Overview: Marine Mineral Reserves and Resources—1988

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Abstract   Marine mining has been conducted on local and generally small scales for thousands of years. Large-scale recovery from beaches and piers began only about 40 years ago, and soon afterward powered ships and tools and new exploration methods revealed the presence of economic concentrations of oil and gas, sand and gravel, and some heavy minerals beyond the beach. These materials are in relatively shallow waters of the continental shelf and now are known well enough to be considered reserve ores. Rapid success for them led to immediate expectation of marine mining of many other minerals that have higher value per unit weight, but they occur in deeper waters beyond the shelf where conditions are more difficult and costs are higher. They include phosphorite, ferromanganese nodules and crusts, and (less than a decade ago) polymetallic sulfides. All are still potential resources that cannot yet be considered reserve ores.

Increased knowledge of the deep ocean floor and its natural processes is likely to be applied first to expanding the reserves of similar deposits now on land and perhaps later to ocean floor mining. Moreover, ocean floor mining must compete economically with improved methods of recovery from existing low-grade resources on land and from waste piles left from earlier and less efficient methods of mineral recovery.

Introduction

There is a little confusion about what is meant by marine mining, marine mineral reserves, and marine mineral resources. Under the broadest definition, marine mining means the recovery of minerals or rocks that are under or just near the water. A stricter definition, and one that we follow here, is that marine mining is the recovery of minerals and rocks from some kind of platform that is at the ocean surface or below it. This definition excludes dry-shod mining of beach sands above low tide or of minerals in these sands, dragline mining from the beach, mining from shafts dug on land with drifts extended beneath the ocean floor, drilling from shore by whipstocked wells or wells on piers built from shore, and concentration of elements dissolved in ocean water. It may include mining from floors of large estuaries, lagoons, and lakes under reasonable circumstances. Reserves include only identified deposits that can be mined now at a profit (*socialist: net economic surplus*); resources are undiscovered and presently subeconomic deposits with potential for economic recovery under foreseeable future conditions (Figure 1).

Mining on land (copper and flint for tools and weapons, and gold and gems for ornaments) has been conducted for at least 6,000 years (the beginning of the Chalcolithic Age that continued into the Early Bronze Age). The legendary *Voyage of the Argonauts* perhaps 3,200 years ago allowed Jason and his heroes to gain the Golden Fleece, probably

TOTAL RESOURCES

	Identified			Undiscovered		
	Demonstrated		Inferred	Hypothetical (in known districts)	Speculative (in undiscovered districts)	
	Measured	Indicated				
Economic	Reserves				+	
Subeconomic — Paramarginal	Resources				+	
Subeconomic — Submarginal	+	+	+		+	

(right axis: Increasing degree of economic feasibility of recovery)

Other occurrences	Includes nonconventional and low-grade materials

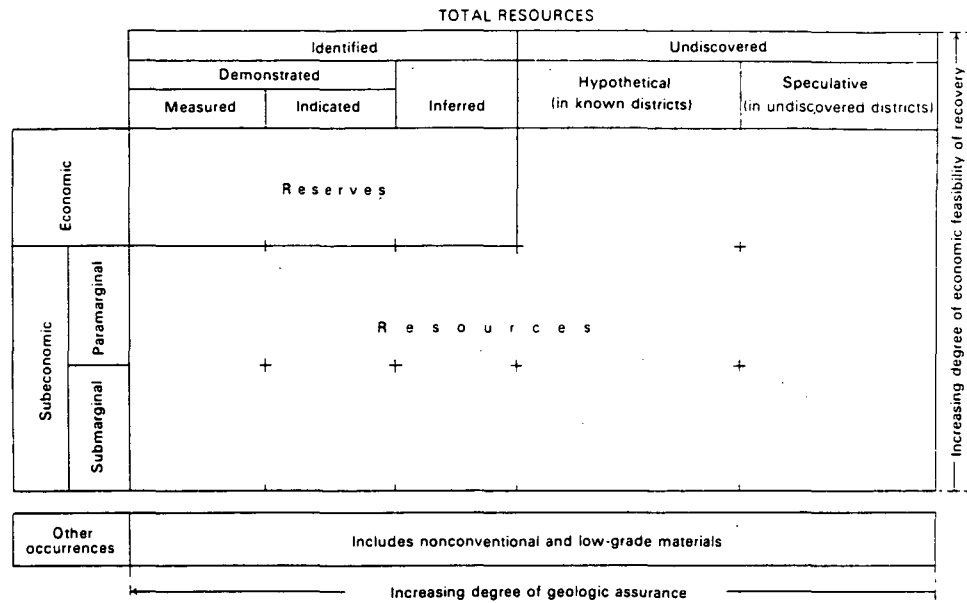Increasing degree of geologic assurance

Figure 1. Classification of mineral resources and reserves according to U.S. Geological Survey and U.S. Bureau of Mines (McKelvey 1986, fig. 2).

