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METAL RESOURCES IN MANGANESE (OR POLYMETALLIC) NODULES*

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Impetus was added to a move in the mid-1960s to declare that the mineral resources on the deep-sea bed beyond the limits of national jurisdiction (the "Area" in the Law of the Sea Convention) are the "common heritage of mankind," by exaggerated claims of both the quantities of metals that could be recovered from manganese (or polymetallic) nodules and of their cost competitiveness with conventional sources on land. As the Third UN Law of the Sea Conference gained momentum, the debates on the regime for the Area involved more technically complex issues than had previously been confronted by a multi-national negotiation on this scale, so that there was a need to try to provide more realistic technical, including economic information.

In 1975, an attempt was therefore made to estimate the potentially economic resources using all the data that was publicly available, recognising that it was sparse and often inaccurate, particularly with respect to nodule abundance, and assuming the required minimum average grade and abundance.

Subsequent estimates are reviewed. The order of magnitude of potentially economic nodule deposits and of the nickel, copper, cobalt and manganese they contain now seems to be established.

Key Words : Manganese Nodule Resources; Deep-sea Bed.

Introduction

Of manganese (or polymetallic) nodules it has been said that they "cover" the ocean floor, that they are so abundant as to be an almost infinite resource, that they are growing at a faster rate than they can be mined and that metals can be won from them at substantially lower cost than from conventional sources. Were such ideas to be well-founded, manganese nodule mining would have dramatic effects: this contribution is intended to dispel any residual beliefs in them. This does not mean that manganese nodules should not be seen as a very important future source of supply of some metals.

The difficulties involved in providing estimates of nodule resources that are sufficiently accurate to be of any value have been illustrated by comparing them with the problems that would confront Martian prospectors anxious to harvest were on this planet, who cannot fly at less than 5,000 metres above an Earth with thick

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continuous cloud cover ! The difficulties in establishing what area is occupied by wheat and where the best wheat is grown would be similar to those of prospecting for nodule deposits and evaluating them beneath 5,000 metres of water. Paradoxically, however, it is easier to provide estimates of the quantities of the metals in nodules than on land. Most of the nickel, copper and manganese deposits on land are three-dimensional, usually isolated and many are concealed (some deeply buried) : the rocks that contain them are heterogeneous and by no means all that might have workable concentrations have been sampled. While nodules are concealed by a vast thickness of water, they are relatively homogeneous, two-dimensional, although discontinuous, ore-bodies, resting on the sea-bed, which have been sampled on an oceanwide basis. Although only at very wide intervals, the sampling of most of the sea-bed has been random with respect to the occurrence of nodules.

Considerable confusion is attached to the terms 'reserves' and 'resources', which have both lay and special meanings, with more than one definition of the latter sense. 'Resources' here is used to describe all mineral deposits, both known and those that remain to be discovered, that are economically workable now, or are likely to become economically workable. The generally small parts of known resources that are workable under current socio-economic conditions are described as 'economic resources' (hitherto called 'reserves'). Nodule deposits that are likely to be worked by the 'first generation' of mining and processing plant are described as 'potentially economic resources' in anticipation that their economic viability will be proved (although strictly they should be described only as 'resources' until this is done).

Economic Resources on Land

Current estimates are shown in Table I.

Table I

Economic resources on land (in situ)

Nickel	54	million tonnes
Copper	460	million tonnes
Cobalt	1.5	million tonnes
Manganese	2,000	million tonnes

It has been suggested, very speculatively, that including the quantities remaining to be discovered, the total economic resources of nickel on land may lie somewhere between 75 and 100 million tonnes.

Potentially Economic Nodule Resources

The evidence from about 60,000 photographs and sea-bed samples suggests that nodules are present over about 15 per cent of the total area of the ocean floor (about 362 million km^2), that is over about 55 million km^2. (Interestingly, the expedition of 'HMS Challenger' recovered nodules at about 62. 17 per cent, of the 362 stations where sea-bed samples were obtained with a trawl). An estimate of the total weight of nodules has neither present nor future economic significance as many nodules contain only very small quantities of nickel and copper (Table II).

