enriched in iron and manganese (up to 25-30% iron and 7-9% manganese); other elements-- such as copper, chromium, arsenic, zinc, cadmium, and vanadium-- are also abundant. Siliceous oozes (which cover almost 40×10^6 km²) could be mined for their silica content which can be used for insulation and soil conditioners.

One specific potential clay resource from the deep sea is zeolite, a mineral of which phillipsite is the most common form. This mineral apparently forms on the ocean floor from the decomposition of volcanic glass. Phillipsite is extremely common in the Pacific and may be one of the most abundant minerals on the earth's surface, it could be a source of potash and used for fertilizer.

The oozes and muds must be considered only as potential resources based on present-day needs and the technological difficulties of mining them, and are presently worth little more than the overlying water. Even so, numerous people have been impressed by their vast extent and have suggested that they could become important potential resources in the near future. There are some aspects of this that are especially appealing. One is that their rate of accumulation, which although amazingly small, extends over such a large area that the net rate of accumulation of several elements is considerably higher than the present rate of their consumption on land. For some elements, such as nickel, copper, cobalt, manganese and some rare earths, contents are higher in deep-sea sediments than in igneous rocks. This does not necessarily mean that deep-sea sediments can be mined, but rather that such deep-sea deposits, when found on land and improved by enrichment processes such as weathering, could be a resource. It is easy to be swayed by the large numbers and volume of these deep-sea sediments, but they are similar to the values of igneous rocks and gold in sea water that I mentioned earlier and which probably never can be of economic value.

Zones of Mineralization

The second major type of economic deposit in the deep sea is principally associated with zones of divergence (where the sea floor is spreading and new ocean floor is being created). Basically two major processes could form mineral deposits. The first is due to the actual emplacement of the volcanic rock that forms the new sea floor. The second results from chemical

reactions between the volcanic rock and sea water (generally called hydrothermal reactions).

First, I shall consider the volcanic rocks of the sea floor which are mainly basalts. Basaltic rocks (a range of types are possible) when compared to the principal igneous rocks on land (granites) have relatively high amounts of magnesium, iron and calcium but relatively low amounts of silicon, potassium and sodium (Table 1). Ocean basalts contain valuable elements such as chromium, copper, nickel and plutonium similar to basalts on land, but the rocks themselves do not have much potential as a resource unless some form of enrichment (weathering, etc.) occurs that would concentrate some of the various elements. In general, the rocks of the sea floor are not competitive with those of land where enrichment processes are more common and recovery is much easier. Actually most of the important mineral deposits on land are found or formed from rocks not common to the deep sea.

It is conceivable that, during slow cooling of basaltic magma within the earth, different mineral crystals settle out by gravity so that layers or sequences of distinctive minerals may form within the rock, and could have economic value. There would be major difficulties, however, with detecting such a deposit and making the necessary assay of its value in particular since gravitational settling will not occur at the ocean surface but deep below it. If a similar event occurred on land, erosion could expose such a deposit. One possible exception could be where large scale crustal movements have exposed or elevated such layers, but so far few of these exposures have been found. One example of such deep sea regions now incorporated into a continent may be the Sudbury, Canada deposits of copper and nickel.

A different type of deposit can form from the chemical reactions between sea water and basaltic rock. Such reactions can cause alteration (metamorphism) of the rock sometimes forming copper or other mineral deposits. The faulted nature of many oceanic ridges (principal divergence zones of the ocean) may permit sea water to penetrate to considerable depths (and be heated) into the basalts. Again, however, the possibility of finding such deposits below the sea floor is difficult. Actually, the potential resources of the oceanic ridge areas really are not well known. Although the ridge system extends through all oceans (indeed it is the world's largest mountain system) we have little direct observations from it except where it comes to the surface as oceanic islands such as Iceland.

The second type of process in the deep sea that could form deposits results from the fact that heated sea water has the capability to leach certain elements from basalt or other rocks or sediment. These hydrothermal waters can pick up certain

TABLE 1
 MAJOR, AVERAGE ELEMENTAL (AS OXIDES) COMPOSITION
 OF OCEANIC AND CONTINENTAL ROCKS¹

	Average Oceanic Rocks	Average Continental Rocks
Si O ₂	50.0	61.9
Ti O ₂	1.4	0.8
Al ₂ O ₃	16.9	15.6
Fe ₂ O ₃	2.3	2.6
Fe O	6.4	3.9
Mn O	0.2	0.1
Mg O	7.0	3.1
Ca O	12.6	5.7
Na ₂ O	2.6	3.1
K ₂ O	0.4	2.9
P ₂ O ₅	0.2	0.3

¹Data from Ronov and Yareshevshy (1969).

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metals from the basalts (such as iron, manganese, copper, zinc, etc.) and deposit them elsewhere (such as in the pathways where the water moves) usually as sulfides. They may also precipitate mineral phases on the sea floor when the hydrothermal solutions come in contact with the overlying sea water. In this case they usually form oxides. The Troodos Massif of Cyprus (a large copper deposit) is an example of an ancient hydrothermal deposit that has been thrust up above sea water. The hydrothermal water may also sufficiently alter the basalt so that it could have potential as a resource.

