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Estimation of Manganese Nodule Resource in the Northern Part of the Central Pacific Basin

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Abstract : Resources of manganese nodules and associated metals (Cu, Ni and Co) in the Central Pacific Basin were estimated from 555 shipboard descriptions and more than 1000 chemical analyses, collected during the Geological Survey of Japan research cruises from 1974 to 1982. A total 9,200 million tons of nodules with greater abundance of 5 kg/m^2, 39 million tons of Cu, 52 million tons of Ni, and 27 million tons of Co are expected in 660,000 km^2 or 45% of the study area. In the area, Co-rich hydrogenetic nodules are dominant with high abundance, while high-Cu and Ni diagenetic nodules occur partly on the local scale with low abundance. The distribution patterns of metal abundance (amount in nodules in a unit area) are controlled principally by the variation in nodule abundance rather than metal contents of nodules.

Considering the areal extent and the continuity of the deposits from geological evidences, five regions of high economic potential some of which await more detailed exploration were selected. These five regions are similar to or greater than some of the proposed mine sites in the Northeastern Pacific manganese nodule belt, in scale, nodule abundance and total metal resources, whereas the Cu plus Ni content is relatively low. The advantages of these deposits to the northeastern Pacific sites are high abundance of nodules and intermediate Co grade.

1. Introduction

The ocean-floor manganese nodules are regarded as potential resources of economic metals for the future (Broadus, 1987), although several technical, economic and environmental issues still remain to be solved for commercial mining. During the geological and geophysical study for manganese nodule deposit conducted by the Geological Survey of Japan (GSJ) from 1974 through 1983, more than 1,400 bottom samples were collected in the Central Pacific Basin and adjacent areas. Eight cruises were carried out with R/V Hakurei-maru for the purpose of geological mapping of manganese nodules in the area of over 1.5 million km^2. Chemical analysis for more than 1,000 nodules was also performed during this 10-year period. This study focuses on quantitative estimation of ore resources of manganese nodules in order to characterize the economic aspects of nodule deposits for future exploration in this area. Data are based on the published GSJ cruise reports (Mizuno and Chujo, 1975 ; Mizuno and Moritani, 1977 ; Moritani, 1979 ; Moritani and Nakao, 1981 ; Mizuno, 1981 ; Mizuno and Nakao, 1982 ; Nakao and Moritani, 1984 ; Nakao, 1986 ; Usui, 1992, 1994), papers in journals (Usui *et al.*, 1987a ; Usui and Moritani, 1992), and a distribution map (Usui *et al.*, 1983). The data include shipboard descriptions for nodules from 178 locations, relevant shorebased chemical and mineralogical analyses together with sedimentological and seismic data.

The study was carried out as a part of the

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training course, "Deep Seabed Resources Development" at GSJ from May 17, 1993 to February 27, 1994, which was arranged under the agreement of the United Nations Preparatory Commission for the International Seabed Authority and for the International Tribunal for the Law of the Sea. The training course was partly supported by the Japan International Cooperation Agency.

2. Geological setting

The study area is enclosed by the lines 5°N–14°N and 175°E–165°W (area, about 900×2000 km) in the northern part of the Central Pacific Basin (Fig. 1). It is bounded to the north by the Mid-Pacific Mountains, to the west by the Marshall-Gilbert Islands, and to the east by the Line Islands chain. The basin area is characterized by WNW-ESE trending abyssal knolls and several isolated seamounts, with water depths between 5,000 m and 6,000 m. The topographic trend of knolls and small depressions is nearly parallel to the Trough. The Magellan Trough and the Magellan Rise are the prominent geographical features in the middle part of the area. The Magellan Trough is regarded as an abandoned spreading center of early Cretaceous age (Furukawa *et al.*, 1992). Siliceous clay and pelagic clay surface sediments are dominant here partly associated with calcareous turbidites. Top of the Mid-Pacific seamounts and the Magellan Rise are covered with calcareous sediments at water depths of 3,000–4,000 m.

During seismic surveys (Winterer *et al.*, 1973 ; Tamaki, 1977 ; Tanahashi, 1986), two prominent continuous reflectors (A' and B') were recognized on reflection profiles over the Central Pacific Basin area and correlated to DSDP core stratigraphy. The uppermost transparent layer above reflector A' consists mainly of deep-sea clay/biogenic oozes of early Eocene to Quaternary age. Lower layers consist of middle Eocene chert and claystone underlain by Late Cretaceous volcanic rocks and limestone.

Active and fluctuating flow of Antarctic Bottom Waters promoted regional and local complex patterns of erosion and resedimentation, resulting in prominent hiatuses in sediments, which are most frequent near the Plio-Pleistocene boundary and within the Paleogene (van Andel *et al.*, 1975 ; Orwig and Kronke, 1980). The sedimentological study suggests that average sedimentation rate has been generally less than 5 m/m.y during nodule growth in the basin area, associated with ubiquitous sedimentary hiatuses caused by bottom currents (Nishimura, 1992).

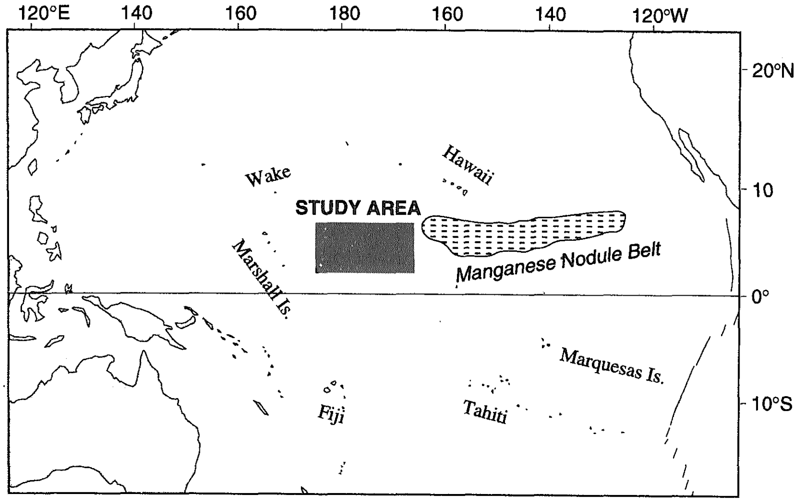

Fig. 1 Location of study area.

3. Distribution of manganese nodules

At 178 stations within the study area, bottom samples of nodules were collected together with associated sediments using a wire-bound samplers (box corer, grab, piston corer and dredge) and a free-fall grab. Total available 555 samples were selected out of sampling operations by 451 free-fall grabs, 164 box corers, 22 piston corers and 17 dredges. At each station small-scale sampling was preformed one to 20 points with the average of 3 points. Most stations were spaced in 1-degree grid (about 110 km), occasionally followed by smaller-scale supplementary sampling. A total 320 frames of seabed photographs were taken for on-site observations using one-shot camera fixed to each sampler.

Among overall 555 samplers, 228 samplers (about 41%) contain nodules of over 5 kg/m^2 while 102 samplers (18%) no nodules (Fig. 2) with the total median value of 4.3 kg/m^2. Among 178 stations, 83 stations (about 47%) indicate higher average nodule abundance than 5 kg/m^2, while 26 stations (15%) no nodules. The averaged Cu plus Ni content is 1.30 wt.% (to air-dry basis) in 344 samples with the maximum value of 3 wt.% (Appendix 1). This suggests that northern part of the Central Pacific Basin is one of the promising provinces in the Pacific Ocean. The abundance varies from 0–36 kg/m^2 and contents of Cu, Ni and Co in nodules vary on the factor of 6 to 18.

