

Ore Grade Manganese Nodules from the Central Indian Basin: An Evaluation

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Abstract Comparative studies on manganese nodules from two different areas (S and R) in the Central Indian Basin show distinct variations in their composition, grade (percent Ni + Cu), and abundance (kg/m^2), which are explained in terms of various genetic processes. Area S is a zone of siliceous sediment in which nodules are characterized by high Mn/Fe ratios (mean 3.77), high percent Ni + Cu content (mean 2.41 percent) and high abundance (mean 7.48 kg/m^2). Area R is a zone of red clay where the nodules are characterized by low Mn/Fe ratios (mean 2.24), low percent Ni + Cu contents (mean 1.61 percent), and low abundance (mean 4.68 kg/m^2). The mean Cu and Ni values are 1.19 percent and 1.22 percent, respectively, in Area S nodules, whereas Area R nodules show relatively lower concentrations of Cu (mean 0.68 percent) and Ni (0.92 percent), respectively.

The results indicate that the nodules from siliceous sediments approximate the diagenetic end members of the series, as described in the Pacific, and are similar in composition to the north equatorial Pacific ore grade nodules. Siliceous sediments in CIB offer the possible sites for first generation mining, where nodules having a mean concentration of percent Ni + Cu > 2.27 percent, at 1.8 percent Ni + Cu cutoff, and $> 5 \text{ kg/m}^2$ abundance are recovered. Early diagenetic processes are predominant in the zone of siliceous sediment between 10°S to 15°S , whereas red clay nodules are more hydrogenous than diagenetic in nature. The sedimentary boundary between siliceous and red clays exist around 15°S , which may be the boundary delimiting ore grade nodules to the north of 15°S . It is evident from the Pioneer Area allocated to India by the United Nations that more than 95 percent of it ($150,000 \text{ km}^2$) encompasses the region between the latitudes 10° to 15°S .

Introduction

There was a gap between the initial studies on deepsea manganese nodules from the Indian Ocean by Cronan and Tooms (1967, 1968, 1969), Glasby (1970, 1972), Siddiquie et al. (1978), Frazer and Wilson (1980), and Cronan and Moorby (1981) until the collection of the first nodules by India from the equatorial Indian Ocean (between Goa and Mauritius) during the 86 and 87 cruises of RV *Gaveshani*, Jan.-Feb. 1981. Some of the results were published on these nodules by Karisiddaiah (1985). Subsequently, the government of India launched an ambitious program in 1982 for "Exploration of Polymetallic Nodules in the Central Indian Basin" to identify prime sites of ore grade nodules. It was evident from the literature that the paramarginal and submarginal grade nodules are limited to deepwaters of the Central Indian Basin (hereafter referred to as CIB) in an area of about $700,000 \text{ km}^2$ between 10° – 16° south of the equator (Frazer and Wilson 1979, 1980; Cronan and Moorby 1981). To increase the data base, India initiated surveys in the CIB between latitudes 0° and 20°S and longitudes 70° and 84°E . Efforts made by India in this exploration program were recognized by the United Nations when the PREPCOM for International Seabed Authority allocated to the applicant (India), a Pioneer Area of

150,000 km² in the Indian Ocean on 17 August 1987 (Anon 1988). Since 1987 results on mineralogy (Rao 1987), morphology (Mukhopadhyay 1987), geochemical variations (Ahmad and Hussain 1987; Jauhari 1987), internal structure (Pattan 1988), topographic control on nodule distribution and facies variation (Mukhopadhyay and Nagendernath 1988; Pattan and Kodagali 1988) of nodules from the CIB have been published. Most of these studies were carried out to determine the nature and genesis of nodules. Based on 25 assays from 15 locations in the CIB, Frazer and Wilson (1980) reported that "of the five areas studied in the Indian Ocean" nodules of paramarginal grade may be recovered only in the CIB, which has proved to be a potential site for first generation seabed mining. However, not much consideration has been given to evaluate ore grade nodules and their distributions in the CIB (Sudhakar 1988, 1989). This formed the objective of the present study. Based on the information available, an attempt has been made to delineate the areas of ore grade nodule resources.

In this regard, a part of the exploration data from the PMN data bank of the National Institute of Oceanography, which includes compositional data for five elements, Mn, Fe, Co, Ni, and Cu, and nodule abundance (kg/m²) in 89 stations, was utilized. The data set was mainly generated from two sedimentary provinces, viz. siliceous and red clay sediments (Udintsev 1975). The nodules studied from siliceous sediments are hereafter referred to as "Area S," whereas "Area R" denotes nodules from red clays (Figure 1).

