DEPARTMENT OF THE INTERIOR
UNITED STATES GEOLOGICAL SURVEY

Preliminary Maps

WORLD SUBSEA MINERAL RESOURCES

By

V. E. McKelvey and Frank F. H. Wang

MISCELLANEOUS GEOLOGIC INVESTIGATIONS
MAP I—632

PUBLISHED BY THE U. S. GEOLOGICAL SURVEY
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A Discussion To Accompany Miscellaneous Geologic Investigations Map I-632

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1969

UNITED STATES DEPARTMENT OF THE INTERIOR
WALTER J. HICKEL, Secretary

GEOLOGICAL SURVEY
William T. Pecora, Director

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INTRODUCTION

The four accompanying preliminary maps showing the world distribution of potential subsea mineral resources are based on sparse information. Samples and photographs that show the character of the bottom sediment and seismic surveys that provide information on the thickness of sediments are widely spaced. Drill holes that reveal the composition and structure of the rocks at depth are largely confined to nearshore areas where petroleum exploration has been undertaken. Information on the bathymetry of the sea bottom, which tells something of its geologic character and its suitability for dredging and other operations related to mining or drilling, is scant in many parts of the ocean basins, and large areas have not been surveyed in any fashion. According to an assessment by the International Hydrographic Bureau in Monaco, even at a reconnaissance chart scale of 1:1,000,000 only 15 to 20 percent of the oceans and continental margins are adequately covered by bathymetric data, and the data are almost entirely lacking for nearly 50 percent of the areas (United Nations, Economic and Social Council, 1969). Detailed bathymetric charts at scales from 1:250,000 to 1:50,000 now only cover a few shelf areas. Because of this paucity of information, and particularly that directly related to subsea minerals, the distribution of potential subsea minerals is highly conjectural. Further exploration doubtless will substantially alter the projected and inferred distribution shown on these maps and in addition may reveal kinds of subsea mineral occurrences not now known or anticipated.

In spite of its inadequacy, the mass of information on the seabed is large and is growing rapidly. Figures 1 and 2 show the geophysical traverses undertaken by the Lamont-Doherty Geological Observatory. A nearly equal amount of geophysical surveying has been completed by other academic and government institutions that publish their results. These institutions have also collected hundreds of thousands of bottom samples, and thousands of shallow cores and bottom photographs (the data filed at the National Oceanographic Data Center alone now exceeds 76,000 bottom samples, including grab, shallow cores, and dredge samples. See National Oceanographic Data Center, 1968). Beginning in recent years with the Mohole and JOIDES projects, 62 holes have been drilled to depths of several hundred meters in the deep ocean floor (fig. 3). In addition, millions of miles of geophysical traverses and a few tens of thousands of drill holes and wells in the shallower parts of the continental shelves have been completed by oil companies, the results of which, although generally not released in raw form, are published in syntheses on regional geology and stratigraphy and add greatly to total knowledge. This fund of data has helped develop an advanced understanding of the geologic character of the sea bottom and many of the processes that operate within it. Coupled with knowledge of coastal geology and of the geologic occurrence of minerals on land, the information available makes it possible to ascertain most of the kinds of minerals that the seabed may be expected to contain, to identify many of the geologic environments in which they may occur, and to make meaningful generalizations about their potential magnitude. The projections shown on the accompanying maps and the generalizations in the following pages about the distribution and magnitude of subsea resources are not accurate or detailed enough to serve as a guide to exploration or to make quantitative appraisals of the extent and value of resources in specific areas, but they may be useful to those concerned with the broad aspects of the character and distribution of seabed resources and the prospects for their development.

A brief outline of the organization of the maps and this supplemental discussion may be helpful to the reader.

Sheet 1, summarizes at a smaller scale than the other maps the essential features shown on the other sheets of the minerals that have some potential occurrence beyond the continental shelf, namely petroleum, phosphorite, manganese-oxide nodules, and metal-bearing mud. Sheet 1, along with others, also shows the 200-meter and 2500-meter isobaths, which in many places approximate the edge of the continental shelf and the toe of the continental slope, respectively; in the ocean basins, where these physiographic features are absent, the 200- and 2500-meter isobaths help define the configuration of seamounts and ridges.

Sheet 2 shows the distriubution of subsea geologic and physiographic provinces which form the primary basis for identifying areas favorable for various minerals. It also shows the distribution, on land, of crystalline and sedimentary rocks—information that is useful in projecting geologic features offshore and in indicating something of the broad geologic character of the submerged parts of the continents. In addition, Sheet 2 shows the location of subsea underground mines, placer concentrations of heavy minerals and onshore mineral deposits that may be the source of additional offshore placers, areas where construction materials or shell are being mined, and offshore areas where exploration for nonpetroleum minerals is in progress.

Sheet 3 shows offshore petroleum-producing areas, areas where wildcat drilling is in progress, and areas locally favorable for petroleum. It also shows petroleum-producing areas and favorable areas on land—information useful not only in helping to identify favorable areas offshore, but also in visualizing their potential magnitude in the submerged parts of the continents and the possible frequency distribution of petroleum accumulations. For example, although favorable areas are large, it may be seen that even in well-explored regions only small parts of them actually contain producible accumulations.

Sheet 4 shows the distribution of saline minerals and sulfur offshore and on land—again information valuable in projecting their occurrence offshore and in suggesting their possible magnitude on the submerged parts of the continents. Saline minerals are of interest offshore, partly because of the potenial value of the

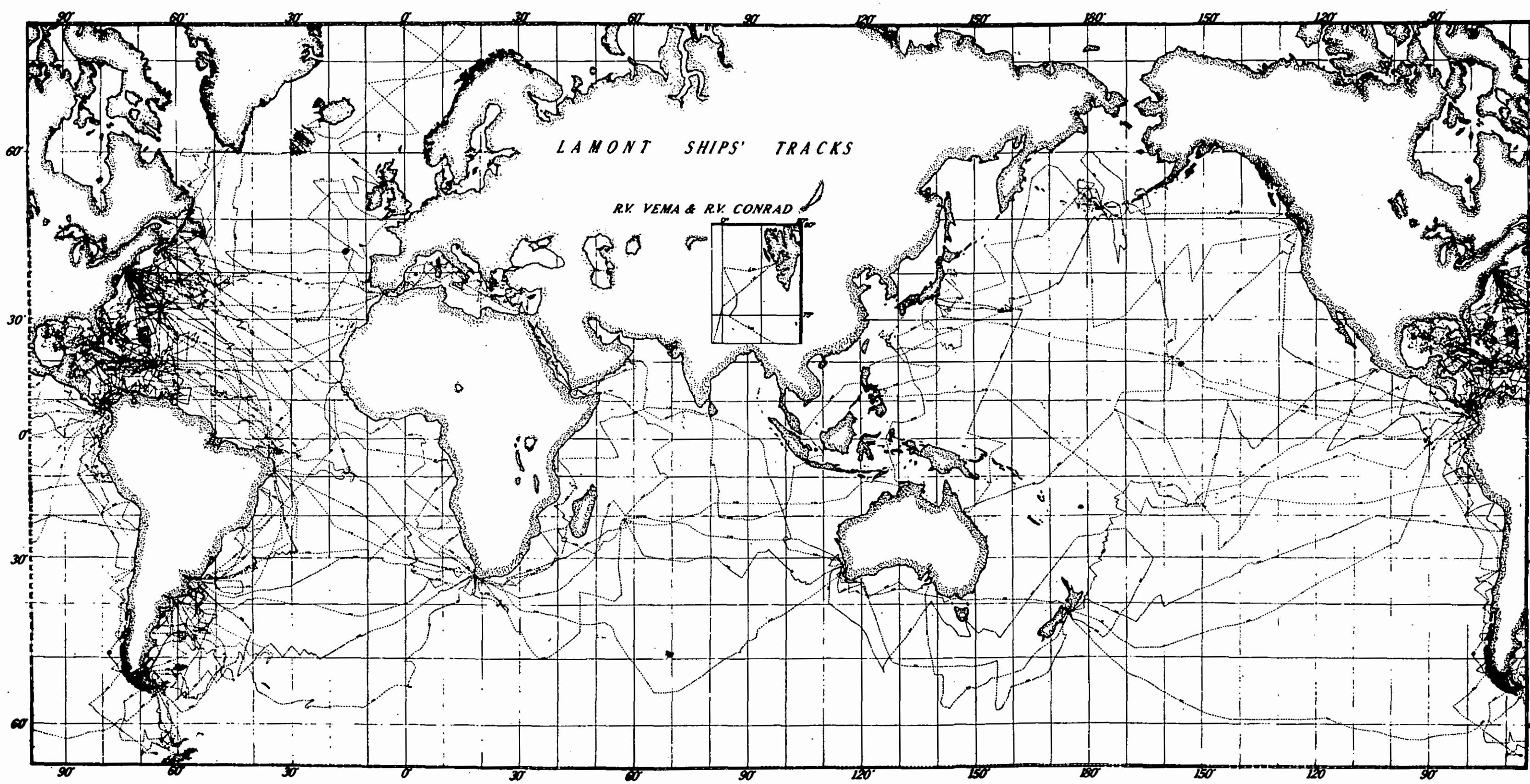


Figure 1. Geophysical surveys made by the Lamont-Doherty Geological Observatory prior to 1967.