TABLE II

Summary of data in Scripps Data Bank (June 1977) : nickel plus copper

Nickel plus Copper %	Number of stations (percentage of totals in brackets)									
	Atlantic Ocean (*a*)			Indian Ocean (*a*)	South Pacific Ocean (*a*)	North Pacific Ocean			All Oceans	
	North	South	All			Clarion-Clipperton	Rest	All	All	Except Clarion-Clipperton
0.00–0.25	15(16)	29(22)	44(20)	22(16)	21(5)	1(0)	23(5)	24(3)	111(7)	110(8)
0.25–0.50	45(47)	50(39)	95(42)	52(37)	123(29)	1(0)	79(16)	80(11)	350(23)	349(27)
0.50–0.75	25(26)	23(18)	48(21)	31(22)	128(30)	2(1)	79(16)	81(11)	288(19)	285(22)
0.75–1.00	8(8)	15(12)	23(10)	13(9)	58(13)	11(5)	72(14)	83(11)	177(12)	166(13)
1.00–1.25	1(1)	6(5)	7(3)	14(10)	32(7)	9(4)	49(10)	58(8)	111(7)	102(8)
1.25–1.50	—	4(3)	4(2)	2(1)	21(5)	21(10)	29(6)	50(7)	77(5)	56(4)
1.50–1.75	—	—	—	4(3)	21(5)	15(7)	36(7)	51(7)	76(5)	61(3)
1.75–2.00	1(1)	1(1)	2(1)	1(1)	11(3)	16(7)	61(12)	77(11)	91(6)	75(6)
2.00–2.25	—	1(1)	1(0)	1(1)	8(2)	30(14)	28(6)	58(8)	68(4)	38(3)
2.25–2.50	—	—	—	—	4(1)	32(14)	26(5)	58(8)	62(4)	30(2)
2.50–2.75	—	—	—	1(1)	3(1)	37(17)	12(2)	49(7)	53(3)	16(1)
2.75–3.00	—	—	—	—	—	28(13)	11(2)	39(5)	39(3)	11(1)
3.00–3.25	—	—	—	—	—	14(6)	1(0)	15(2)	15(1)	1(0)
3.25–3.50	—	—	—	—	—	3(1)	1(0)	4(1)	4(0)	1(0)
3.50–3.75	—	—	—	—	—	1(0)	—	1(0)	1(0)	—
Total	95	129	224	141	430	221	507	728	1523	1302

Note : not all percentages add up to 100% due to rounding.

(*a*) The boundaries between Indian and Atlantic Oceans are taken at 30°E, between Indian and South Pacific at 150°E and between South Pacific and Atlantic at 70°W.

Manganese nodule mining is likely to be economically viable with the 'first generation' of mining and processing equipment only if the average combined nickel and copper content of dry nodules* is at least 2.25 per cent (in which the Cu : Ni ratio may be about 1 : 1.22 or, if account is taken of the different market values of the co-product nickel and copper by assuming that the value of nickel is three times that of copper, an average 'nickel equivalent' grade of at least 1.57 per cent. Such nodules, provided that they occur with an abundance of at least 5 (wet) kg/m^2 and an average of at least 10 (wet) kg/m^2, contain, therefore, the potentially economic resources of the metals.

*It is very important to distinguish between wet and dry nodules, as when wet ('drip-dry') they contain about 30 per cent by weight of water.

It has been shown that there seems to be a geometric decrease in the cumulative number of samples for an arithmetic increase in the average grade, if nodules with a very low (less than 0.25 per cent) combined Ni and Cu content are excluded. The tonnage of nodules above any grade may be taken as proportional to the number of samples above that grade (Table II), if it is assumed that the sampling is random and that abundance varies independently of grade. Even if there is an inverse correlation between grade and abundance, as described by some authors, it is not so strong as to introduce a significant bias.

The minimum, or cut-off grade corresponding to an average grade of 2.25 per cent combined Ni and Cu is 1.71. After weighting the data for the Clarion-Clippertton area (see below) and allowing for the samples with grades under 0.25 per cent combined Ni and Cu (which account for about 9 per cent of the total), about 15 per cent all of the samples are above this cut-off grade. Therefore, if the sampling is indeed random, only about 15 per cent of all nodules meet this grade criterion. The result is similar if nickel equivalent is examined : about 17 per cent of the samples are above a nickel equivalent samples cut-off of 1.2 per cent (corresponding to 1.71 per cent combined Ni and Cu).

The economics of mining will probably be less sensitive to abundance than to grade, but areas with an abundance of less than perhaps 5 (wet) kg/m^3 will probably be avoided, as far as possible. Deposits with more than this minimum may occupy about 60 per cent of the area in which nodules are present, that is about 33 million km^2, in which the average is perhaps about 15 (wet) kg/m^2. If grade and abundance are independent variables, the suggested criteria for first generation mining operations may be satisfied by about 15 per cent of these nodules, that is by about 75 billion (wet) tonnes. However, not only is this based on inadequate data, particularly on abundance, but the method used is subject to 'dispersal' errors. It includes nodules in areas that are too small and widely dispersed to be mined economically, as well as nodules that are above cut-off but below the specified average grade or abundance (or both) and are too far (even in a different ocean) from deposits which are correspondingly above average for them to be combined together. This estimate serves only to indicate the order of magnitude of an upper limit.