the theft of gold from fleece-lined sluice boxes at the northern coast of present Turkey. Limitations for mining on land are grade and accessibility of the ore body, distance from users, and conflicts between miners and local inhabitants over customs, land rights, taxes, and politics. Mining from the ocean floor also began long ago. Possibly oldest is "mining" of pearls (for ornaments) as extensions of harvesting mollusks for food. Shallow parts of the Indian Ocean, Red Sea, and Persian Gulf were famous for their pearls 6,000 years ago, and the *Ramayana* of India (written 2,300 years ago) comments on the training of pearl divers. Also ancient is the collection of amber washed by storm waves onto beaches of the southern Baltic Sea and used for ornaments and trade; it has been found with copper and shells at many archaeological sites in Europe and the Middle East. Subseabed mining from shafts on land for lead and zinc occurred more than 2,000 years ago at Laurium in Greece, and for tin and copper at Cornwall. Factors that limit strict marine mining are the same as those for land mining plus weather, sea state, and depth (pressure) of overlying waters.

Under our strict definition very few materials are mined from the ocean floor and can be considered reserves. The costs of mining, enriching, transporting, and selling must be balanced against prices obtainable. For example, the tonnage of gold dissolved in ocean water may be about 80 times what has been mined during all of human history, but the dissolved gold cannot be considered an ore, a marine mineral reserve, or even a resource because the cost of recovery far exceeds its value. This viewpoint makes explicit the economic, as well as the geologic, nature of mineral resources. As technology and economic conditions change, so do the deposits that can be considered resources. Over time, new resources are created through a combination of increased attractiveness of previously uneconomic sources, new discoveries, and increased accessibility through technological advances. Whereas growing consumption of conventional resources on land signals greater promise for marine minerals, it also triggers economic mechanisms that

expand resources on land (through price effects and new discoveries), while moderating consumption (through higher costs, conservation, recycling, and substitution).

In the light of cost/price considerations, we classify ocean floor materials either as ore reserves (that now are being mined at a profit), as resources (or possible future reserves that may become profitable if costs can be decreased or if prices should be increased), or as mineral curiosities (occurrences that are unlikely to be mined at a profit in the foreseeable future). This classification leads to our focus here on ores, with some discussion of possible future ore reserves.

We consider here the various marine materials in rough order of descending value of production from the ocean floor starting with hydrocarbons (petroleum: crude oil and natural gas). Although the thrust of miners is for hard minerals, petroleum is a mineral and should not be omitted just because the value of its annual ocean-floor production is more than a hundred times that of all ocean floor hard minerals combined (Table 1). This table and Figure 2 demonstrate the disparity between hopes of marine mining and the actual mining of hard minerals at present. Note that column G of Table 1 is approximate because estimates of ocean floor resources are far less reliable than those for the same resources on land.

Petroleum and Sulfur

Petroleum has been used by humans for more than 2,000 years variously as a source of heat for warming, cooking, evaporating brines, and weaponry. The dominant use of oil, coal, and gas is energy production, and there is a remarkable correlation between gross national product/capita and energy production/capita in all nations of the world (Emery and Catchings 1979). In fact, without the availability of this fossil energy, there would be little need or prospect of mining of hard minerals either from land or submarine areas.

Petroleum has been ascribed to several different origins during the past and even at present, but geologists (whose job is to find it) strongly favor its derivation from microscopic plants, mainly marine, followed by chemical alteration during burial and final concentration in geological traps. Annual world production of crude oil is about 2.7×10^9 metric tons, of which about one-fourth is presently recovered from the ocean floor. Cumulative world production of oil from both land and ocean floor at the end of 1973 was 39×10^9 metric tons (COMRATE 1975); subsequent production during 1974–87 added another 39×10^9 metric tons, or a total cumulative production of 78×10^9 metric tons through 1987. Proved reserves of oil at the end of 1973 were about 84×10^9 metric tons and at the end of 1987 they were 118×10^9 metric tons, owing mainly to reevaluation of past exploration, especially by members of the Organization of Petroleum Exporting Countries (OPEC). Essentially the same history is true of production and reserves of natural gas, with 1973 reserves of 59×10^9 metric tons and 1987 reserves of 110×10^9 of oil equivalent (Anonymous 1987). This continued presence of large proved reserves of petroleum may disappoint pessimists, but it is testimony to the ability of the world's geologists and geophysicists. Of course, future ultimate production depends on future prices. This dependence is illustrated by Figure 3, which shows the increasing price of oil through 1982 as fixed by OPEC, and subsequent decreases in the tonnages of oil produced from these nations, increases from non-OPEC nations, increases in percentage of oil from the ocean floor, and increases in the maximum water depth of offshore-producing wells. Present annual value of oil and gas from the ocean floor is about 80×10^9 (Table 1).