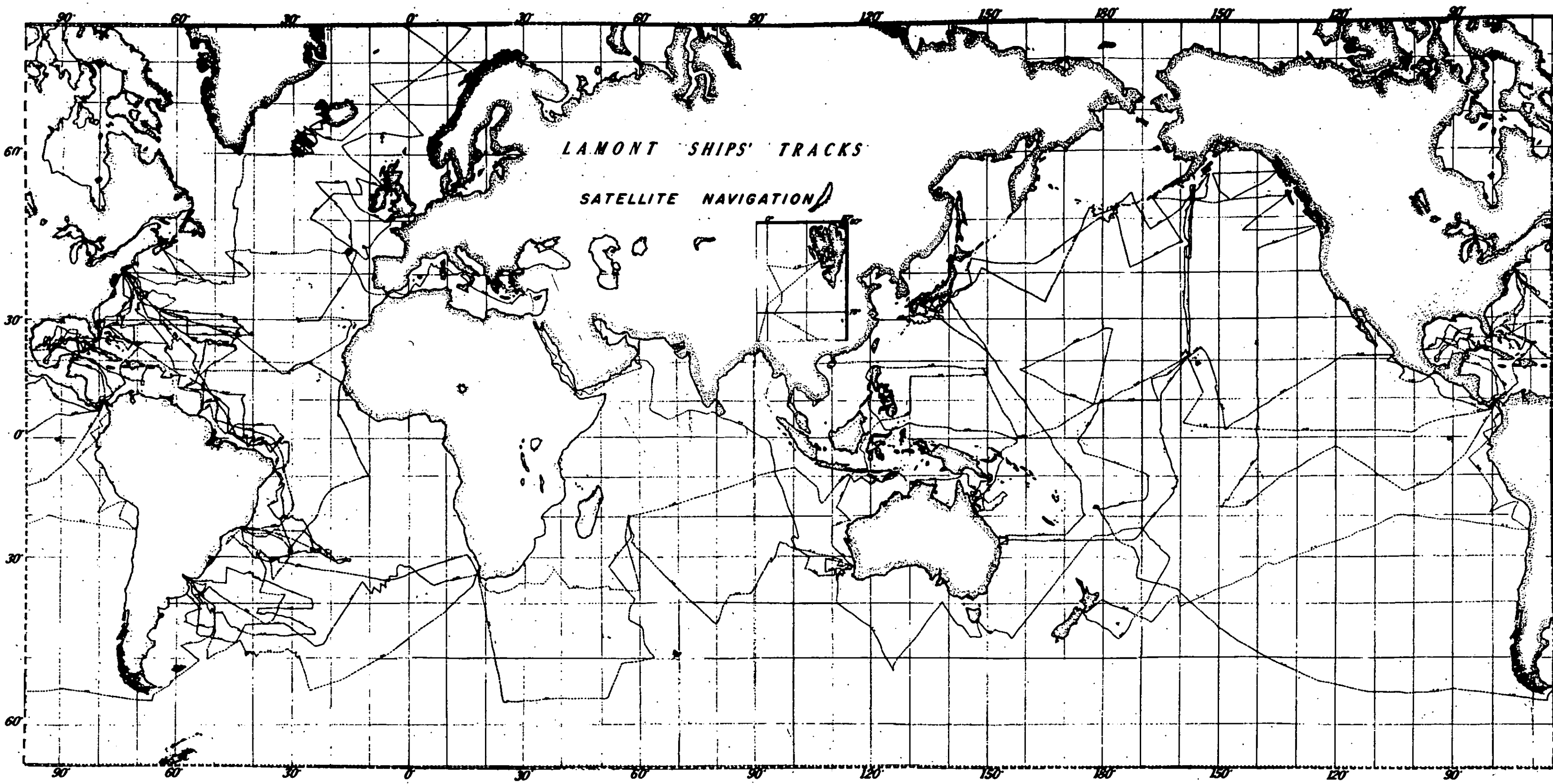


Figure 2. Geophysical surveys made by the Lamont-Doherty Geological Observatory, using satellite navigation, 1965-May 1969.

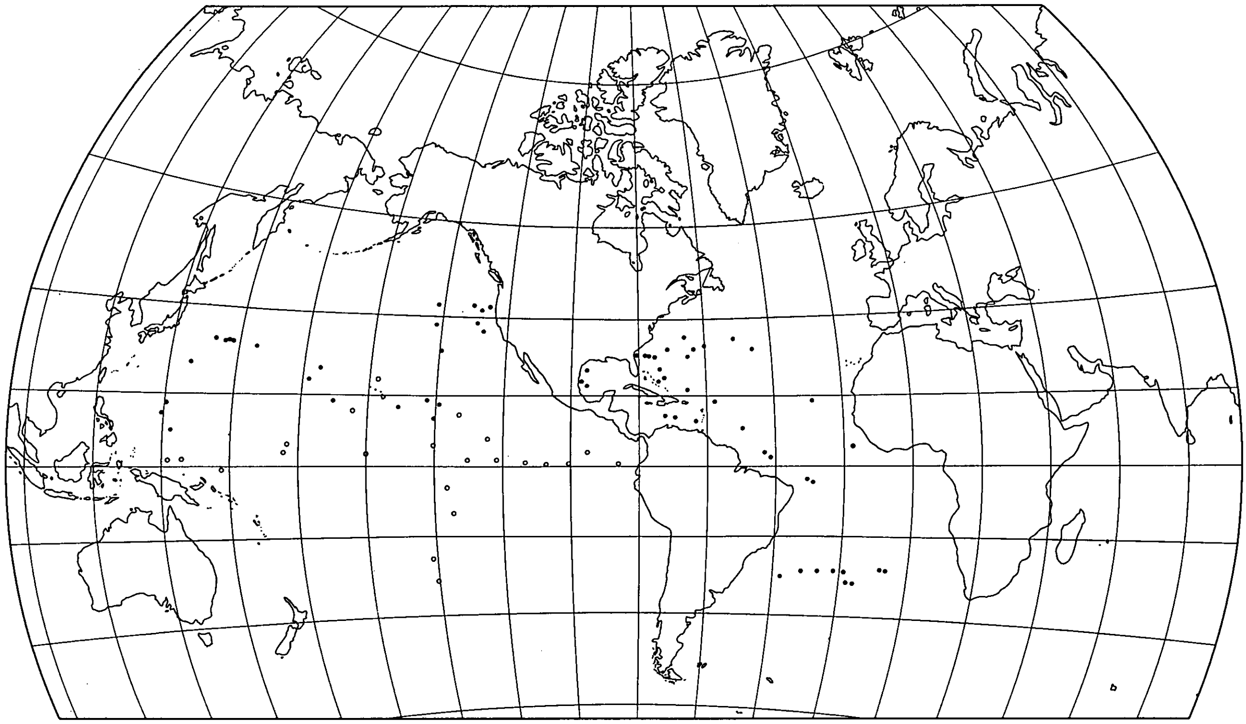


Figure 3. Location of core holes being drilled under the Deep Sea Drilling Project of the JOIDES program sponsored by the National Science Foundation. Those completed by mid-July 1969 shown by solid dot; remainder are scheduled for completion by early 1970.

potash, magnesium, and sulfur deposits sometimes associated with them, but also because salt basins of marine origin are one of the geologic factors that suggest areas favorable for petroleum. This is because salt domes and other salt intrusions provide structures in which petroleum is sometimes entrapped and because salt and anhydrite beds are effective seals that prevent the escape of petroleum in its migration from underlying source beds. Petroleum fields associated with salt domes are generally easier to find and to produce than those in other structural and stratigraphic traps. Sheet 4 also shows offshore areas favorable for phosphorite and the reported location of manganese-oxide nodules and metal-bearing muds. Areas favorable for subsurface deposits of metallic minerals may exist, but are not identified.