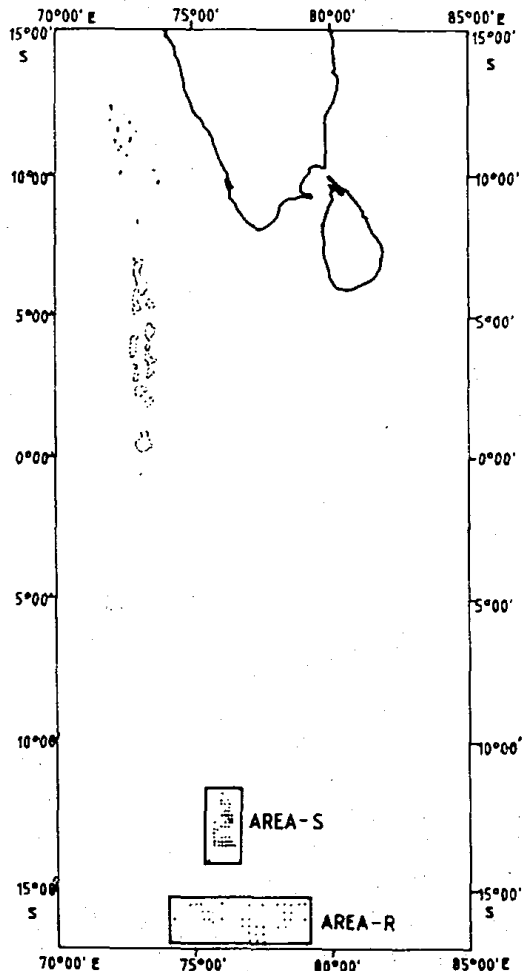


Figure 1. Map showing sampling stations from the two areas in the CIB.

The variations of Mn, Fe, Co, Ni, Cu, and the abundance of nodules from these sedimentary provinces have also been explained. In addition, attempts have been made to understand the various geochemical processes responsible for the enrichment of Mn, Fe, Co, Ni, and Cu in nodules from the two sediment environments.

Methods and Techniques

Data from 89 stations (Figure 1) collected during various oceanographic cruises was analyzed. Forty-five stations fall in Area S and 44 stations in Area R.

Nodule Sampling

The nodule samples were recovered by using freefall grabs. Five to seven grabs were deployed in an hexagonal or square pattern (with an average interval of about 500 m between the samplers) at each station. Nodule abundance (in kg/m²) was computed from the nodule recovery (by weight) in the grab and the area of the grab sampler (0.13 m²). Average abundance was estimated for each station using the arithmetic average of all the samples recovered at that station. The nonrecovery of nodules in the grab was also considered while calculating the average.

Chemical Analyses

One or two nodules from each grab were taken and finely powdered for digestion. The powdered sample was split into three aliquots. One part was preserved for future reference and the remaining two parts for two to three assays were used. The analyses were carried out for the determination of metals like Mn, Fe, Co, Ni, and Cu using AAS and XRF instruments. The accuracy of analyses was checked by analyzing the known standards such as USGS-1 and NIO nodules. The bulk composition of nodules was expressed on percent dry basis. An average of all the assays was considered to represent the composition at each station. These computed average abundance and the calculated average of the assays (as described above) form the data base for the present study.

Results and Discussion

Nodule Composition and Enrichment Processes

Table 1 shows the minima, maxima, mean, and shift standard deviation of various elemental data of the CIB nodules from the two sediment provinces studied here. Comparison of the CIB data with the data of Frazer and Wilson (1980; Table 1) shows that the mean composition of CIB nodules is similar to the values reported by them, but significantly different from the mean of the Indian Ocean nodules (Siddiquie et al. 1978; Cronan and Moorby 1981). Nodules from both the sediment provinces show a higher mean composition of Mn, Ni, and Cu than the Indian Ocean averages, whereas the mean Fe values for Area S (7.73 percent) and Area R (10.72 percent) are lower than the mean

Table 1
Concentration Maxima, Minima, and Mean of Manganese Nodules from Two Sediment Provinces in CIB