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Table 1

Seabed Materials in World Perspective[a]

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Seabed deposits	Material commodity	(A) Seabed production (MT × 10³)	(B) 1985 World mine production (MT × 10³)	(C) 1985 Estimated average price ($/MT)	(D) (A)×(C) Seabed revenues ($ × 10⁶)	(E) (B)×(C) World revenues ($ × 10⁶)	(F) (D)×100/(E) Seabed share of world revenues (%)	(G) Seabed reported potential resources (MT × 10³)	(H) World onshore resources (MT × 10³)	(I) (G)×100/(H) Seabed comparison to world resources (%)
Petroleum[b]	Crude oil	788,834	2,788,913	70	55,218	195,224	28	>61,429,000	181,857,000	34
	Natural gas	246,670	1,296,405	95	23,434	123,158	19	>60,000,000	228,214,000	26
	Sulfur	381	54,000	105	40	5,670	<1	27,125 [c]	5,000,000	<1
Sand & gravel	Sand & gravel	112,300	7,620,480	3	334	22,861	1	665,778,000	very large	small
	Industrial sand	—	181,440	14	—	2,540	—	large	very large	small
	Shells & aragonite	16,667	1,666,667	6	100	10,000	1	90,000,000	very large	small
Mineral placers	Rutile	0	356	364	0	130	0	13,060	181,440	7
	Ilmenite	0	4,187	49	0	205	0	230,500	907,200	25
	Zircon	0	709	182	0	129	0	29,040	54,432	53
	Monazite	—	30	597	—	18	—	3,500	43,307	8
	Tin (cassiterite)	28	201	6,614	185	1,329	14	2,500	34,500	7
	Gold	1	1	10,600,000	10	10,600	<1	<1 [c]	72	<1
	Platinum	0	≪1	9,000,000	0	1,980	0	≪1 [c]	99	≪1
Phosphorite	Phosphate rock	0	159,000	24	0	3,816	0	7,939,000	129,500,000	6
Ferromanganese	Manganese	0	23,406	141	0	3,300	0	2,600,000	10,886,400	24
	Nickel	0	745	5,026	0	3,744	0	131,000	129,730	101
	Cobalt	0	32	25,353	0	811	0	24,000	10,886	220
	Copper	0	7,805	1,475	0	11,512	0	108,000	1,600,000	7
Massive Sulfides	Copper	"	"	"	"	"	"	216,000	"	<14
	Zinc	0	6,560	893	0	5,858	0	518,000	1,800,000	<29

[a] Modified from Broadus 1987.

