# Seabed Minerals and the Law of the Sea

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*Summary*. If, as seems likely, a comprehensive law-of-the-sea treaty is successfully concluded, minerals of the continental margins would be almost entirely controlled by coastal nations, and the right to produce minerals of the deep ocean floor would be licensed by an International Seabed Authority. Mineral production from the continental margins is likely to increase and diversify with time. The only minerals from the deep ocean floor for which there are reasonably good prospects of production within the next decade are the metalliferous muds from some of the deeps in the Red Sea (which lie within what is likely to be the jurisdiction of Saudi Arabia and Sudan) and nodules in the northeastern equatorial Pacific that contain recoverable metals, namely nickel, copper, cobalt, and possibly manganese, molybdenum, and vanadium.

In 1891, Sir John Murray and A. Renard reported the discovery of manganese and iron oxide nodules on the deep ocean floor during the exploratory voyage of H.M.S. *Challenger* in 1873–76. During the following decades other oceanographic expeditions collected additional samples of nodules in many parts of the world, some of which showed the presence of 1 percent or more of other metals, notably nickel, copper, and cobalt. Until about 1957, interest in the nodules was wholly scientific, but in that year John Mero, then a graduate student at the University of California in Berkeley, became interested in the possibility of mining the nodules, recognizing that their metal content exceeded that of many of the ores being mined on land. Mero's papers and his book on the mineral resources of the sea (*1*) sparked the interest of some mining companies in the possibility of deep ocean mining and drew interest as well from the international political community.

International political attention had begun several years earlier to focus on seabed minerals, after the 1945 proclamation of President Truman claiming sovereign rights over the minerals of the United States Continental Shelf. The first United Nations Law of the Sea Convention held in Geneva in 1958 succeeded in producing the 1958 Geneva conventions on the Territorial Sea and Contiguous Zone, the High Seas, Fishing and Conservation of the High Seas, and the Continental Shelf. The Shelf Convention gave coastal states jurisdiction over seabed resources of their continental shelves "to a depth of 200 meters or, beyond that limit to where the depth of the superjacent waters admits of the exploration of the said areas." Note that the term "continental shelf" was used in that convention as a legal term of art applying to more of the continental margin than the geomorphic shelf alone. Minerals beyond the continental shelf were not considered then, but under the 1958 High Seas Convention, ocean resources could be harvested and used by any state, although none could claim jurisdiction over any part of the high seas.

At the dedication of the research vessel *Oceanographer* in 1966, President Johnson said, "We must ensure that the deep seas and ocean bottoms are and remain the legacy of all human beings"; and, in a famous speech to the United Nations General Assembly in 1967, Malta's Ambassador Arvid Pardo described these regions as the "common heritage of mankind" and proposed that a preparatory committee be established to set the stage for agreement on principles under which deep-sea resources would be developed for the benefit of all mankind, taking into account the special needs of the developing countries. The General Assembly then adopted a resolution establishing the United Nations Committee on the Seabed and Ocean Floor Beyond the Limits of National Jurisdiction, which held its first substantive meeting in June 1968. In subsequent years, interest broadened to include other legal issues as well, and the United Nations Third Law of the Sea Conference, convened for its first substantive meeting in Caracas in 1974, has dealt with a wide range of issues. Agreement has now been reached on most issues, but still unresolved are two related to seabed minerals—the limits of national jurisdiction over the mineral resources of the continental shelf, and the provisions governing the exploration and exploitation of seabed resources beyond the limit of national jurisdiction.

The potential subsea mineral resources, the provisions being proposed by the Law of the Sea Conference with respect to these resources, and the prospects for seabed production are reviewed in the following pages.

## Resources of the Continental Margins

Oil and gas and some 13 other minerals are now being produced from nearshore subsea sources (*2*). Sand and gravel, lime from shells and aragonite mud, precious coral, and several placer minerals, notably titanium sands, tin, zircon, monazite, and magnetite, are mainly recovered by dredging. Sulfur and salt are recovered by solution mining through drill holes. Barite is recovered by subsea quarrying. Coal and iron ore are recovered from nearshore areas by underground mining with entry from the adjacent land or from artificial islands. Gold, platinum, and diamonds have been produced in the past and may be again. Potash is almost certain to be produced from subsea salt basins. The production of phosphorite offshore southeastern United States and southern California is being considered. One company has expressed interest in mining manganese nodules from the Blake Plateau for use as a catalytic filtering medium in the production of fuels from heavy crude oil and coal, with the possible recovery of metals from the spent nodule catalyst (*3*).

Oil and gas are by far the most important and valuable resources of the continental margins, both in terms of present and future production. Weeks (*4*) estimated the subsea potential as about 2.3 trillion barrels of oil and equivalent gas, all of which he considered as lying within the continental margins, and all but one-

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eighth of the total as lying within 200 miles of shore. Others [for example, (5)] also consider that the prospects for the occurrence of petroleum are restricted to the continental margins and that prospects beneath the deep-sea floor beyond the continental margins are essentially nil.

## Manganese Nodules of the Deep Ocean Floor

The deep-sea nodules are composed chiefly of manganese and iron oxides, but in places are relatively rich in nickel, copper, cobalt, molybdenum, and vanadium. Nodules are abundant on the surface of the deep ocean floor over large areas. Current commercial interest is focused on nodules with a combined nickel-copper content of 1.8 percent or more. The most promising area thus far known for such metal-rich nodules lies in the northeastern equatorial Pacific between the Clarion and Clipperton fracture zones shown in Fig. 1 (6). The size of this area is about 2.5 million square kilometers, and from the publicly available data it appears that about half of it contains nodules in concentrations or abundances greater than 5 kilograms per square meter and averaging nearly 12.0 kg/m$^2$. If only 20 percent of the nodules is recoverable and the moisture content is 30 percent, the Clarion-Clipperton prime area would contain about 2.1 billion dry metric tons of potentially recoverable nodules averaging about 1.3 percent nickel, 1 percent copper, 25 percent manganese, 0.22 percent cobalt, and 0.05 percent molybdenum. This amount would be enough to support about 28 mining operations, each producing 75 million tons over its lifetime.