At least five methods of deriving a more realistic estimate have been described. The first minimises the 'dispersal' errors by applying the above method to 'prime areas', those in at least part of which there are nodules with significantly higher grades than elsewhere : they are the areas where the environment is favourable to the formation of 'high-grade' nodules in which the 'mine sites' (areas with sufficient nodules with the grade and abundance necessary to sustain a commercially viable mining operation) are likely to occur. Prime areas account for only a small proportion of the sea bed, the largest, about 3.5 million km^2, being between the Clarion and Clippertton fracture zones (from about 7°N to 15°N and 120°W to 155°W) : another in the North Pacific, of about 0.8 million km^2, is to the southwest of Hawaii. Both seem to be related to the equatorial zone of high productivity. Although the corresponding area in the South Pacific is restricted by the East

Pacific Rise and the Marquesas and Tuamotu archipelagoes, it may include about 1 million km^2 of prime area. Some high-grade nodules have been recovered from the floor of the Indian Ocean, where there may be about 0.5 million km^2 of prime area. The physiography and relativity high rate of sedimentation in much of the Atlantic Ocean severely limit favourable areas and the nickel and copper content is generally too low in the Southern Ocean. Including an allowance for such areas, an estimate of the total prime area of 6.5 million km^2 is probably generous. It is, however, less than 2 per cent of the ocean floor.

Based on data from the Clarion-Clipperton area, where the density of sampling is much higher than elsewhere, there may be a maximum of only 33 billion (wet) tonnes of 'first generation nodules', present over about one-third of the total prime area. As the 'dispersal' error is not eliminated entirely, 33 billion (wet) tonnes should be regarded as a theoretical maximum for potentially economic resources (to be reduced by an unknown factor).

The need to estimate (or guess) the total prime area is avoided by considering the grade and occurrence of nodules in 5° grid squares : eleven between 5°N to 20°N and 110°W to 155°W (that is in the Clarion-Clippertton area) and one (0.295 million km^2) in the South Pacific (15°S to 20°S, 85°W to 90°W) qualified as prime areas, a total of 3.6 million km^2, reduced to 1.3 million km^2 in which the minimum abundance requirement is also met.

In view of the uncertainties and because it was recognised that there may be prime areas outside the Pacific Ocean not identified by this method, a tolerance of a factor of two (below as well as above) was allowed to give an estimate of between about 7 and 29 billion (wet) tonnes.

A Monte Carlo technique has been applied to give a probability distribution of the quantities of recoverable nodules. If the overall mining recovery efficiency is assumed to be 20 per cent, the results can be converted to there being a 95 per cent chance that there are between 4.3 and 41 billion (wet) tonnes in the North East Pacific (0°N to 30°N and 100°W to 170°W) and between 6.4 and 56 billion (wet) tonnes elsewhere, results that are not inconsistent with those mentioned above, particularly as the quantities are more likely to be towards the middle of the ranges.

Evidence from over 1800 samples and more that 1600 photographs obtained at 262 localities in 2.25 million km^2 of the Clarion-Clippertton area has been analysed by a geostatistical method. It was emphasised that the information on abundance at each site is subject to an error of $\pm$ 50 per cent. It was estimated that about 3.35 billion of the 7.75 billion (wet) tonnes in this area occur with an abundance of at least 5 (wet) kg/m^2, the average grade being 2.5 per cent combined Ni and Cu, with an optimistic possibility that this could be increased by a factor of two or more. Thus the more detailed, information obtained during a prospecting programme provides an estimate that is also not incompatible.

The fifth study, based on all the information then published on the Clarion-Clipperton area, suggested that nodules with more than 1.8 per cent combined Ni and

Cu are present over about 2.5 million km^2 and that the abundance is not less than 5 (wet) kg/m^2 [and averages about 11.9 (wet) kg/m^2] over about 1.25 million km^2. As it was believed that the area could be a half or twice this figure, the Clarion-Clippertton area could contain between 7.5 and 30 billion (wet) tonnes of 'first generation' nodules.