Parameter	Minimum	Maximum	Mean	S.D.		Coefficient
				± of variation (%)		
Mn	18.07 ^a (13.15) ^b	33.58 (28.63)	26.05 (22.25)	3.52 (3.30)		13.51 (14.83)
Fe	4.94 (5.57)	13.62 (18.70)	7.73 (10.72)	2.67 (2.71)		34.54 (25.28)
Co	0.09 (0.12)	0.33 (0.43)	0.14 (0.21)	0.05 (0.06)		35.71 (28.57)
Ni	0.64 (0.44)	1.58 (1.54)	1.22 (0.92)	0.28 (0.22)		22.95 (23.91)
Cu	0.44 (0.27)	1.86 (1.27)	1.19 (0.685)	0.38 (0.25)		31.93 (36.50)
Grade (% Ni + Cu)	1.11 (0.71)	3.40 (2.66)	2.41 (1.61)	0.65 (0.45)		26.97 (27.95)
Mn/Fe	1.35 (1.01)	6.09 (5.14)	3.77 (2.24)	1.27 (0.80)		33.69 (35.71)
Cu/Ni	0.66 (0.48)	1.21 (1.23)	0.96 (0.73)	0.14 (0.15)		14.58 (20.55)
Abundance (kg/m ²)	0.85 (0.72)	15.66 (13.69)	7.48 (4.68)	3.59 (3.25)		48.0 (69.44)

^aValues above parenthesis are for Area S nodules; n = 45.

^bValues within parenthesis are for Area R nodules; n = 44.

Indian Ocean (Fe 14.8 percent) composition. On the other hand, Co from Area R (0.21 percent) is comparable to that of the mean composition (0.23 percent) of Indian Ocean nodules, but not the Area S nodules, which show a lower mean composition (0.14 percent). Copper content in Area S nodules is unusually high; the maximum values reach up to 1.86 percent with a mean value of 1.19 percent. The lowest Cu values (0.44 percent) from Area S nodules are comparable with the average (0.43 percent) Indian Ocean concentration (Siddiquie et al. 1978). The mean value of Cu in Area R nodules (0.68 percent) is distinctly lower than the mean composition of Area S nodules. However, the maximum value of Cu in Area R (1.27 percent) is close to the mean composition in Area S nodules. About 72 percent of the stations in Area S show copper contents equal to or exceeding that of nickel, whereas nodules in Area R exhibit lower values of Cu than Ni. Only 11 percent of Area R have nodules with copper > 1 percent but 36 percent with nickel > 1 percent. More than 70 percent of the population in Area S nodules exceed > 1 percent Cu, and 71 percent exceed > 1 percent Ni. Nodules from both sedimentary environments have Cu/Ni ratios greater than 1.0, a value approached nowhere else in the Indian Ocean. The mean Cu/Ni ratios from Area S nodules support the earlier views that the CIB Cu/Ni ratios are similar to that of high-grade nodules reported from a region southeast of Hawaii (Frazer and Wilson 1979).

Data from geochemical investigations on deepsea sediments from the CIB reveal that the average concentrations of Cu, Ni, and Co in siliceous sediments and pelagic clays show distinct variations (Nath et al. 1989). The two areas studied viz., Area 2 and Area 3, fall within Area S and Area R, respectively. Siliceous sediments have lower concentrations of Cu (306 ppm), Ni (244 ppm), Co (67 ppm) than the pelagic clays, where the concentrations of Cu, Ni, Co are of the order of 401, 350, 105 ppm, respectively. Comparison with the nodule data (Table 1) between the two sites shows that the Area S is a site where early diagenetic processes might be predominant. Nodules are therefore enriched in Cu and Ni, thus leading to depletion of these metals in the sediments. This also agrees with the mineralogical studies of Rao (1987), in that the dominant mineral phase in nodules from the northern part of the CIB is todorokite. Todorokite, very poor in Fe, is the main Mn phase in the early diagenetic nodules (Halbach et al. 1981). The northern CIB nodules are characterized by rough surface textures (Rao 1987). The internal features of nodules from the abyssal plains show prominent, well-developed columnar structures, whereas the abyssal hill nodules show largely parallel laminations (Pattan 1988). Following the classification of Halbach et al. (1977) based on the Mn/Fe ratios, Area S nodules are classified as Type A with Mn/Fe ratios ≥ 4 . These nodules are generally embedded in the uppermost cm to dm of the siliceous sediments. Calvert (1978) has proposed that nodules with high Mn/Fe ratios represent precipitates that have derived metals through diagenetic processes in addition to those derived by precipitation from seawater. It is evident from Figure 2 that more than 55 percent of the Area S nodules have Mn/Fe ratios > 4, suggesting that the early diagenetic processes are predominant in Area S where greater water depths are often encountered. The nodules and sediments studied by Rao (1987) and Pattan (1988) were recovered from depths ranging from 5,000 to 5,460 m.