These estimates are based on approximately 650 observation points, including about 360 stations for which analyses are available. Although the data base for the estimates must be described as weak, the consistency in the metal content of nodules in the Clarion-Clipperton area justifies considerable confidence in the average grades of the metals described.

Much more uncertain are the estimates of nodule concentration or abundance, both because of uncertainty in the measurement itself and because concentration has been estimated at only about one-fourth of the stations. The uncertainties involved in estimating as a result of differences in concentration data are shown by comparing the above estimate with those of Bastien-Thiry *et al.* and Lenoble (7) for the same area. They summarized the results of the extensive but unpublished surveys made by a French group and concluded that recoverable tonnage is sufficient to support only 8 to 11 and 3 to 10 mining operations, respectively, each producing 3 million to 4 million wet metric tons for 20 years.

Because the French data base appears to be larger than the publicly available information described above, the French estimates of the magnitude of the Clarion-Clipperton resource may be the more reliable. Both estimates, however, indicate that the area contains extensive deposits of metal-rich nodules, clearly not of unlimited dimensions, but large enough to justify the commercial interest that the area has received in recent years.

The nodules in the Clarion-Clipperton area lie on radiolarian ooze and clay. Arrhenius (8) has suggested that radiolarite silica, valuable in ceramic uses, might be an associated product of nodule mining. The extremely high moisture content of the ooze, however, poses difficult transport and processing problems.

Are deposits similar to those in the Clarion-Clipperton area likely to be found elsewhere? Not enough information is publicly available to answer that question quantitatively, but it can be answered affirmatively in qualitative terms, since at least small groups of metal-rich samples are known at several other localities in the Pacific and Indian oceans. Several authors (9) have attempted to estimate the magnitude of such resources, with results ranging up to a total, including the Clarion-Clipperton area, equal to approximately 6.6 times the resources of the Clarion-Clipperton zone (10). Many believe the potential in such rich deposits is much lower. The prospects for discovery of another area containing recoverable nodules of the Clarion-Clipperton tenor and size appear to be poor at this stage, but it does seem likely that some now unknown number of smaller, but nevertheless potentially minable, areas will be found.

For the longer range, advances in nodule mining and processing technology, coupled with the depletion of higher grade sources, probably will bring within economic reach nodule deposits of a

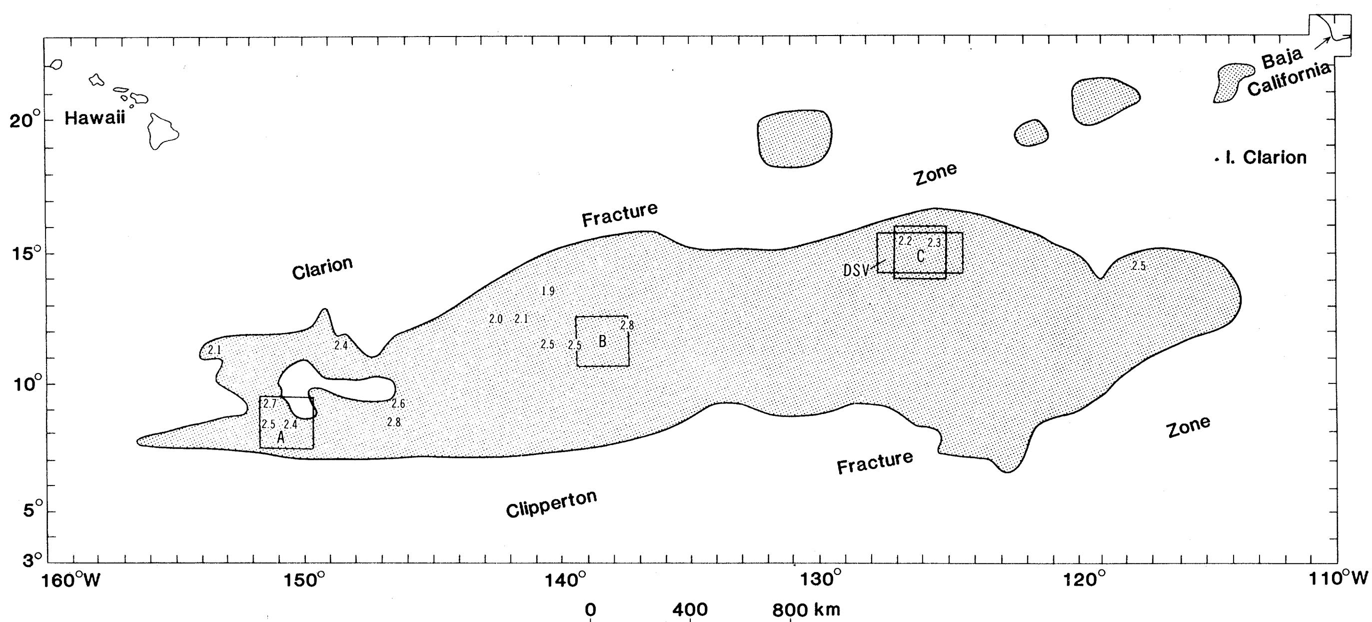



Fig. 1. Areas in the northeastern equatorial Pacific in which manganese nodules contain more than 1.8 percent nickel plus copper. The numbers represent the average percent nickel plus copper of samples in 1° squares where analyses are available at five or more stations. The rectangles outline the Deepsea Ventures, Incorporated (*DSV*) "claim" and the Deep Ocean Mining Environmental Studies program sites (*A*, *B*, and *C*).

lower grade than are being considered for mining now. Several possibilities may receive attention. Although the nodules vary widely in their composition over the world oceans, metals are concentrated in three distinct types. One type is the nickel-copper-rich nodules of the Clarion-Clipperton variety, which is mainly formed in the equatorial regions. Another type, high in cobalt (1 percent or more) and low in nickel and copper, appears to be most commonly formed on sea mounts. The third is high in manganese (35 percent or more) but low in the other metals, known mainly on the eastern side of the Pacific Basin. At the present price of $25 a pound for cobalt, the cobalt-rich nodules would be an attractive target. New production of cobalt, however, almost certainly would lead to a sharp drop in price, conceivably to its pre-1978 price of $3 to $4 a pound. The time may come, however, when such deposits may be of commercial interest, and the same may be said of the manganese-rich nodules.

