CHAPTER 11

ECONOMIC ASPECTS OF NODULE MINING

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INTRODUCTION

Although deep-sea manganese nodules were discovered over a century ago by scientists of the HMS *Challenger* expedition, few analyses of the nodules for the economically significant elements such as nickel, copper, cobalt and molybdenum were made in those early days and no consideration was given to these deposits as a possible commercial source of metals until the early 1950's when the mining of the nodules was advocated as a possible source of manganese (Mero, 1952). As the result of a haul of nodules taken in relatively shallow water (900 m) about 370 km east of Tahiti on the western edge of the Tuamoto Plateau during the 1957—58 International Geophysical Year (the nodules contained about 2% of cobalt, a valuable metal at that particular time), a study was initiated by the Institute of Marine Resources of the University of California to determine if it might be economic to mine and process the nodules for their cobalt, nickel and copper contents. The results of that study were favourable with respect to the technical and economic factors involved in mining and processing the nodules. All the research and development in this matter dates from the release of the report describing the results of that study (Mero, 1958). To the present time (1975) over $150 million* has been expended in the exploration of the nodule deposits and in the development of mining and processing systems. An additional $100 million is to be spent in the next few years in these activities. The lead in the development of the nodules as a commercial resource has been taken by such groups as Kennecott Copper Corporation, Deepsea Ventures, International Nickel Company, Inc. and the CLB Consortium, a group of about 20 major mining companies from six countries. However, considerable interest in the nodules has been expressed by at least 30 companies and governmental agencies from such countries as Western Germany, Great Britain, Japan, Canada, the U.S.S.R., France, Australia and New Zealand. Numerous academic studies concerning the nodules are being conducted at universities and governmental research agencies in many industrial nations and it appears that within the next five to ten years, assuming no political and/or legal interferences, the nodules

*All values in U.S. dollars

should be in full-scale, economic production as a valuable source of important industrial metals.

Some of the studies concerning the economics of mining and processing the nodules indicate that the nodules promise to be a much less expensive and essentially pollution-free source of metals (Mero, 1972), in which case the nodules can be considered as a revolutionary source of industrial metals. Other investigators, however, indicate that the production costs of metals from the nodules will be similar to those of present land sources of metals in which case the deep-sea deposits can be considered only as an alternative source of metals (Rothstein and Kaufman, 1973).

In addition to being an apparently economic and essentially inexhaustible source of metals, the nodules, because of their very large specific surface area (of the order of 100 to 300 m^2/gm of matrix material) and their porosity (of the order of 50 to 60% pore space) (Fuerstenau et al., 1973), are indicated to be valuable in gas absorption (Zimmerly, 1967) and catalytic applications (Weiss, 1968). The nodules have also been shown to be very efficient collecting agents for heavy metals in the purification of crude oil before refining (Weiss and Silvestri, 1973). As well as serving as a source of metals, the nodules may therefore be potentially useful in a variety of other industrial applications.

A number of sources on information are available describing the nodule deposits of the ocean floor in some detail (Murray and Renard, 1891; Agassiz, 1960; Bezrukov, 1960; Skornyakova and Zenkevitch, 1961; Skornyakova et al., 1962; Mero, 1965a; Cronan, 1967; Meylan, 1968; Glasby, 1970; Horn, 1972; Frazier and Arrhenius, 1972; Morgenstein, 1973b). These sources cover theories of formation, known occurrences, chemical and mineralogical composition, surficial concentrations and other associated data bearing on the economic geology of these deposits. These aspects are covered in other chapters. However, some of the information which has a bearing on the economics of the exploration and mining of nodule deposits is included here.

GEOLOGICAL CONSIDERATIONS

Deep-sea manganese nodules are found in all the oceans and many of the seas of the world. The dominant environmental conditions associated with nodule formation are a relatively oxidizing environment, which promotes the precipitation of manganese from seawater, and a low rate of sedimentation which prevents the slowly forming nodules from being buried. Nodule deposits will form in depths of a few metres of water and within a few kilometres of shore, given the proper chemical and physical environment. Although many factors may be involved in controlling the rate of formation of the nodules and their ultimate composition, concentration and size, these other factors do not appear to play a dominant role in the actual formation of the nodule deposits per se. Manganese deposits appear in many forms on the ocean floor, as crusts on rock outcrops, as coatings on blocks of pumice or other loose rocks, as fillings in coral debris, etc. At the present time, economic interest is being shown only in the deposits of the nodules which are most commonly found as loose-lying, roughly spherical concretions at the surface of the soft seafloor sediments. The nodules range in colour from light brown to earthy black, are friable, with a hardness that does not exceed three or four on the Mohs scale, and have a bulk density varying from 2.0 to 3.1. They generally vary from 0.5 to 25 cm in diameter but, on an ocean-wide basis, appear to average about 4 cm in diameter. The size range and distribution of the nodules are important in economic considerations for several reasons. A deposit of the nodules may be of very high surface density (that is the surface of the sea floor may be totally covered by closely packed nodules) but, if the nodules are of a small size (less than about 0.5 cm), the surficial concentration will be relatively low (of the order of 5 kg/m^2 of sea floor or less). Since the mining equipment will be required to deliver the nodules to the surface at rates in the order of 5,000 tons per day, the gathering head would be required to cover about 2 km^2 per day assuming a 50% recovery efficiency in such low concentration deposits. Using a 10 m wide gathering device, the collector head would therefore have to traverse the ocean floor at a velocity of about 10 km/h (5.4 knots). A more practical velocity for such devices would be in the order of 2 km/h. The larger-sized nodules also have the practical mechanical advantage in the ease with which they can be gathered from the sediments on which they are resting. In general, the larger the nodule, the easier it will be to winnow from the associated sediment.

A number of specific shapes of the nodules have been recognized by several investigators and attempts have been made to categorize the morphology of the nodules (Grant, 1967; Meyer, 1973). An interesting fact concerning the morphology of the nodules is that the grade of the nodules appears to vary with the nodule shape (Meyer, 1973). A rough estimate of the grade of a nodule deposit can therefore be made simply by recognizing its morphological classification; this may be possible by viewing the deposits with an underwater television system.

In some deposits the nodules vary considerably in size and appearance while in other deposits the nodules may exhibit a strong group resemblance and may show a relatively small size range. In some cases, the external form of the nodule depends on the shape of the nucleus. In other cases, the nucleus is not a single body, but several. When these nuclei are close to one another, the growing nodules may coalesce to form a single, slab-like nodule with several protrusions. In many areas, however, slab-like objects associated with the nodules are generally blocks of pumice thinly coated with manganese and iron oxides. The chemical nature of the nucleus does not seem to affect the deposition of manganese or the composition of the manganese and iron phases of the nodule. The nuclei may be carbonates, phosphates, zeolites, clays, remains of biota, silicates or various forms of altered and unaltered silica. Any hard object seems to be able to serve as a nucleus for the formation of manganese nodules. The most commonly observed are shards of highly altered pumice, the alteration probably taking place while the nodule is growing.

The hydrochloric acid-insoluble fraction of the nodules, which ranges from about 2 to 40% and averages about 25% of the bulk weight of the nodules, is practically free of the heavy metals that are characteristic of the acid-soluble fraction. The hydrochloric acid-insoluble fraction consists principally of clay minerals together with lesser amounts of quartz, apatite, biotite and sodium and potassium feldspars (Riley and Sinhaseni, 1958). These materials are generally very fine-grained and intimately mixed in the matrix of the nodule such that it appears that it would be impractical to attempt any physical separation of these gangue minerals before chemical processing of the nodules.

In addition to the matrix-included gangue minerals, any practical mining device will recover such extraneous materials as erratic boulders or other rocks, blocks of pumice, sharks' teeth and cetacean earbones; these materials can be mechanically separated from the nodules at the mine site. Such materials, in most instances, will not constitute more than about 5—10% of the total material dredged. Varying amounts of the clay or other sediments on which the nodules are resting will also be recovered; however, these materials are very fine-grained and can be screened from the nodules on the ship.

Although an understanding of the mineralogy of the nodules is important in any economic study, this subject is covered in some detail in other chapters of this volume (cf. Chapter 7). It is important to note, however, that the mineralogical or chemical character of the nodules does vary from location to location in the ocean and that changes in these characteristics do affect the processing of the nodules. Thus, the chemical character of the nodules is another factor to be considered in any nodule exploration programme. Until recently it had been assumed that the nickel, cobalt and copper elements in the nodules were present in solid solution as replacements for manganese and iron in the crystal structure of these elements. Recent work at the University of California at Berkeley has indicated that the bulk of the nickel, cobalt and copper are probably contained in the nodules as ions loosely attached to the surfaces of the manganese and iron crystallites (Fuerstenau et al., 1973). This observation is interesting from a processing standpoint as it indicates that these elements can be stripped from the nodules without putting either the manganese or iron into solution. This study also indicates that cobalt seems to be part of the iron crystal structure in certain nodules. To achieve high recovery efficiencies of this element, the iron crystal structure must therefore be disrupted. The percentage of the cobalt associated in this way in the nodules appears to vary from place to place. Thus, the chemical structure of the nodules is one more factor involved in determining the economic value of the deposits.