The best example of hydrothermal activity on the sea floor that is producing a mineral deposit is the hot brine area of the Red Sea. The so-called Red Sea metalliferous muds will probably be mined before the end of the 1980s. This deposit, found essentially by chance, is situated along the central part of the Red Sea. In certain areas hot salty waters (hydrothermal solutions) containing enrichments of heavy metals are escaping from the sea floor and accumulating in small pools on the bottom. The process is similar to hot springs or geysers on land. More recently similar activity has been found in all oceans and most dramatically in the Galapagos region of the Pacific where it has given rise to a unique fauna that is feeding from these waters. These areas of hydrothermal activity have the potential to form deposits of economic value, if the conditions are right. So far only one such "right" deposit has been found--in the Red Sea--and it is of value to discuss it briefly, even though it falls within the EEZ of Saudi Arabia and Sudan.

The Red Sea is a zone of divergence--the Saudi Arabian Peninsula and Africa are slowly (about 1-2 cm/year) moving apart. The movement has formed a deep axial valley composed of new sea floor. Within several areas in the valley submarine discharge of hot salty water (salinities up to 257 ‰ or 25.7% and temperatures of over 60°C) has accumulated (water depths are of the order of 2,000m). This accumulation aspect appears to be unique to the Red Sea and results from the fact that the sediments buried beneath the flank of the sea contain salt deposits that have been leached by the migrating fluids and thus the fluids have increased in density. The hot water, when it reaches the sea floor, is thus denser than sea water and remains there rather than being dispersed as it appears to be doing in other oceans. Salt deposits, similar to the Red Sea, are not expected in open areas of the ocean. The fluids, once in the depressions of the Red Sea, then react with the overlying sea water producing sediments enriched in many heavy metals. Over ten of these pools have been found, but the Atlantis II Deep, covering an area of over 70 square kilometers, and situated about equidistant between Saudi Arabia and Sudan, seems to have the best immediate potential. The in situ value of the top 10 meters of its deposits exceeds two billion dollars (some estimates are over 4 billion dollars). The two adjacent countries (Sudan and Saudi Arabia) have negotiated an agreement to

develop these and other similar Red Sea deposits. It is not obvious, however, that even such a concentration of elements (Table 2) such as found in the Atlantis II Deep is actually economic. Problems of retrieval and refining are still unsolved. The Atlantis II sediments are worth about \$50/1000 kg (or about a ton) and are relatively more enriched in many of the metals found in deep sea sediments (for example, the Atlantis II sediments contain 30 times more copper than brown clays).

It does not, at present, seem probable that such high concentrations of metals similar to the Red Sea are present along other zones of divergence (Mid-Atlantic Ridge, East Pacific Rise, Mid-Indian Ridge) or buried along the flanks of the ridge. Many of the sediments of ocean ridges, however, have enrichments of iron, copper, manganese, nickel, lead, chromium, cobalt, and other elements. These concentrations are generally far from economic but higher concentrations may exist locally. There have been some indications of such local concentrations. For example, small veins of copper have been found in basalt rock below 400m of sediment on the Ninety East Ridge in the Indian Ocean and in sediment underlying the continental rise off New York. Manganese oxide accumulations (not nodules) have been found on parts of the Mid-Atlantic Ridge that appear to accumulate at a relatively high rate compared to nodules. In spite of these examples no known methods exist for adequate exploration and exploitation of mineral resources on the divergent portion of the sea floor. It is clear, however, that heat (therefore water movement) is coming from certain areas along the ridges and that there are chemical alterations of rocks due to these hydrothermal fluids. Further exploration, using research submersibles and other equipment, is necessary before the possibility of such deposits can be more realistically evaluated.

Mineral deposits also may occur along the convergent parts of plates due to mineralizing solutions coming from the melting of downthrust plates. These resources, however, will generally fall within the proposed EEZ and are outside the range of discussion of this paper. Examples of such deposits are the sulphide deposits of Kuroko, Japan and the Philippines.

Conclusions

The prime, non-manganese nodule, potential mineral resources of the deep sea are brown clays and carbonate oozes from sedimentation and zones of mineralization resulting from the cooling of volcanic rock and the activity of hydrothermal solutions. It is essentially impossible at this time to place a value on these deposits for many reasons, in particular since the cost of recovery from oceanic depths (5,000m or more), combined with the costs of exploration, transportation and refining, is unknown. The difficulty of finding deposits in zones of mineralization is awesome since many of these deposits, if

TABLE 2

GROSS VALUE OF METALS IN UPPER 10 METERS
OF SEDIMENTS COLLECTED FROM ATLANTIS 11
DEEP BASED ON 1967 METAL PRICES (ADAPTED
FROM BISCHOFF AND MANHEIM, 1969)

<u>Metal</u>	<u>Average Assay (%)</u>	<u>Tons</u>	<u>Value (\$)</u>
Zinc	3.4	2,900,000	\$ 860,000,000
Copper	1.3	1,060,000	1,270,000,000
Lead	0.1	80,000	20,000,000
Silver	0.0054	4,500	280,000,000
Gold	0.0000005	45	<u>50,000,000</u>
TOTAL			\$2,480,000,000

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indeed they are there, would be below the sea floor and be covered by sediments and perhaps rocks. Weathering and erosional processes, which in many instances improve mineral deposits on land, are not common under the ocean. Further research could lead to the discovery of some resources, but, aside from the hot brine areas of the Red Sea, no mining of deep sea minerals (exclusive of manganese nodules), should be anticipated in the near future, if ever.

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