Another, and perhaps more likely, possibility is that economic changes and technological advance may make it possible to mine lower quality nodules for recovery of their nickel, copper, cobalt, and possibly manganese, molybdenum, and vanadium as is now contemplated for the Clarion-Clipperton nodules. According to Cronan (*11*), the world average for nodules from abyssal depths is 0.54 percent nickel, 0.37 percent copper, 0.26 percent cobalt, and 16.8 percent manganese, and in some areas the nodules consistently contain more than average amounts. In the northeast equatorial Pacific area shown in Fig. 1, for example, the nodules outside the Clarion-Clipperton prime area average 1.5 percent nickel plus copper, 0.24 percent cobalt, and 23 percent manganese. Estimates of the amounts that might eventually be recoverable from any of these deposits would be entirely conjectural, but it seems safe to assume that advancing technology will eventually allow production from resources that are lower grade than those being considered for mining now. It also appears probable that advancing mining technology will in time allow the recovery of nodules from the sea floor to increase from the 20 percent assumed for first-generation mining to perhaps as much as 50 percent in third-generation mining, as estimated by Holser (*10*), with the same net effect as discovery of additional high-grade deposits.

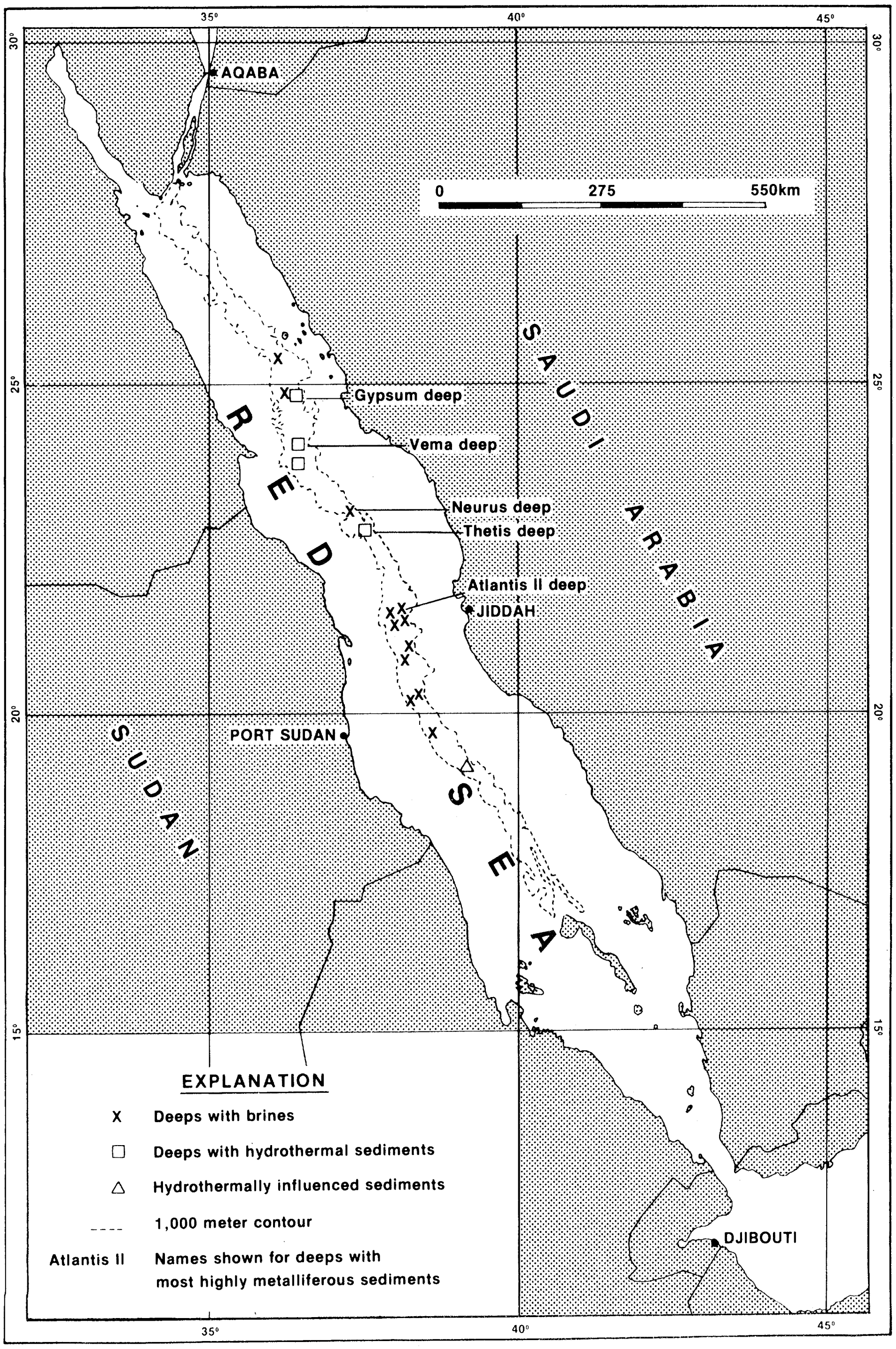



Fig. 2. Hot brine deeps in the Red Sea. [Modified from (*16*)]