Surface density considerations

So far, surface densities of nodules ranging up to about 30 kg/m^2 of sea floor have been found at a number of locations centred around 20°N 114°W (Fig. 11-1). It should be noted, however, that the concentration of nodules in any given area can, and usually does, vary considerably over rather short lateral distances of a few kilometres or, in some cases, a few metres (Kaufman, 1974). Figs. 11-2 and 11-3 illustrate the great changes which can take place in the character of the nodule deposits over a lateral distance of

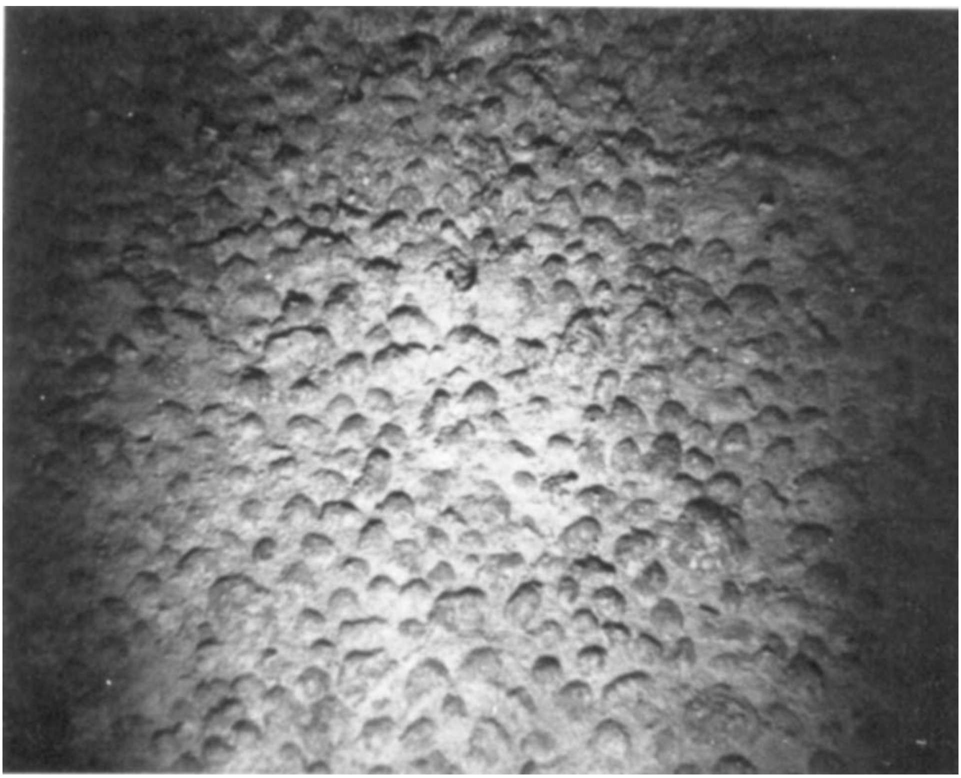


Fig. 11-1. A sea-floor photograph taken in 3,778 m of water at 20°00′N 113°57′W. The photograph covers a sea-floor area about 160 cm by 160 cm. The nodules average about 6 cm in diameter and the coverage would be about 80%. The concentration estimate is 30 kgm/m^2. (Photograph by N. Zenkevitch, Institute of Oceanology, Moscow, U.S.S.R.)

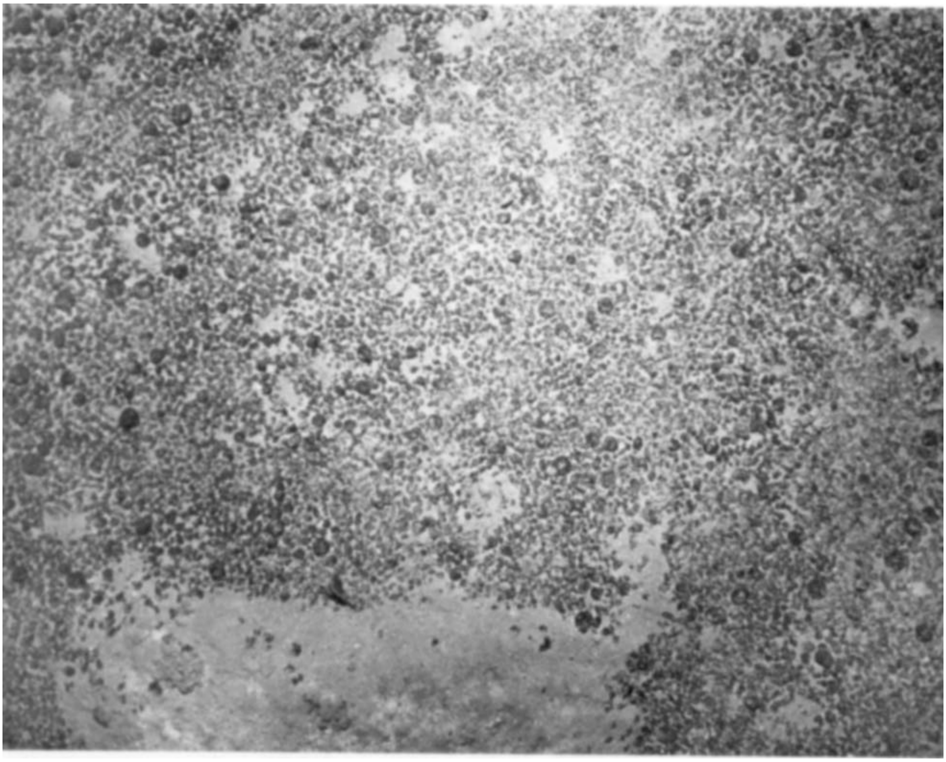


Fig. 11-2. A sea-floor photograph taken in 4,960 m of water at 12°55.8′N 141°32.6′W, showing a 90% coverage of nodules. The nodules show two distinct size groupings, one averaging about 6 cm and a second, which is more abundant, averaging about 2 cm in diameter. Possibly the nodules represent two families which started growing at different times due to variations in the physiochemical environment or sediment erosional patterns. The estimated concentration is about 25 kg/m^2. The white patches of sediment are probably weathered blocks of pumice which drifted to this location from volcanic eruptions before becoming water logged and sinking to the ocean floor. Smaller patches of sediment covering the nodule bed may be generated by burrowing animals on the sea floor. (Photograph by J. E. Andrews, University of Hawaii.)

about 90 km. Equally large changes are known to take place over lateral distances of a few metres. In some locations, however, such as the area around 20°N 114°W or in an area about 280 km north of Tahiti, a high and uniform surficial concentration of the nodules is maintained over many tens of kilometres and, possibly, hundreds of kilometres.

An overall oceanic average concentration of the nodules in economic grade deposits would be in the range of 5-20 kg/m^2. Within individual deposits, such as the 20°N 114°W field, the deposit may contain as much as one billion (10^9) tons of the nodules in a 100,000 km^2 area.

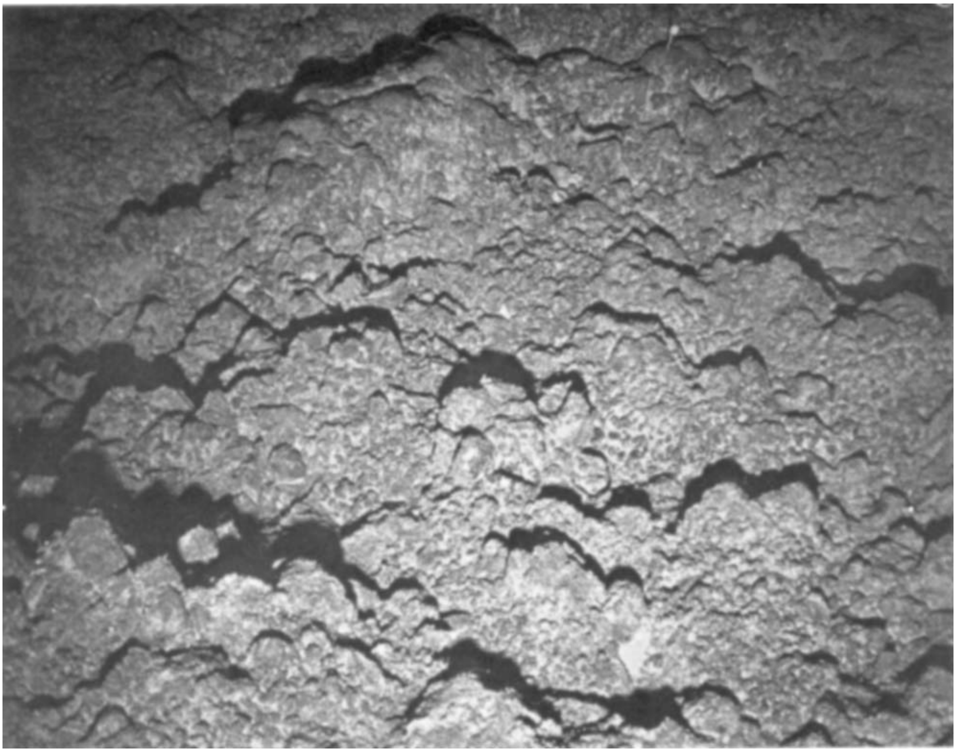


Fig. 11-3. A sea-floor photograph taken in 4,885 m of water at 13°18.0′N 140°45.4′W, showing manganese crusts, possibly covering soft sediments but, more probably, covering an outcrop of hard rock. Taken about 90 km from the location of Fig. 11-2, this photograph illustrates the extreme changes which can occur in the nodule deposits over relatively small lateral distances. Such changes are known to occur over distances of a few tens of metres. (Photograph by J. E. Andrews, University of Hawaii.)