To give some perspective to the information shown on the maps, we briefly describe here the main subsea geologic and physiographic provinces and their bearing on potential seabed resources, discuss the classification of mineral resources estimates, and give a rough indication of the magnitude and potential production of seabed resources.

ACKNOWLEDGMENTS

Most of the information shown on the maps has been drawn from published compilations of others, who are identified on the maps and listed in the citations below. In addition, we are much indebted to H. W. Menard and Gustaf Arrenhius, of the Scripps Institution of Oceanography; Maurice Ewing and John Ewing, of the Lamont-Doherty Geologic Observatory; A. A. Meyerhoff of the American Association of Petroleum Geologists; M. J. Cruickshank of the U.S. Bureau of Mines; and C. F. Austin, of the U.S. Naval Weapons Center; all of whom supplied either unpublished data or large-scale versions of maps already published, and to the National Geographic Society, which provided the plates from which the base map was assembled.[1] In addition, we acknowledge the generous cooperation and advice received from the following people who kindly reviewed the maps in draft form: Lewis G. Weeks, petroleum consultant; William J. Ludwig, of the Lamont-Doherty Geologic Observatory; Ralph N. Shaver, of Ocean Science and Engineering, Inc.; Raymond Kaufman and Richard Greenwald, of Deepsea Ventures, Inc.; Hollis Hedberg, of Princeton University; F. C. Kruger, of Stanford University; K. O. Emery, Elazar Uchupi, and David A. Ross, of the Woods Hole Oceanographic Institution; Glen Schweitzer and B. L. Long, of the National Council on Marine Resources and Engineering Development; and C. L. Jones, A. J. Bodenlos, George Moore, Philip Guild, Norman Herz, Stanley Schweinfurth, W. C. Overstreet, John M. Reinemund, Robert J. Hite, J. I. Tracey, Jr., D. M. Kinney, D. E. White, and F. T. Manheim, of the U.S. Geological Survey. None of these people or organizations bear any responsibility, however, for the delineation of favorable areas or for errors in the location of geologic features and known mineral deposits.

[1] The reader may find it convenient to use the 1968 edition of the National Geographic Society's World Map at the same scale as the maps on Sheets 2-4 as a source of much additional geographic information.

GEOLOGIC AND PHYSIOGRAPHIC PROVINCES AND THEIR BEARING ON POTENTIAL SEABED MINERAL RESOURCES[2]

The solid earth's surface consists of two great physiographic divisions, the ocean basins, and the continents that rise to mean heights of 4300 to 5800 meters above the ocean floor. The ocean basins, of course, are filled with sea water—more than filled, in fact, for the ocean extends over the margins of the continental masses for distances ranging from a few to more than 1300 km. The boundary between the continental masses and the ocean basins thus lies beneath the sea, generally at depths ranging from 2000 to 4000 meters.

The physiographic contrast between the continents and the ocean basins reflects fundamental geologic differences between them. The continental crust is richer in silica and the alkalis and poorer in iron and magnesia than the oceanic crust. Although the continental crust averages about 35 km in thickness compared with about 5 km for the oceanic crust, its density is less (fig. 4). The continental and oceanic masses are in flotational equilibrium with the underlying mantle, and the lighter continents rise above the ocean basins, much as does an iceberg in the sea.

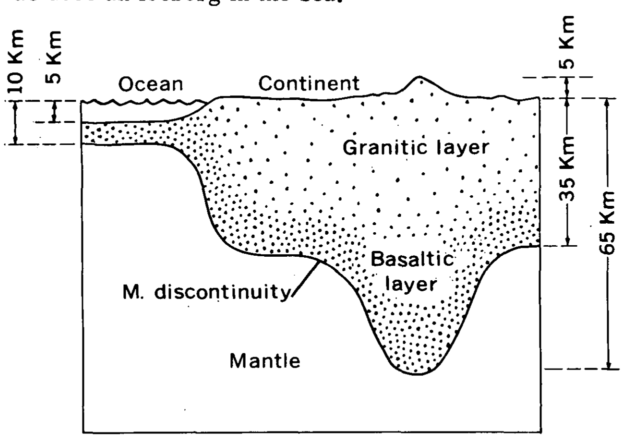


Figure 4. Idealized cross section showing the flotational equilibrium between oceanic and continental crust (Takeuchi and others, 1967).

The igneous rocks of the continental crust consist mainly of granite and related rocks relatively rich in silica and the alkalis, although some basalt and other rocks rich in iron and magnesia are also present. In many areas these granitic rocks intrude, or are overlain by, thick accumulations of sediments deposited in ancient seas that spread over the continents, and in marginal oceanic basins—sediments derived in large part from the weathering and erosion of adjacent land. Oil, gas, sulfur, saline minerals, coal, and other deposits occur in these sedimentary basins. Oceanic crust, in contrast, is largely composed of basalt and related rock; and, except near the continental margin where erosional debris from the land may be present, it is generally overlain by no more than a few hundred meters of sediments.

[2]This section is repeated in part from McKelvey, Stoertz, and Vedder (1969).

Both the continents and the ocean basins display marked variations in their physiography and geology. In broad terms, the continental masses consist of several kinds of geologic provinces: (1) Mountain chains composed of highly folded and faulted sedimentary rocks many thousands of meters in thickness, metamorphic rocks, and intrusive and extrusive igneous rocks. (2) Shield areas, where ancient and generally highly deformed and metamorphosed sedimentary and igneous rocks are exposed in large areas of relatively low relief. (3) Ancient basins and embayments, where hundreds to tens of thousands of meters of sediment accumulated from seas that spread over ancient shields and platforms—now generally areas of low relief underlain by flat-lying or gently dipping sedimentary rock. (4) Coastal plains and continental shelves, the relatively flat or gently dipping surfaces along the continental margin[3] that have been planned off by wave erosion or prograded by deposition of marine sediment. (5) Continental slopes, the surfaces of the continental margin that slope more steeply from the edge of the shelves to the ocean floor. A demarcation between the shelves and slopes does not everywhere exist, and the two are often described together as the continental terrace, or, in areas of irregular topography, as the continental borderland. (See Emery, 1968, for a description of the structural varieties of shelves and slopes.)

The outer limits of the continental margin in many places are concealed beneath the continental rises—gently dipping surfaces underlain by an apron of erosional debris derived from the continent and extending from the slopes onto the adjacent abyssal plains of the ocean basins (fig. 5 and Sheet 2; see also the excellent physiographic diagrams of the Atlantic and Indian Ocean floors published by the National Geographic Society, based on the work of B.C. Heezen and Marie Tharp).

These provinces are the products of various geologic processes—processes which have also resulted in the differentiation of the continental crust into a diverse assemblage of rocks and minerals. Petroleum, coal, sulfur, salt, potash, phosphate rock, limestone, and many other minerals have been concentrated by biologic and sedimentary processes in sedimentary rocks. Copper, lead, zinc, nickel, gold, silver, mercury, fluorspar, beryllium, tungsten, tin, and many other minerals have been concentrated by the igneous and hydrothermal processes that operate within the continental crust. Many minable concentrations of iron, alumina, manganese, gold, tin, and other minerals have been formed as a result of weathering processes.

The physiography of the large ocean basins beyond the continental margin and rise is also varied but is

[3]Continental margin is used here as a geologic term referring to the submerged part of continental crust. It includes the continental shelf and slope, and, in many places part of the continental rise where its apron of debris spreads over and conceals continental crust. The same term is sometimes used as a physiographic term to include the continental shelf, the continental slope, and the continental rise.