The previous small-scale sampling (Usui *et al*, 1987 b ; Usui and Moritani, 1992) has shown great variations in nodule abundance and composition on scale of 1–2 km in some areas of this study area in a close relation to the sedimentary history of each site. Despite the small-scale variation, the data set is generally sufficient for regional-scale estimation of nodule and metal resources, since the ranges of variation are significantly greater than those within samples for each station.

The manganese nodule deposits in the study area are classified into two types of hydrogenetic and early-diagenetic nodules, which comprise also morphologically different types, smooth-surface nodule (type s) and rough-surface nodule (type r), respectively (Usui and Moritani, 1992). Type r nodules are associated with siliceous surface sediments in the southeastern part of the area, while type s with pelagic or zeolitic clay surface sediments in the northern and western parts. Type r (early-diagenetic) nodules are rich in Mn, Ni, Cu, and Zn and poor in Fe, Co and Pb as compared with type s (Usui, 1979 ; Sorem and Fewks, 1979 ; Usui and Moritani, 1992). Since nodule growth is promoted by slow or non-sedimentation, nodule abundance is generally related to the thickness of the youngest sedimentary layer (Neogene-Quaternary) sediments ; for instance, higher abundance on thin or no such layer (Usui *et al*., 1987 b ; Usui and Moritani, 1992 ; Nishimura, 1992). As a result, nodule abundance is closely related to sub-bottom stratigraphy not simply to seafloor topography.

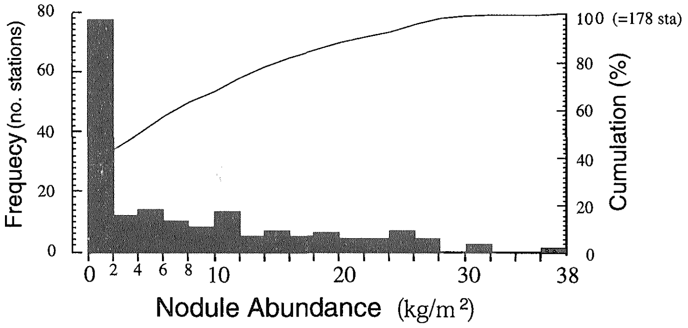

Fig. 2 Frequency diagram of nodule abundance (in number of stations out of 178).

4. Criteria for economic evaluation of nodule resources

Mero (1977) first pointed out the parameters to be considered in evaluating the economic values of nodule deposit development are : 1) abundance, 2) metal contents, 3) areal extent and continuity, 4) water depth, 5) seafloor topography, 6) nodule size, 7) characteristics of surface sediments, 8) obstructions to mining systems, 9) distance to port , 10) weather, and 11) current.

In this study we consider that the most important three factors are abundance, metal contents, and areal extent and continuity of the deposits. A nodule deposit is considered economic, if nodule abundance exceeds 5 kg/m^2, Ni plus Cu content exceeds 2.8% on dry basis, covering an area of about 10,000 km^2, slope of seafloor less than 10%, gangue material less than 20% (Mero, 1977). Kunzendorf (1986) considered nodule abundance of 5 kg/m^2 with Cu plus Ni content of over 2% on wet weight basis as an economic deposit. Another optimistically inferred cut-off grade is 1.71 wt.% Cu plus Ni and 5 kg/m^2 nodule abundance (Archer, 1985). However the criteria of economic level is quite variable with world metal prices and other factors. In this study, the nodule abundance of over 5 kg/m^2 or Cu plus Ni content of over 2% to dry basis are considered as economic interest by modification from Kunzendorf (1986). Other metals, such as Mn, Co, Zn and Pb, can be regarded as profitable metals as well as Cu and Ni (Hillman and Gosling, 1985).

5. Method of resource estimation

Manganese nodules generally rest on the seafloor as irregularly scattered pavements, although buried nodules are occasionally observed (Felix, 1980). Only the surficial nodules are of commercial interest at present (Yamazaki *et al.*, 1995). The manganese nodule deposit is here regarded as a two-dimensional formation.

The method of polygons (Peters, 1978 ; Patterson, 1983 ; Kuzvart and Bohmer, 1986) is adopted here for ore resource estimation of nodules. It has been often used in calculation of ore reserves of land ore deposits that show morphologically simple distribution like coal beds, placer, and bedded Mn ores (Kuzvart and Bohmer, 1986). The method can be reasonably applied to estimating the resources of nodule deposits in this area by assuming that the nodule deposit is a simple 2-D. Based on this method, the whole area with available nodule data was divided into a series of polygons centered at individual stations, by drawing perpendicular bisectors of combined lines between sampling stations (Fig. 3). A uniform value was assumed to be equal to the average of the samples within each polygon. Calculation procedure is as follows : 1) construction polygons for 178 stations, 2) area of each polygon, 3) averages of nodule abundance and metal contents from all samples within each station. 4) Calculation of metal abundance, nodule and metal resources from nodule abundance, metal contents and area of polygons are :

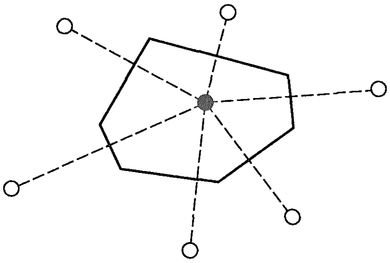

Fig. 3 Method of polygon construction in Figures 6-9. Sides of polygon are drawn from perpendicular to bisectors of combined lines between stations.

metal abundance (g/m^2)=[metal content] (wt. %)×[nodule abundance] (kg/m^2)×10

nodule resource (MT) = [nodule abundance] (kg/m^2)×[area of polygon] (km^2)×10^{-3}

metal resource (MT) = [metal abundance] (g/m^2)×[area of polygon] (km^2)×10^{-6}

(MT : million metric ton).

5) Labeling the polygons in an order of nodule abundance, Cu plus Ni and Co abundance. The result of calculation is shown in Appendix 1.

6. Nodule resources and metal resources in the study area

Above the assumed cut-off of nodule abundance of 5 kg/m², the total Ni resource of 52.2 million tons (89%) is expected among the total Ni resource of 58.7 million tons. Similarly, 87% and 93% of the total resources of Cu and Co are contained in the nodule deposits of over 5 kg/m² abundance (Table 1, Fig. 4).

Earlier geological and geochemical study has shown that the variations in Cu plus Ni and Co contents are in principle determined by the occurrence of two different genetic types of nodules (Usui and Moritani, 1992). A dispersed pattern in an abundance-grade diagram (Fig. 5) is mainly due to occurrence of the two types (Mero, 1977). However, the distribution pattern of metal abundance is more strongly affected by nodule abundance in this area than metal contents, as shown by similar distribution patterns of Cu plus Ni and Co abundances and nodule abundance (Figs. 6, 7, and 8). Here, most of the nodule deposits are hydrogenetic in origin with minor occurrence of Cu and Ni-rich diagenetic nodules (Usui and Moritani, 1992).

Based on the calculated nodule and metal resources, some of the potential polygons are clustered, taking geological continuity between polygons (Fig. 9). Some isolated polygons of high grade are ignored because of less economic interest. A cut-off grade is assumed as 5 kg/m² for nodule abundance and 100 g/m² for Cu plus Ni abundance. We selected five geographic regions ; Northeastern Plain (Area NE), Northern Plain (NP), Magellan Trough (MT), Western Trough (WT), and Western Seamounts (WS), covering 580,000 km² or about 40% of the overall area. A total nodule resource above cut-off grade and abundance within the selected five areas is about 7,600 million metric tons, containing 31 million tons of Cu plus Ni and 23 million tons of Co.