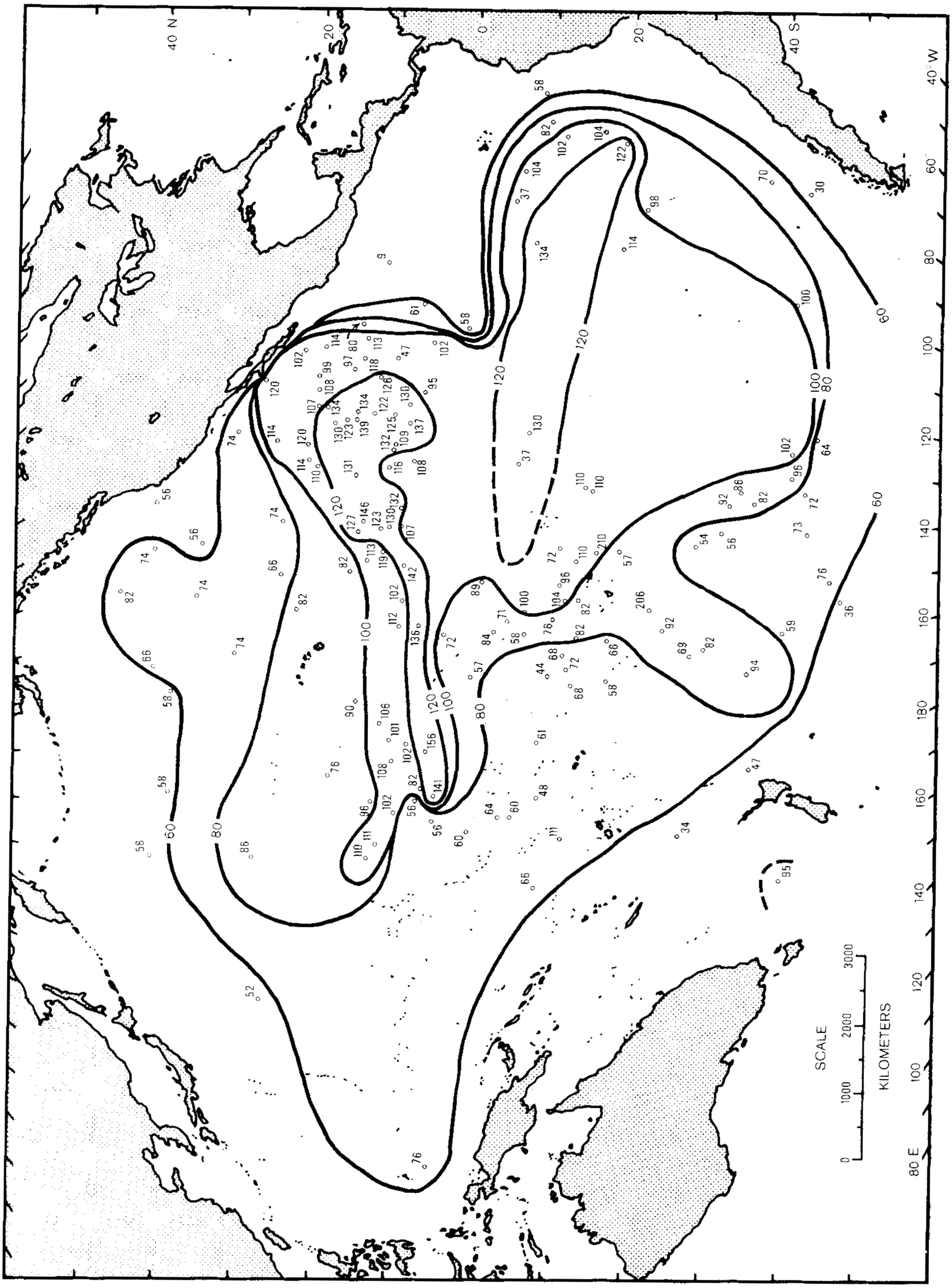
Much of the information concerning the continuity of manganese nodule deposits is available as the result of extensive exploration activities conducted by the *Valdivia* research group of West Germany. In one of that group's publications, the percent of ocean floor area covered by manganese nodules is shown for approximately a 2,000,000 km^2 area of the Pacific Ocean between the Clarion and Clipperton fracture zones in a region centred about 2,000 km southeast of Hawaii (Schultz-Westrum, 1973). On the basis of about 1,000 sample points, including some 200 photographic stations, a map was prepared showing the percent of sea floor covered by nodules. While the percent of the ocean floor covered by nodules is an interesting statistic and is of some general value in economic considerations, it is of little help in calculating the concentration of nodules in weight per unit area of the ocean floor, which, from an economic standpoint, is a more important statistic, unless the size distribution of the nodules is also known for the specific area. Using the coverage data given by Schultz-Westrum (1973) and, assuming an average nodule size of 4 cm and an average coverage of nodules in the area surveyed of 20%, the tonnage of nodules contained in this area can be estimated to be about 15 billion metric tons. An average coverage of 20% of 4-cm diameter nodules of bulk nodule density of 2.0 would yield a surficial concentration of nodules of about 10 kg/m^2 or about 10,000 metric tons per square kilometre. In some 15 areas covering a total of about 100,000 km^2, the surface coverage is indicated to be in excess of 50%. The area of which this coverage data is given is also that of relatively high-grade nodules.

Compositional considerations

If the dollar values of the metals contained in the manganese nodules of the Pacific Ocean, based on the following metal prices, $1.00 per percent manganese*, $7.90 per kilogram of cobalt, $4.00 per kilogram of nickel, and $1.80 per kilogram of copper, are plotted on a map and points of equal dollar value contoured (Fig. 11-4), it can be readily seen that the high-grade nodule deposits as outlined by the $120 of contained metals per dry weight ton of nodules, tend to be concentrated in a band extending eastward from about longitude 117°W between the 5°N and 10°N lines of latitude to about 143°W where the band broadens considerably to between 5°N and 20°N extending eastward to about the 120°W line of longitude. This high-grade area in the North Pacific appears to cover about 6,000,000 km^2.

*In the case of manganese, the cost of the ore is quoted in U.S. dollars per long ton unit, which is U.S. dollar per percent of contained manganese in the ore.

Fig. 11-4. A map of the Pacific Ocean showing the dollar value of the metals contained in a dry-weight ton of manganese nodules taken from various locations throughout this ocean. The dollar-value numbers of the various samples are calculated on the following basis: $2.20 per percent of manganese; $7.90 per kilogram cobalt; $4.00 per kilogram of nickel; and $1.80 per kilogram of copper. The regularity of the lines connecting points of equal dollar value would tend to indicate that additional extensive high-grade zones of nodules are unlikely to be found in this ocean. Local points showing dollar-value figures in excess of $200 per ton are of nodules showing very high cobalt assays. Such nodules are taken from the tops of seamounts and do not represent mineable deposits due to their limited extent and the roughness of the topography on which they are found. This map clearly reveals the high-grade regions of nodule deposits in the Pacific Ocean, i.e., those areas enclosed by the $120 per dry-weight ton of nodules contours.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KILOMETERS

In the South Pacific there appears to be a second high-grade area, covering about 6,800,000 km^2 of ocean floor. This area, however, is highly speculative being based on only three sample points with nodules containing greater than $120 of metals per ton of nodules. This South Pacific high-grade area may be a reflection of the same processes forming the high-grade area of the North Pacific. It is unlikely that the two high-grade areas would merge in the equatorial region because of the high organic productivity of these waters and consequent high calcareous sedimentation rates of this region.

Because of the relatively uniform distribution of the nodule dollar values, as indicated in Fig. 11-4, it is suspected that other high-grade areas of large lateral extent in the North or South Pacific Ocean are unlikely to be found. Smaller high-grade areas, covering a few tens of thousands of square kilometres, however, are very possible, especially in the basin and range areas of the west-central Pacific Ocean. Due to a paucity of data in the southeast-central Pacific it is rather difficult to predict what may occur in this area. Because of the rather high sedimentation rates throughout the area, it is not expected that extensive deposits of high concentration will be found there; however, that does not preclude the occurrence of occasional deposits containing high-grade nodules.

Those areas in the Pacific Ocean north or south of about the 40° lines of latitude are unattractive for mining operations, not only because of the general low-grade of the nodules in these areas but also because of the relatively high percentage of ice-rafted gangue materials found intermixed with the nodules. The weather in these areas is also not favourable for extended mining-vessel operations.

The western section of the North Pacific high-grade area may not be continuous as indicated in Fig. 11-4. Each individual sample point, especially in the westernmost region, may be an indication of a separate nodule deposit of limited extent within a separate valley. West of about 160°W, the floor of the Pacific Ocean is characterized by numerous mountain ranges and valleys. The separate valleys may contain nodule deposits and the character of the deposits, especially as concerns composition, may change markedly from one valley to the next.