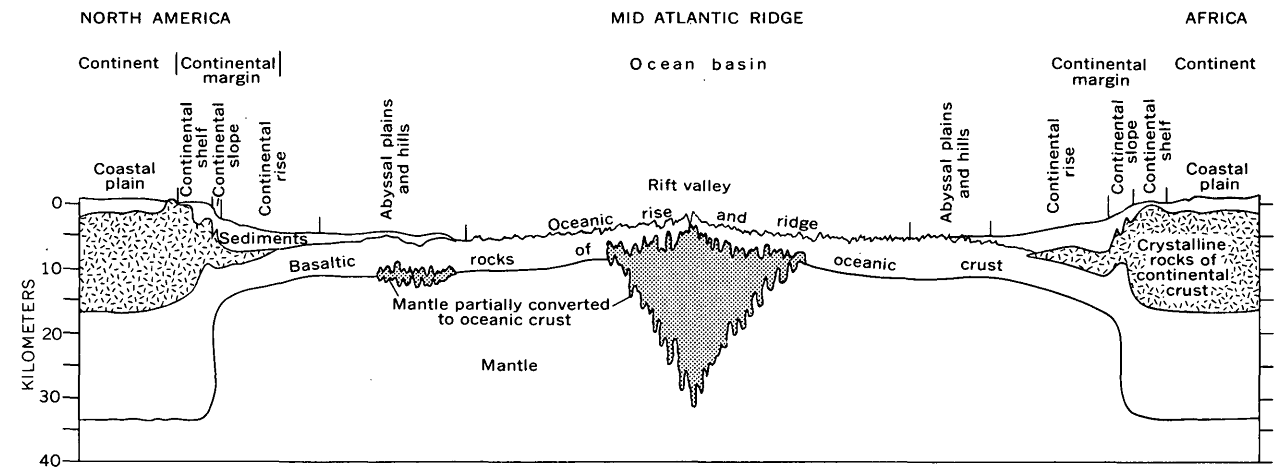


Figure 5. The major physiographic provinces of the ocean basins, illustrated by a trans-Atlantic profile from New England to the Spanish Sahara (modified from Heezen, 1962).

dominated by the following features (see fig. 5, Sheet 2, and the National Geographic Society physiographic diagrams mentioned above): (1) Oceanic ridges and rises, often called "midoceanic" although they do not everywhere occur in midocean. These form a nearly continuous but branching worldwide mountain chain with a total length of about 75,000 miles. A rift valley along the crest is a prominent feature of the ridges in many places, as are volcanoes and volcanic fields, many of which are islands. (2) Abyssal plains and hills, lying on both sides of the oceanic rises and underlain by a thin veneer of pelagic sediments. (3) Individual volcanoes and composite volcanic ridges formed by overlapping volcanoes, and scattered over the ocean basins but often clustered to form groups of islands or seamounts and linear chains along oceanic margins. (4) Trenches, commonly present along volcanic island arcs or young mountain chains at the periphery of the large ocean basins.

In some places small ocean basins lie between two continents or between continents and offshore island arcs. Characteristically, they have an abyssal plain below a depth of 2000 meters, and a few also have trenches along the concave side of the bordering island arcs. Those that border land areas with large surface runoff have trapped erosional debris and hence contain thick accumulations of sediments analogous to those beneath the continental rises.

Many physiographic features of the ocean basins are related to volcanism, crustal subsidence, and possibly to a process of ocean-floor spreading that brings basaltic igneous rock to the surface along the oceanic ridges, and carries new crust away from the mid-oceanic ridge at the rate of a few to 10–15 cm a year. Much is still to be learned about this process, but many now believe that the continents have split apart, along what are now these oceanic ridges, and drifted away from each other, and that the continental mass is still in the process of separation in the Atlantic Ocean, Gulf of California, Red Sea, and African rift-valley system (for a review see Vine, 1969).

In contrast to continental crust, oceanic crust is thin and relatively uniform in composition. Basaltic bedrock lies at or near the surface over much of the oceanic rise and ridge; and, although sediments increase in thickness toward the edge of the ocean basin (reflecting the longer time available for their accumulation on the older parts of the ocean floor), they probably do not attain a thickness of more than a few hundred meters in most places. The basalt originates by partial melting of rocks in the underlying mantle; and while other rocks and minerals are produced in this process, they are not as varied in composition as those that result from the action and interaction of the processes operating on and within the continental crust. Nevertheless, the ocean basins contain large concentrations of manganese, nickel, copper, cobalt, and other metals in manganese-oxide nodules, crusts, and pavements on the surface of the sea bottom; and the ocean basins probably also contain these and other metals, such as zinc, mercury, chromite, and platinum, in other kinds of deposits formed from the differentiation of the mantle material from which the basalt itself was derived.

The areas of the subsea physiographic provinces are summarized in table 1.

Many uncertainties are involved in the identification of these provinces from the sketchy knowledge presently available on the character of the ocean floor. For example, K. O. Emery (1969) independently estimates that the total area of continental rises of the world is about 30 million km^2 compared with the 19 million km^2 estimated by Menard and Smith (1966). Nevertheless, it is clear that most of the seabed is geologically a part of the large ocean basins rather than the continental masses.

In spite of their smaller size compared to the floor of the large ocean basins, the submerged parts of the continents, the continental rises, and the small ocean basins contain the greater part of the potential subsea mineral resources, both in terms of the variety of min-

Table 1.—*Areas of subsea physiographic provinces (after Menard and Smith, 1966)*

PROVINCE	AREA (millions of km^2)	Percent of TOTAL AREA
Continental shelf and slope[1]--	55.4	15.3
Continental rise--------------	19.2	5.3
Abyssal plains and hills------	151.5	41.8
Trenches and associated ridges----------------------	6.1	1.7
Oceanic ridges and rises------	118.6	32.7
Volcanic ridges and cones and other features----------	11.2	3.2
	362.0	100.0
Small ocean basins (included above in continental rise and abyssal plains)---------	7.5	2.1

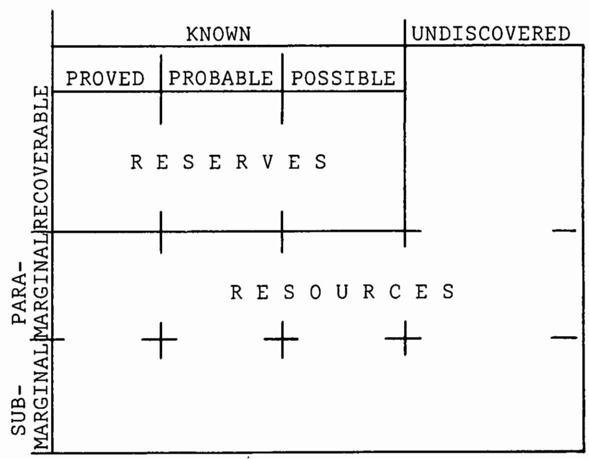
[1]The extent of the physiographic shelf has never been estimated, but is often taken to approximate the area landward of the 200-meter isobath. Menard and Smith estimate this area to be 27.1 million km^2, about half that shown above for the shelf and slope combined.

erals that exist and the value of those that are likely to be recovered within the next few decades. Most important among these minerals is petroleum, the bulk of which likely occurs in the continental terraces and rises and the small ocean basins. Only a relatively small number of other minerals are presently recoverable from the continental shelf, but potentially it contains virtually the same large array of minerals now mined from the land. In contrast, the seabed of the large ocean basins contains a much smaller number of minerals—mainly the metals in the manganese oxide nodules and such related metals as zinc, mercury, gold, platinum, and chromium that may occur in other kinds of deposits. The total amount of these metals in the ocean basins and crust is very likely far larger than in the continents, but much technologic advance will be required to find them and make them economically available.

CLASSIFICATION OF MINERAL RESOURCE ESTIMATES

Although subsea resources of petroleum and several other minerals are potentially large and widely distributed, only a small part are likely to be economically recoverable within the next few decades, and an unpredictable part may never be recoverable. In order to give economic and geologic perspective to estimates of resources, it is desirable to view them in a framework that takes account of the degree of certainty of knowledge about their existence and character, and the feasibility of their recovery and sale. In the classification below (McKelvey, 1968), the degree of certainty of knowledge of the dimensions and quality of mineral deposits is shown on the abscissa, and the feasibility of recovery and marketing is shown on the ordinate. The classification of individual deposits shifts with progress in exploration, advance in technology, or changes in economic conditions. Recoverable reserves are marketable materials that are producible under locally prevailing economic and technologic conditions. Paramarginal resources are prospectively marketable materials that are recoverable at prices as much as 1.5 times those prevailing now or with a comparable advance in technology. Submarginal resources are materials recoverable at prices higher than 1.5 times those prevailing now but that have some forseeable use and prospective value.

Classification of reserves and resources



Seen in this framework, the presently recoverable proved reserves of most minerals are relatively small compared to the resources that may eventually be found by exploration or become recoverable as a result of technologic advances or changes in economic conditions. This is particularly true for subsea resources, because only a small part of the seabed has been explored and most of the resources it contains are not yet economically recoverable.