[b] Petroleum in metric tons of oil equivalent.
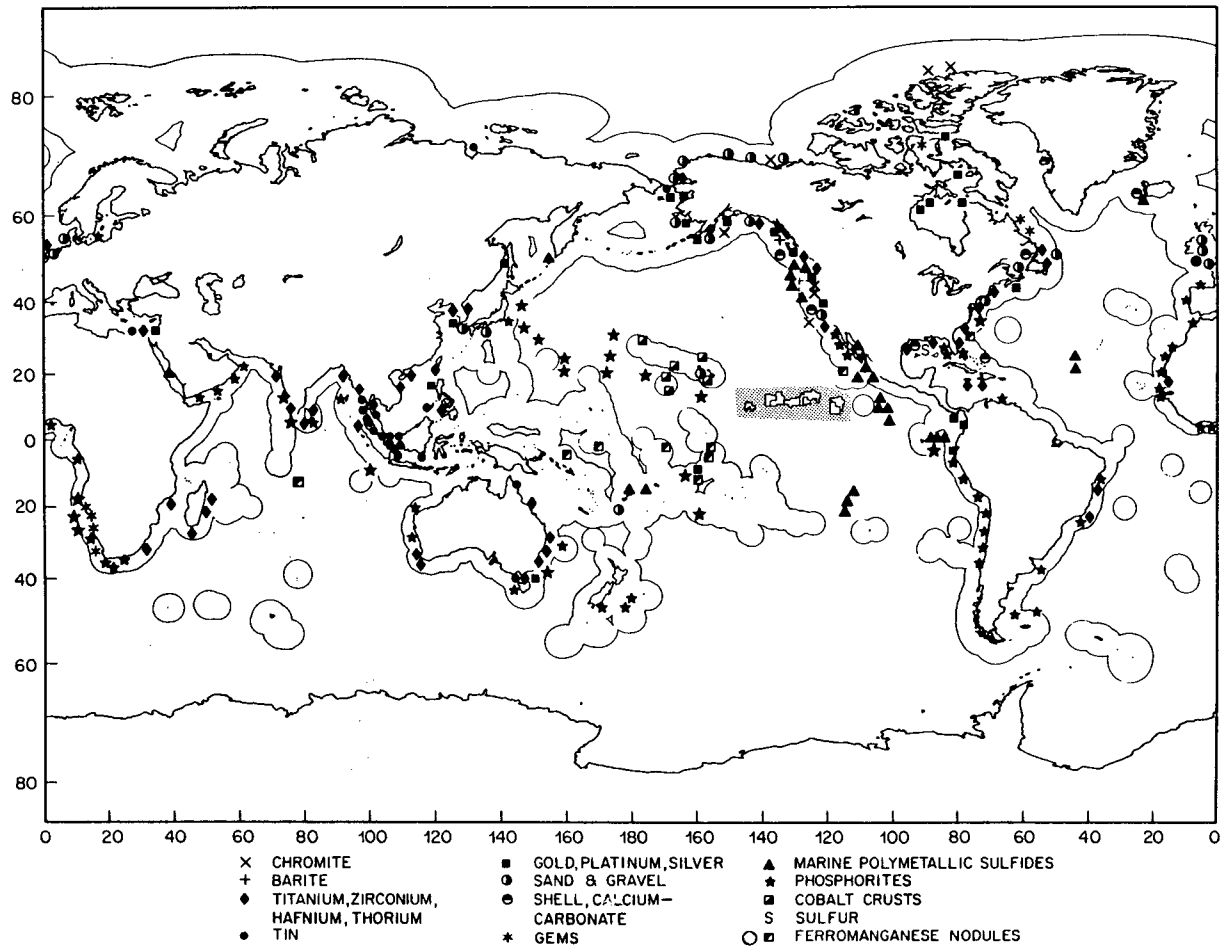
[c] Seabed estimate for the United States only.

80

60

40

20

0

20

40

60

80

0 20 40 60 80 100 120 140 160 180 160 140 120 100 80 60 40 20 0

Symbol	Mineral	Symbol	Mineral	Symbol	Mineral
X	CHROMITE	■	GOLD,PLATINUM,SILVER	▲	MARINE POLYMETALLIC SULFIDES
+	BARITE	◑	SAND & GRAVEL	★	PHOSPHORITES
◆	TITANIUM,ZIRCONIUM, HAFNIUM, THORIUM	◒	SHELL, CALCIUM— CARBONATE	▨	COBALT CRUSTS
●	TIN			S	SULFUR
		✳	GEMS	○▣	FERROMANGANESE NODULES

Figure 2. Marine hard mineral distributions relative to boundaries of 200-nautical-mile Exclusive Economic Zones. Identified deposits of marine hard minerals including licensed areas for manganese-nodule mining activities in eastern central Pacific Ocean (from Broadus 1987, fig. 1). Other maps are presented by Ross (1978). Only a few of the sites for sand and gravel, some of the tin, and one of gold actually are being mined as marine ores.

Figure 3. World offshore oil production (from Emery and Uchupi 1984, fig. 391). (a). Price of oil, with dots indicating changing dollar value for $12 oil during 1978 adjusted according to Consumer Price Index for earlier and later years. (b). Percentage of world oil production from ocean floor wells. (c). Maximum water depth of ocean floor producing wells. (d). Changing contribution of oil from ocean floor wells of Persian Gulf and of offshore regions in the Atlantic Ocean.

Some wells drilled on salt domes failed to tap petroleum but were converted to production of sulfur. The sulfur is mainly in caprock of the domes, and it was dissolved by hot water pumped down one well and retrieved as sulfur-laden water through another well (the Frasch process). Production of sulfur from ocean floor wells almost ceased during the past decade, because cheaper onshore sources have been discovered and utilized, including the recovery of sulfur from oil refinery smokestacks partly in the interest of reducing air pollution and acid rain.

Sand and Gravel

Sand and gravel are abundant on continental shelves of the world, most having been brought there from land by high-latitude glaciers and midlatitude streams during Pleis-

tocene glacial epochs of low sea level. Once deposited at the shore, the sand and gravel were resorted and redistributed by waves and shore currents, which probably were stronger at that time. Some of the sand also was blown landward to form dunes. When sea level rose during postglacial times, the former stream beds, deltas, beaches, and dunes became submerged. They still are exposed as relict sediments on the outer parts of most shelves, generally separated from shore by a belt of finer grained sediments escaped from streams, estuaries, and lagoons that trap most coarser components. Where land sources of detritus were minimal, especially at low latitudes, the relict sands and gravels may contain high percentages of calcium carbonate in the form of shell debris and even aragonite muds.