## Metalliferous Deposits Associated with Hydrothermal Systems

Other potentially important deep seabed resources are metalliferous deposits associated with hydrothermal systems along the oceanic ridges or ocean floor spreading centers. The most promising found thus far consist of metal-bearing hot brines and muds first reported by a Woods Hole expedition in 1965 (*12*) in a series of deep basins along the central rift valley beneath the Red Sea (Fig. 2). The largest is the Atlantis II deep with an area of about 56 $km^2$. The sulfide muds there are about 1 m thick and consist mainly of pyrite, sphalerite, and chalcopyrite. They are overlain by 7 to 8 m of iron oxide and iron silicate muds that also contain small amounts of other metals. Bischoff and Manheim (*13*) estimate that the upper 10 m of sediment in the Atlantis II deep averages 29 percent iron, 3.4 percent zinc, 1.3 percent copper, 0.1 percent lead, 54 parts per million (ppm) silver, and about 0.05 ppm gold. Contemplating recovery of all of these metals except iron, they estimate that the upper 10 m of sediment in the Atlantis II deep would contain about 2.9

million tons of zinc, 1 million tons of copper, 800,000 tons of lead, 4,500 tons of silver, and 45 tons of gold. Hackett and Bischoff (*14*) later revised the estimates for zinc and copper to 3.2 million and 0.8 million tons, respectively. Compared with land reserves, these amounts are not significant, since they represent only 2 percent of zinc reserves and much lower percentages for the other metals. But viewed as a deposit potentially suitable for mining, these quantities are large indeed. Bischoff and Manheim (*13*), Hackett and Bischoff (*14*), and Mustafa and Amann (*15*), in fact, estimated their gross value to be of the order of a few billions of dollars. Inasmuch as metalliferous muds are known in other Red Sea deeps and extend in places to sediment depths greater than 10 m (*16, 17*), these estimates could prove to be conservative applied to the region as a whole.

The Red Sea deposits, formed in brine pools fed by hydrothermal solutions that draw part of their dissolved matter from older salt beds on the flanks of the rift, may be unique in their brine pool association. A similar association is not likely to be found with ridge systems in the open ocean. Several occurrences of metalliferous deposits have been found in the open ocean, however, in association with spreading ridges. One of the most exciting is the discovery by the CYAMEX expedition in 1978 (*18*) of metalliferous sulfide deposits associated with inactive hydrothermal vents along the axis of the East Pacific Rise in the vicinity of latitude 21°N. Preliminary analyses show as much as 29 percent zinc and 6 percent copper. Additional analyses by Hekinian and others (*19*) show as much as 50 percent zinc and 290 to 480 ppm silver. The RISE project of 1979, several kilometers to the southwest of the CYAMEX area, identified numerous active hydrothermal vents, some emitting hot-water jets with temperatures as high as 380 ± 30°C from sulfide mineral chimneys rising from basal massive sulfide mounds that rest on fresh basalt pillows or flows (*20*). Some of the vent waters are black with sulfide particulates. Some 25 distinct sites with water temperature anomalies were found along a zone about 100 m wide and 6 km long. They include lower temperature water discharges (around 20°C in 2°C surrounding) surrounded by dense populations of crabs, clams, and giant tube worms similar to those discovered to the south at the Galápagos spreading center in 1977 (*21*).

The hydrothermal waters of the East Pacific Rise are believed to result from the invasion of seawater into newly formed basaltic crust along fractures (*19*). Bischoff (*22*) proposes that seawater in convecting systems driven by heat from cooling basaltic rock near the top of the magma chamber at depths as much as 2 km below the sea floor reaches temperatures as high as 420°C at pressures of 450 bars. Reacting with basalt, the heated seawater leaches copper, zinc, barium, and sulfur from the basalt, along with much larger amounts of calcium, silica, and iron. As the water rises, it expands rapidly, becoming more gaslike as the pressure declines to the hydrostatic pressure (250 to 290 bars) of the sea floor along the ridge crest. Because the solubilities of metal sulfides in water of this temperature decrease by tens of orders of magnitude over such a pressure drop, sulfides are precipitated in the upper part of the crust and on the sea floor, along with barite, anhydrite, and pyrite. Sphalerite is much more abundant than pyrite in many of the samples, even though the concentration of iron in the fluid must greatly exceed that of zinc. Bischoff thinks that either pyrite predominates in the subsurface or that the excess iron precipitates from the bottom waters as colloids that become dispersed throughout the crestal area as metalliferous sediment.