DISTRIBUTION, MAGNITUDE, AND FUTURE PRODUCTION OF SUBSEA MINERAL RESOURCES

PETROLEUM

Subsea petroleum (oil and gas), produced off shore 25 countries, presently contributes 17 percent of the world's output and makes up nearly 90 percent of the total value of current subsea mineral production. Through the remainder of the present century and probably longer, petroleum will continue to be the principal mineral produced from the seabed. Offshore sources may come to supply 30–35 percent of the world's petroleum production by 1980, and the annual value of subsea petroleum production probably will soon exceed that of all other marine resources combined, including seawater chemicals and fish.

Petroleum resources are largely confined to the continental shelves, continental slopes, continental rises, and the small ocean basins (see Sheets 1, 2, and 3). Because these areas in general contain a greater thickness of marine Tertiary sediments, from which most of the world's petroleum production comes, than do the lands, taken as a whole the shelf and slope areas are more favorable for petroleum than the exposed parts of the continents. Environments favorable for petroleum are highly localized; and as mentioned earlier, only a small part of the broadly favorable areas actually contain producible petroleum accumulations.[4] Among the geologic provinces considered broadly favorable, the incidence of petroleum accumulations in the shelves, slopes, and the small ocean basins may be greater than in the continental rises bordering the large ocean basins (L. G. Weeks, personal commun., 1969). The rises contain great thicknesses of sediments (Emery, 1969), probably including organic-rich source rocks deposited when the proto-ocean basins were narrow and had restricted circulation (Schneider, 1969, and Rona, 1969), but in many places they may not contain suitable reservoir rocks.

Although the geologic provinces named are the only ones that can be identified now as broadly favorable for petroleum, the possibility that it occurs in other parts of the ocean basins cannot be ruled out (Hedberg, 1969). The abyssal plains, for example, are believed to contain insufficient thicknesses of sediments to yield petroleum accumulations, but the basement now identified by seismic reflection probes is, of course, an acoustic basement, and its composition is uncertain. In most places it is probably basaltic crust, but in some places it may prove to be merely a hard layer that conceals thicker sediment below. Parts of the deep trenches may also be favorable for petroleum, as may some of the subsea ridges or plateaus of unknown composition (see Sheet 2) and presently unidentified foundered remnants of continental blocks broken off during the process of continental drifting. The potential in such areas, however, seems likely to be small compared to that of the seabed bordering the continents.

No complete estimates of potential world subsea petroleum resources have been made, but enough is known to be certain that they are large, perhaps even larger than those of the continents. World subsea proved recoverable reserves are 90 billion barrels, and Weeks (1969) estimates that world "offshore petroleum resources" (including proved reserves) beneath a water depth of as much as 1,000 feet (300 m.) amount to 700 billion barrels of petroleum liquids, plus 350 billion barrels recoverable by secondary methods, and the equivalent of 350 billion barrels in natural gas. In the classification shown above, all of this would be presently in the known and undiscovered recoverable and paramarginal categories. The area covered by Week's estimate is 28 million km^2, of which he believes 16.1 million km^2 is the favorable area. The area beyond the 300-meter depth to the toe of the continental rise is 46.6 million km^2. A larger proportion of this area is probably underlain by a thicker accumulation of sediments than in the area covered by Week's estimate, and the total volume of sediments beneath the continental rises and the small ocean basins may be far larger than under the shelves and slopes. (See K. O. Emery, 1969.) Until more is known about the composition and structure of these sediments, it is impossible to judge their potential. Whatever may be their magnitude, potential resources in such areas must be classed as undiscovered submarginal, and they are likely to remain so for a few decades or longer. Known and undiscovered recoverable and paramarginal resources in the continental shelves and slopes, however, are large and probably will supply most of the offshore production during the next few decades.

Areas favorable for the local occurrence of subsea petroleum resources lie adjacent to nearly every coastal nation (Sheets 1 and 3), and in fact, geologic or geophysical exploration is already underway off the coast of more than 75 countries and drilling is in progress off 42 of them. Wide shelves, where petroleum in large accumulations, if they are present, can be recovered economically now, occur off the coasts of Greenland, Norway, the United Kingdom, Canada, Mexico, Trinidad-Tobago, Venezuela, Guyana, Surinam, French Guiana, Brazil, Uruguay, Argentina, Australia, New Zealand, mainland China, Korea, Taiwan China, and the Soviet Union as well as along the Atlantic, Gulf of Mexico, and Alaskan coasts of the United States. The continental rise is especially wide[5] in the

[4] Some of the offshore areas shown as favorable for petroleum on sheet 3 have already been tested by drilling without yielding a discovery. As is customary in outlining favorable areas on small-scale maps such at this, the location of dry holes has not been shown, for one or even several dry holes do not prove the absence of petroleum in the general area in which they have been drilled.

[5] Although the thickness of sediments in continental rises may increase with increasing width, the same is not true for the shelves. Width in itself is not a measure of favorability for either (L. G. Weeks, personal commun.).

Arabian Sea, the Bay of Bengal, off eastern Africa, off most of western Africa, and off much of the eastern coasts of North America and South America. Small ocean basins that have a large petroleum potential include the Gulf of Mexico, the Caribbean Sea, the Mediterranean Sea, the Black Sea, the Caspian Sea, the Bering Sea, the Sea of Okhotsk, the Sea of Japan, the South China Sea, and the seas within the Indonesian Archipelago. Several of these favorable areas reach depths of as much as 5500 meters and extend 1500 km or more from shore. Petroleum occurrence at such depths was shown in August 1968 by the *Glomar Challenger* drilling in the Gulf of Mexico, when one hole encountered a show of oil and gas (and sulfur also) in the Sigsbee Deep beneath a water depth of 3,582 meters (Burk and others, in press).

Not only does the seabed contain a large part of the world's petroleum potential (seabed petroleum resources may exceed those of the lands), but its development in regions where little or none is now produced may change significantly the outlook for petroleum production and supply for individual countries and regions.

Current offshore petroleum production comes from water depths of less than 105 meters and from areas within 120 km of the coast. The technologic limit of offshore petroleum production, however, may be extended to water depths of as much as 6000 feet (1830 m) by 1980, although at much higher costs (National Petroleum Council, 1969). Because of the higher cost of deep-water production and the wide availability of petroleum in shallower parts of the shelves, production from areas beyond the 200-meter isobath is likely to be largely restricted during the next decade to giant fields in the most favorable locations. It probably will not amount to more than 0.5–1.0 billion barrels a year by 1980, but might increase to a few billion barrels a year by the end of the century when deep-water exploitation technology is further advanced.

POTASH AND OTHER SALINE MINERALS

Most of the world's deposits of anhydrite and gypsum (calcium sulfates), common salt, and potash-bearing minerals are formed by evaporation of sea water and other natural brines in basins of restricted circulation. Important deposits of magnesium-bearing salts are also deposited in such basins, and elemental sulfur forms in some of them by biogenic processes involving the alteration of anhydrite. Because rock salt tends to flow at relatively low temperature and pressure, salt in thick beds squeezed by the weight of a few thousand feet or more of younger sediment often pierces or intrudes the younger sediments, forming salt domes, plugs, and other structures. Such masses, which may be a few miles in diameter, may bring salt to or near the surface. They form structures in the intruded sedimentary layers that may be favorable for the accumulation of petroleum, and the limestone cap rock associated with some of these masses may be the site of sulfur deposition. Elemental sulfur in these deposits can be recovered by the Frasch process, in which the sulfur is melted by the injection of hot water into drill holes. Salt, and some potash and magnesium minerals, can also be recovered by solution-mining methods.

Saline deposits formed in ancient marine basins are extensive on the land (Sheet 4). Many deposits extend beneath the sea, not only under the continental shelves but also under some of the small ocean basins. For example, in the Gulf of Mexico the 1968 drilling by the *Glomar Challenger* in the Sigsbee Deep confirmed the previously held belief that the Sigsbee Knolls are salt domes, and showed that these deep structures may contain petroleum and sulfur. Because of the widespread anhydrite, gypsum, and salt on the land, and the ease of obtaining salt by evaporation from sea water in many coastal regions, these minerals are widely available at low cost. Consequently, there is little need to seek them from subsea sources, except perhaps in local areas far removed from other sources. A new and potentially important use of salt deposits in offshore areas, however, may be as underground storage chambers (presumably opened subsea by solution mining through drill holes) for petroleum and radioactive waste (Halbouty, 1967; Pendery, 1969).

No attempt has been made to estimate potential subsea resources of salt and anhydrite, but assuredly they amount to at least tens of trillions of tons.