The highest Si/Al ratios and high biogenic silica contents are reported in siliceous sediments (Nath et al. 1989). This is attributed to their close proximity to the subequatorial region of high biological productivity. Nodules with the highest Ni and Cu contents appeared to be restricted to latitudinal belts between 10° to 15°S, where the biological productivity reported (Parsons et al. 1977) is of the order of 100–150 mg C/m²/day. Enrichment of these metals Mn, Ni, and Cu in the Area S nodules illustrates the influence

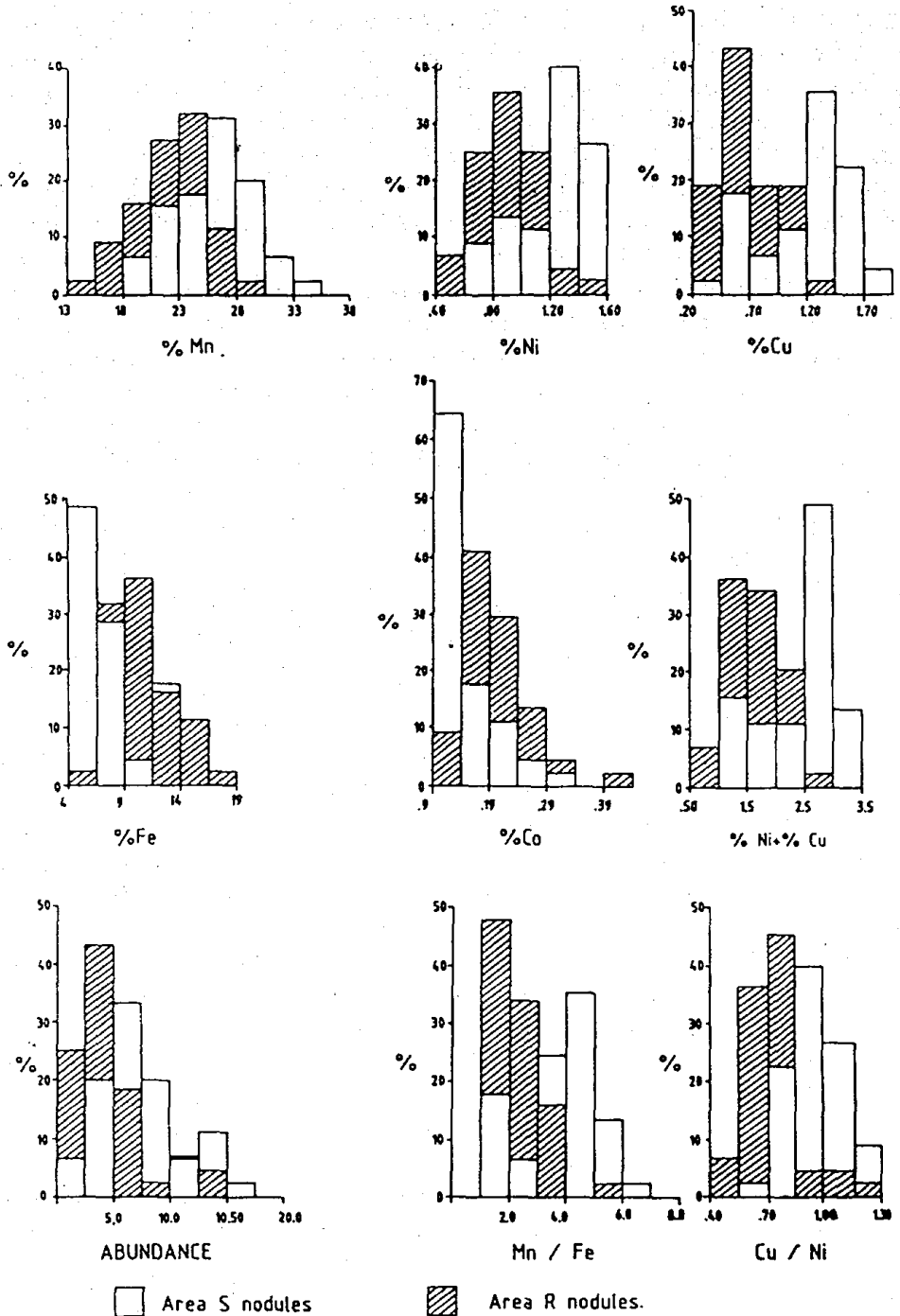


Figure 2. Histograms of elemental variations and nodule abundance distribution in CIB nodules.

of the subequatorial high biological productivity zone on the supply of these metals to nodules.