These five estimates suggest that the quantity of nodules that meet the grade and abundance criteria adopted to satisfy the assumed economics of first generation deep-sea mining operations is probably nearer to 10 than 100 billion tonnes, with most in the Clarion-Clipertton area. Extremely speculatively, perhaps there are between 15 and 25 billion (wet) tonnes of potentially economic resources of manganese nodules *in situ*.

First Generation Mining Operations

Corresponding attempts have been made to represent the potentially economic resources as the number of possible mining operations (or as 'mine sites') that they can support. This involves further major assumptions about the quantity of nodules to be dredged each year by each operation (probably between 1 and 4½ million (dry) tonnes) : the overall mining recovery efficiency (taking account of the proportion that cannot be mined because of physical obstructions and because grade and abundance are below the cut-offs, the proportion of the area that will be swept and the proportion of the nodules in the swept area that will be delivered to the ship : it will probably be between 10 per cent and 50 per cent, perhaps between 20 per cent and 25 per cent), and the commercially viable life of an operation (which is unlikely to be less than 20 years, but could be atleast 25 years).

Combination of these inescapable uncertainties leads to a range of 20 to 220 'first generation' operations that might be based on the (extremely speculative) 15 to 25 million (wet) tonnes of nodules. To narrow the range, the device is commonly-adopted of assuming that all operations will recover 3 million (dry) tonnes of nodules a year, although this does not reduce the uncertainty as there is no reason to believe that all operations will have the same, or even similar, intended annual recovery. Even if this device is nevertheless used, overall recovery efficiency is taken to be 20 per cent or 25 per cent and a mine life of either 20 or 25 years is assumed wide ranges have been calculated of the number of first generation mining operations that could be supported by the estimates of the potentially economic resources : 30 to 75, 20 to 40 (probably nearer 20) and 25 to 225 in all oceans; 27 in the Clarion-Clippertton area and 8 to 22 in two-thirds of it; 3 to 10 in Clarion-Clippertton if the average grade and minimum abundance are increased to 2.5 per cent combined nickel and copper and 9kg/m^2. Clearly, more must be known about both the resources and deep-sea mining before more useful figures can be derived.

Potentially Economic Resources of Metals

The rounded estimates given in Table III assume that the nodules contain an average of 1.24 per cent nickel, 1.01 per cent copper, 0.23 per cent cobalt and 27.5

per cent manganese. An overall mining recovery of 20 per cent and metallurgical processing recoveries of 90 per cent for nickel and copper, 60 per cent for cobalt and 85 per cent for manganese are assumed to provide Table IV.

TABLE III

Potentially economic resources (in situ)

Nodules (wet)	15,000–25,000	million tonnes
Nodules (dry)	10,500–17,500	million tonnes
Nickel	130– 215	million tonnes
Copper	105– 175	million tonnes
Cobalt	25– 40	million tonnes
Manganese	3,000– 5,000	million tonnes

TABLE IV

Recoverable potentially economic resources

Nickel	25– 40	million lonnes
Copper	20– 30	million tonnes
Cobalt	3– 5	million tonnes
Manganese	500–800	million tonnes

CONCLUSIONS

The uncertainty of the estimates of the (potentially) economic resources must constantly be borne in mind. Nevertheless it can be said that :

(*a*) Manganese nodules do not cover the ovean floor. They are probably present over about 15 per cent.

(*b*) Although the total quantity of nodules may be about 550 billion (550×10^9) (wet) tonnes, less than 100 billion (wet) tonnes are likely to meet the criteria adopted to satisfy the predicted economics of 'first generation' operations; it seems possible (but still very uncertain) that these are between about 15 and 25 billion (wet) tonnes, of which only about 3 to 6 billion (wet) tonnes may be recoverable. As assay values (the grades) are expressed as percentages of dry weights, these quantities must be reduced to 2 to 4 billion (dry) tonnes when the quantities of contained metal are to be considered.

(*c*) If these estimates are of the right order of magnitude, then the recoverable potentially economic resources of nickel, copper, cobalt and manganess (Table IV) in nodules are neither enormously more nor less than economic resources on land (Table I).

(*d*) Even were as much material being deposited as in mined, the resources cannot be regarded as renewable, in any practical sense, as deep-see nodules grow extremely slowly (an average of a few millimetres in a billion years).

It can be asserted with considerable confidence that if the legal regime, including a satisfactory investment climate, is judged to be acceptable and costs are demonstrated to be, and remain, competitive, the manganese nodule mining industry will be making an important contribution to world supply at the turn of the century, to the benefit of all consumers (and only two or three countries in which cobalt plays a significant role in the economy could suffer perceptible adverse economic effects).

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*Only the added references are published here.