Potash deposits in the salt basins are not as widespread as salt and gypsum, but individual deposits are large—generally in the range of hundreds of millions or billions of tons. World supplies from land sources are presently abundant, but because potash is a relatively valuable mineral, there are opportunities for the development of strategically located subsea deposits, particularly those amenable to solution mining or to underground mining from a land entry. The feasibility of producing potash from deposits beneath the North Sea is now being investigated, and deposits suitable for mining may exist in salt basins in other coastal regions. Potential world resources in subsea deposits are probably in the range of tens of billions of tons of K_2O, some of which may be economically recoverable.

Thick beds of a magnesium salt—tachhydrite ($CaCl_2 \cdot MgCl_2 \cdot 12H_2O$)—previously known only in trace amounts, have recently been found associated with potash in the Sergipe salt basin along the eastern coast of Brazil and in the Congo basin along the southwestern of Africa. Tachhydrite is highly soluble, forms a concentrated brine, and probably can be mined by solution methods (R. J. Hite, personal commun.). Because magnesium is now recovered economically from seawater and other natural brines, presently recoverable reserves are enormous. Even so, if it can be produced more cheaply from tachhydrite, these and other favorably situated deposits may prove to be valuable.

SULFUR

Nearly 60 percent of the world's production of sulfur comes from Frasch-type deposits associated with anhydrite, either in bedded deposits or salt domes. Subsea production, however, is presently limited to two salt-dome deposits off shore Louisiana (Sheet 4), which yield about 20 percent of United States production. Growth in demand for sulfur has exceeded supply in recent years, and while new discoveries are helping to ease world shortages, new sources are needed. In part, these may be met by development of new processes—already in an advanced state—for the recovery of sulfur from gypsum on land, and for the distant future these and other land sources—including by-product sulfur from sour natural gas, from asphalt-base petroleum, and from stack gases of various kinds—are likely to supply the bulk of world needs. During the next decade or so, however, subsea sulfur may become an important factor in world production.

Individual sulfur deposits tend to be much smaller than those of the saline minerals, generally in the range of a few millions to a few tens of millions of tons. Known recoverable reserves offshore the United States amount to about 37 million tons, and a similar magnitude may exist in undiscovered but recoverable deposits. Potential world resources of subsea sulfur have not been estimated, but are likely to amount to scores of millions of tons or more, much of which might be recoverable under present economic conditions. Not enough is known about the origin of sulfur to focus exploration on the most favorable environments within the salt dome and anhydrite basins, but the numerous offshore occurrences, some of which may be more extensive than shown on Sheet 4, are certain to contain many recoverable deposits that are as yet undiscovered.

HEAVY MINERAL CONCENTRATES, COAL, AND OTHER SUBSEA MINERALS CURRENTLY MINED BY DREDGING OR UNDERGROUND METHODS

The production potential for heavy-mineral concentrates (placers), sand, gravel, shell, and lime mud, currently mined by dredging and for coal, iron ore, copper, limestone, and other minerals currently mined underground from a land or artificial-island entry is limited to the shallow nearshore parts of the continental shelves (Sheet 2). Because favorable areas for the subsea occurrence of these minerals are difficult to outline in a meaningful way, only the location of known or producing coastal or offshore deposits is shown on Sheet 2. For the placers, however, these occurrences are in themselves among the best clues to the general location of favorable areas offshore (Emery and Noakes, 1968; McKelvey and Chase, 1966; both papers also discuss geologic guides that may be helpful in selecting favorable areas). For some of the deposits mined underground, the location of existing subsea mines is also one of the best indications of the general areas in which other deposits are likely to be found and mined within the next decade or so. One reason for this is that subsea prospecting methods for most bedrock minerals are as yet so inefficient that coastal occurrences, together with coastal geology, are the best clues to offshore prospects. Another is that existing subsea mines of some minerals—coal, for example—identify regions in which subsea underground mining may be economically viable.

Although the value of the annual world production of the minerals now mined by dredging or underground methods totals more than $500 million, it represents less than 2 percent of the onshore production of these minerals. World subsea reserves and resources of these minerals have not been estimated, but as with petroleum, known recoverable reserves are probably small compared to undiscovered paramarginal and submarginal resources. Even though their potential may be large, however, it is not likely to be nearly as large as that of onshore deposits. During the next few decades the economic development of these minerals probably will be almost entirely limited to shallow water (less than 100 m deep) for the deposits in sea-floor sediments minable by dredging, and to nearshore areas (less than 50 km from land entry) for large bedrock deposits mined by underground methods. Eventually, technologic advance may make possible seafloor entry from a vertical shaft (Austin, 1967) or may permit solution mining of certain metals through drill holes. For both economic and technologic reasons, however, it appears probable that during the next few decades land sources will be preferred for most of these minerals in many areas. Exceptions may be offshore deposits that (1) are extremely large, (2) are of high grade and easy access (such as tin deposits off the coasts of Thailand, Indonesia, and Malaysia), (3) contain minerals in short supply (such as gold and platinum), (4) are desired by individual countries to reduce balance-of-payments dificits or to provide for security of mineral supply, or (5) are in local demand because of the high cost of transport from distant sources or the need to conserve land resources and preserve land environment. Sand and gravel, shell, and coal in some places are examples of minerals in the last category. The growing demand in coastal cities for sand and gravel especially is likely to stimulate offshore production in many areas.

PHOSPHORITE

Phosphorite is widely distributed on the continental shelves and upper slopes in areas of upwelling currents at low latitudes (Sheets 1 and 4). Other than the record of their occurrence and perhaps their composition, published information about them is scant. It is sufficient, however, to say that they are abundant in some areas such as off the coast of Baja California, southern California, and east of New Zealand, but that in many places consist of scattered nodules too sparsely distributed to be recoverable. Their phosphate content varies considerably also, but is seldom more than 29 percent P_2O_5—a few percent lower than the present commercial cutoff grade. No offshore deposits are being mined now because of the availability of lower cost and higher quality deposits on land. Land deposits are large enough to meet world demands for many decades; even so, subsea production may prove to be economic in local areas far removed from land deposits, particularly for developing countries having difficulty in making foreign payments.

World subsea resources are probably at least of the order of hundreds of billions of tons. Possibly a few billion tons may be classed as paramarginal now, with some prospects of becoming recoverable within a decade, but the bulk of subsea phosphorite resources must be classed as submarginal.

MANGANESE-OXIDE NODULES

Surficial deposits of manganese-oxide nodules, crusts, and pavements, which are currently of more interest for their content of nickel, copper, and cobalt than for manganese, are largely confined to the deep ocean floor, generally at depths of 3500 to 4500 meters, and to the seamounts within it. In several areas, however, they occur near land—notably on the Blake Plateau off eastern United States, off the west coast of Baja California, near some of the islands in large ocean basins as well as scattered occurrences in several inland seas such as the Baltic (Sheets 1 and 4). In most of these nearshore areas, however, their metal content is much lower than that of the nodules far from land. Although bottom photographs and closely spaced samples show that nodules are extensive in many areas, the same kinds of data show that both their abundance and composition vary. Available information is not sufficient to infer their continuity between stations from which they have been reported or their absence in areas where they have not yet been found. Cores show that they are present in the sediments a few meters beneath the surface at some stations—not shown on Sheet 4—where they are not present at the surface. Inspection of the results of available bottom photographs in the Pacific (Sheet 4), however, suggests that nodules are absent from the surface of the bottom in some large areas and that they are particularly abundant in others. In a broad way this distribution tends to confirm the pattern shown in figure 6, compiled by Skornyakova and Andrushchenko. Even if subsequent exploration shows that the nodules and related deposits are continuous over large areas, their minability may be adversely affected locally by irregularity of the bottom surface, presence of extensive crusts or pavements troublesome to break and lift, and deleterious impurities.

The composition of the nodules also varies greatly. Again there appear to be regional variations, but published attempts to define the pattern of variation have not been satisfactory. The averages below are indicative of the range in metal content over large areas, but should not be taken as characteristic of the composition of the nodules in the entire region from which the component samples were collected (fig. 7). The content of each of the metals may be much higher in individual samples. Manganese is nearly 50 percent in some samples, which are generally low in the other metals. Copper and nickel tend to vary in rough proportion to each other and may be as much as 2 percent; cobalt also may be as much as 2 percent. Whether or not minable quantities contain such concentrations remains to be demonstrated.

The nodules constitute a huge resource. Mero (1967) estimates that they aggregate 1.7 trillion tons and contain 400 billion tons of manganese, 16.4 billion tons of nickel, 8.8 billion tons of copper, and 9.8 billion tons of cobalt. Zenkevich and Skornyakova (1961, quoted by Mero, 1965, p. 175) place a much lower figure on the total tonnage of the nodules—90 billion tons. Whatever the aggregate tonnage proves to be, the amount in deposits of suitable quality, abundance, and environmental setting to warrant dredging is likely to be much smaller.

