Marine Metallic Mineral Resources of the Pacific Basin

Allen L. Clark
Jennifer Cook Clark

Resource Systems Institute
East-West Center
Honolulu, Hawaii

Abstract In the 1970s and 1980s, the ocean became a focus of attention for mineral producers and consumers. This paper surveys that trend with particular emphasis on several specific metals and types of resource deposit. In particular, the known and speculative details of manganese nodules, cobalt-rich manganese crusts, and polymetallic massive sulfides are discussed and analyzed in an economic context.

Introduction

Marine mineral occurrences include a large number of metallic, nonmetallic, and energy minerals which occur throughout the ocean regimes from shallow (sea-level) beach deposits to deep-ocean (>5,000 meters) manganese nodules. Although many of the marine minerals have been, and continue to be, commercially exploited, many others require changes in economics or technology before they can be commercially developed. In particular, manganese nodules, cobalt-rich manganese crusts, and polymetallic sulfide occurrences, which are the focus of the present paper, must all be

Presented at the Marine Resource Economics Workshop, April 24–28, 1984.

Marine Resource Economics, Volume 3, Number 1
0738-1360/86/030045-00$02.00/0

considered as possible future sources of metals because no commercial mining operation now exists for these occurrences. In order to evaluate the potential of both the marine metallic occurrences that are exploited at present and those that may be developed in the future, we will use the McKelvey (1972) classification of resources and the definition of a resource as, "A concentration of naturally occurring solid, liquid or gaseous material, in or on the Earth's crust in such form that *economic extraction* of a commodity *is currently* or *potentially feasible*" (U.S. Dept. of Interior, 1973, 1974). The term *resource* will be used in this article to denote both the currently and potentially economic concentrations of marine minerals. Utilizing this definition to include both present and future developments, we will see that the role of marine mineral resources in international minerals supply may increase significantly in the next two decades and beyond.

The objective of this paper is to present a concise summary of a limited subset of marine metallic resources, emphasis being placed on the economic geology of known occurrences of metallic minerals, primarily those that have formed in the newly defined jurisdictional zones of nations within the Asia-Pacific region. The discussion is specifically limited to these minerals and avoids a discussion of hydrocarbons which are covered elsewhere in this issue (Valencia and Marsh). This paper is organized into five sections, including this introduction. In the next section we present a brief historical sketch of the development of marine mineral (including petroleum) resources under the assumption that these facts are not part of the general knowledge. Next, in what is perhaps the most important section, we survey three relatively deep ocean metallic mineral occurrences, manganese nodules, cobalt-rich manganese crusts, and polymetallic massive sulfides. In the fourth section we look at the potential impact of hypothetical future marine mineral mining operations on projected markets. In the concluding fifth section the results are summarized and evaluated.

Historical Sketch of Marine Minerals

Historically, the earliest recognition of the metallic resource potential of the ocean floor is attributed to Sir John Murray, who reported on the recovery of manganese nodules during the research cruise of the H.M.S. *Challenger* in 1873. Although manganese nodules were the first marine mineral resources to be recognized, the discovery and production of offshore oil and gas in Louisiana in the early 1940s contributed immeasurably to the recognition of the economic potential of offshore areas.

Scientific investigation has been consistently pursued to the deeper ocean, leading to the subsequent "rediscovery" of manganese nodules during the 1960s. In particular, the recognition that such occurrences contain significant amounts of copper, nickel, cobalt, and manganese with minor amounts of gold, silver, molybdenum, platinum, and rare earths led to serious consideration of deep-ocean mining for manganese nodules. The pioneering work of John Mero (1965) contributed significantly to the initial interest in manganese nodules.