The Areas NE, NP and WS are characterized

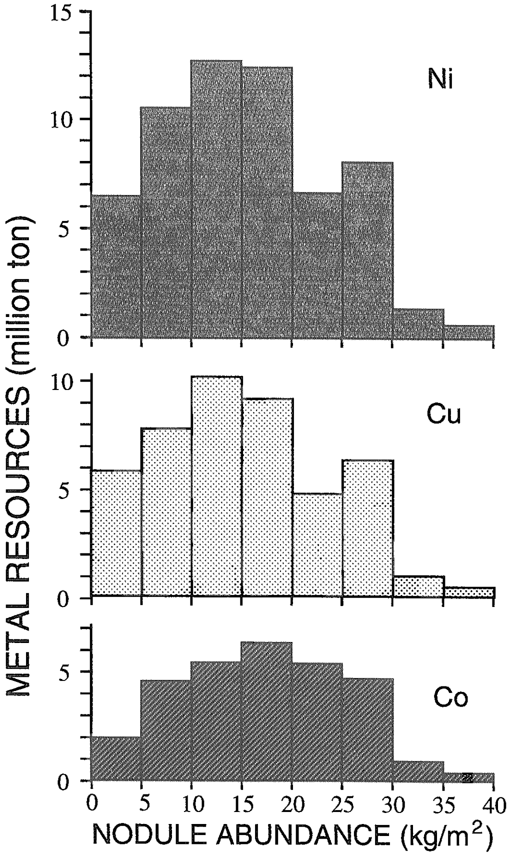

Fig. 4 Sums of metal resources in polygons with nodule-abundance fraction. For example, the left bar in Ni axis denotes the total Ni amount in all polygons in the area with nodule abundance between 0 to 5.

Table 1 Estimation of total resources of nodules and metals in the study area (n=178).

Nodule abundance	Area (km²)	Total ore resources (in million metric ton)					
		Nodules (dry wt.)	Cu	Ni	Co	Zn	Pb
over 10 kg/m²	427,000	7,500	31.3	41.7	22.5	4.8	5.3
over 5kg/m²	663,000	9,180	39.0	52.2	27.0	6.1	6.3
total	1,468,000	9,970	44.7	58.7	28.9	6.8	6.7

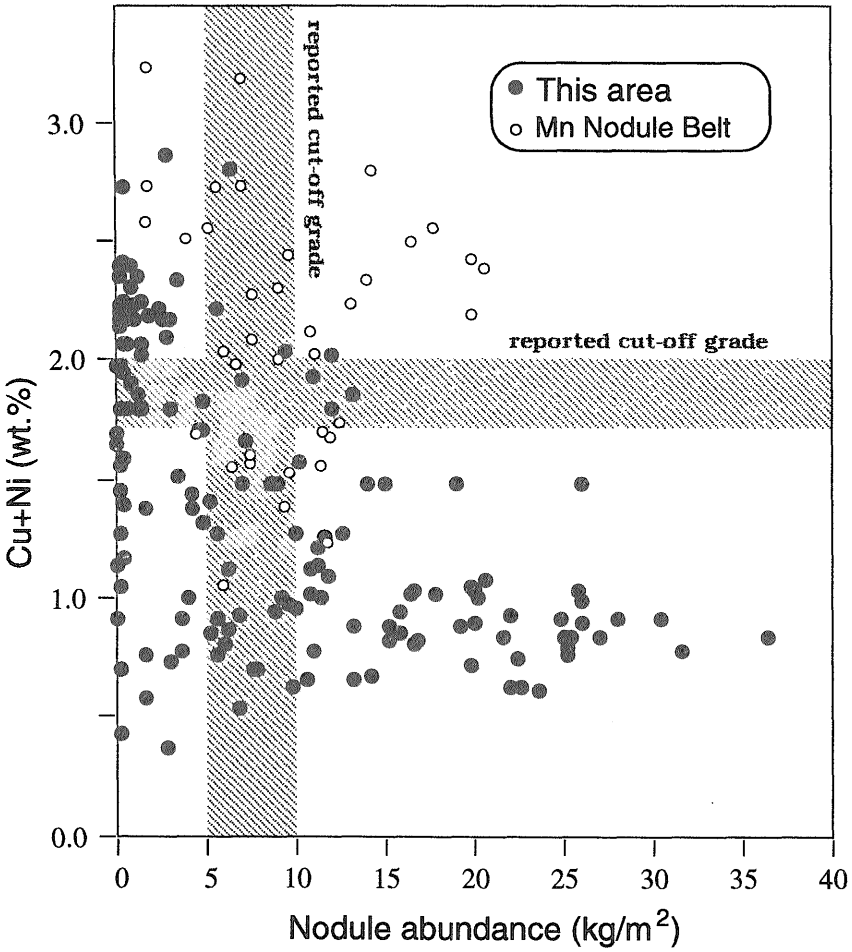

Fig. 5 Nodule abundance-(Cu+Ni) grade diagram over suggested cut-off grades by Mero (1977) and Kunzendorf (1986).

by abundant hydrogenetic nodule deposits of high Co content, while the Areas MT and WT are associated with minor amount of diagenetic nodules. Area WS is characterized by the highest nodule abundance (up to 36 kg/m^2) and highest Co, and Cu plus Ni is also the highest. The area seems economically most promising. A possible disadvantage is a relatively rugged sea floor topography. The continuity of the high abundant area is probably extended to the southwest, the Gilbert Islands (Metal Mining Agency of Japan, 1992). Both the Areas NE and NP have the second highest nodule abundance and high Co, but Cu plus Ni is much less. Nodules from these Areas, especially NE, are of typically hydrogenetic origin, as shown by highest Co content. Many of nodules from the Areas MT and WT contain more than 1 wt.% Cu plus Ni, but the Cu plus Ni abundance is around the average or less among the five areas. In the vicinity of the Magellan Trough and the adjacent southeastern basins, nodules are more influenced by diagenetic process and show higher Cu and Ni contents (Usui *et al.*, 1983). The nodule abundance is, however, mostly less than 5 kg/m^2 and shows only a sparse distribution pattern.

When compared with proposed mine sites in the Northeastern Equatorial Manganese Nodule Belt (Clarion-Clipperton Fracture Zone

Table 2 Selected regions of high economic potential in comparison with the proposed mine sites in the NE Pacific Manganese Nodule Belt.

Area		Northeastern Plain (NE)	Northern Plain (NP)	Magellan Trough (MT)	Western Trough (WT)	Western Seamounts (WS)	NE Pacific Mn-Nodule Belt (DOMES)		
							Site A	Site B	Site C
							Piper et al. (1979)		
Areal extent (km^2)		58,620	116,256	152,734	139,819	117,964	110,000	51,000	73,000
Nodule resources (MT)		944	1,556	1,681	1,370	2,144	484	195	522
Nodule abundance (kg/m^2)		16.1	13.4	11.0	9.8	18.2	4.4	3.8	7.1
Cu+Ni content (wt. %)		0.73	0.95	1.34	1.03	0.96	2.20	1.81	1.35
Cu+Ni abundance (g/m^2)		120	130	124	100	160	-	-	140-330
Co content (wt. %)		0.34	0.33	0.23	0.26	0.30	0.25	0.21	0.26
Co abundance (kg/m^2)		55	44	27	25	60	-	-	18-35
Nodule size (cm in long axis)		3.1	2.6	2.9	3.0	2.8	-	-	2 - 4
Water depth (m)		5,570	5,280	5,770	5,680	5,330	5000-5100	4800-5000	4400-4700
Ore resources (MT)	Cu	2.68	5.83	8.59	6.02	8.16	5.0	2.5	5.6
	Ni	4.16	8.69	10.38	7.99	10.85	6.0	3.0	7.0
	Co	3.21	5.16	4.21	3.56	7.03	1.0	0.4	1.2
	Zn	0.54	0.95	1.10	0.95	1.43	-	-	-
	Pb	0.70	1.19	1.01	0.83	1.69	-	-	-