The source for Cu may be the siliceous skeletons such as radiolarians (Marchig and Gundlach 1981), whereas Ni is associated with opaline silica (Sclater et al. 1976). The reported high biogenic silica contents in siliceous sediments may be the carriers of Cu and Ni. Even the manganese micronodules may be the sources of these elements. Halbach et al. (1979) and Marchig et al. (1979) have suggested that the in situ dissolution of

manganese micronodules in the sediment column may play a vital role in this element supply process. Subsequently, Verges and Clinard (1983) showed micronodules as an important source of Mn, Cu, and Ni.

Rao (1987) reported the occurrence of micronodules in siliceous sediments of the CIB. Studies on a number of sediment samples revealed that the red clays are more enriched in micronodules than the siliceous sediments (M. Sureshraj 1988, pers. commun.). The lower abundances of micronodules in siliceous sediments may be attributed to their dissolution in the sediments due to negative redox potentials caused by the decomposition of organic matter. Marchig and Gundlach (1979) found that micronodules undergo selective dissolution, probably as a result of reaction with organic material within the upper few centimeters of the radiolarian ooze underlying ore grade nodules in the northeast equatorial Pacific. This liberates Mn, Ni, and Cu. Nath and Mudholkar (1989) reported 0.67 percent organic carbon in the topmost sediments (0–3 cm) of a core collected around 13°S and 75°E at 5,270 m water depth. Aplin and Cronan (1985) and Dymond et al. (1984) observed that oxic diagenesis in the areas of oxic siliceous sediment was caused by the decomposition and oxidation of organic matter and dissolution of labile biogenic components. This releases biologically bound Mn, Ni, and Cu for incorporation into the nodules through interstitial waters. Fe concentrations in nodules from siliceous sediments are explained by the interaction between biogenic silica and iron hydroxides during early diagenesis giving rise to formation of Fe-rich montmorillonite (Lyle et al. 1977).

Rao and Nath (1988) also confirmed that more Fe in siliceous sediments is utilized in the formation of Fe-rich montmorillonite, thus leaving free Mn to form todorokite-rich nodules. Glasby and Thijssen (1982) suggested that the supply of the divalent ions $\text{Ni}^{2+} + \text{Cu}^{2+} + \text{Mn}^{2+}$ is a predominant factor in controlling the formation of todorokite. The occurrence of todorokite as a principal manganese mineral phase in Area S nodules and the high values of Mn, Ni, and Cu in these nodules suggest the enhanced supply of suitable divalent ions (principally of Ni, Cu, and Mn) for incorporation in the manganese oxide phases through the in situ decomposition of siliceous tests and manganese micronodules in this siliceous sedimentary province. Fe-rich montmorillonite is present in $< 1 \mu\text{m}$ and $1\text{--}2 \mu\text{m}$ fractions of the siliceous sediment and $1 \mu\text{m}$ fraction of the pelagic clays. The average excess SiO_2 is less (12.27 percent) in pelagic clays than siliceous sediments (27.97 percent) (Nath et al. 1989). Such conditions may not be occurring in pelagic clays, thereby leaving Mn and Fe free to form δMnO_2 -rich nodules.

Area R nodules are from shallower depths ranging from 4,200–4,900 m. Cu, Ni, and Co concentrations are higher in these sediments in contrast to their depletion in nodules. The mean Cu/Ni ratio in nodules is 0.73. Only three stations in Area R show nodules with Cu/Ni ratios reaching unity in contrast to 19 stations in Area S nodules. Co enrichment in these nodules is high (average = 0.21 percent). About 75 percent of the population show Mn/Fe ratios ≤ 2.5 (Figure 2). Such nodules are classified as Type B, where the enrichment is mainly due to hydrogenetic processes (Halbach et al. 1981). One station has Mn/Fe ratio of 5.14, which is exceptionally high and indicates localized areas of diagenetic activity. The nodules from pelagic clays are characterized by smooth surface texture with $\delta\text{-MnO}_2$ as the dominant mineral phase (Rao 1987). Biological productivity in red clay areas is $< 100 \text{ mg C/m}^2/\text{day}$ (Parsons et al. 1977).