Coincident with the recognition of the economic potential of marine minerals, in particular oil and gas, there came national and international recognition of the need to establish legal jurisdiction over these resources. As a result, a series of legally defined regimes has evolved, within which exploration and development rights are allocated. These are shown diagramatically in Figure 1. The recognition of a national need for exclusive jurisdiction of the near-shore environments for marine mineral resources was a major factor, among several, which led national governments to underline the existing definition of a territorial sea (mean high tide to 3 miles offshore) with a larger contiguous zone (9 miles offshore). Following discovery offshore of oil and gas in the United States, the 1945 Truman Declaration asserted U.S. sovereignty over mineral resources on the continental shelf. Similarly, the recognition of the resource potential of deep-ocean manganese nodules led to serious questions concerning the ownership of all deep-ocean resources. In 1967 Ambassador Arvid Pardo of Malta, in a speech to the General Assembly of the United Nations, proposed that such resources were the "common heritage of mankind." As a result, the United Nations established the Ad Hoc Committee on the Peaceful Uses of the Seabed and the Ocean Floor Beyond the Limits of National Jurisdiction, from which nearly a decade and a half later the Convention on the Law of the Sea (LOS) evolved.

A particularly significant outcome of the LOS convention was the designation of the exclusive economic zone (EEZ). The EEZ is a

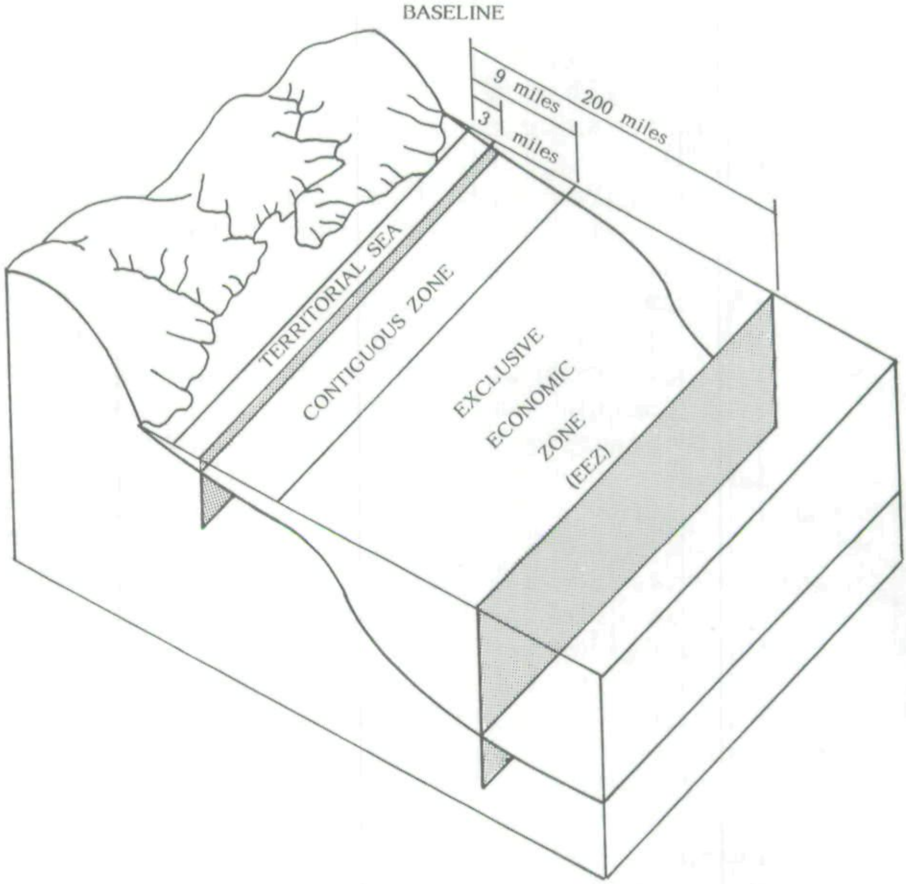

FIGURE 1. Schematic diagram (not drawn to scale) showing the location of the baseline, territorial sea, contiguous zone, and exclusive economic zone (EEZ) with respect to a national coastline (after Rowland, Goud, and McGregor 1983).

zone normally extending not more than 200 nautical miles from the baselines from which the breadth of the territorial sea is measured (U.N. Doc. A/CONF.62/L.28, 1981). This definition is of critical importance from a resource perspective in that within the EEZ a coastal state has sovereign rights over the natural resources of the seabed, subsoil, and superjacent waters. The present study emphasizes the resources occurring within the expanded zone of national jurisdiction, the EEZ, although deep-ocean resources such as nodules will be briefly discussed both because of their possible occurrence within the EEZs and because of the impact that newly discovered mineral resources within the EEZ may have on the future of deeper ocean resources (Johnson and Clark 1985).