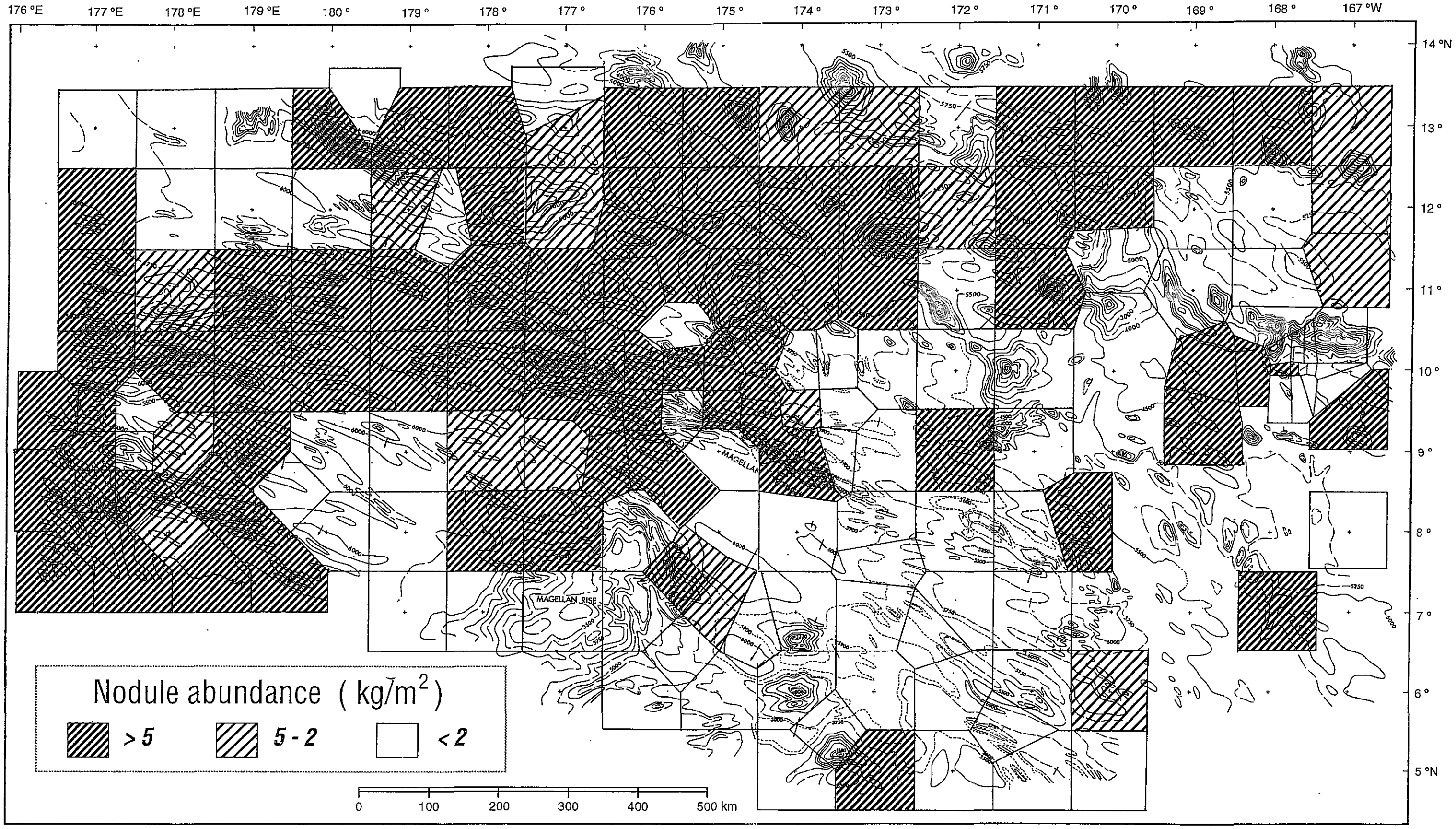

Fig. 6 Distribution of nodule abundance. Base map after Onodera and Mizuno (1981).

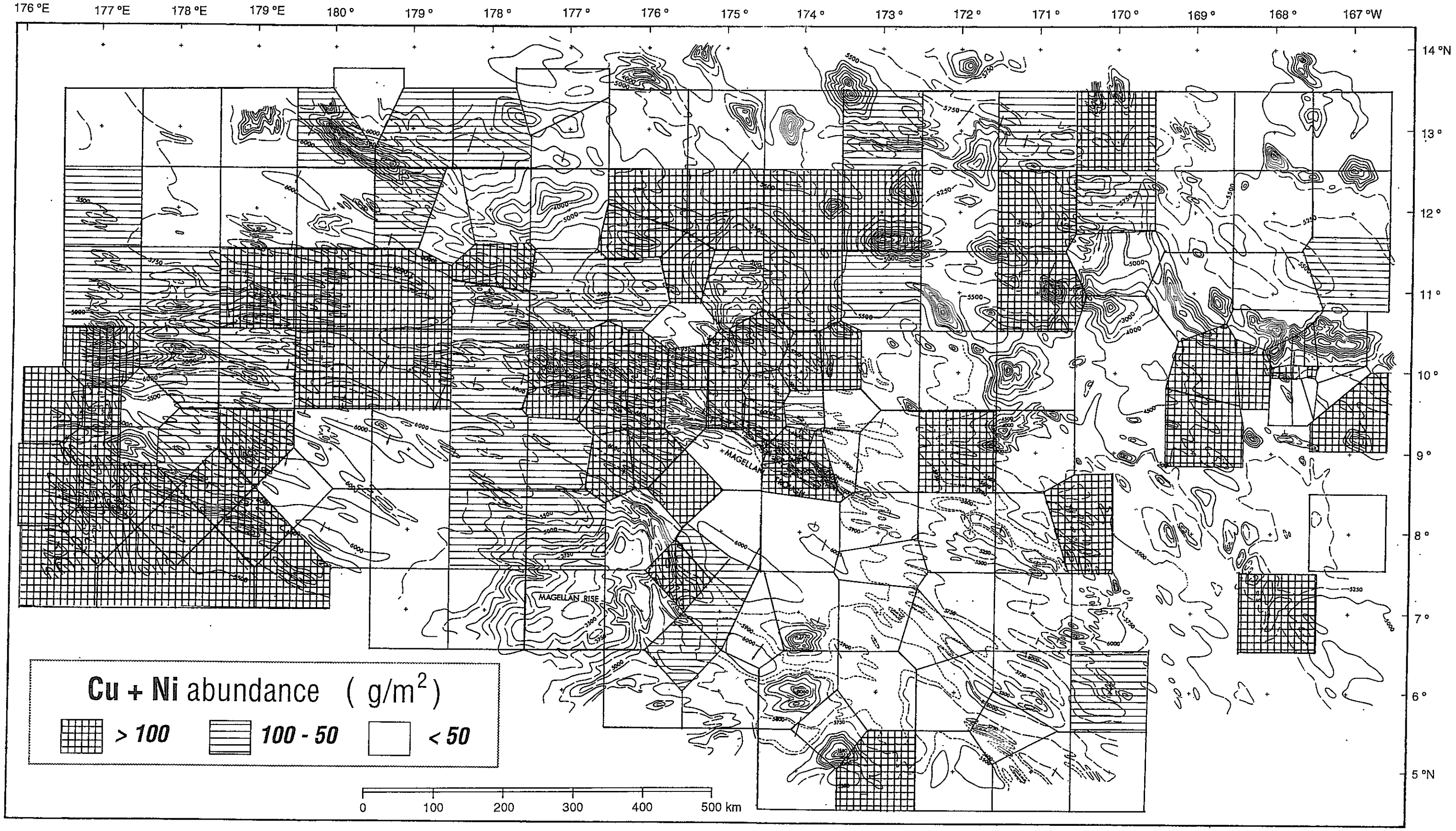

Fig. 7 Distribution of Cu+Ni abundance (total metal abundance per unit area).