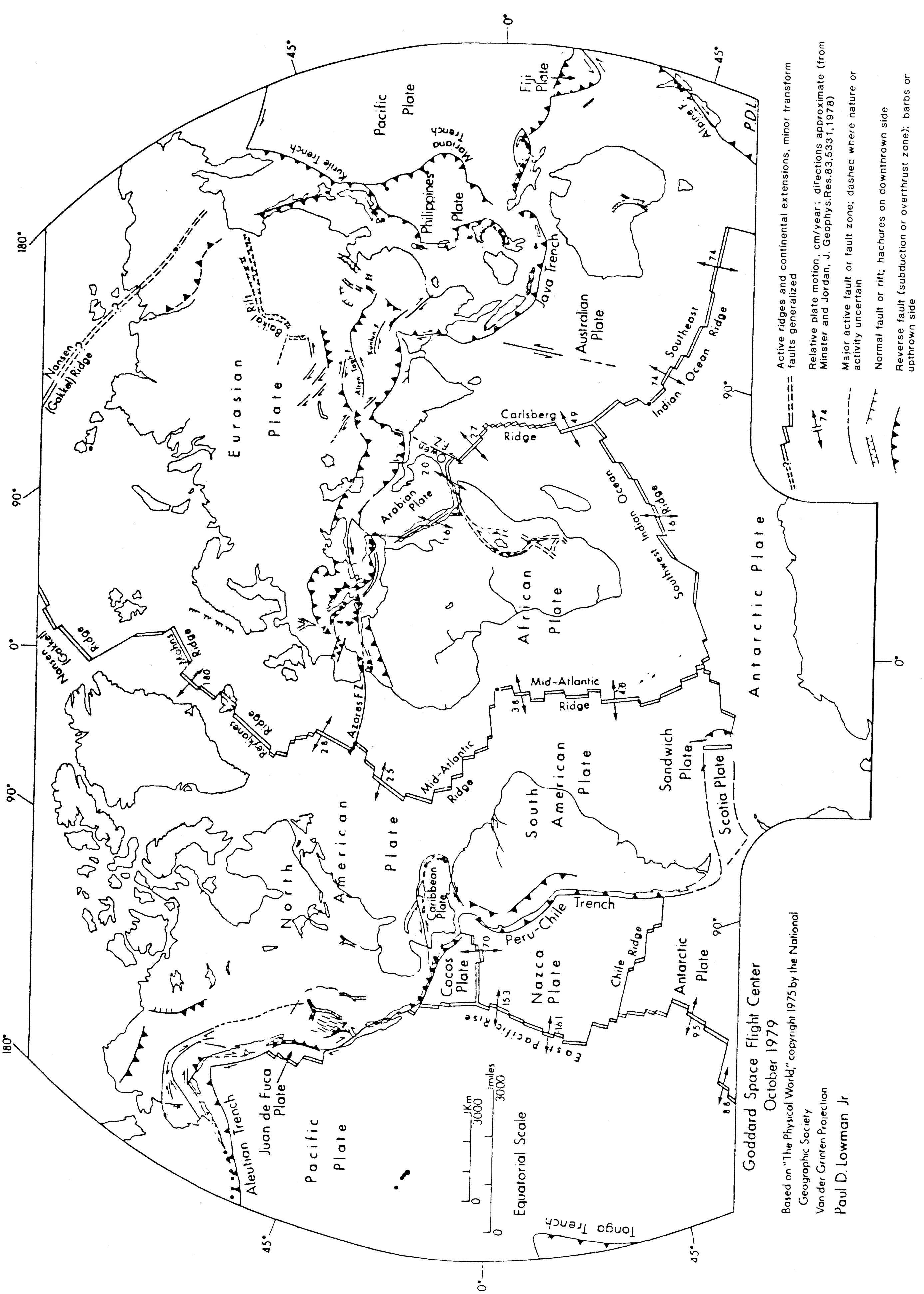
Metalliferous sediments containing as much as 9.9 percent iron, 4.5 percent manganese, 938 ppm copper, 250 ppm zinc, 85 ppm nickel, 240 ppm cobalt, 153 ppm molybdenum, and 300 ppm vanadium had previously been reported from the East Pacific Rise (*23*). Similar deposits, 10 to 20 m thick, have been found in several drill holes to overlie basalt over much of the equatorial Pacific sedimentary basin, both east and west of the East Pacific Rise (*24*). They were evidently deposited on newly formed basaltic crust in or near the axial zone of spreading and brought to their present geographic position as a result of continued sea-floor spreading. Metalliferous sediments are also known in the Bauer Basin along the eastern flank of the East Pacific Rise (*25*). Sediments there average 4 percent manganese, 0.12 percent copper, 0.1 percent nickel, and 0.0354 percent zinc (*26*). The Bauer Basin, about 3.9 million square kilometers in size, contains 360 trillion tons of such sediment on a dry salt-free basis (*27*).

Multicolored sediments containing small amounts of sphalerite and pyrite were found in Deep Sea Drilling Project hole 105 in a zone about 50 m thick near the continental margin off Cape Hatteras. Although the zone is some 335 m above basalt and must have been deposited a long distance from the mid-Atlantic spreading center, Lancelot *et al.* (*28*) consider the spreading center to be the source of the metals.

The hydrothermal systems associated with oceanic ridges must be extensive (Fig. 3). No evidence of sulfide deposits has been found on the Mid-Atlantic Ridge and the Cayman Trough where they have been examined, and it may be that mineral deposits in the ridge systems are mainly associated with medium-rate (total separation ~ 6 centimeters per year) and faster spreading centers (*29*). Even so, it seems likely that large metalliferous deposits—including deposits of the type just described that were formed on the sea floor and later buried by lava flows or sediments, as well as deposits emplaced beneath the surface—exist in oceanic crust in the present ridge systems and older ones as well. In addition to the hydrothermal deposits, the kimberlite and chromite discovered by Soviet expeditions in the Indian Ocean indicate that ores which differentiated from mafic and ultramafic magmas deep within the oceanic crust and upper mantle have been brought to the present ocean floor in some places. Chromite deposits are known on land in association with ophiolites and, in fact, the highest grade deposits known have such an association (*30*).

**Proposed Provisions for Seabed Mining**

Negotiations on seabed mineral exploitation are still under way in the Law of the Sea Conference and hence the final form of the relevant terms is yet to be determined. If, however, a treaty is agreed to, as seems likely, it is almost certain to provide for the following general principles bearing on subsea mineral resources (*31*): (i) coastal state jurisdiction over the seabed resources of a 12-nautical-mile Territorial Sea and an Exclusive Economic Zone of 200 nautical miles measured from the same baseline; (ii) coastal state jurisdiction over the major part of the seabed resources of the continental margin where it extends beyond the Exclusive Economic Zone, with the coastal state sharing revenues with the international community after the first 5 years of production; (iii) international licensing of exploration and exploitation of seabed resources in the "Area" beyond the limits of national jurisdiction through an International Seabed Authority governed by an Assembly and a Council and assisted by a Secretar-



Eurasian Plate
Pacific Plate
Fiji Plate
Philippines Plate
Australian Plate
Arabian Plate
African Plate
Antarctic Plate
North American Plate
South American Plate
Caribbean Plate
Cocos Plate
Nazca Plate
Juan de Fuca Plate
Pacific Plate
Sandwich Plate
Scotia Plate
Antarctic Plate
Kurile Trench
Mariana Trench
Java Trench
Aleutian Trench
Peru-Chile Trench
Tonga Trench
Nansen (Gakkel) Ridge
Baikal Rift
Altyn Tagh F.
Kunlun F.
Carlsberg Ridge
Owen F.Z.
Southeast Indian Ocean Ridge
Southwest Indian Ocean Ridge
Mid-Atlantic Ridge
Azores F.Z.
Reykjanes Ridge
Mohns Ridge
Chile Ridge
East Pacific Rise
Alpine F.
PDL
Active ridges and continental extensions, minor transform faults generalized
Relative plate motion, cm/year; directions approximate (from Minster and Jordan, J. Geophys.Res.83,5331,1978)
Major active fault or fault zone; dashed where nature or activity uncertain
Normal fault or rift; hachures on downthrown side
Reverse fault (subduction or overthrust zone); barbs on upthrown side
Equatorial Scale
0 3000 Km
0 3000 miles
Goddard Space Flight Center
October 1979
Based on "The Physical World," copyright 1975 by the National Geographic Society
Van der Grinten Projection
Paul D. Lowman Jr.