The rapid expansion of interest in ocean resources on both a scientific and a political level, coupled with new scientific concepts such as plate tectonics and the origin of ocean basins, has resulted in a major expansion of knowledge regarding marine minerals. Although no commercial deposits of marine minerals have been exploited from the deep ocean, nodules and metalliferous muds (which have been mined experimentally), cobalt-rich manganese crusts, and polymetallic massive sulfides all represent mineral resources for possible future economic exploitation. Oil and gas are currently being produced from the continental shelves of more than 60 nations. Several placer minerals, in particular titanium, tin, magnetite, chromite, zircon, monazite, and staurolite are recovered by dredging. Similarly gold, platinum-group metals, and diamonds have been recovered from offshore beach deposits, and large low-grade concentrations still exist which may be mined in the future. More common resources such as sand, gravel, lime, aragonite, and phosphorite are recovered from the near-shore areas of many nations. Recent advances have led to the mining of barite from the subsea by quarrying and to the underground mining of iron ore utilizing on-land entry or artificial islands.

Historically, exploration and development of marine mineral resources have shown the commercial viability of several types of resources, and future activities may lead to the exploitation of more and new deposits. In the near term, it is to be expected that mineral resource exploitation may take place principally within the EEZs of several nations and be based in large part on already known reserves of currently exploited marine mineral resources. The longer term perspective of opportunities for development and exploitation will be based on both the reserves known at present and the estimated undiscovered recoverable resources contained in new deposit types that are not now being commercially exploited.

Marine Mineral Resource Occurrence

Three major modes of potentially economic deep-sea marine mineral occurrences have been identified and are the subject of intense research. These are manganese nodules, cobalt-rich manganese crusts, and polymetallic sulfide vents.

Manganese Nodules

Composed primarily of manganese and iron oxides, manganese nodules occur normally on the surface of the ocean bottom at depths as great as 5,000 meters or more, although nodules are known at much shallower depths. The major economic interest in nodules is focused on those with significant amounts of nickel, copper, and cobalt. Current commercial interest is focused on nodules with a greater than 1.8% copper equivalent, with nickel being the most important economic component. The most prospective area for the occurrence of such deposits is between the Clarion and Clipperton fracture zones, between about 114° and 157° west longitude (Figure 2). According to McKelvey, Wright, and Rowland (1979) this area is about 2.5 million km^2 in size, and from available data it appears that about half the area contains nodules in concentrations greater than 5 kg/m^2 and averaging about 11.5 kg/m^2. Assuming 20% recovery of nodules from the area, with a moisture content of 30%, the Clarion-Clipperton prime area would contain about 2.1 billion dry metric tons of recoverable nodules averaging 1.3% nickel, 1% copper, 23% manganese, 0.22% cobalt, and 0.05% molybdenum. This amount would support 28 average-sized mining operations (McKelvey 1980), each producing 75 million tons over its lifetime.

Although there exist many uncertainties with respect to almost every aspect of nodule resources and eventual mining costs, it is obvious that nodules represent a major resource of the deep ocean.

Crusts

Cobalt-rich manganese crusts, which we will refer to as crusts, have recently become the source of considerable scientific interest and an emerging economic interest (Clark, Johnson, and Chinn 1984). There are a number of factors that appear to be contributing to this shift, including a recent recognition that crusts (1) may be