Sand, gravel, shells, and carbonate muds are exposed at the surface of shelves and banks, and most are tens of meters thick, so they are mined readily by self-propelled suction hopper dredges. This ease, plus subsequent low-cost transport and discharge, is reflected in low recovery costs, only a few dollars per ton. Low cost also is permitted by double use of mining, whereby sediments are dredged to provide sheltered coastal waterways and marinas and to deepen and enlarge harbors. The dredgings are dumped at or pumped to nearby sites for landfills (especially in the United States), other construction purposes, including use as concrete aggregate (especially in Europe and Japan), and road surfacing. Shells and aragonite muds (especially from the Bahama offshore reef platforms) are added to leached soils for improving agriculture.

The price and tonnage of sand, gravel, and shells from the continental shelf and especially from the nearshore region have increased to a world production value of about 434×10^6 (Table 1). Although annual production value of sand, gravel, and calcium-carbonate shell and mud from the ocean floor is only 0.6 percent that of petroleum and sulphur from offshore wells, it is more than double the annual value of all other hard minerals from the ocean floor.

Marine Placers

Placers are mechanical concentrations of heavy minerals caused by winnowing and removal of unwanted lighter minerals by flow of overlying water or locally of wind. Three groups of placers can be recognized on beaches and stream beds according to their sources and densities: light heavy minerals, heavy heavy minerals, and gems—listed in order of descending production tonnage (Emery and Noakes 1968).

The most common light heavy minerals are magnetite, ilmenite, rutile, zircon, and monazite in order of descending abundance (not of production) and probably in reverse order of demand for chemical and metallurgical uses. Their source is intrusive igneous rocks from which they are released by weathering and erosion and separated from unwanted and less stable light minerals. Streams that transport these minerals achieve some concentrations but only in small uneconomic deposits. Great separation and extensive concentrations are by action of waves and nearshore currents after the minerals reach the ocean, especially during winter storms in areas of large waves. Sites of concentration on beaches can be hundreds of kilometers from source rocks, and there can be several cycles of deposition, erosion, and reconcentration, because the minerals are tough and resist weathering. Thus their placers occur on ancient raised and submerged beaches as well as on present beaches. Average annual world production during 1960–65 for beach placers of the world was about 4×10^6 tons with a value of about 50×10^6. Since that time, mining of magnetite and most of the others has been banned in Japan, the Philippines, and elsewhere in the interests of protecting the environment. Further discussion is omitted

here, because beach placers are not strictly sites of marine mining—generally being done from the land by dragline.

Heavy heavy minerals include tin, gold, and platinum in order of decreasing abundance and production. Their source is coarser grained intrusive igneous rocks, especially pegmatites, from which they are released by weathering and erosion. The tin is cassiterite, an oxide, whereas gold and platinum occur as native metals combined with various impurities. The three have densities higher than the maximum of 5.2 gm/cm^3 for the light heavy minerals. Because of their high densities, few of the heavy heavy minerals reach the ocean except under special geological circumstances. For example, much tin of southeastern Asia occurs in stream sands now submerged by the rise of sea level since glacial times. Offshore deposits represent about half the tin resources for both Indonesia and Thailand (Sujitno 1984), but offshore production has been curtailed by the 1985 price collapse for tin. Gold in beach sands of Nome, Alaska, was carried to the present beach and to emerged and submerged beaches by ice and deposited in glacial till from which wave action concentrated it. Because of high costs associated with low concentrations, overburden, and weather, production has been near zero for gold and platinum (Table 1), but seasonal mining for gold resumed recently off Nome.

The third group of placer minerals is gems, whose density is less than that of light heavy minerals. All except diamonds are so easily fractured that few reach the ocean. In southwestern Africa the postglacial rise of sea level has submerged stream deposits and reworked some of the diamonds into sands of the present, emerged, and submerged beaches. During the best year of the 1960s, offshore production from shipboard amounted to $\$4 \times 10^6$. Production was abandoned in 1971 but may have begun again as mining on land behind coffer dams.