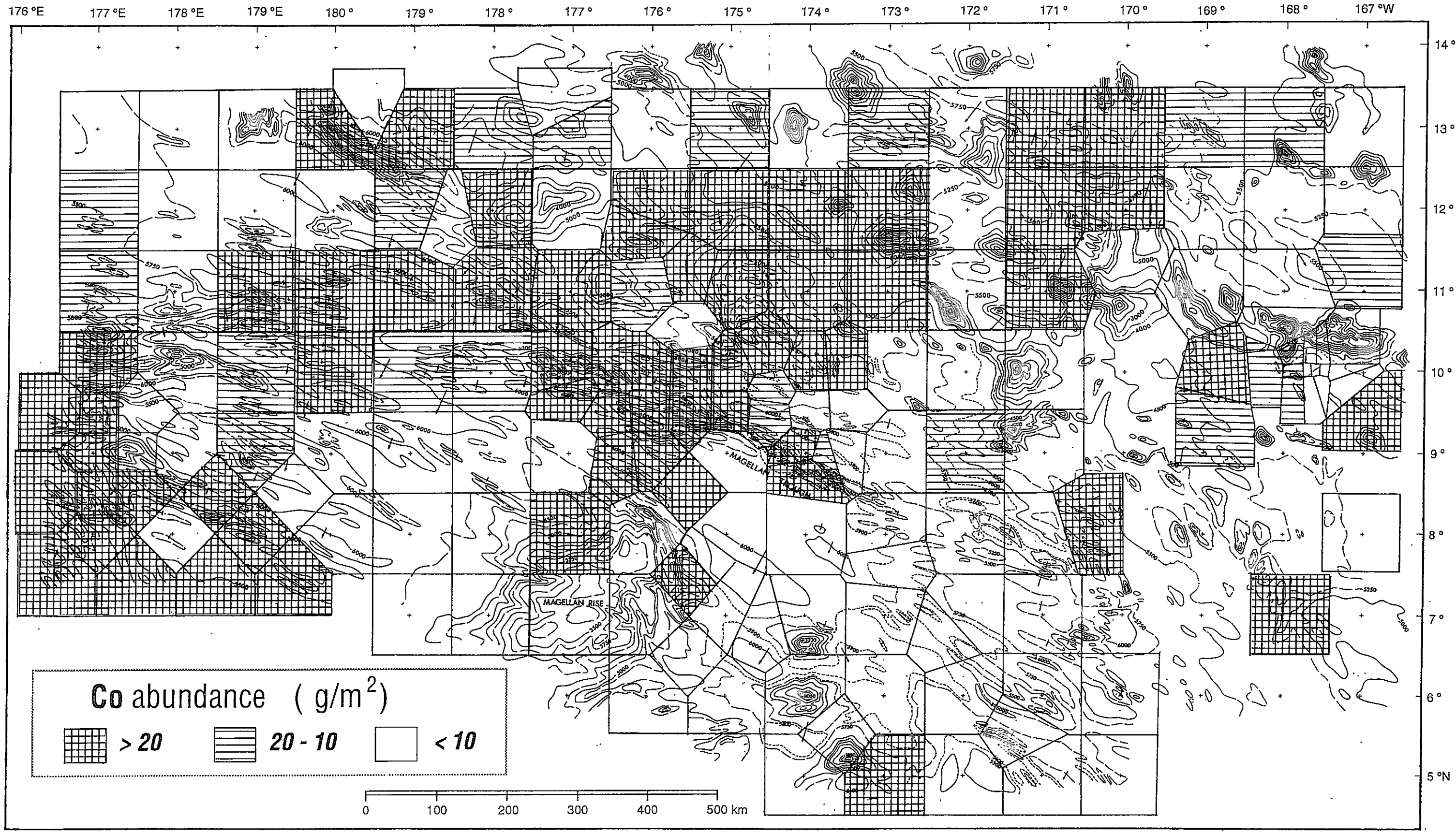

Fig. 8 Distribution of Co abundance (total metal abundance per unit area).