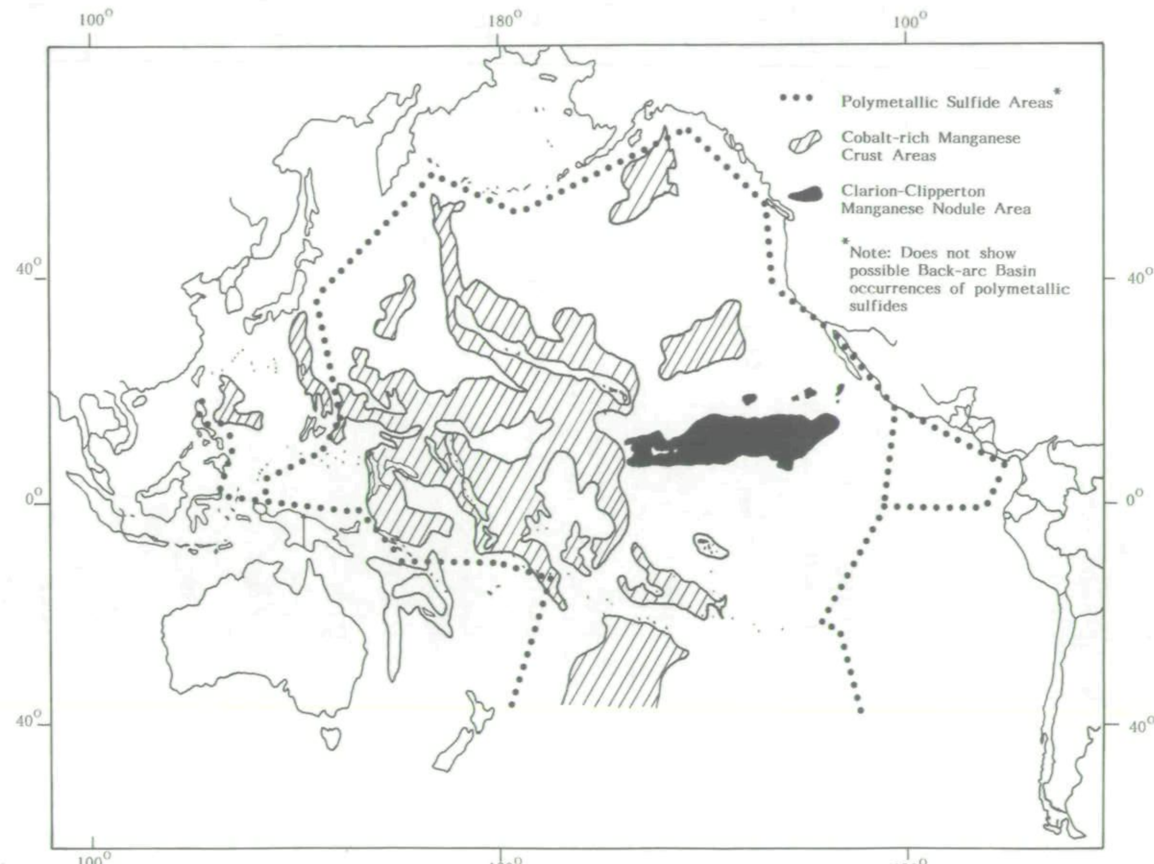

FIGURE 2. Permissive areas for marine mineral resource occurrences in the Pacific.

richer in metal content and more extensively distributed than previously recognized, (2) may be technologically easier to recover, (3) may be located in a more stable investment environment, and (4) may provide alternative sources of strategic minerals. Although crusts are known to be widespread in marine environments (Figure 2) wherever a suitable substrate exists, insufficient data exist for an ocean-wide analysis of their resource potential. However, resource assessments are possible in some limited areas (Commeau et al., 1984). For example, a geographically more restricted study by Clark, Johnson, and Chinn (1984) of the crust resource potential of the Hawaiian, Johnston, and Palmyra islands estimated a resource potential of 10 million tons of cobalt, 6 million tons of nickel, 1 million tons of copper, and 300 million tons of manganese within the study area. Unlike the nodules, which occur at depths of 5,000 meters or deeper, the crust resources exist upward from a depth of 2,500 meters to 800 meters. The relatively shallow depths in which crusts are found, as opposed to nodules, would imply generally lower production costs (Johnson and Clark, 1985). However, the main cause of the increased interest in crusts over nodules, from 1972 to 1982, is attributable to a price rise for cobalt. Approximately two-thirds of the value of crusts is accounted for by contained cobalt, whereas cobalt accounts for only 15% of the metallic value in nodules.