Histograms of element distribution for the CIB nodules (Figure 2) show that most of the elements are positively skewed, except Mn and Cu/Ni ratios, which are normally distributed. The skewed distributions may be due to the mixed populations and different genetic sources of elements in nodules of these two areas.

Grade and Abundance

According to Cronan and Moorby (1981), the Cu-Ni enriched nodules occur in the central part of the CIB, which is floored by siliceous sediments. Nodules from Area S show high enrichment in Ni and Cu (mean 2.41 percent). The mean compositions of Mn, Ni, and Cu of Area S nodules are comparable with those of the equatorial north Pacific nodules (Hein 1977; Table 1). Even though the extreme high values of Area R for percent Ni + Cu fall within the ore grade region, the mean value represents the low-grade nodules (mean = 1.61 percent). In order to assess the economic viability of manganese nodules from the two areas, an average grade of 2.27 percent Ni + Cu, with a cut-off grade of 1.8 percent Ni + Cu and abundance of 5 kg/m² has been considered (Glasby 1982). Frazer (1979) and Sudhakar (1989) demonstrated that nodule grade is relatively constant over large distances and the analyses of samples from only a few locations usually give a fairly good picture of mean composition of the area. Therefore the present data base should be sufficient to understand the distribution of ore grade nodules in this region. Table 2 shows that 38 percent of the total nodule population falls above the average grade of 2.27 percent Ni + Cu, of which 91 percent of the population is represented by Area S nodules and 9 percent by Area R nodules. About 55 percent of the total nodule population exhibits > 1.8 percent Ni + Cu as cut-off grade, of which 69 percent of the population is represented by Area S nodules and the remaining 31 percent by Area R nodules. Evaluation of potential resources in the CIB (Figure 3) illustrates that 53 percent of the Area S nodules fall within the category of minable resources (Figure 3). Sudhakar (1989) showed that 33 percent of the explored CIB area exhibits combined percent Ni + Cu + Co values of > 2 percent cut-off. In contrast to the above, less than 1 percent of the Area R nodules fall within the minable resource category.

Menard and Frazer (1978) have suggested that manganese nodule grade (percent Ni + Cu) and abundance (kg/m²) of nodules are negatively correlated both regionally and locally in the Pacific (cf. Mizuno and Moritani 1977; Frazer and Wilson 1980; Frazer and Fisk 1981; Sudhakar 1988). This contention gained support from the inverse relation ($r = -0.54$) study carried out by Sudhakar (1988) on 435 stations from the Central Indian Basin. Data for Area S and Area R show correlation coefficients of the order of -0.52 and -0.38 , respectively (Figure 3). These weak correlation values are statistically significant at the 99.9 percent confidence level and would support the assertions on Pacific and CIB nodules that nodule abundance and grade are negatively correlated in contrast to the assumption of Archer (1976) that they are independent. A correlation coefficient of -0.40 was obtained for 121 data points in the equatorial north Pacific where approximately half the stations fall in the field of potential economic interest (Glasby et al. 1982).

Lasky Distribution

Of particular interest is the assertion of Healing and Archer (1975) that manganese nodules exhibit the Lasky distribution (Glasby 1982). The cumulative frequency of nodules by grade (percent Ni + Cu) from two sedimentary provinces in the CIB is shown in Table 2. Lasky curves are drawn for Area S, Area R, and for the CIB (Figure 4). It can be seen in Figure 4 that the plot of the cumulative frequency of nodules by grade (percent Ni + Cu) exhibits a similar form to that established by Healing and Archer (1975) and Glasby (1982) for south Pacific nodules. Area S curves are comparable to the Lasky curves, however. The trend suggests that the Lasky distribution also holds good for nodules

Table 2
Cumulative Frequency of Nodules by Grade (% Ni + Cu) from Two Sediment Provinces in CIB