Phosphorite

Phosphorite is a complex tri-calcium phosphate that has three main origins in the ocean, as discussed by Baturin (1982), Emery and Uchupi (1984, pp. 744–799), and others references therein. It occurs in nodular and pelletal beds at the surface of many continental shelves and bank tops where the supply of detrital sediment is small. Nodules contain evidence of discontinuous deposition of phosphate on both tops and bottoms of slablike nodules, with intervening thin layers of manganese oxide, glauconite, foraminiferans, detrital sands, and bones of marine animals. Small nodules and pellets contain less evidence of discontinuities. These forms are considered authigenic—deposited from phosphate-rich overlying waters including anaerobic ones and from underlying interstitial waters. Other nodules and beds consist of diagenetic phosphatic replacement of earlier sediments and rocks, mainly calcareous ones. Many examples of both authigenic and diagenetic phosphorites contain evidence of erosion and redeposition; these are considered residual in origin. Fossils and isotopic dates indicate that most phosphorites of the present ocean floor are Miocene to Quaternary; the best known are Florida to South Carolina, South Africa, Peru-Chile, and southern California-Mexico. Ages of phosphorites on land range back to early Paleozoic, with largest deposits in Morocco, southeastern and western United States, South Africa, European U.S.S.R., and Australia (Stowasser 1987).

Production to date has been entirely from land because of generally higher grade, easier access and environmental factors, but production from the western United States has diminished recently because of exhaustion of higher grade deposits. No offshore mining has occurred, other than an abortive attempt off southern California in 1962.

However, offshore deposits distant from land sources especially off southern California, the southeastern United States, South Africa, Peru-Chile, and Chatham Rise near New Zealand are likely sites for possible future production and conversion of some resources into reserves.

Ferromanganese Nodules and Crusts

Ferromanganese nodules on the deep ocean floor have been known since the *Challenger* expedition of 1873–76, but about two decades ago interest in them was greatly augmented by their perceived profit potential that was largely induced through studies by Mero (1965). A few tons of nodules have been recovered aboard oceanographic ships and several hundred tons by prototype mining ships. Thousands of samples in the world ocean show highest concentrations on seamounts and plateaus and in pelagic sediments on abyssal plains far from sources of diluting detrital and biogenic sediments (Figure 4). The nodules commonly occur as loose subspherical masses having concentric structure. Some are closely spaced as to form a residual lag deposit on the bottom; other nodules are slablike and more than a meter long; still others form continuous pavements at least 10 m in horizontal extent. At least 6,000 articles on the deposits have been published, but few yield much information about origin. Most nodules appear to be due to authigenic deposition from overlying waters. At least in the Atlantic Ocean, manganese is deposited about 50 times faster in fine-grained sediments than in the nodules (Emery and Uchupi 1984, pp. 737–746; see cited references for other aspects of nodules), but of course it is greatly diluted in the sediments that also cover a large area. Perhaps a tenth as much of the nodular deposits are due to diagenesis and much less to submarine volcanism and to weathering of underlying rocks.
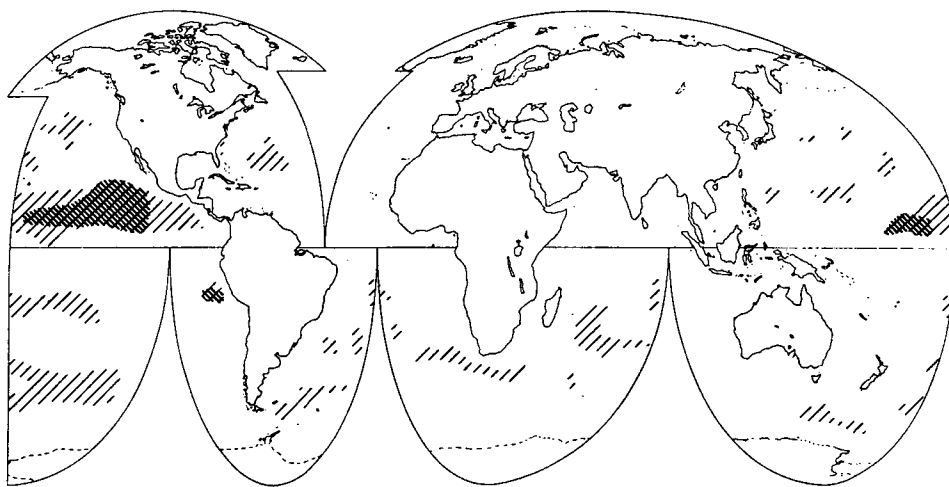

Figure 4. World distribution of ferromanganese nodules. Blank areas contain only occasional nodules or coatings; light hatching areas have nodules in at least a third of the samples and photographs, double hatching denotes areas where most nodules contain at least 1 percent copper and 1 percent nickel (from Emery and Skinner 1977, fig. 10, and associated references; see also McKelvey 1986).