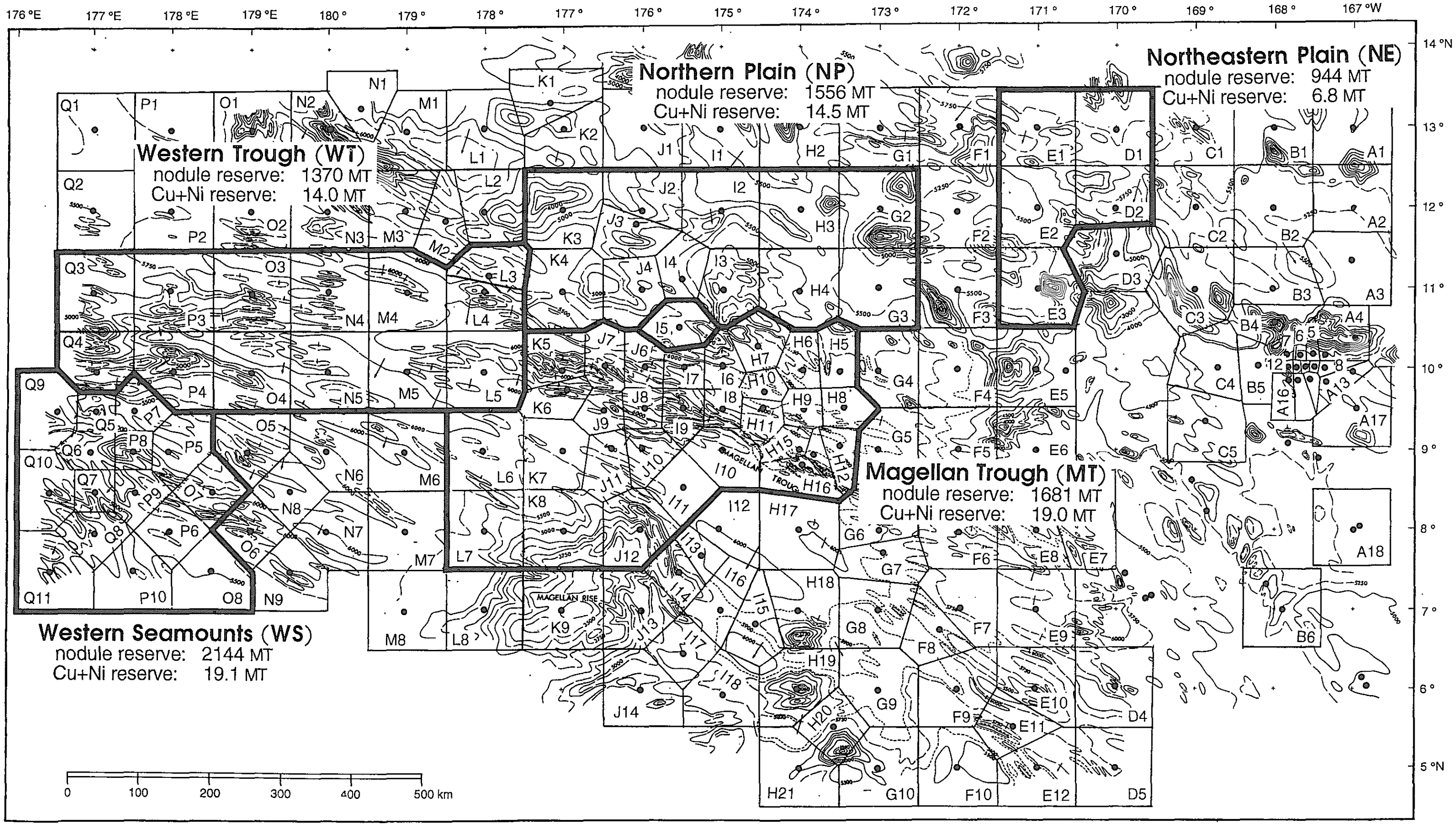

Fig. 9 Selected regions of possible economic interest (outlined by thick lines). See Appendix 1 for nodule abundance and chemical composition in each polygon.

; CCZ), the deposits of this area are greater in nodule abundance, total metal resources, and probably extent of prime area (Table 2), although the average contents of Cu and Ni are significantly low. Their average of Cu plus Ni abundance in these selected areas is the minimum level in the prime area of the Nodule Belt. On the other hand, the advantages for seabed mining in these areas are the continuous high-abundant nodule pavements and the relatively high Co content. These nodule deposits can be more potential if Co is economically more emphasized, although if only Cu and Ni are concerned in the first generation of nodule mining the deposits are of the second priority .

The calculated manganese nodule resources here can be called "indicated reserve" or "probable reserve" if compared to land ores after the classification by U.S. Bureau of Mines and U.S. Geological Survey (Peters, 1978 ; Blondel and Lasky, 1983), since tonnage and grade are computed partly from irregularly spaced sampling locations which may not permit the mineral bodies to be outlined completely. The calculated resources here should require more detailed exploration on smaller scales.

7. Conclusions

The economic potential of manganese nodule deposits in the northern Central Pacific Basin was estimated as "indicated reserves", based on the descriptions for nodules from 555 sampling samplers at 178 stations and more than 1000 chemical analyses. The nodule pavements over 5 kg/m^2 are inferred to cover about 660,000 km^2 or 45% of the whole study area. A total 9.2 billion tons of manganese nodules, 39 million tons of Cu, 52 million tons of Ni, and 27 million tons of Co were indicated in areas of high nodule abundance over 5 kg/m^2.

The distribution patterns of nodule abundance and Cu plus Ni and Co abundance are similar to each other, indicating that metal resources are principally controlled by the variation of nodule abundance rather than their chemical composition. The area is dominated by Co-rich hydrogenetic nodules, while Cu and Ni-rich diagenetic nodules occur only on a local scale with low abundances. The advantage of these deposit development is high nodule abundance and Co content.

Considering the areal extent and continuity of the deposits, five regions of economic interest covering 40% of the study area were selected and characterized in nodule abundance and metal grade. Some of these regions are expected to extend out of the area and await for more detailed exploration. These regions are similar to or greater in nodule abundance and total metal resources than some of the proposed mine sites in the Northeastern Pacific Manganese Nodule Belt.

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Appendix 1 Nodule abundance and metal contents of nodules at each station. Index of polygons is the same as in Figure 9.