Polymetallic Massive Sulfides

Rivaling the manganese crusts in both scientific interest and potential economic importance are the polymetallic massive sulfides. These marine mineral resources were first discovered by Francheteau et al. (1979) on the East Pacific Rise. Since the initial discovery, similar deposits have been found in the Galápagos Rift (Malahoff 1981), the Guaymas Basin (Lonsdale et al., 1980), the East Pacific Rise at 13°N (Hekinian et al., 1981; Fouguet and Hekinian 1985), and most recently along the Juan de Fuca Ridge off the coast of Oregon (Normark et al., 1982). According to Bischoff et al. (1983), the presence of active polymetallic sulfide vents at all of these sites suggests that the deposits may be common throughout the 40,000-km length of geological spreading centers in the Pacific and Indian Oceans (Figure 2). In general, polymetallic sulfide vents are composed of a basal mound surmounted by a chimney stack; both portions are high in polymetallic sulfides. Although varying considerably in metal type and content from area to area, the principal economic components are zinc, copper, and silver, with locally significant concentrations of cobalt, gold, cadmium, molybdenum, and germanium. Metal content estimates of the known marine mineral deposits associated with spreading center are given in Table 1. Such estimates are highly tentative, being based on limited samples and analyses, and do not indicate average ore grades for possible commercial development.

Unlike either the nodules or the crusts, the primary mineral values of the polymetallic sulfides, based on limited sampling, appear to be quite variable. For example, limited data on the Juan de Fuca polymetallic sulfide vents show that the metal value is approximately 75% attributable to zinc and secondarily to silver, whereas in the Galápagos Islands the principal value is in copper. The trace-element geochemistry of the polymetallic sulfides is also quite variable, with major values potentially in silver, cadmium, tin, and germanium. Germanium, however, is typical of the problems of potential recovery in that, although germanium has a high apparent value as a trace element, recent studies by Adams (1980) indicate that extraction costs may be close to metal value. In the case of the Galápagos Rift the principal metal value is in copper, similar to nodules, but without the additional credits in nickel and cobalt associated with nodules. In addition, unlike the nodules or crusts the polymetallic sulfide vents tend to be geographically limited in extent and to contain only approximately 20 million metric tons of ore based on a density of 2.5 g/cm^3 (Malahoff 1982).

Impact of Marine Mineral Resource Development

Because (1) there are no present commercial operations (2) mining and metallurgical systems are still only prototypic, and (3) precise mine sites have not been determined, it is not possible to undertake a complete economic analysis for mining of any of the previously discussed marine mineral resources. It is, however, possible to compare the potential economic impact of mining each of the three

Table 1
Known Ocean Deposits by Spreading Centers[a]

Area	Year of Discovery	National Involvement	Metal[b] Zn, %	Cu, %	Pb, %	Ag, ppm	Au, ppm
Juan de Fuca	1981	U.S.	55	0.35	0.32	300	
Gorda Ridge	1981	U.S.		not available			
Guaymas Basin	1980	U.S./Mexico	30	1.0	0.1	300	
East Pacific Rise 21° N	1978	U.S./Mexico/France	50	0.75	0.35	400	trace
East Pacific Rise 13° N	1981	France		not available			
Galápagos Rift	1981	U.S.	0.1	10.0	0.1	300	
East Pacific Rise 20° N	1981	U.S./France		not available			
Mid-Atlantic 37° N	1974	U.S./France		Fe/Mn oxides			n.a.
Red Sea, Atlantis II	1948 1963	Saudi Arabia/U.S./U.K.	5	1	trace	trace	

[a] Based on estimates of dimensions of deposits observed by bottom photography and manned submersible (density approximately 2.5 g/cm^3) (Cruickshank 1982).
[b] Metal values derived from limited samples and analyses.

previously described types of marine-mineral-resource occurrences in terms of revenues to be earned from the major metals produced, assuming that technological and cost constraints allow profitable production at "feasible levels" (Table 3, footnote). For definition of possible mining scenarios and feasible levels of production, the reader is referred to the studies by Black (1980), Halbach, Manheim, and Otten (1982), Little (1979, 1984), Andrews, Flipse, and Brown (1983), Nyhart et al. (1978, 1984), and Johnson and Clark (1985).