Typical high concentrations of important metals are as follows: manganese, 22 percent, nickel, 1.3 percent, copper, 1.1 percent, and cobalt, 0.3 percent. It is these metals that led to the economic interest in ferromanganese nodules during the 1970s and early 1980s. Note, however, that such low concentrations of manganese would not be mined even on land. Land mining of the others yields about 16×10^9 per year (Table 1). If ocean floor mining should displace 10 percent of the land mining and the profit were 10 percent, the resulting 160×10^6 distributed to populations of all lesser developed countries would yield about $0.05/capita/year! This was the important target of the lesser developed countries during Law of the Sea negotiations of the United Nations up to 1982, and no mining has begun. Cost estimates have been attempted for deep ocean nodule mining based upon detailed engineering scenarios. The most recent estimates for total capital costs range from 1.3×10^9 to 1.8×19^9, with annual operating costs between 224×10^6 and 440×10^6 (Hillman and Gosling 1985). The conclusion is that nodule mining is unlikely for the foreseeable future. Analysis also shows that early cost estimates for commercially unproven technologies tend to be uncertain and unreliable.

Since about 1980 interest has developed in a special aspect of ferromanganese nodules: ferromanganese crusts attached to surfaces of extrusive igneous rocks of seamounts. This interest stems from relatively high concentrations of cobalt—to 1.0 percent but averaging 0.63 percent, and of platinum—0.1 to 1.0 ppm (Manheim 1986). Thickness of these crusts ranges up to perhaps only 15 cm, raising problems of efficient mining.

Polymetallic Sulfides

In 1966 an oceanographic ship investigated the sediments underlying hot brines in Red Sea basins, finding concentrations in the sediments of 3.4 percent zinc, 1.3 percent copper, 0.0054 percent silver, and traces of many other metals (Degens and Ross 1969). The deposits were viewed as ocean floor parallels of shallow-vein hot water mineralization on land. Submersible explorations of the midocean ridge in the Atlantic and Pacific oceans (Edmond et al. 1979; Rona et al. 1983) showed the presence of polymetallic sulfide deposits associated with escaping hot waters along the midocean ridge of the world (Figure 5). The metals in the Red Sea hot brines are from part of that system. Published concentrations in the polymetallic deposits around hydrothermal vents are highly variable, ranging up to 54 percent zinc, 9 percent copper, and 4.5 percent lead, but more typically they are less than 1 percent (Hoagland and Broadus 1987, pp. 103–114). Such variability is expected for selective sampling or "high grading," but it also may indicate changes of composition in different areas or with different plate spreading rates. The deposits and their associations indicate similarity to far better explored ones on land (in ophiolites) that are believed to have a similar origin along former deep ocean floor spreading belts. Absence of adequate drilling for samples in the ocean prevents accurate determination of concentration of potentially valuable metals.

Why Exploit Marine Minerals?

The most obvious reason for industrial nations to mine marine minerals is to supplement or substitute marine for land reserves of raw materials needed by industry. This is particularly important for industrial nations that lack certain important land-based mineral reserves but have possible ocean floor ones nearby (as for Norway—petroleum, the United States—cobalt and nickel, and France and England—sand and gravel). Nations whose
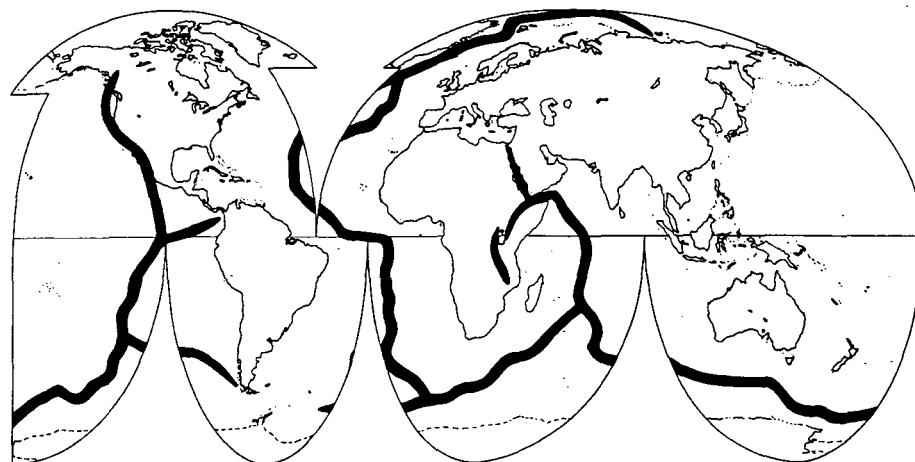
Figure 5. Pattern of midocean ridge, the belt of active sea floor spreading, along which occur the hot brine vents and their associated polymetallic sulfides (from Emery and Skinner 1977, fig. 4).

livelihood depends mainly on recovery and export of raw materials naturally wish to supplement reserves nearing depletion on land by ones from nearby marine areas (Venezuela—petroleum, Thailand—tin).