Polygon No.	Area (km^2)	Average abundance (kg/m^2)	Average metal contents (dry wt.%)							No. of samplers
			Mn	Fe	Cu	Ni	Co	Zn	Pb	
A1	12,100	1.50	13.7	11.4	0.24	0.34	0.30	0.057	0.071	3
A2	10,395	2.70	8.0	6.9	0.11	0.26	0.13	0.040	0.040	3
A3	11,389	4.72	23.6	7.4	0.81	1.02	0.23	0.111	0.042	5
A4	5,577	0	-	-	-	-	-	-	-	3
A5	957	0.03	25.7	4.7	0.72	0.92	0.17	0.123	0.029	3
A6	754	0	-	-	-	-	-	-	-	3
A7	1,027	4.73	18.3	8.3	0.62	0.69	0.23	0.077	0.052	3
A8	792	0.07	24.4	4.6	1.05	1.18	0.12	0.121	0.028	3
A9	242	0	-	-	-	-	-	-	-	2
A10	143	12.00	23.0	6.1	0.96	1.06	0.18	0.112	0.037	1
A11	190	1.33	23.0	6.1	0.96	1.06	0.18	0.112	0.037	12
A12	493	8.85	19.7	8.7	0.66	0.82	0.22	0.082	0.050	20
A13	2,310	0.37	23.8	5.4	1.01	1.06	0.14	0.113	0.034	3
A14	641	0.40	23.8	4.7	0.88	1.06	0.15	0.137	0.034	3
A15	1,452	2.77	23.3	5.6	0.96	1.13	0.18	0.117	0.037	3
A16	2,016	1.30	22.7	5.2	0.97	1.09	0.15	0.113	0.035	2
A17	9,170	15.00	19.7	8.7	0.66	0.82	0.22	0.082	0.050	1
A18	12,100	0	-	-	-	-	-	-	-	1
B1	12,100	5.90	13.6	9.7	0.32	0.49	0.27	0.056	0.057	5
B2	11,944	0.28	16.3	6.6	0.49	0.68	0.15	0.087	0.029	4
B3	9,072	0.80	23.8	7.6	0.88	1.02	0.21	0.108	0.047	3
B4	4,773	0	-	-	-	-	-	-	-	1
B5	4,037	7.00	19.7	8.7	0.66	0.82	0.22	0.082	0.050	1
B6	12,100	14.00	19.7	8.7	0.66	0.82	0.22	0.082	0.050	1
C1	12,100	5.20	18.4	12.3	0.32	0.53	0.31	0.064	0.072	4
C2	11,920	0.10	20.4	7.3	0.73	0.82	0.20	0.099	0.042	5
C3	12,049	0.04	22.7	8.0	0.76	0.93	0.23	0.100	0.050	5
C4	8,185	26.00	19.7	8.7	0.66	0.82	0.22	0.082	0.050	1
C5	10,620	8.50	19.7	8.7	0.66	0.82	0.22	0.082	0.050	1
D1	12,100	13.12	19.2	12.8	0.36	0.52	0.34	0.062	0.078	5
D2	9,900	13.10	18.7	13.5	0.25	0.41	0.37	0.059	0.083	5
D3	9,969	0.10	15.0	8.8	0.41	0.64	0.18	0.071	0.043	5
D4	12,100	2.77	27.4	5.8	1.50	1.35	0.13	0.134	0.026	3
D5	12,100	0	-	-	-	-	-	-	-	3
E1	12,100	14.13	17.4	13.1	0.26	0.42	0.30	0.054	0.065	4
E2	11,939	16.80	18.7	11.7	0.33	0.49	0.29	0.061	0.070	5
E3	12,581	22.60	18.7	13.3	0.24	0.39	0.39	0.052	0.077	4
E5	12,100	0	-	-	-	-	-	-	-	1
E6	11,562	0.10	27.5	4.7	1.17	1.22	0.14	0.206	0.022	1
E7	11,030	19.00	19.7	8.7	0.66	0.82	0.22	0.082	0.050	1
E8	9,718	0.80	27.5	4.7	1.17	1.22	0.14	0.206	0.022	3
E9	12,100	0.20	24.4	6.5	1.06	0.91	0.17	0.146	0.019	3
E10	9,892	0.03	24.4	6.5	1.06	0.91	0.17	0.146	0.019	3
E11	6,200	0	-	-	-	-	-	-	-	3
E12	9,763	0	-	-	-	-	-	-	-	2
F1	12,100	0.04	16.7	10.6	0.35	0.56	0.23	0.063	0.057	5
F2	12,100	3.53	16.7	10.6	0.35	0.56	0.23	0.063	0.057	3
F3	12,100	0.35	19.3	8.5	0.64	0.76	0.20	0.082	0.047	4
F4	12,100	0	-	-	-	-	-	-	-	3
F5	12,100	5.63	24.2	6.3	1.05	1.17	0.19	0.113	0.033	3
F6	11,755	0.63	27.3	5.2	1.03	1.03	0.16	0.212	0.017	3
F7	8,407	0.40	29.9	4.5	1.39	1.34	0.14	0.193	0.018	3
F8	6,042	0.25	27.6	5.4	1.10	0.91	0.18	0.175	0.025	2
F9	10,345	0	-	-	-	-	-	-	-	3
F10	11,325	0	-	-	-	-	-	-	-	3
G1	12,100	4.20	21.4	9.0	0.68	0.75	0.29	0.079	0.047	5
G2	12,100	15.73	19.0	12.0	0.40	0.54	0.28	0.060	0.070	4
G3	11,918	9.53	18.0	10.8	0.40	0.57	0.25	0.065	0.063	4
G4	8,946	1.10	25.7	5.9	1.24	1.11	0.14	0.114	0.026	3
G5	9,201	0.10	25.7	5.9	1.24	1.11	0.14	0.114	0.026	3
G6	8,061	0.77	26.3	5.0	1.14	1.16	0.14	0.155	0.019	3
G7	6,697	0.30	30.1	4.1	1.14	1.06	0.18	0.195	0.024	3
G8	9,372	0.10	30.1	4.1	1.14	1.06	0.18	0.195	0.024	2
G9	10,642	0	-	-	-	-	-	-	-	3
G10	10,969	10.96	21.8	9.1	0.97	0.95	0.18	0.088	0.040	5
H2	12,100	2.95	17.4	11.5	0.30	0.44	0.31	0.056	0.066	6
H3	12,100	16.60	19.1	11.3	0.40	0.63	0.30	0.060	0.065	2
H4	11,424	19.65	20.5	11.8	0.44	0.61	0.32	0.065	0.070	2
H5	4,950	13.20	22.7	7.6	0.93	0.93	0.20	0.087	0.040	2
H6	4,088	20.10	17.9	10.4	0.44	0.56	0.25	0.062	0.049	3
H7	5,037	22.30	17.4	14.2	0.29	0.45	0.35	0.055	0.080	2
H8	3,556	1.30	28.4	5.5	1.13	1.12	0.16	0.166	0.022	3
H9	2,724	3.40	25.7	7.0	1.18	1.15	0.15	0.113	0.029	2
H10	2,264	6.33	26.3	5.5	1.40	1.40	0.16	0.121	0.044	3
H11	3,110	9.40	22.9	6.4	1.02	1.02	0.19	0.098	0.043	2
H12	3,502	0.25	28.4	5.5	1.13	1.12	0.16	0.166	0.022	2
H14	2,417	11.05	19.4	10.9	0.56	0.64	0.26	0.062	0.056	11
H15	1,415	6.85	23.4	7.7	0.92	1.00	0.22	0.096	0.045	2
H16	4,401	10.20	20.7	8.3	0.78	0.78	0.21	0.069	0.042	2
H17	11,390	0.07	18.3	8.1	0.79	0.66	0.13	0.108	0.010	3
H18	9,830	0	-	-	-	-	-	-	-	1
H19	9,605	0	-	-	-	-	-	-	-	1
H20	5,992	0.35	14.9	7.9	0.77	0.81	0.12	0.077	0.034	4
H21	10,244	0.40	14.9	7.9	0.77	0.81	0.12	0.077	0.034	1
I1	12,100	5.58	13.8	8.4	0.28	0.48	0.19	0.058	0.049	5
I2	11,663	21.90	18.5	12.8	0.22	0.40	0.40	0.049	0.085	2
I3	7,900	10.00	18.6	11.7	0.37	0.58	0.35	0.067	0.083	3
I4	5,106	24.80	21.7	14.1	0.39	0.51	0.37	0.059	0.098	2
I5	5,045	0	-	-	-	-	-	-	-	2
I6	3,645	26.03	18.4	12.6	0.39	0.51	0.30	0.056	0.071	3
I7	3,320	30.30	17.1	12.5	0.38	0.53	0.31	0.058	0.075	2
I8	2,862	25.75	17.3	11.3	0.46	0.57	0.24	0.058	0.060	2
I9	4,030	0	-	-	-	-	-	-	-	1
I10	6,914	1.80	23.2	7.0	1.08	1.10	0.21	0.105	0.042	3