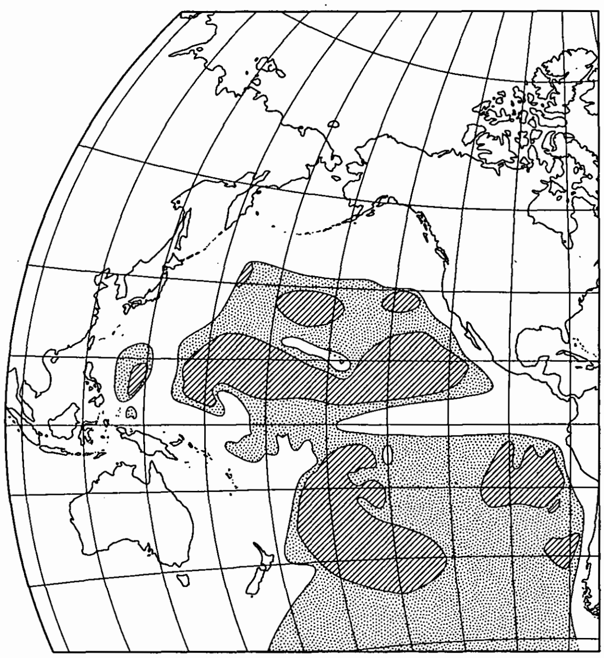


Figure 6. Generalized regional variations in abundance of manganese-oxide nodules on the surface of the sea floor in the Pacific (Skormyakova and Andrushchenko, in Strakov and others, 1968, p. 128). Nodules are absent or sparse in blank areas and where present may be small or consist of films or coatings of oxides on other materials. They may cover as much as 20 percent of the bottom in stippled areas, and 20 to 50 percent of the bottom or more in ruled areas. Although the outlines of these provinces are generally consistent with the available data, bottom photographs and samples are not sufficient to infer continuity or absence of nodules in any given area.

The production of manganese oxide nodules is not economically feasible now, partly because of the high cost of dredging from such great depths and partly because suitable refining methods have yet to be demonstrated. The availability of large and relatively low-cost sources of the component metals on land—adequate at least for several decades—is another obstacle to their development. Added to these constraints are uncertainties about which of the metals could be recovered and sold, and hence bear some part of the cost of the overall operation. The metals are not present in the nodules in the same ratio in which they are used. Thus, the ratio of copper, nickel, and cobalt in present use is 266:27.5:1, whereas in

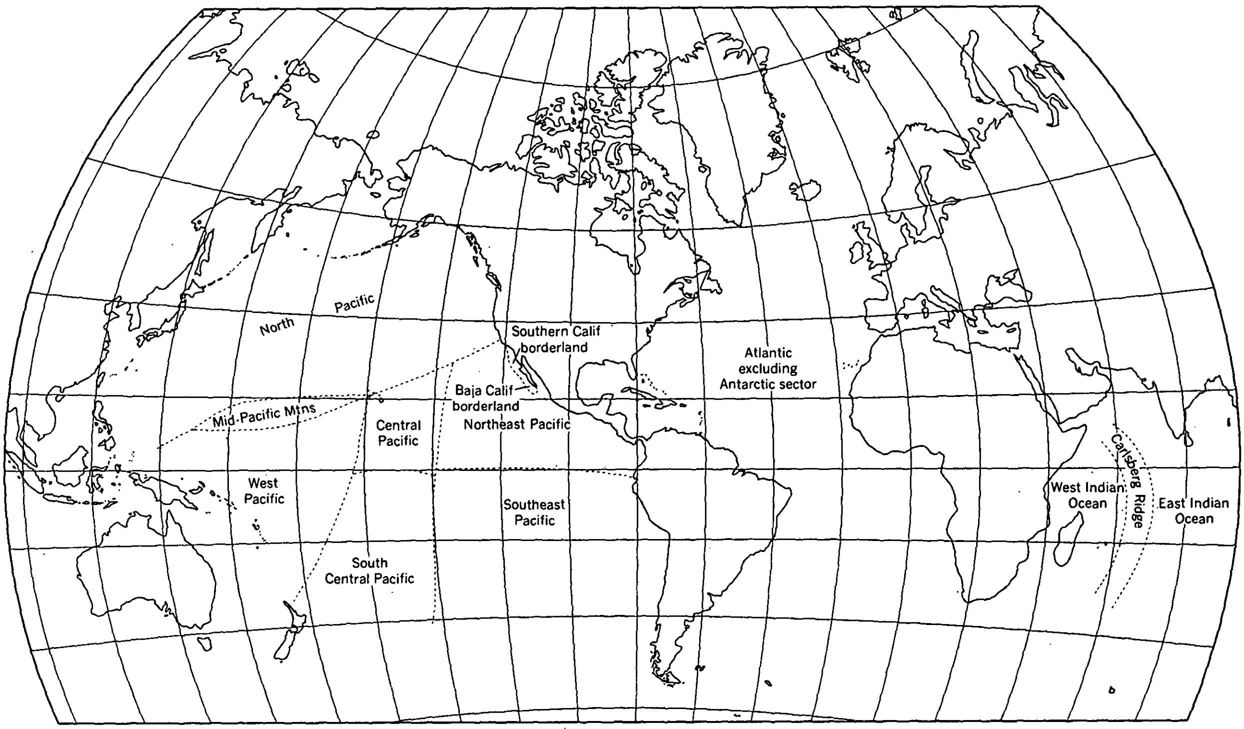


Figure 7. Regions from which analyses of manganese-oxide nodules shown by the averages in table 2 were collected. Analyzed samples are insufficient to define the pattern of regional variation of the metal content.

Table 2.—*Average metal content of surface manganese oxide nodules from different regions (after Cronan, 1967, in the Pacific and Indian Oceans, and Manheim, 1965, in the Atlantic)*

	1	2	3	4	5	6	7	8	9	10	11	12	13
Mn--------	34.0	14.9	22.4	18.4	15.9	16.4	16.1	14.0	12.6	13.7	15.8	15.1	13.5
Fe--------	1.6	12.7	8.9	10.9	9.6	14.1	13.5	13.1	12.1	15.9	11.3	17.7	15.5
Ni--------	.1	.4	1.1	.9	.9	.4	.5	.4	.5	.3	.5	.3	.3
Co--------	<.1	.5	.2	.2	.2	.6	.4	1.1	.2	.3	.1	.5	.2
Cu--------	.1	.1	.7	.3	.6	.2	.4	.1	.3	.1	.3	.1	.2
Depth (m)-	3535	1131	4553	4141	5025	3551	5024	1756	5142	3722	5046	3240	

1) Southern California borderland (3 samples).
2) Baja California borderland-seamount (6 samples).
3) Northeast Pacific (10 samples).
4) Southeast Pacific (11 samples).
5) Central Pacific (12 samples).
6) South Central Pacific (12 samples).
7) West Pacific (30 samples).
8) Mid-Pacific Mountains (5 samples).
9) North Pacific (5 samples).
10) West Indian Ocean (13 samples).
11) East Indian Ocean (14 samples).
12) Carlsberg Ridge (10 samples).
13) Atlantic Ocean (excluding Antarctic sector).

nodules of average composition it is about 3:4:1. Hence, in an operation designed to produce large quantities of copper, for example, it might not be possible to sell all the nickel and cobalt contained in the nodules mined. Similarly, if the costs of refining one or more of the metals prove too high—and manganese itself appears to pose such a problem—the value of the recoverable coproducts would be reduced proportionately. The significance of these uncertainties in evaluating the prospects for exploration of the nodules may be seen in the range of value of potentially saleable products from nodules of average composition at present prices—$6.75 per ton of nodules if only copper is recoverable and saleable to $137 per ton if all four metals are viable coproducts.[6] The variation

[6] This does not represent the range in value to the producer, of course, for refining and other costs attach to each metal produced. But each additional coproduct that can be recovered profitably helps to defray basic costs such as exploration, dredging, transportation, and crushing.

in the composition of the nodules from place to place may make it possible to select deposits that give optimum yield under a given method of treatment—if only copper is recoverable nodules with 1.5 percent copper will be the target, and so on. Although the nodules must be classed as submarginal for the present, Deepsea Ventures, Inc. (Flipse, 1969)— a company which is actively pursuing both exploration and research on mining and process development and plans to begin a pilot mining operation in 1970—believes that the nodules in some environments will be paramarginal by 1970 and economically recoverable within a few years.