Fig. 3. Tectonic map showing active oceanic ridge systems of the deep ocean floor with which hydrothermal systems are likely to be associated and where, in places, sulfide minerals may have been deposited. Ridges where the spreading rates are ~ 6 cm a year or faster appear to be the most favorable. [Courtesy of Paul D. Lowman, Jr., Goddard Space Flight Center]

iat, with an associated operating organization called the Enterprise to explore and exploit minerals from the Area in parallel with other operators; and (iv) protection of the marine environment from harmful effects arising from activities in the Area related to mining.

A number of provisions have been devised to allow states party to the convention or their nationals to carry out exploration and exploitation of mineral resources of the Area while at the same time, and presumably at the same pace, enabling the Authority, through the Enterprise, to develop seabed resources as the agent of mankind as a whole and especially the developing countries. Under this parallel system, as it is called, aspiring contractors would bring to the Authority a description of two mine sites of estimated equal value. The Authority would reserve one for exploration and exploitation by the Enterprise alone or in joint arrangements with others. The international community (largely the industrialized countries) would furnish funds for one initial commercial-scale project by the Enterprise, although it might use them in several joint ventures. The funds would be evenly divided between interest-free loans and guaranteed interest-bearing loans. During an initial period (probably 5 to 10 years), contractors would be obliged to transfer mining technology to the Enterprise on "fair and reasonable commercial terms and conditions" if the Enterprise finds that it is not available in the open market. Assistance would also be provided by governments in obtaining processing technology if the Enterprise finds that it is not otherwise available. To protect the markets of land-based producers of nodule metals for an initial 20-year period, aggregate production would be limited to a portion of the projected growth in the consumption of nickel. To prevent any one country from monopolizing seabed production or from holding all the choice sites because of its leadership in the development of seabed mining capability, some antimonopoly provisions are likely to be included.

Resources beyond the limits of national jurisdiction are considered in the draft convention (*31*) to be the common heritage of mankind. To enable the international community, and particularly the developing countries, to share in the benefits of resource exploitation, four kinds of payments by nodule producers are likely to be required (the probable amounts are shown in parentheses): (i) an application fee ($500,000); (ii) an annual fixed charge ($1 million) prior to the commencement of production (after production begins the contractor would pay either the fixed fee or a production charge, whichever is larger); and either (iii) a production charge (5 percent of the market value of processed metals during the first 10 years of commercial production and 12 percent during the next 10 years), called the single system, or a share of the net proceeds attributable to the mining part of the operation (35 to 50 percent) plus a production charge (2 percent) during the first period of commercial production and a larger profit share plus a production charge during the second period (50 to 70 percent and 4 percent, respectively). The details of the mixed system, as the profit share plus royalty is called, are complicated, but its most important features are that both the percentage of the profit share to be paid and the time when the second period would begin are tied to the profitability of the operation.

Although some of the provisions of the negotiating text, for example, those referring to production limitation, antimonopoly and financial arrangements, are applicable only to manganese nodules, the Authority would administer and license exploration and exploitation of all other mineral resources in the Area as well.

Still to be negotiated are critical provisions concerning the protection of investments made prior to the signing of the treaty, the formation of a preparatory commission to draft rules and regulations that would go into effect when the treaty enters into force, and the terms under which the treaty would enter into force. Failure to reach agreement on these issues conceivably could lead to a conference stalemate.

Table 1. Massachusetts Institute of Technology baseline cost and revenue estimates of a nodule production operation. Assumptions: production, 3 million tons per year for 25 years; nodule concentration, 9.8 kg/m$^2$; metal content, 1.5 percent nickel, 1.3 percent copper, and 0.25 percent cobalt.

| Operation | $ Millions |
|---|---|
| | *Expenditures* |
| Research and development | 50.00 |
| Prospecting and exploration | 16.40 |
| Capital costs | 493.00 |
| | 559.40 |
| Annual operating expenses | 100.5 |
| *Annual production (lb × $10^6$)* | *Revenues* |
| Nickel 85.5 | 171.0 |
| Copper 74.1 | 52.61 |
| Cobalt 8.64 | 34.56 |
| Internal rate of return, 18.14 percent | 258.17 |

## Prospects for Seabed Mineral Production

What are the prospects for seabed mineral production? For the areas under national jurisdiction, production is certain to increase, particularly with respect to oil and gas and construction materials, supplies of which are becoming short onshore near expanding coastal cities. Subsea resources on or beneath the continental margins are potentially as diverse as those currently produced from the continents; and if underground exploration and extraction technologies are improved, it is possible that the range of minerals produced from the continental margins will expand. The prospects for such expansion in the foreseeable future, however, are moderate at best, although the potential for the long term should not be discounted. Substantial offshore mining is in progress off eight European countries and Japan, but none is in progress or in prospect on the federally controlled U.S. Outer Continental Shelf because the regulations to authorize it have not been formulated.

The Red Sea deposits are midway between Saudia Arabia and Sudan and within what would be their Exclusive Economic Zones under conference proposals. These countries have negotiated an agreement to develop the deposits jointly, and research and development on the recovery technology have been in progress under a contract with a West German firm. According to Ross (*32*), the prospect is that the "Red Sea metalliferous muds probably will be mined before the end of the 1980's." Whether or not that proves to be true, the Red Sea metalliferous muds constitute a resource certain to be used sometime in the future.

Also within national jurisdiction are parts of the deep ocean floor, and not to be ruled out is production of manganese nodules (for example, those near Isla Clarion) or sulfide deposits (those of the East Pacific Rise) where they lie within the Exclusive Economic Zone.