Appendix 1 Continued

Polygon No.	Area (km^2)	Average abundance (kg/m^2)	Average metal contents (dry wt.%)							No. of samplers
			Mn	Fe	Cu	Ni	Co	Zn	Pb	
I11	5,886	11.90	19.9	7.7	0.84	0.95	0.20	0.082	0.047	2
I12	7,450	0.53	22.1	6.6	1.11	1.06	0.20	0.088	0.052	3
I13	2,716	2.85	22.1	6.6	1.11	1.06	0.20	0.088	0.052	2
I14	4,437	25.15	18.2	13.6	0.32	0.43	0.29	0.052	0.075	2
I15	6,392	0.10	22.1	6.6	1.11	1.06	0.20	0.088	0.052	3
I16	6,305	2.63	22.1	6.6	1.11	1.06	0.20	0.088	0.052	3
I17	5,885	1.00	22.1	6.6	1.11	1.06	0.20	0.088	0.052	2
I18	9,320	0	-	-	-	-	-	-	-	3
J1	12,100	0.04	22.1	11.4	0.42	0.72	0.37	0.074	0.084	5
J2	7,740	11.10	22.1	11.4	0.42	0.72	0.37	0.074	0.084	3
J3	5,902	15.80	19.4	12.8	0.35	0.51	0.36	0.058	0.096	2
J4	7,189	5.20	18.4	7.9	0.63	0.77	0.21	0.078	0.048	3
J6	3,809	24.86	16.9	12.4	0.35	0.48	0.28	0.055	0.071	11
J7	4,642	19.65	14.1	12.4	0.31	0.41	0.27	0.047	0.066	2
J8	3,040	19.93	17.4	11.6	0.46	0.57	0.27	0.057	0.065	3
J9	3,277	27.95	17.8	12.9	0.39	0.53	0.31	0.057	0.072	2
J10	4,620	20.57	18.4	11.0	0.50	0.58	0.25	0.061	0.059	3
J11	5,112	15.13	14.8	11.2	0.32	0.50	0.22	0.049	0.059	3
J12	9,084	0	-	-	-	-	-	-	-	3
J13	9,627	0	-	-	-	-	-	-	-	3
J14	10,534	0.20	22.1	6.6	1.11	1.06	0.20	0.088	0.052	3
K1	8,460	0.10	14.2	10.5	0.19	0.24	0.22	0.046	0.049	2
K2	7,920	3.48	19.1	13.1	0.40	0.38	0.42	0.085	0.085	5
K3	11,620	4.03	20.3	12.4	0.35	0.65	0.40	0.071	0.093	3
K4	11,594	8.80	19.8	11.6	0.38	0.56	0.34	0.067	0.072	2
K5	6,136	11.43	17.4	10.5	0.44	0.56	0.24	0.060	0.060	3
K6	4,392	22.00	16.1	11.7	0.43	0.50	0.24	0.053	0.069	3
K7	8,494	2.43	22.8	6.6	1.05	1.17	0.18	0.089	0.036	3
K8	11,848	9.10	16.2	10.3	0.43	0.58	0.23	0.063	0.060	3
K9	12,100	0	-	-	-	-	-	-	-	3
L1	11,460	6.20	19.6	10.5	0.41	0.71	0.26	0.081	0.063	5
L2	9,380	6.80	14.0	11.1	0.19	0.34	0.31	0.052	0.069	2
L3	5,792	16.46	20.4	14.6	0.35	0.46	0.39	0.055	0.110	5
L4	6,864	11.03	16.5	11.8	0.32	0.45	0.30	0.107	0.072	3
L5	11,988	6.80	18.4	11.7	0.42	0.51	0.29	0.120	0.068	3
L6	12,060	4.77	19.1	6.9	0.81	0.90	0.18	0.118	0.039	3
L7	12,100	5.47	15.3	7.4	0.60	0.66	0.16	0.096	0.039	3
L8	12,100	0	-	-	-	-	-	-	-	3
M1	10,380	5.60	20.6	13.0	0.35	0.56	0.41	0.063	0.082	3
M2	6,406	1.10	23.3	7.0	0.83	0.97	0.25	0.104	0.059	2
M3	9,425	4.50	24.8	9.3	0.75	0.96	0.30	0.096	0.057	3
M4	11,571	10.73	19.6	10.7	0.50	0.62	0.28	0.071	0.065	3
M5	12,100	11.65	14.7	8.4	0.49	0.60	0.16	0.062	0.039	2
M6	12,100	0	-	-	-	-	-	-	-	3
M7	12,100	0	-	-	-	-	-	-	-	3
M8	12,100	0.17	15.3	7.4	0.60	0.66	0.16	0.096	0.039	3
N1	6,764	1.20	25.2	7.8	0.88	0.98	0.24	0.104	0.076	2
N2	9,606	9.70	19.5	15.4	0.20	0.42	0.53	0.053	0.103	3
N3	12,100	0.53	23.3	7.0	0.83	0.97	0.25	0.104	0.059	3
N4	12,100	12.63	21.4	12.8	0.56	0.72	0.33	0.070	0.068	3
N5	12,100	11.50	18.3	10.4	0.57	0.68	0.25	0.061	0.056	3
N6	10,588	0	-	-	-	-	-	-	-	3
N7	9,295	0.87	24.1	6.0	1.06	1.17	0.15	0.101	0.034	3
N8	6,084	0.17	22.1	6.6	1.05	1.09	0.14	0.097	0.037	3
N9	9,072	17.70	19.2	12.8	0.42	0.60	0.32	0.070	0.066	2
O1	12,100	1.50	19.1	13.1	0.29	0.47	0.47	0.064	0.078	3
O2	12,100	1.37	23.3	7.0	0.83	0.97	0.25	0.104	0.059	3
O3	12,100	9.87	17.6	9.0	0.52	0.74	0.26	0.074	0.048	3
O4	12,100	6.13	12.7	11.5	0.33	0.54	0.21	0.058	0.048	3
O5	9,350	7.17	20.3	7.6	0.78	0.89	0.19	0.088	0.048	3
O6	6,084	10.83	19.2	12.8	0.42	0.60	0.32	0.070	0.066	3
O7	6,084	16.40	19.2	12.8	0.42	0.60	0.32	0.070	0.066	2
O8	9,240	26.93	19.2	15.1	0.36	0.47	0.32	0.059	0.083	3
P1	12,100	0.10	23.3	7.0	0.83	0.97	0.25	0.104	0.059	3
P2	12,100	1.20	23.3	7.0	0.83	0.97	0.25	0.104	0.059	3
P3	12,100	2.97	23.3	7.0	0.83	0.97	0.25	0.104	0.059	3
P4	10,534	10.55	11.7	11.0	0.23	0.42	0.09	0.052	0.043	2
P5	7,002	4.10	20.3	9.9	0.64	0.74	0.22	0.077	0.048	2
P6	6,084	3.27	19.9	9.3	0.72	0.79	0.19	0.077	0.043	3
P7	4,789	1.60	20.3	9.9	0.64	0.74	0.22	0.077	0.048	2
P8	2,849	0	-	-	-	-	-	-	-	3
P9	5,002	21.63	19.2	15.1	0.36	0.47	0.32	0.059	0.083	3
P10	9,185	25.30	19.2	15.1	0.36	0.47	0.32	0.059	0.083	2
Q1	12,100	0.10	17.5	11.0	0.26	0.44	0.25	0.062	0.057	3
Q2	12,100	7.50	17.5	11.0	0.26	0.44	0.25	0.062	0.057	1
Q3	12,100	7.73	17.5	11.0	0.26	0.44	0.25	0.062	0.057	4
Q4	8,370	15.10	19.2	14.7	0.38	0.49	0.33	0.057	0.069	5
Q5	3,136	19.88	18.8	12.8	0.39	0.50	0.32	0.064	0.079	9
Q6	3,905	19.13	19.7	14.6	0.37	0.52	0.34	0.069	0.072	3
Q7	3,136	36.35	19.2	15.1	0.36	0.47	0.32	0.059	0.083	2
Q8	5,368	31.60	18.7	16.0	0.32	0.46	0.32	0.062	0.071	3
Q9	8,120	25.05	19.3	14.0	0.33	0.47	0.38	0.058	0.084	2
Q10	8,822	25.85	20.4	15.0	0.44	0.54	0.34	0.063	0.093	2
Q11	10,736	23.60	19.7	16.4	0.25	0.36	0.39	0.089	0.089	3

中央太平洋海盆北部マンガン団塊の金属資源量の推定

P. コーピナ・臼井　朗

要　旨

地質調査所が実施した過去の白嶺丸航海の研究成果に基いて，中央太平洋海盆北部（147万 km^2）のマンガン団塊鉱床の総鉱量，金属資源量を検討し有望域を選定した．178測点における総計555地点での底質記載データ，1,000以上の団塊の化学分析値に基づいて試算すると，濃集率（単位面積あたりの団塊重量）5 kg/m^2 以上の地域は調査海域の約45%（66万 km^2）を占め，その団塊総鉱量は92億トン，銅＋ニッケル総量は9,100万トン，コバルト総量は2,700万トンと試算される．この値は陸上鉱量評価の信頼性基準では予測埋蔵量に当てはまる．

当海域内の団塊の特徴は高濃集率の hydrogenetic（海水起源）団塊が卓越することである．銅・ニッケルに富む diagenetic（続成起源）団塊は海域南東部の狭い海域に低濃集率の分布を示すに過ぎない．従って銅・ニッケル・コバルト金属資源量の広域的分布は，団塊の化学組成よりも団塊の濃集率に規制される．計算結果によると，三元素とも調査域の総金属量のうち80-90%が高濃集率団塊（$>5\,kg/m^2$）に含まれる．

試算結果から，さしわたし数百km程度の5つの有望地域を海域内から選定することができた．これら有望地域は北東太平洋の各団塊鉱区域に匹敵する総鉱量，総金属資源量を示す一方で，当面資源の対象とされる銅・ニッケルの含有量が低い．比較して有利な点は団塊の高濃集率と中程度のコバルト含有量といえる．

なお本研究は国連海洋法条約に基づく「国連海底機構」技術要員訓練のための研修成果の一部である．

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