If sufficiently low cost production and refining methods are developed to permit nodule mining, subsea production could conceivably satisfy a large part of the world's needs for each of the component metals. Production of nodules would be a gathering operation with no permanent installation at the mining site. Although the operation would sweep a large area compared to mining operations on land, the area involved would be only a tiny fraction of the ocean floor. For example, an operation designed to supply the world's nickel requirements in the year 2000—say 1.7 million tons a year—from nodules of average nickel content (1.0 percent) and with an average concentration on the sea floor (31,000 tons per mi^2, according to Mero), would need to sweep about 11,000 mi^2 (28,500 km^2) a year if only 50 percent of the nodules were recovered. Taking an output of 20,000 tons per day as the kind of unit operation that would be involved (Ensign, 1968), 23 mining units would be required, each sweeping 470 mi^2 (1200 km^2) per year. Of the 281 million km^2 that makes up the ocean floor beyond the continental rise, the area being mined would be trival, and the producers might be widely separated and relatively few in number. If technology and other factors impose special requirements on the composition of the nodules and other characteristics of the deposit or mine site, however, the few areas selected for mining initially may have to be chosen from a relatively small range of possibilities.

OTHER METALLIFEROUS DEPOSITS

Mud rich in copper and zinc was first reported by a Woods Hole expedition in 1965, in the deeps of the Red Sea (Miller and others, 1966); iron and manganese precipitates have been reported from the submarine Banu Wuhu Volcano, Indonesia (Zelenov, 1964); and sediments containing as much as 5 percent Mn and 0.1 percent Cu have been found in the rift zone of the East Pacific Rise (Bostrom and Peterson, 1966). There is reason to believe that deposits of these and other metals may occur in similar surficial deposits or in relatively shallow bedrock deposits associated with rift or fracture zones in other parts of the deep ocean basins. Thus, it is becoming evident that oceanic basalt has formed from the magmatic differentiation of rocks of the underlying mantle. Such differentiation processes may be expected to yield other rocks (some of which have already been found in fracture zones) and metals. Abetting this process of concentrating metals by magmatic differentiation or acting essentially independently of it very likely is another—namely, the leaching of metals from the bedrock of the ocean floor by heated circulating sea-water brine (D. E. White, personal commun., 1969). The known occurrences of metal-bearing mud are all in regions of high heat flow—which appears to be characteristic of the rift and fracture zones in general. Where fractures in the bedrock permit sea water to enter the crust, such high heat flow is likely to set up a convection system, drawing cold sea\water into the crust and heating it. The higher temperature of the water increases its capacity to dissolve metals, as shown by the high metal content of the hot brines of the Red Sea and Salton Sea. As this enriched brine is returned to the bottom surface, metals in solution might be precipitated along fractures in the bedrock or at the surface of the sea bottom. The process of forming localized and concentrated metalliferous deposits would be more effective where the fracture systems intersect salt deposits. This apparently occurs in the Red Sea where the circulating brines become concentrated and heavy enough to pond in depressions on the bottom surface. Without the formation and ponding of such heavy brine, metals brought to the surface would more likely be dispersed and perhaps be deposited elsewhere in the form of manganese-oxide nodules or much lower grade deposits.

Although a substantial part of the metals released from the oceanic curst by these processes may now be in the surficial deposits, minable concentrations of some of these metals are also known to be associated with oceanic crust on land where it has been uplifted by tectonic processes, such as in Cyprus, the Philippine Islands, and New Guinea (see, for example, H. L. Davis, 1968). Similar deposits very likely exist beneath the deep ocean floor.

The assemblage of metals in surficial muds or bedrock deposits probably is qualitatively similar to that in the nodules, but individual deposits might contain only one or two metals, and their concentration in many deposits might be higher. Their recovery from muds or other surficial deposits might prove to be easier than from the nodules, but the technology for mining bedrock deposits at abyssal depths is not in sight and may not be available for many decades or longer. The availability now of these metals in low-cost deposits on land and the prospects for their availability later in nodules and muds gives little incentive to develop technology for mining bedrock deposits beneath the deep ocean floor.

On the basis of sparse data, Bischoff and Manheim (1969) have estimated that the upper 10m of mud in the Atlantis II deep contains 2.9 million tons of zinc, 1.1 million tons of copper, and much smaller amounts of other metals. In the aggregate, metals in undiscovered surficial deposits elsewhere might amount to billions of tons, and those in bedrock deposits might be far larger. Some of the metal-bearing muds may prove to be minable within a decade or so, but the bedrock deposits are submarginal and may remain so for many decades or longer.

FRESH GROUND WATER AND GEOTHERMAL ENERGY

The potential distribution of subsea ground water and geothermal energy has not been shown on the accompanying maps, but a few observations are appropriate here.

Fresh ground water occurs in some aquifers beneath the continental shelf—off the southeast coast of United States, for example (Manheim and Horn, 1968)—and might be produced for local use in some areas. Most such aquifers probably lie landward of the 200-meter isobath.

Large potential resources of geothermal energy in the form of hot water and steam may be present in areas such as the Gulf of Mexico (Jones, 1967) where there are thick geosynclinal accumulations of geologically young sediments, in the zones of high-heat flow associated with the rift and fracture zones mentioned above, and in areas of present or recent volcanic activity. Geothermal energy associated with rift zones and volcanic activity has little prospective value in areas far from land because of the difficulty of utilizing it. In coastal regions, however, geothermal energy has a potential use in the generation of electric power, in the desalination of water (the superheated brines beneath the Gulf Coast are self-flashing), in solution mining of sulfur and potash, and in the secondary recovery of petroleum. Of these potential uses, the last may be the most significant in offshore production. The potential magnitude and value of geothermal energy in such use cannot be appraised now, but whatever resources are present are likely to lie within (but be smaller than) the areas shown on Sheet 2 as favorable locally for petroleum.

SUMMARY

Subsea petroleum (oil and gas), produced from the seabed offshore 25 countries, makes up nearly 90 percent of the total value of current subsea mineral production; and through the remainder of the present century and probably longer, it will continue to be the principal mineral produced from the seabed. Subsea sources already contribute 17 percent of the world's output of petroleum and may supply 30-35 percent of it by 1980. The areas favorable for petroleum are mainly the continental shelves and slopes, the small ocean basins, and the continental rises. Potential subsea resources of petroleum in these geologic provinces are as large and perhaps larger than those of the continents. Areas favorable for its occurrence lie adjacent to nearly every coastal nation. Development of petroleum in areas where it is not now produced could change significantly the outlook for petroleum production and supply for many countries and regions. All the petroleum now produced offshore comes from water depths of less than 105 meters, but the technologic limits for subsea production may be extended, at much higher cost, to about 1800 meters by 1980. Because of the higher cost of deep-water production and the wide availability of petroleum in the shallower parts of the shelves, the bulk of future production probably will continue to come from shallow-water areas, but production from beyond the 200-meter isobath might reach 0.5-1.0 billion barrels a year by 1980 and perhaps a few billion barrels by the end of the century.

Subsea production of other minerals from the continental shelves now includes heavy-mineral concentrates (placers), sand, gravel, shell, and lime mud mined by dredging in shallow water near shore; coal, iron, copper, limestone and a few other minerals mined underground from a land or artificial-island entry; and sulfur and salt mined through drill holes. Phosphorite (minable by dredging) and potash, magnesium, fresh ground water, and geothermal energy (recoverable through drill holes) are other minerals that may be brought into production from the continental shelves in the future. Potential resources of these minerals are large, but because of the availability of lower cost land sources for most of them, subsea production is likely to furnish only a small part of their world output. Nevertheless, offshore production of them may have an important impact on local and regional economies, and for a few (such as tin) it may supply a substantial part of world requirements.

The manganese-oxide nodules and other metalliferous deposits that occur on and beneath the deep ocean floor are an enormous potential source of manganese, copper, nickel, cobalt, zinc, and other metals. Production of the nodules is not economically feasible now because of the high cost of mining and refining the nodules and the availability of large lower cost land sources. One company actively engaged in exploration and research, however, believes that the nodules in some environments may become economically recoverable within a few years. If they can be brought into profitable production in competition with the large and low-cost land sources, they could conceivably come to satisfy a large part of the world's needs for the component metals. If production does take place it will be a gathering operation with no permanent installation at the mine site. The area being mined at a given time would only be a tiny fraction of the ocean floor; and inasmuch as the demand for these metals is limited, the operators might be few in number and widely separated.

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