The typical metal grades for nodules, crusts, and polymetallic sulfides are given in Table 2. Based on these highly preliminary metal grades, an analysis of the potential impact of marine mineral resource mining on world markets has been undertaken by Johnson and Clark (1985) and is presented in Table 3, which shows the estimated impact on world metal markets in the year 2000 assuming a moderate 2.0% growth rate in demand from a 1983 base.

Table 2

Typical Metal Grades of Nodules, Crusts, and Sulfides*

	Nodules	Crusts	Sulfides (Type 1)	Sulfides (Type 2)
Cadmium (grams per metric ton—g/T)	—	—	31.00	n.a.
Cobalt (%)	0.27	0.90	—	—
Copper (%)	0.54	0.06	4.98	1.0
Lead (%)	—	—	0.07	0.1
Manganese (%)	20.10	24.70	—	—
Nickel (%)	0.76	0.50	—	—
Platinum (g/T)	—	0.40	—	—
Silver (g/T)	—	—	10.00	300.00
Zinc (%)	—	—	0.14	30.00

* Nodule grades are the average of more than 1,700 stations from the Pacific Ocean (McKelvey, Wright, and Bowen 1983). Crust grades are the average of 57 samples from depths less than 2,400 m from the EEZs of the Hawaiian Archipelago and Johnston and Palmyra islands (Craig, Andrews, and Maylon 1982; Halbach 1981). The platinum grade is an estimate based on a limited number of analyses of thick crusts by Halbach (personal communication, 1981). The sulfide data are from Broadus (1984). Sulfides high in copper concentrations, such as found near Galápagos, are referred to as Type 1 in this article. Sulfides with high zinc and silver concentrations, such as found at Guaymas Basin and Juan de Fuca, are referred to as Type 2. A number of metals of less economic interest are not included.

Source: After Johnson and Clark (1985).

Table 3
Impact of a Marine Mining Operation on World Markets in the Year 2000

		Production from One Commercial Operation[b]						
		Nodules		Crust		Sulfides		
	Market Size,[a] thousand metric tons	Metric Tons	Percent of Market	Metric Tons	Percent of Market	Type 1, metric tons	Type 2, metric tons	Percent of Market
Cobalt	37.5	5,100	14	7,650	20	—	—	—
Copper	11,130.0	30,600	[c]	nil	nil	63,495	12,750[c]	—
Lead	4,784.5	—	—	—	—	—	—	—
Manganese[d]	13,249.7	637,500	5	212,500	2	—	—	—
Nickel	927.8	35,700	4	4,250	[c]	—	—	—
Platinum	0.3	—	—	0.3	[c]	—	—	—
Silver	16.0	—	—	—	—	13	383	[c]
Zinc	8,315.7	—	—	—	—	1,785	382,500	[c]

[a] Compared to primary mine production assumed to grow at an average of 2% per year from 1983 base (used average of 1980–83) to 2000. Mine production estimates from Bureau of Mines Mineral Commodity Summaries 1984, 1983, 1982.

[b] Assumed 3 million metric tons nodules/year, 1 million tons crusts/year, 1.5 million tons sulfides/year on a dry basis and 85% recovery of contained metals.

[c] Less than 0.5 percent.

[d] Contained metal.

Source: After Johnson and Clark 1985.

The only metal produced by a nodule operation to have a substantial impact on markets is cobalt. As shown in Table 3, one nodule operation would supply about 14% of the estimated world market in the year 2000.

With respect to crust mining operations, cobalt is even more important. As shown in Table 3, one mining operation would supply about 20% of the world market. The impact on world markets of production of other metals would be insignificant.

For sulfide deposits, a range of metal grades is possible; the two major known types are shown in Table 3. Mining of neither the copper-rich deposits (Type 1) nor the silver-zinc rich deposits (Type 2) would have any appreciable impact on world markets.

For nodule operations, manganese, if recovered as ferromanganese, would represent about half the sales revenue. However, it is important to note that with existing processing manganese recovery from either nodule or crust operations is believed to be marginal. Hence, if manganese is not recovered, then nickel dominates with over 60% of the sales revenue. Cobalt, however, looms relatively large with 21% of the mine's revenue (assuming no price impact) and an output that is approximately 14% of the world's market level (Table 3).