Besides the need or desire for access to new submarine sources of critical minerals, a major product of marine exploration is knowledge of how mineral deposits form. Discovery of genesis of mineral deposits may be augmented by measurements of geological and geochemical processes that now are forming minerals on the ocean floor. In fact, many ancient mineral deposits on land originated on the floors of oceans that now are long gone. Thus knowledge is power that can be used for exploration that may lead to the expansion of areas and volumes of deposits on land beyond the limits of contemporary knowledge. For example, the native populations of central America and northern South America had long mined gold and silver for fabrication into ornaments, but when the Spanish applied sixteenth-century European methods, production increased so vastly that purchasing power of their coinage diminished. Present gold production using cyanide leaching of waste piles now is making a similar expansion of production. Likewise, copper production by Old Testament Israelites and others increased when medieval techniques developed by alchemists were applied. Worldwide copper production is again increasing through leaching of waste piles with sulfuric acid. It again may be expanded for copper sulfide deposits when knowledge of the genesis and relationships of polymetallic sulfides of the midocean ridge is applied to similar deposits now on land.

Oceanographic knowledge already has been successful in aiding location of on-land phosphorites, and observation of marine polymetallic sulfides eventually may help locate commercial analogs on land (where real discovery costs have doubled in the past 30 years). This tie between science and mining or engineering is likely to be more productive than the early experience when ocean floor minerals began to be "discovered" during the late 1960s. Many companies in industrial nations enthusiastically designed and built submersibles so that by 1970 probably at least 50 submersibles existed, but few were sold and fewer were operated effectively (Ballard and Emery 1970). Clearly, manufacturers, including aircraft companies, saw submersibles more as a source of revenue from construction and sale than as a means of their own company's gaining of knowledge
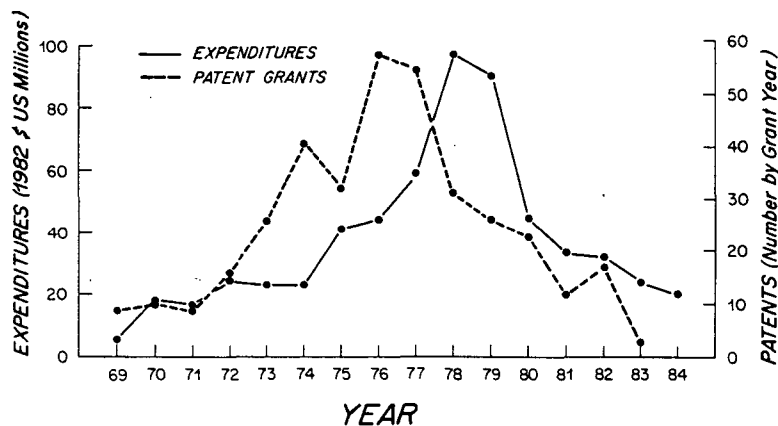
Figure 6. Estimated patent activity and expenditures for ocean floor mining other than for petroleum between 1969 and 1984 (from Hoagland 1985; Broadus 1986). Note that more than 650×10^6 has been spent mainly to explore and develop techniques for ferromanganese nodules. Spending estimates have been reconstructed from fragmentary evidence in publications and clues from industrial sources.

about the ocean. Knowledge gains were to be made by purchasers and users of the equipment; this was essentially analogous to the manufacture and sale of railroad equipment, automobiles, and airplanes. In fact, by 1978 purchasers and users did not appear in sufficient numbers, so nearly all of these first-generation submersibles disappeared; only a few now remain in updated forms. Many other instruments for ocean study devised by engineers having little previous marine experience went the same route to oblivion (Figure 6).

As in the past, the new discoveries increasingly will be made by scientists and engineers of the industrial nations that recognize the value of knowledge and take steps to promote education. During the past few centuries their discoveries were shared by the lesser developed countries, first through royalties but later by confiscation of mines and wells. Marine mining sites developed by industrial nations are less liable to confiscation by those who supplied neither know-how, capital, nor sites. It is time for the lesser developed countries to increase efforts toward education of scientists and engineers (rather than lawyers as in the past). Legal restrictions on scientific research impede progress by all nations toward exploration and development of marine minerals. Such restrictions have been imposed not only on foreign scientists working in the jurisdiction of lesser developed countries, but also recently in the United States by bureaucrats seeking to control their own nation's scientific activities. The scientific problems associated with marine mineral deposits are many and interesting, the economic potential may be great during the coming century, and the time is at hand for all countries interested in marine resources and processes to put forth effort to understand and utilize them and to remove obstacles to this end.

Acknowledgments

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