As for the area beyond national jurisdiction, the prospects for production are shrouded with uncertainties, perhaps the most important of which relate to the outcome of the negotiations now under

Table 2. Comparison of Authority's 25-year income and contractor's internal rate of return (IROR) under various assumptions. Case A, a low-profit situation with higher costs and lower grade ore; case B, the same as A, but with metal prices increasing 1 percent per year; case C, the MIT baseline case; case D, the MIT baseline case but with mid-1979 metal prices; case E, the MIT baseline case with costs increased by 25 percent and prices increasing 2.5 percent a year; case F, the MIT baseline case with prices increasing 2.5 percent a year.

| Case | Single system of payments | | Mixed system of payments | |
|---|---|---|---|---|
| | Income ($ millions) | IROR (%) | Income ($ millions) | IROR (%) |
| A | 527 | 5.1 | 258 | 6.1 |
| B | 638 | 7.9 | 429 | 8.5 |
| C | 599 | 13.9 | 574 | 13.8 |
| D | 807 | 20.1 | 1015 | 19.5 |
| E | 1312 | 20.9 | 1791 | 20.2 |
| F | 1312 | 25.0 | 1964 | 23.9 |

way or to legislation that might be passed by industrial countries if efforts to conclude a treaty are unsuccessful. Some of the provisions of the draft convention (*31*) have been severely criticized as being so onerous as to make mining impossible [for example, see (*32*)]. If it is assumed, however, that the industrial countries will not sign and ratify a treaty that does not give access to seabed minerals under reasonable terms, the uncertainties reduce to those concerning technological and economic feasibility. With respect to the technology, eight consortia, representing some 77 participating companies and organizations from the United States, Canada, Western Europe, and Japan, have been formed to investigate the feasibility of mining and processing nodules from the deep ocean floor (*33, 34*). Their methods and progress are, of course, held as trade secrets; but several of them have announced success in attempts to lift nodules and have expressed confidence in their ability to recover the metals.

As for the economic uncertainties, it is impossible for those outside the industry, or inside it for that matter, to make accurate estimates of nodule production costs and revenues. Arthur D. Little, Inc. (*35*), and the Department of Ocean Engineering at the Sloan School of Management at the Massachusetts Institute of Technology (*36*), however, developed cost and profit models in 1977 and 1978, respectively, in which the components of a nodule production operation can be varied to test alternative assumptions.

Arthur D. Little, Inc., analyzed costs and revenues for three extraction processes involving recovery of nickel, copper, cobalt, and molybdenum in the ammonia leach process, and the same metals plus manganese in the hydrochloric acid leach and pyrometallurgical processes. In their base case, they estimated a discounted cash-flow return on investment of 10.9, 19.7, and 14.0 percent, respectively, for the three processes, with income tax payments under U.S. tax laws and before any payments to the international community.

The MIT group assumed recovery of only nickel, copper, and cobalt. For its baseline model—which assumes nodule production of 3 million tons a year for 25 years, a combined nickel-copper content of 2.8 percent, and income tax payments under U.S. tax laws—it estimated an internal rate of return (IROR) of 18.14 percent. Other assumptions and estimates are summarized in Table 1. Compared with the resource data discussed earlier for the Clarion-Clipperton area, the assumed combined nickel-copper content of 2.8 percent is too high, but the assumed nodule concentration is a little lower than the average of the publicly available measurements. Although the study was made in 1978, prices for the metals are now much higher than assumed in the baseline model.

The MIT study has been strongly criticized recently in a report prepared by members of the Research Institute for International Techno-economic Co-operation of the Technical University of Aachen and the Battelle Institute at Frankfurt on the grounds that the MIT team badly underestimated costs in every phase of the production process and hence overestimated its profitability. Tinsley (*37*) also estimated much lower profitability, 8.5 to 9.5 average cash flow as a percentage of investment before tax and an average annual net income after tax of 3.0 to 4.5 as a percentage of investment and with no allowance for the time value of the investment or revenue stream. In view of the great uncertainties at this stage, differences in cost estimates are inevitable. Perhaps the best indication of the chance for profitable production is that the private consortia continue to invest hard dollars in research and development, although at a reduced rate now compared to the last few years.

Under proposed financial arrangements previously outlined, income to the Authority over a 25-year period and the contractors's IROR have been estimated for several cases (*31*), as shown in Table 2. Under these assumptions, payments to the Authority would range from $527 million to $1312 million with the single system and $258 million to $1964 million with the mixed system. The IROR under the latter would range from 6.1 to 23.9 percent. To put these last figures in perspective, most manufacturing companies have an IROR in the range of 13 to 15 percent. Mining companies may operate in the same or even a lower range, but they prefer not to take on a high-risk venture unless it offers the prospect of at least 20 percent IROR or more. Considering the risk associated with ocean nodule projects, Arthur D. Little, Inc., believes that the prospect should be for a 30 percent rate of return for the first projects (*35*).

The mixed system of payments, although it is complicated, gives the Authority substantial revenues if the operation is highly profitable and gives the operator a chance to keep going if it is not.

The outcome of further negotiations on financial arrangements remains to be seen, but assuming that agreement is reached and that mining proves to be profitable, the amount of metals that could be produced over the first 20 years would be controlled by a production limitation formula. The details of this formula are yet to be agreed upon, but the one being considered would limit the production of nickel from nodules in the area beyond national jurisdiction to the sum of all growth in nickel consumption in the 5 years prior to the beginning of commercial production plus 60 percent of the projected annual growth in nickel consumption thereafter. Table 3 shows the allowable production of nickel from the manganese nodules under the production limitation formula of the Informal Composite Negotiating Text (ICNT) (revision 2) and alternative U.S. Bureau of Mines forecasts as to the rate of growth of the world market (*38*). Table 4 shows the Bureau of Mines forecast of probable demand for the nodule metals in the year 2000 along with current estimates of land reserves. As may be seen from the tables, at the probable level of world demand in the year 2000, allowable production of nodule nickel could supply about 32 percent of the projected demand, copper about 2 percent, cobalt 116 percent, and manganese 47 percent. Comparison of cumulative demand from 1975 to 2000 with land reserves indicates that physical depletion of land reserves would not limit production at the projected rates, if the metals are available to the world market. A possible exception might be cobalt, which is the one metal for which allowable seabed production, if realized, would produce a surplus over projected world demand in the year 2000. Identified resources of cobalt are large, however, and it is by no means certain that land sources would be close to exhaustion by that time.