The highest grade of nodules so far discovered occurs at a location of 6°N 170°W where the nodules assayed 2.3% Cu, 1.9% Ni, 0.2% Co and 35% Mn on a dry weight basis (Mero, 1965a). The nodules from this deposit, however, appear to be of a small diameter. Thus, although the coverage of nodules on the ocean floor is high at this locality, the surficial concentration may nonetheless be too low for economic mining. Further, little is known of the ocean floor topography in this specific area and the topography may be too rugged to permit efficient operation of mining equipment.

In that section of the high-grade area east of about the 150°W, the ocean floor is relatively devoid of high mountains or mountain ranges and the nodule deposits can be expected to be more uniform in grade and concentration. The nodule deposits can also be expected to be of much greater lateral extent in this area. The deposits may even be continuous throughout this area, although varying on average by a factor of 3 or so in surficial concentration and by a factor of about 2 in grade. Large patches of sea floor in this area will be devoid of surficial nodule deposits as the result of local high sedimentation rates. In addition, at least 20% of the area will be occupied by seamounts or abyssal hills showing manganese crusts or having slopes too steep to permit the operation of mining equipment.

Table 11-I lists the metal content of a representative number of samples throughout the high-grade region of the North Pacific and, where known, the surficial concentration of the nodules at the same or a nearby point. It should be noted that these are assays of a cross-section of a nodule or of the entire nodule from the various locations. Analyses of bulk samples of the nodules from any given location, including the detrital materials which may be dredged along with the nodules, generally tend to show assays about 10—20% lower than that of an entire nodule itself from the same dredge haul. In many cases, however, these detrital or gangue materials can be physically separated from the nodules on the mining vessel. The fine-grained detrital minerals included in the nodule matrix itself cannot be physically separated from the manganese-iron minerals of the nodules. The detrital minerals in the nodule matrix are, of course, included in the assays shown in Table 11-I. In general, the water content of freshly recovered nodules is in the range of 25—35% of the total weight of the nodule. Much of this physically entrained water will evaporate if the nodule is left exposed in air for any length of time. For this reason nodule assays are generally normalized to a dry weight basis with the drying taking place at 110°C to constant weight. Once dried, the nodule material must be kept in water-tight containers for the dried nodule will rapidly absorb moisture from the atmosphere.

Associated sediments

Manganese nodules are found associated with practically all types of pelagic sediments and, in special circumstances, with terrigenous sediments. In general, the nodules are associated most commonly with those pelagic sediments that are deposited the least rapidly. In fact, a principal environmental condition for the formation of deep-sea manganese nodules seems to be a very slow rate of formation of the associated sediments relative to the growth rate of the nodules. Micronodules, a common constituent of all sea-floor sediments formed under oxidizing conditions, are most probably the result of embryo nodules being buried in the sediments. Nodules are therefore most commonly found associated with the red clay type of pelagic sediment. Calcareous sediments appear, in general, to inhibit the formation of extensive beds of nodules, possibly because of the rapid rate of deposition

TABLE 11-I

Metal contents (%) of a representative sampling of manganese nodules from the North Pacific high-grade region

Station:	RC10-91	Chub 5	Amp 3P	DwBd 2	Msn 153	Msn 148	Wah 24	Msn K	
Lat. (N):	12°16′	15°00′	15°04′	10°26′	13°07′	9°06′	8°20′	6°03′	
Long. (W):	120°10′	125°26′	125°05′	130°38′	138°56′	145°18′	153°00′	170°00′	
Depth (m):	4,471	4,380	4,500	4,890	4,927	5,400	5,143	5,400	
Chemical analysis (dry-weight basis)									Averages
Manganese	31.5	27.8	23.2	28.0	29.0	30.9	24.9	35.2	28.8
Iron	5.1	12.2	6.0	9.4	5.9	6.2	7.3	6.4	7.3
Cobalt	0.16	0.47	0.23	0.32	0.38	0.31	0.25	0.19	0.29
Nickel	1.68	1.25	1.91	1.54	1.75	1.79	1.86	1.87	1.71
Copper	1.40	1.02	1.24	1.50	1.56	1.50	1.65	2.30	1.52
Contained metal values ($/ton)*	125.90	122.90	128.60	130.50	144.40	141.70	135.30	153.00	135.50
Sea-floor concentration (kg/m^2)	—	—	15	15	8	10	—	5	

*At the following metal values: $1.00 per percent of manganese; $7.90 per kg of cobalt; $4.00 per kg of nickel; and $1.80 per kg of copper.

of these sediments on the ocean floor. An interesting association of the nodules occurs in conjunction with siliceous pelagic sediments, a prime example of which is the high-grade band of nodules lying generally between the Clarion and Clipperton fracture zones. The very high porosity of these siliceous sediments may be responsible for the diagenetic processes at the seafloor—seawater interface which enhances the grade of the nodules in these regions (Horn et al., 1973a).

Motion of the superjacent water seems to be a common environmental characteristic in areas where nodules are forming. Ripple and scour marks are frequently seen in the fine sediments on which the nodules rest. To support growth of the nodules, these sea-floor water currents sweep the precipitating manganese and iron colloidal particles into contact with nuclei and they help to maintain an oxidizing regime on the ocean floor. Should a reducing regime develop as a result of stagnating water in an area where nodules have formed, any existing nodules would probably dissolve. The velocity of these ocean-floor currents is probably not in excess of 0.2 km/h, except near seamounts or in constricted deep-sea valleys where such currents may exceed a velocity of 2 km/h.

Nodules at depth in the sediments

Micronodules are frequently found distributed throughout the bulk of sediment cores taken in deep-sea sediments. In only a few instances do these micronodules constitute more than about 5% of the bulk of the material in the cores. Nodules greater than a centimetre in diameter are frequently found at discrete horizons in the sediment cores; however, such nodules are not found as frequently as they are found at the surface of these cores. Generally, the gravity cores do not penetrate the sediment column more than about a metre and this relatively shallow sampling of the sediments may erroneously favour this conclusion. The nodules found to date at depth in the sediments should not increase the estimated amount of nodules in the Pacific Ocean by more than a factor of 10. In any case, it probably would not be economic to work through, or dredge, a large bulk of sediment to recover those nodules which are buried in the sediment. At the present time, economic calculations concerning the mining of ocean-floor nodules should therefore consider only those nodules which are found at the surface of the sea-floor sediments.

Compositional zones of the manganese nodules in the Pacific Ocean

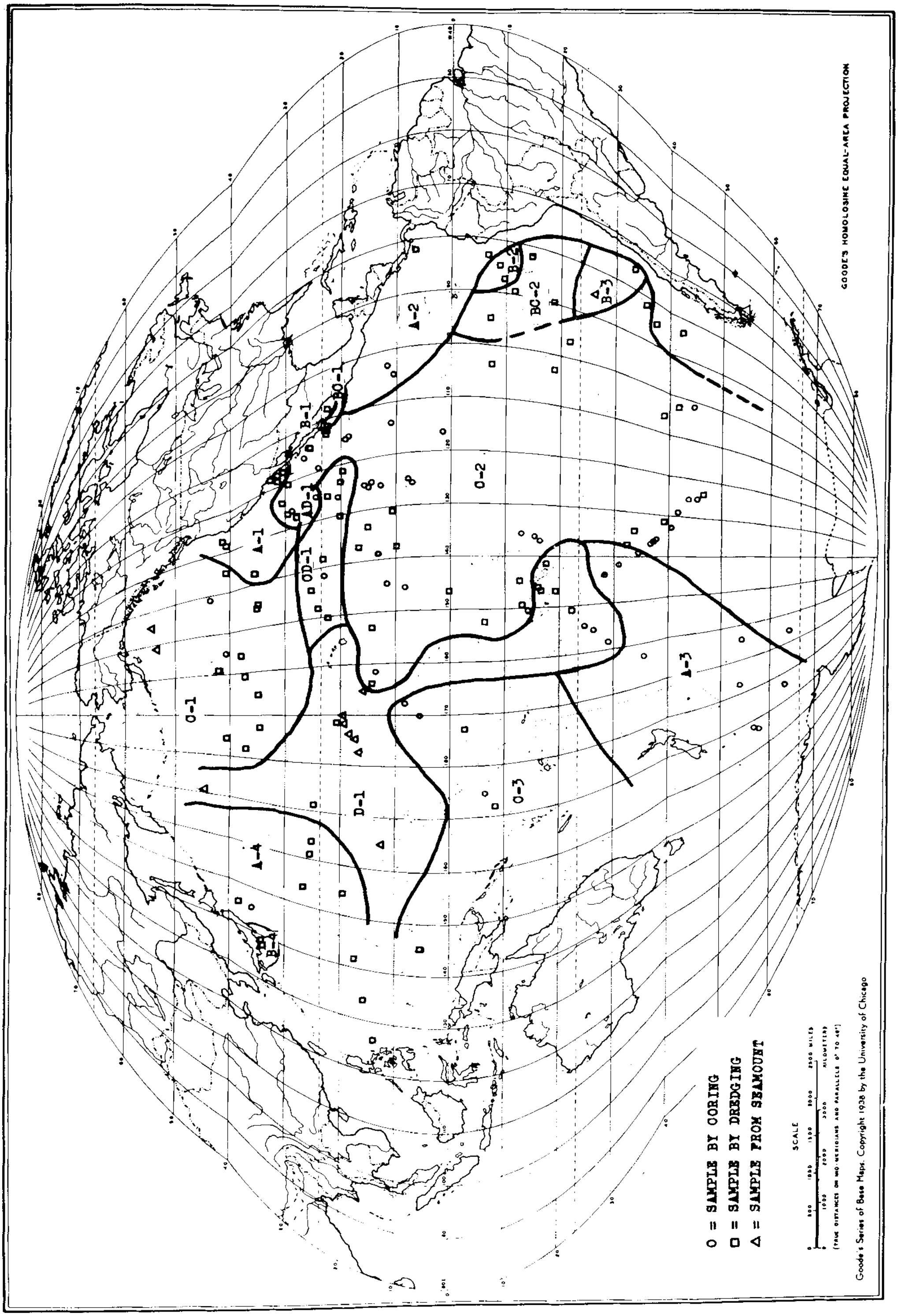
Chemical analyses have been made on about 700 samples of nodules from the world's oceans, about 500 of which are of nodules from the Pacific Ocean. Mero (1965a) lists assays for 16 elements from about 200 of these locations; Cronan (1967) lists assays for 11 elements from about 125 locations; and Horn et al. (1973a) list analyses for 7 elements from 605 locations in the oceans, 434 of which are from the Pacific Ocean, 94 of which are from the Atlantic Ocean and 77 of which are from the Indian Ocean. When the assay data are plotted on a map of the Pacific Ocean, definite regional variations in the composition of the nodules are noticeable. Fig. 11-5 shows the indicated boundaries of the compositional regions noted. While this chemical compositional distribution of the nodules is of some geochemical importance it is also of economic significance for it will allow the mining of a composition of the nodules with a mix of metals which conforms best with the demand for those metals. Since the mining facility is not fixed in space in the ocean as on land, the operator can move his operation from place to place as the market demand for different metals changes.