Crust operations are basically cobalt mines. As shown in Table 4, with manganese recovery, cobalt and manganese would each contribute about 43–45% of total gross sales revenue. Without manganese recovery, sales revenue from cobalt rises to almost 80% of total revenues. Here again, we have assumed no market price impact even though the crust mine's output of cobalt would reach approximately 20% of the world's market level (Table 3).

Hypothetical sulfide deposits are either copper rich, with copper representing more than 90% of the sales revenue, or silver-zinc rich, with zinc representing more than 70% of the sales revenue (Table 4). In both of these markets, the relevant sulfide deposit output would represent no more than 1% of the market and would therefore be relatively free of market price impacts.

Putting these facts together leads to some interesting observations concerning the market power and riskiness of marine mining operations. First, it is clear that, as with all new mining ventures, operations would be subject to price and revenue fluctuations stem-

Table 4
Gross Revenues from Marine Mining Operations
(One Commercial Operation)

	Million US$	Percent
Nodules (manganese recovery)		
Cobalt	90	11
Copper	68	8
Manganese	393	48
Nickel	276	33
Total	827	100
Nodules (no manganese recovery)		
Cobalt	90	21
Copper	68	16
Nickel	276	63
Total	434	100
Crusts (manganese recovery)		
Cobalt	135	45
Manganese	131	43
Nickel	33	11
Platinum	4	1
Total	303	100
Crusts (no manganese recovery)		
Cobalt	135	79
Nickel	33	19
Platinum	4	2
Total	172	100
Sulfides (Type 1)		
Copper	140	96
Silver	4	3
Zinc	2	1
Total	146	100
Sulfides (Type 2)		
Copper	28	6
Silver	105	22
Zinc	344	72
Total	477	100

Source: After Johnson and Clark (1985).

ming from changes in existing competitors (in this case land-based mines primarily). Even in the cobalt market the individual marine producer would control no more than 20% of the sales, leaving the other 80% to land-based (or other marine-based) producers. Second, variations in grade, discussed in the previous section, might lead to relatively wide variations in output. These variations could mean the introduction of a new source of instability in the cobalt market or revenue instabilities for the mining concerns in other markets.

Conclusion

At present the resource potential of marine mineral occurrences (crusts, nodules, and sulfides) is only partially known for the Pacific Basin, but both academic and industry interest is increasing in terms of applied research, exploration, and economic considerations for future development. Particular interest is focused on the crust and sulfide occurrences within the newly defined EEZs of the Pacific Basin nations—in contrast to the 1960–70 interest in deep-ocean manganese nodules. With this increased interest a significant number of new crust and sulfide occurrences will be, and are being, found. However, it must be emphasized that at present there are no commercially viable mining operations producing; indeed, according to Johnson and Clark (1985), "Given the lead time required to develop a commercial mining and processing operation, it is reasonable to conclude that no full-scale, private-sector financed commercial operation is likely to occur before approximately 2000" (p. 184). Even this is a slightly optimistic picture of the future when considered in the light that available data are limited in terms of defining the location, quality, and quantity of marine mineral resources that might form a "prime" mine site. Future potential exploitation will necessarily depend on additional exploration, improved technology, and changing economic and political conditions—all difficult, if not impossible, to predict and quantify.

It is particularly noteworthy, when considering future development of marine mineral resources, that the three occurrence types described in this paper have not only economic but strategic importance to many developed nations (Office of Technology Assessment 1985); that is, they have limited domestic availability and are subject to potential supply disruption. In particular, the United States, the Federal Republic of Germany, Japan, and France all regard cobalt, nickel, manganese, and platinum as strategic metals. As a result, the development of these resources has an added national value for supply security.

In the development of marine mineral resources, crusts would appear to have the greatest potential as an economically viable enterprise (Johnson and Clark 1985). If crusts were to be developed, the only market that would be influenced significantly by one mining operation would be the cobalt market. One or more mining operations for crusts would substantially depress cobalt prices in the year 2000 (Johnson and Clark 1985). Other metal markets would be relatively unaffected.

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