It seems clear, then, that if nodules are produced at the rates proposed in the ICNT (revision 2) formula, it will be because the metals recovered compete successfully with those from other sources—with nickel from laterites, for example, the refining of which requires large amounts of energy—rather than because other sources will be exhausted.

Are any of the other kinds of metalliferous deposits likely to be commercially recoverable? Although the metalliferous sediments of the Bauer Basin and elsewhere represent a manyfold enrichment of copper, nickel, zinc, and manganese over their average abundance in the earth's crust, and although their aggregate gross value is nearly equivalent to the value of the lowest grade porphyry copper deposits now being mined on land, it is difficult to imagine that they would be minable in the foreseeable future. As for the sulfide deposits on the crest of the East Pacific Rise, not enough is known about their lateral extent, thickness, and physical character to judge whether or not they even offer promise of commercial recovery. At a price of $30 an ounce their value in silver alone would be $280 to $470 a ton if the grade is in the range of 290 to 480 ppm as reported by Hekinian and others (*19*).

Sulfide deposits of the type found on the East Pacific Rise are somewhat similar to the massive sulfide deposits associated with ophiolite complexes, mafic and ultramafic igneous rocks and associated sediments believed to have formed at ancient sea-floor spreading centers such as those in the Troodos complex on Cyprus (*29*). In fact, it has been known for some years that massive sulfide deposits are of submarine origin and that the Troodos deposits specifically formed at an ancient site of sea-floor spreading [see Sawkins (*39*) for a review of massive sulfide deposits and their geotectonic settings]. From the known deposits on land, two

Table 3. Allowable nickel production from deep ocean nodules under the provisions of the ICNT (revision 2) and the U.S. Bureau of Mines forecasts of growth in world demand for nickel, given for three values of annual growth in world demand. Assumes 3.5 percent growth in nickel production from 1975 to 1984 and start-up of module production in 1988.

| Year | Allowable nickel production ($10^3$ metric tons) | | |
|---|---|---|---|
| | 2.2 percent | 3.4 percent | 3.8 percent |
| 1988 | 202.5 | 202.5 | 202.5 |
| 1990 | 250.1 | 250.1 | 250.1 |
| 1995 | 361.9 | 397.4 | 409.5 |
| 2000 | 420.5 | 493.3 | 546.1 |

observations are pertinent to their possible occurrence on and beneath the present sea floor. One is that massive sulfide deposits should occur in other areas of active sea-floor spreading and in other tectonic settings where they have not yet been found subsea, such as the zones of convergence associated with island arcs, similar to the belt where the Kuroko-type deposits of Japan are believed to have formed. The other observation stimulated by knowledge of the massive sulfide deposits on land is that the deposits are localized, discontinuous, and irregular in their form. Therefore, rather detailed and costly exploration, including drilling, will be required to delineate and evaluate subsea massive sulfide deposits and, together with the problems that may be expected in subsea mining, may make recovery too costly. Scientific exploration doubtless will continue, however, and it is conceivable that subsea sulfide deposits will be found that would justify commercial exploration.

Beyond these possibilities are low-grade metalliferous muds and subsea floor hydrothermal and magmatic deposits that, although probably extensive, cannot be thought to be minable in the foreseeable future.

## Conclusion

Negotiations still under way at the Law of the Sea Conference are likely to result in the assignment of control over seabed resources to coastal states in a 200-mile-wide Exclusive Economic Zone and over the major part of the resources of the continental margin where it extends beyond that distance. Virtually all of the potential resources of oil and gas will thus be under coastal state jurisdiction.

Seabed resources in the area beyond national jurisdiction are likely to be regulated by an International Seabed Authority which will have an operating arm, the Enterprise, to produce seabed minerals. States party to the convention or their nationals aspiring to mine deep-sea mineral resources would identify two sites of estimated equal value of which the Authority will choose one to be reserved for later exploration and exploitation by the Enterprise or by developing countries. Transfer of mining technology to the Enterprise will be required in an initial 10- to 20-year period when it is not available on the open market, and some assistance also may be provided by government in obtaining processing technology if it is not otherwise available. To protect the markets of land-based producers, production of manganese nodules will be under controls related to growth in the production of nickel. Other provisions will prevent any country from monopolizing seabed resources. Under the financial arrangements proposed, the Authority will receive substantial revenues from operations when they are highly profitable, but operators may be able to continue when they are not.

The prospects seem reasonably good for production of nickel, copper, cobalt, and possibly manganese, molybdenum, and vanadium from nodules on the deep ocean floor in the northeastern equatorial Pacific by 1990. Present indications are, however, that nodule mining will not

Table 4. Forecasts of world demand for nodule metals (primary) and world reserves.

| Metal | World demand ($10^3$ metric tons) | | | |
|---|---|---|---|---|
| | Probable demand by 2000 | Allowable seabed production by 2000 (percent of probable demand) | Probable cumulative demand 1975 to 2000 | Land reserves |
| Nickel | 1,535 | 32 | 26,460 | 54,000 |
| Copper | 17,550 | 2 | 290,706 | 494,100 |
| Cobalt | 71.7 | 116 | 1,232 | 1,440 |
| Manganese | 19,890 | 47 | 358,200 | 1,800,000 |

be highly profitable, although continued investment on the part of several consortia in development of technology justifies the premise that it will be economically feasible. The prospects of production of metals from muds in some of the deeps in the Red Sea (within the proposed Exclusive Economic Zones of Saudi Arabia and Sudan) are also reasonably good.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