The nodules in the areas labeled *A* in the map of Fig. 11-5 are characterized by manganese/iron ratios generally less than one whereas a general ocean-wide ratio for these metals is generally near two. The iron/cobalt ratios are on average higher than those of the other regions and range as high as 520. These high-iron regions generally lie along the continents and are probably the result of less oxidizing conditions than found in deeper areas of the ocean. Iron is preferentially precipitated relative to manganese in less oxidizing environments.

The three areas in the eastern Pacific are characterized by very high manganese/iron ratios. These ratios range from 12 to 50 and average 23. There are apparently transitional zones between the high-manganese regions and the other compositional regions in which manganese nodules possess compositional characteristics of both regions. Thus, the nodules from transition zone, *BC—2*, assay high in manganese, nickel and copper. The nodules in the *B* regions seem to be forming very rapidly. The very low content of nickel, cobalt, copper and lead of the nodules of the *B* regions is probably an indication of the short time span between precipitation of the manganese from solution in seawater and the agglomeration of the manganese sols at the sea floor into the nodules.

The areas farthest removed from land, both continental and island, seem to be regions of relatively high nickel—copper nodules. These regions, labeled *C* in Fig. 11-5, are, by far, the dominant compositional regions in the Pacific. The manganese/iron ratios of the *C* regions are relatively stable, ranging from 1 to 6 and averaging 2.1. The copper assays of the nodules from these

Fig. 11-5. Map of the Pacific Ocean showing the major compositional regions of manganese nodules. The *A* regions contain nodules relatively enriched in iron; the *B* regions contain nodules enriched in manganese; the *C* regions contain nodules enriched in nickel and copper; and the *D* regions contain nodules enriched in cobalt. Transitional zones in which the nodules show dual compositional characteristics are indicated by two letters.


PACIFIC OCEAN
O = SAMPLE BY CORING
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SCALE
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Goode's Series of Base Maps. Copyright 1938 by the University of Chicago
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D-1

regions show a greater range in value than do the nickel assays. On the average, the copper content of the nodules tends to increase near the Equator. It is thought that biologic agencies are responsible for fixing at least part of the copper in the manganese nodules in the high productivity zone near the Equator. Greenslate et al. (1973) have proposed a biological mechanism for the equatorial regions whereby the precipitating remains of planktonic organisms incorporate and transport to the sea floor large quantities of transition metals such as copper and nickel.

Centred on topographic highs in the central part of the Pacific Ocean are two regions in which the nodules assay relatively high in cobalt. Eleven samples of nodules from these two regions average 1.2% Co, with the highest value being 2.6% Co. The manganese/iron ratios of these regions vary less than in any of the other regions, ranging from 0.9 to 1.8 and averaging 1.3. The iron/cobalt ratios are also more stable in these regions, ranging from 8 to 39 and averaging 22. The source of the cobalt in these nodules may be the volcanic rocks with which they are associated. However, these shallow areas are also generally highly oxidizing environments, largely due to high currents which sweep over the tops of the seamounts. This condition may be primarily responsible for fixing cobalt in the nodules of these areas (Burns and Fuerstenau, 1966).

In the east-central North Pacific is a zone of relatively high cobalt—nickel—copper nodules; this zone, labeled CD—1, more or less coincides with the high-grade zone of the North Pacific.

Most probable area for nodule mining operations

Considering all factors, it would appear that the high-grade area of the North Pacific would be that most likely in which commercial mining operations will be initiated. Most of the commercial nodule exploration work, with the exception of that conducted by CNEXO in the South Pacific in the areas near Tahiti and the Marquesas Islands, has so far been undertaken in this area. The continuing exploration work of the Kennecott and Deepsea Ventures groups is being concentrated in this region. Not only are extensive deposits of sufficient grade, concentration and continuity found in this area but also the weather is relatively favourable during most of the year. In addition, the deposits are relatively close to North America where a major market exists for the metals to be produced from the nodules.

While extensive deposits of the nodules have been found in the Atlantic and Indian oceans, those deposits tend to be of a considerably lower grade, on the average, than the deposits of the Pacific Ocean, with respect to nickel and copper which are the most important economic metals in the nodules. This lower metal content is probably a reflection of the relatively high rate of continental runoff per unit area received by the Atlantic and Indian oceans and the resulting dilution of the nodules with clastic materials. As grade is a very important factor concerning the economics of nodule mining and processing, all of the commercial attention on the nodule deposits has so far been concentrated in those deposits in the eastern Pacific Ocean.

Tonnages of metals in the nodule deposits of the high-grade area

Assuming an average concentration of 9 kg/m^2 of ocean floor over the 6,000,000 km^2 within the North Pacific high-grade area, a reserve of about 38 billion tons of dry nodules averaging 29% Mn, 0.3% Co, 1.7% Ni and 1.4% Cu would be indicated. The water content of the nodules is assumed to be 30%. Such a reserve would contain about 11.0 billion tons of manganese, 115 million tons of cobalt, 650 million tons of nickel, and 520 million tons of copper. These nodules also contain an average of about 0.14% Zn and 0.06% Mo and the deposit will probably be an important source of these two metals as well.

EXPLORATION OF DEEP-SEA NODULE DEPOSITS

In general, there are two basic techniques of exploring for deep-sea nodule deposits. One technique employees the use of a winch and cable with which an underwater camera or television can be lowered to view the nodule deposits or a dredge bucket, coring device, grab or other sampling device can be lowered to the ocean floor to secure samples of the nodules. In efficient systems, nodule samples and photographs can be obtained on the same lowering. With television systems, a continuous record can be made by the use of video-tape recorders. A second technique of sampling the deposits employs free-fall devices which are dropped into the ocean and sink to the ocean floor at a rate ranging from 35 to 70 m per minute depending on the ratio of the displacement of the flotation element to that of the submerged weight of the ballasting elements. At the ocean floor the free-fall devices, depending on their design, will take a grab sample of the nodules or bottom sediments over an area ranging from 0.1 to 0.2 m^2, release their ballast, and return to the surface, again at rates varying from about 35 to 70 m per minute. Instead of a grab sampler, a camera, corer, water sampler or other data-gathering device can be mounted on the free-fall vehicle. In some designs, both a camera and grab are mounted on the same vehicle.

Deep-sea television systems can yield high-quality data concerning the continuity of the deposits both with respect to surface density and size range of the nodules. Such high-quality data are not attainable with other sampling techniques. In addition, the television systems can be used to monitor current velocities, to determine changes in sea-floor elevation and the direction of maximum slope, to gather information on obstructions which may hinder the operation of mining equipment and to detect sudden changes in the bottom topography all of which are important factors in studying any deposit prior to mining. The German AMR Group have mounted their television camera on a sled which can be towed just above the ocean floor at relatively high velocities of up to about 2 knots. Using a low light level camera, it is possible to view the ocean floor from distances as much as 15 m. On board ship, the German system employs a very elaborate array of signal processing equipment with which it is possible to determine the maximum and minimum sizes of the nodules being viewed as well as the average nodule size automatically. The equipment will also determine the percent coverage which combined with the average nodule size can yield a number concerning the surface density of the nodules.

Still cameras are lowered to the ocean floor via a wire line and, through the use of acoustic devices, can be held just above the ocean floor to take as many as 1,000 separate photographs per lowering while the ship is drifting. Still cameras can also be designed with bottom contact switches so that the camera will record only a single photograph each time it is dropped to the sea floor.

Sampling devices consist of rock dredges, dredge buckets designed specifically for the gathering of the nodules, sediment corers, grabs of various types, and spade corers. The spade corers are generally designed to take a square core, 20 by 20 cm to 30 by 40 cm in lateral dimensions and to a depth into the sediments ranging from 20 to 50 cm. These devices are particularly useful in securing undisturbed samples of the nodules and sediments for various measurements such as the bearing strength of the sediments as well as for securing accurate data on the concentration of the nodules at the point sampled. These devices are also useful in gathering data concerning the nodule—sediment interface. At present, the best possible combination for the delineation of nodule deposits (especially in detailed surveys of a specific deposit) probably consists of a television system and a spade corer. The exploration of nodule deposits with these devices is, however, slow and time-consuming and therefore expensive per unit of area covered. Regional surveys can be made at considerably less cost through the use of free-fall devices.

Free-fall devices designed specifically for nodule deposit studies were initially developed by Kennecott Copper Corporation (Schatz, 1971) and subsequently by CNEXO and other groups. These devices consist of a light-weight frame in which is mounted one or more glass spheres to provide buoyancy, a grab or camera with which samples or photographs of the nodules can be obtained, weights to carry the device to the ocean floor and which are released at the ocean floor to allow the device to return to the surface, various tripping devices to fire the camera and flash and/or close the grab, and flags, radio beacons and flashing lights to facilitate relocation of the device on its return to the surface. A number of these devices can be dropped at one station or on a predetermined pattern to provide a relatively high degree of certainty concerning the surface density, size distribution and grade of the nodules in a specific area. The success ratio in recovering these devices is generally greater than 90% and, with care, can approach 100%. A major advantage of the free-fall devices is that they can be easily deployed from a small vessel and their initial capital investment is relatively low. In addition, devices can be deployed while the ship is occupied with other survey activities whereas such dual activities are difficult to accomplish with wire line systems.

In any nodule exploration programme, a determination of the sea-floor topography, the average depth and relief of the area and the slope of the abyssal hills is important. In general, standard deep-sea echo sounders are used in making these determinations. Towed vehicles carrying various acoustic devices close to the ocean floor will yield a much higher degree of resolution than those acoustic systems utilizing surface vessel mounted acoustic transducers. Some attempt has been made to use high-resolution, high-frequency and narrow-beam, echo sounders to obtain a better degree of topographic resolution than the standard 12 kHz echo sounders provide. High-frequency seismic probes have also been used to try and differentiate those areas which contain nodule deposits and those areas consisting of rock outcrops or barren sediments. Side-scan sonars mounted on deep-towed vehicles appear to have shown some success in outlining barren patches within nodule deposits (Lonsdale, 1974).

Positioning of the samples and sampling devices, especially at the ocean floor is important. In general, satellite navigation systems are now used for vessel positioning. Under good control, positioning within about 0.2 km can be secured with these systems. Arrays of acoustic transducers have been employed at the ocean floor to position sampling devices at the ocean floor very accurately with reference to the emplaced acoustic transponders. Highly accurate surveys of deposits can therefore be made; however, the position of the deposit area with reference to some benchmark on land is still only as good as the surface positioning system itself.

CONSIDERATIONS IN THE SELECTION OF MINING SITES

There are many factors involved in the calculations used to determine the economic value of a deposit of manganese nodules. The more important of these are the metal contents of the nodules, areal extent of the deposit, surface density of the nodules per unit area of sea floor, continuity of the deposits with respect to metal content and size, size distribution of the nodules within the deposit, water depth, distance to port or process facility, topography of the ocean floor in the deposit area, current velocities throughout the water column, physical characteristics of the associated sediments, frequency and distribution of obstructions to mining systems within the deposit, ease with which the nodules can be processed, and weather. Of these considerations, as long as certain minimum standards are met with reference to all the other factors, the dominant factor in determining the economics of mining any specific deposit in most cases is the metal content of the nodules. Because of this consideration, it is the nodule deposits of the Pacific Ocean and more specifically the deposits between the Equator and the 20°N and between the 110° and 180°W which are of greatest interest at the present time. In general, if the grade of the nodules exceeds 2.8% Ni + Cu + Co on a dry weight basis, if the average surficial nodule concentration exceeds 5 kg/m^2 of sea floor, if the slope of the sea floor does not exceed about 10%, if the percentage of gangue materials mined with the nodules does not exceed about 20% and if the weather of the area permits at least 250 days per year of operations, the deposit would be considered to be of economic grade.

Kaufman (1974) outlines some of the considerations involved in determining the acceptability of a nodule deposit for mining and concludes that, for the mining system envisioned by his company, the deposit should assay at least 20% Mn, 1.0% Ni, 0.8% Cu and 0.2% Co. In addition, the surficial concentration should be greater than 5 kg/m^2. Some of the factors noted by Kaufman (1974) which affect the size of an area needed to contain a mineable deposit are: about 15—25% of the deposit area will consist of obstructions which must be avoided by the mining system; the nodule recovery efficiency of the mining systems is not likely to exceed 60% of the nodules actually swept over by the system; and, the percent of the area which can actually be covered by the mining system nodule gathering head at the sea floor due to lack of control in positioning this device accurately is not likely to be more than about 65%. Considering all of these factors, Kaufman develops a formula which can be used to determine the total area required to contain a mine; that is, an area with a sufficient quantity of nodules of sufficient grade to pay the operating costs of the venture and generate sufficient profits to amortise the capital investment of the venture as well as pay an acceptable rate of return on the investment.

MINING MANGANESE NODULES

Although many techniques of mining the deep-sea manganese nodules have been proposed (Mero, 1958), work is presently proceeding on two types of systems, a hydraulic suction dredge and a mechanical cable-bucket dredge. Three forms of the hydraulic system are under consideration, one powered by centrifugal dredge pumps, another powered by air injected into the pipeline and a third being a combination of the other two.

Essentially the hydraulic system, as shown in Fig. 11-6 consists of a length of pipe which is suspended from a surface float or vessel; a gathering head, designed to collect and winnow the nodules from he surface sediments and feed them to the bottom of the pipeline while rejecting oversized material; and some means of causing the water inside the pipeline to flow upward with sufficient velocity to suck the nodules into the pipeline and move them to the surface of the ocean. In 1970, Deepsea Ventures Inc., a subsidiary of Tenneco Corp., successfully tested an air-lift dredge of the general design as described by Flipse (1969) at a depth of about 760 m on the Blake Plateau, a 250,000 km^2 area off the southeastern coast of the United States (LaMotte, 1970). In that test, some 60,000 tons of the nodules were reported to have been recovered at rates varying from 10 to 50 tons/h through a 24-cm diameter pipeline. As the nodules from the Blake Plateau are generally of low grade, most of these recovered nodules were simply dumped back into the ocean. Plans are now being made to extend that system of dredging to depths of 4,500 m.

In general the estimated capital costs of the hydraulic systems of mining the nodules at average annual production rates of one million tons of nodules are between $30 million and $100 million. The indicated production costs of moving the nodules from the ocean floor to the surface with these systems is estimated to be between $10 and $20 per ton of nodules produced.

The second general type of system planned for the mining of the nodules on a full-scale basis is the Continuous Line Bucket (CLB) System. This system consists essentially of a surface vessel, a loop of cable to which dredge buckets are attached at 25—50 m intervals, a traction machine on the surface vessel capable of moving the cable such that the buckets descend to the ocean along one side of the loop, skim over the sea floor on the bottom side of the loop to gather the nodules, and return to the surface on the third side of the loop. This system of dredging the nodules in illustrated in Fig. 11-7. So far this system of recovering the nodules has been tested in a series of experiments, first in 1,500 m of water in 1968, then in 3,600 m of water in 1970 (Masuda et al., 1971), and finally on a full-scale basis in 4,700 m of water in 1972. Because of its great simplicity, the capital costs of the CLB System are relatively low, in the order of $10 million for a two million ton per year system, exclusive of the cost of the surface vessel, which system would be capable of recovering the nodules from any depth up to about 5,500 m of water. The estimated operating costs of this system, including the cost of a chartered surface vessel, are now about $5 per ton of nodules recovered. The CLB System can be mounted on practically any type of vessel capable of crossing the open ocean and of carrying a total load of about 3,000 tons. In addition to its simplicity, the CLB System incorporates a very high degree of flexibility in being able to work in deposits of the nodules of varying concentration and size range, over relatively great sea-floor topographic relief and in a range of sediment bearing strengths and characteristics. A given CLB System can be easily modified to operate in any

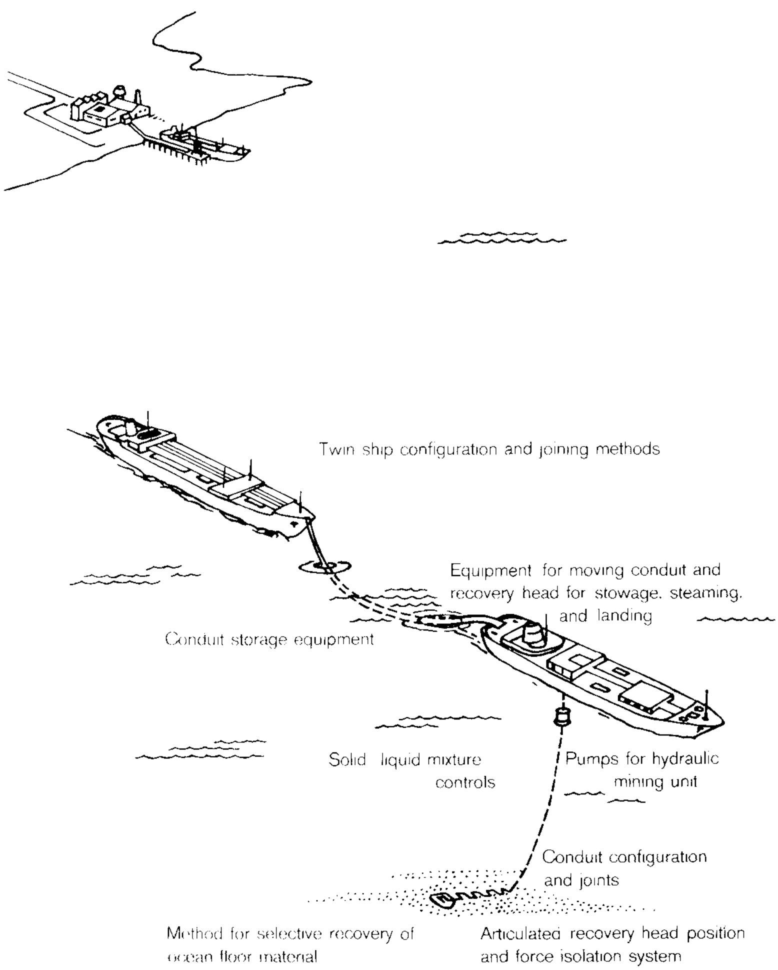
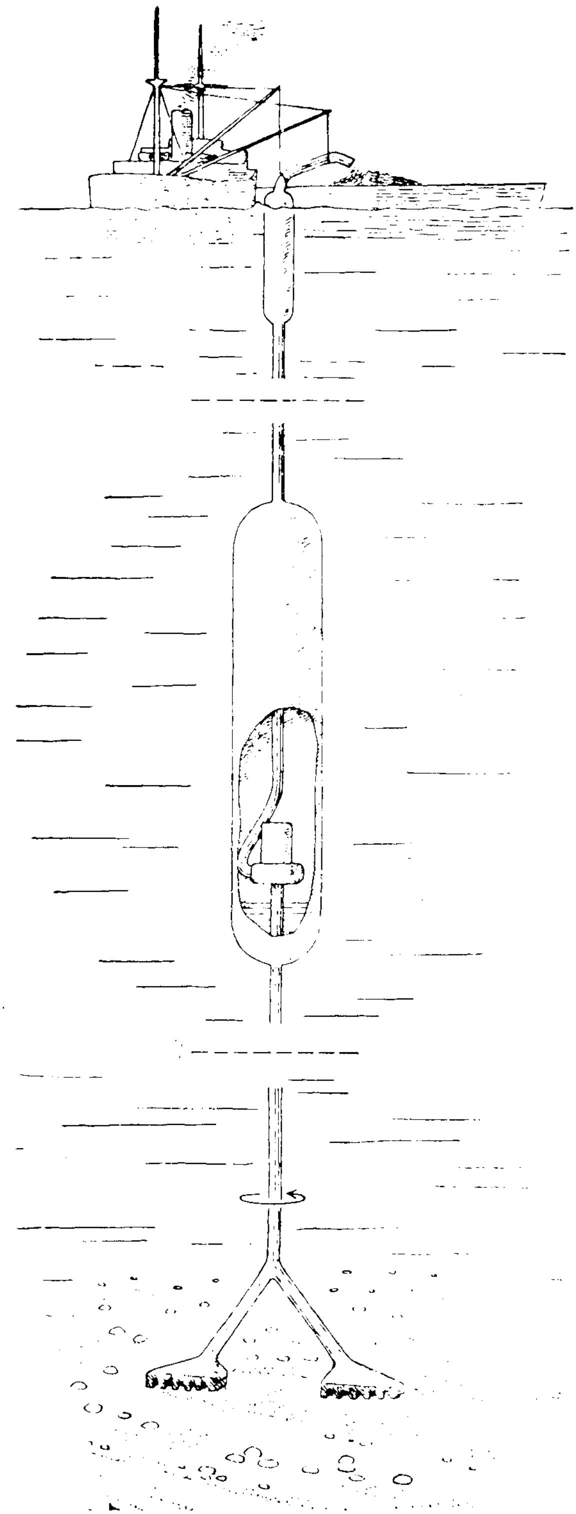


Fig. 11-6. Two types of deep-sea hydraulic dredges proposed for the mining of manganese nodules. The system above is that proposed by the Deepsea Ventures Group. It is supported by a surface vessel and is powered by an air-lift pump with air being injected into the pipeline at about 35% of the dredging depth. The system on the right, proposed by J. L. Mero, is supported by a submerged float to prevent surface wave motions from being transmitted to the dredge pipeline. A centrifugal dredge pump of several stages is located inside the main flotation tank at about 15% of the dredging depth. The entire dredge rotates around its long axis with collecting heads fanning out at the seafloor so that the dredge can cut a very wide swath throughout the nodule deposit with a low lateral motion of the dredge as a whole. This avoids high energy inputs to move the dredge at high velocities over the deposit.



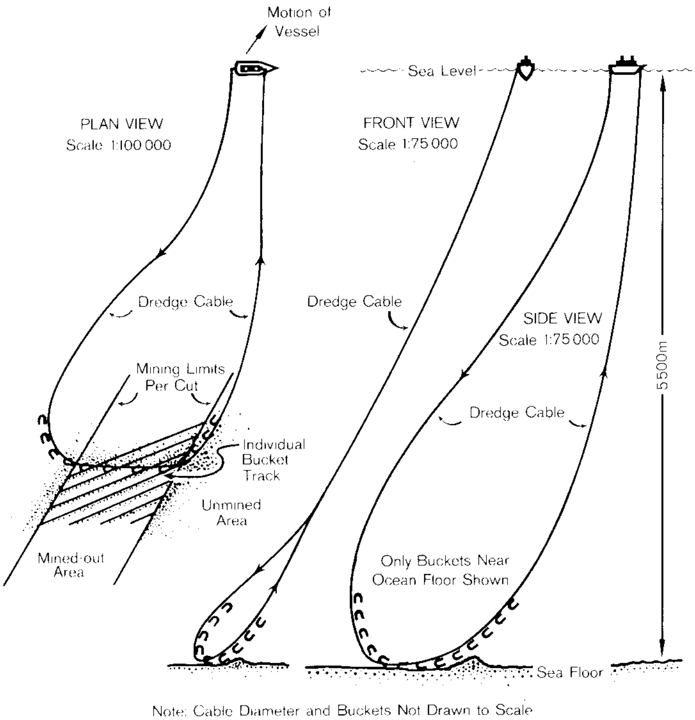


Fig. 11-7. A diagram illustrating the design and operation of the Continuous Line Bucket (CLB) System for mining deep-sea nodules as proposed by Y. Masuda. Various forms of this system such as a two-ship system have been developed in order to achieve better control over cable separation and therefore width of the bucket cut at the sea floor.

depth of water and all parts of the system which operate submerged are surfaced several times a day for inspection and repair.

Transport of the nodules to a process facility

There is some indication that the manganese nodules could be processed for their metals aboard a vessel at sea (Mero, 1972). Because of the rather large-power requirements for such a system and the general unavailability of cheap power at sea, it is more likely that the nodules will be transported to some port where inexpensive hydro-electric power, or power produced from natural gas, is available. In general, large-bulk ore carriers can transport ore materials for costs in the range of \$0.0003 to \$0.0005 per ton—km depending on the size of the carrier and the amount of automated loading and unloading equipment available. It can be expected that the distance from the mining site to a process facility will range from about 2,000 to

10,000 km. Since the carrier must return to the mine site empty, the cost of transporting the nodules can be expected to fall in the range of $3 to $11 per ton depending largely on the size of the transport vessel. This cost estimate assumes a $1 per ton charge is involved in handling the nodules on shore.

As the nodules are of a relatively low density and are easily crushed, it can be expected that they will be pumped from the mining vessel to the carrier and from the carrier to the process plant allowing for high filling and unloading rates. Because of the relatively low capital investment involved in the mining system itself, the CLB System could be installed on an ore carrier and simply shut down while the carrier is returning to port. It is estimated that it will require about six hours to install a CLB System at sea for mining operations from the carrying vessel and a similar amount of time to bring the system inboard when the carrier was filled. At a 15,000 ton/day production rate it would require about seven days to fill a 100,000 ton carrier.

Hydraulic systems, on the other hand, require a relatively large amount of time to install and remove from the sea and because of their rather high capital investment, it is necessary to keep the system working for as much of the time as possible. The hydraulic system therefore requires a surface vessel to act only as the mining system platform and the recovered nodules will have to be transferred to transport vessels at sea.

The economics of mining and processing the nodules

Most estimates of the cost of mining the manganese nodules fall in the range of $5 to $20 per ton of nodules in an operation producing at least one million tons of dry weight nodules per year (Mero, 1958, 1965a, 1972; Clauss, 1972; Kaufman and Rothstein, 1973). The cost of transporting the nodules to a process site and shore handling should fall in the range of $3 to $11 per ton. The cost of processing the nodules is expected to fall in the range of $10 to $20 per ton (Mero, 1968, 1972; Meiser and Müller, 1973). Using the high values of these estimates, it would appear that the cost of mining, transporting and processing a ton of the nodules should not exceed $50 per ton. With manganese nodules averaging 30% Mn, 0.3% Co., 1.5% Ni, and 1.2% Cu and assuming an overall recovery factor of 90% of the contained metals in the nodules, the gross value of the metals recovered from a ton of the nodules would be about $114 using metal prices as indicated in Table 11-I. Each ton of nodules would thus produce a gross operating profit of about $64. Assuming overhead costs of $6 per ton and an effective tax burden of 48%, the net profit on each ton of nodules mined would be about $30. The net profit on a 2 million ton/year operation would therefore be about $60 million. The estimated total capital investment in such an operation, including the mining, processing and transport systems, can be expected to be about $250 million or the rate of net return would be about

24% per annum which is an acceptable figure for a venture carrying the very high risks associated with deep-ocean mining.

Assuming the rate of return on the invested capital desired is 20% per year, it would leave about $10 per ton of the net profits to be applied against repayment of the capital investment. An amortisation tonnage would therefore be about 30 million tons of nodules. At an average concentration of 10 kg/m^2 of wet nodules (concentration estimates are generally determined on a basis of wet weight of nodules which will, on the average contain about 30% of water as the nodules come from the sea) or 7 kg/m^2 of dry nodules, the amortisation tonnage of 30 million tons of dry-weight nodules would cover an area of about 4,300 km^2 of sea floor which is about 0—1% of the total area within the high-grade region of the North Pacific Ocean. In actual practice, it may be assumed that about 25—50% of the nodules in any given deposit area would not be recoverable due to local obstructions in the deposit area which must be circumvented by the mining system and due to inefficiencies of the mining system in the recovery of all the nodules in the deposit (Kaufman, 1974). Consequently, the area required to contain an amortisation tonnage can be calculated to be of the order of 10,000 km^2.

The cost of surveying 30 million tons of dry-weight nodules (about 43 million tons of wet-weight nodules), assuming free-fall sample stations are located at 1—km intervals over a 10,000 km^2 area and that television scans are made along parallel lines 1 km apart, would be about $5 million. This estimate assumes that some 40 free-fall stations can be made per day and that the television scans are made at an average velocity of 1 knot. The estimate also assumes that the ship operating costs are $3,000 per day and that there will be a 50% overall loss of ship time due to returns to port for resupply, weather, mechanical difficulties, etc. The $5 million estimate also includes $2.3 million for survey equipment, data reduction and various overhead expenses of operation. Such an operation, covering some 10,000 km^2 would require a period of about 900 days total time assuming at least 450 days are occupied in actual survey activities. At a $5 million total exploration expenditure, the cost per ton of nodules surveyed would be about $0.17 per ton.

In calculating the future potential value of metals produced from manganese nodules, it would not be wise to include any value for manganese as that metal will be produced in quantities much greater than any reasonable future estimate indicates the market will be able to absorb. In addition, cobalt would be produced in quantities greatly in excess of projected demands so the future value of this metal should be calculated as equal to that of nickel for which metal cobalt can substitute in many industrial applications. Basing the economics of mining the nodules on these criteria, it can be anticipated that, at a recovery efficient of 90% of the contained metals in nodules containing 0.3% Co, 1.5% Ni, and 1.2% Cu, the value of metals recovered from a ton of the nodules would be \$81. Using the high values for mining, transport, processing and overhead expenses and again assuming an effective 48% tax burden, this would allow an indicated net profit of \$16 per ton or \$32 million per year on a 2 million ton per year operation. The rate of return on a \$250 million capital investment would be about 13% per year which is about the minimum any mining company could accept for a high-risk venture. A 15% depletion allowance would raise the net profit to about \$46 million for a rate of return of about 18% per year.

ENVIRONMENTAL CONSIDERATIONS IN NODULE MINING

Both tests of deep-sea nodule mining systems so far conducted (i.e., the Deepsea Ventures' test of the air-lift hydraulic system in 1,000 m water depth on the Blake Plateau in 1972 and the CLB System in 4,100 m water depth in 1972) have been monitored for possible environmental effects to the ocean. These environmental studies were conducted under the auspices of the U.S. National Oceanographic and Atmospheric Administration. The results of those studies have failed to detect any substantial deleterious effects to the ocean environment (Roels et al., 1973). While it can be expected that small amounts of sediment and gangue materials will be raised to the sea surface in the mining of nodules, either with the hydraulic systems or the CLB System, and that the mining operator will want to separate the gangue materials and return them to the sea floor at the mining site, they can be returned via a standpipe which exists below the thermocline so that no sediments or nutrient-rich bottom waters appear at the surface of the ocean. The sediment and other gangue materials would resettle to the ocean floor and should cause no discernible disturbance to the existing ocean environment. No foreign materials would be added to the seawater in these operations. From theoretical considerations and from actual observations of full-scale mining tests, no damage or altering of the marine environment should occur in the mining of the nodules. Mining operation will occupy only a very small percentage of the total oceanic area, in the order of 0.0001% of the total area of the Pacific Ocean alone, so that even if any adverse effects should occur they will be confined to relatively small areas.

There may be some disturbance of the biota at the ocean floor in nodule mining operations; however, the areas where the nodules are found are the great deserts of the world as far as macroscopic life forms are concerned. Any bacteria or other life forms which may be destroyed in any mining operation can be replaced by populations in the adjacent unmined areas since the mining system will not affect almost 75% of the deposit area. The sea floor itself should be relatively little disturbed by the mining of the nodules as the object in any mining operation will be to gather only those nodules lying loosely at the surface of the sediment and to disturb the seafloor sediment as little as possible. It would be uneconomic to lift gangue sediment and material to the surface.

On the other hand, the mining of the manganese nodules may allow the shutting down of many of the large sulphide mines on land. These mines do cause considerable visual pollution of the landscape and very considerable pollution of the atmosphere in the release of large amounts of sulphur dioxide and other gases in the processing of these ores. Since manganese nodules will be processed with some form of hydrometallurgical process in which the reagents will be largely recovered and recycled, there should be no measurable pollution from this operation. Present indications are that the extraction of metals from manganese nodules requires about 50% of the energy required to produce an equivalent amount of such metals from land sources. In addition, the nodules, which possess large specific surface areas and which are known to be highly efficient absorbers of sulphur dioxide from gas streams (Zimmerly, 1967), may be used in the stacks of existing power plants or other industrial flues to purify the gases presently emitted to the atmosphere by these facilities. The mining of deep-sea nodules should therefore prove, on all accounts, to be a considerable net gain to the present continental environments.

SUMMARY

The major considerations concerning the economic geology of the deep-sea manganese nodules are metal content, surface density and size range of the nodules, continuity of the deposits, sea-floor topography and character of the associated sediments. Although manganese-iron oxide precipitates can be found in many forms on the ocean floor only the loose-lying nodules found at the surface of the soft pelagic sediments are of commercial interest at the present. Environmental factors controlling the commercial recovery of deposits include distance to port, water depth, density of obstructions within a deposit area, water current velocities through the water column, weather, etc. Of all the factors involved in determining the economic value of any given deposit of the nodules, given certain minimum standards concerning the other factors, the most important ones appear to be metal content of the nodules, surface density, continuity and areal extent of the deposits. A minimum grade of nodules, at the present time, would be one containing about 2.8% Ni + Cu + Co on a dry-weight basis. The minimum economic concentration of the nodules appears to be about 5 kg/m^2 of sea floor and the minimum economic size of a deposit should be one containing about 30 million recoverable tons of dry-weight nodules. As only 25—50% of the nodules in any given deposit is estimated to be recoverable, such a deposit is estimated to cover an area of about 10,000 km^2.

Two types of deep-sea dredges are presently under development for the mining of the manganese nodules, a deep-sea hydraulic dredge and a mechanical cable-bucket system. Both systems appear to offer some advantages with the hydraulic system appearing to be advantageous in the mining of a specific deposit for which it is designed while the cable-bucket system appears to be somewhat more flexible in working in a variety of deposits, topographic environments and water depths.

The cost of surveying a deposit of the nodules covering 10,000 km^2 is estimated to be \$5 million. The cost of mining, transporting and processing a ton of the nodules is estimated to be between \$25 and \$50 per ton of nodules at production rates in excess of 1 million tons per year. The value of the metals recoverable from a ton of the nodules in the high-grade region of the North Pacific Ocean would be in the range of \$80 to \$140 per ton, depending on whether manganese is included as a product of any value or not and depending on the value accorded to cobalt. Total capital investments in a system to handle 2 million tons of the nodules per year are estimated to be in the range of \$200 to \$250 million and the rate of return on a nodule-mining venture is indicated to be in the range of 13 to 24% per annum.

Environmental studies conducted in conjunction with deep-sea tests of the two types of mining systems presently indicate that substantially no environmental damage will be done in the mining of the deep-sea nodules. Because of the nature of the deposits and the way in which they can be mined, the manganese nodules presently appear to be a relatively pollution-free and energy-saving source of a number of industrially important metals.