Grade (% Ni + Cu)	No. nodules in that grade		% frequency nodules in that grade		Cumulative frequency nodules above cut-off grade	
	Area S	Area R	Area S	Area R	Area S	Area R
0.00-0.25	—	—	—	—	—	—
0.25-0.50	—	—	—	—	—	—
0.50-0.75	—	1	—	2.27	—	100
0.75-1.00	0	2	—	4.55	—	97.73
1.00-1.25	4	8	8.89	18.18	100.01	93.18
1.25-1.50	3	8	6.67	18.18	91.12	75.00
1.50-1.75	3	8	6.67	18.18	84.45	56.82
1.75-2.00	2	6	4.44	13.64	77.78	38.64
2.00-2.25	2	8	4.44	18.18	73.34	25.00
2.25-2.50	3	2	6.67	4.55	68.9	6.82
2.50-2.75	12	1	26.67	2.27	62.23	2.27
2.75-3.00	7	—	15.56	—	35.56	—
3.00-3.25	6	—	13.33	—	20.00	—
3.25-3.50	3	—	6.67	—	6.67	—

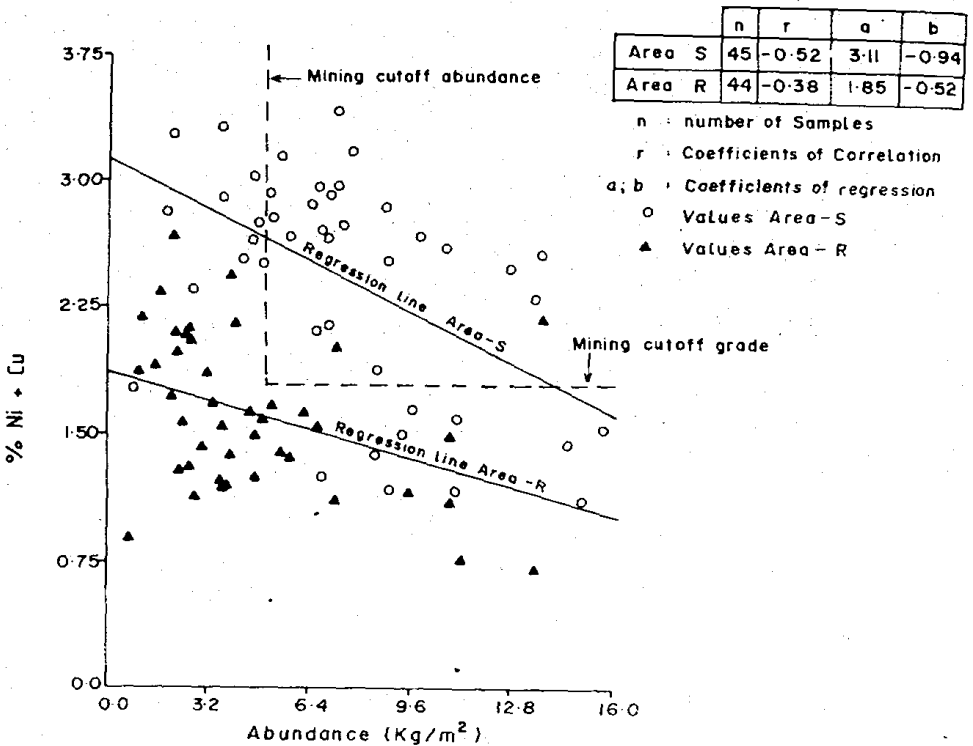


Figure 3. Grade versus abundance in manganese nodules from the two sediment provinces in CIB.

of this region. The CIB curve and the Area R curve are in agreement with the trends shown by Healing and Archer (1975).

Ore Grade Nodules and Resources

In the foregoing section, only percent Ni + Cu has been considered to express the ore grade. In order to assess the paramarginal and submarginal resources from the CIB, percent Ni + Cu + Co is considered below. Frazer and Wilson (1980) used the combined percent Ni + Cu + Co in determining the grade for evaluating the resources. An average grade of 2.47 percent, with a cut-off grade of 1.8 percent and abundance of 5 kg/m², has been established as a standard for "Paramarginal resource," whereas 1.6 percent is a "submarginal resource" (United Nations Expert Meeting on Seabed Mineral Resource Assessment, Nov. 1977).

Figure 5 shows the frequency distribution of percent Ni + Cu + Co for CIB nodules. Paramarginal grades are largely concentrated in the nodules of Area S, whereas the submarginal grades are shown by Area R nodules. A trend surface nodule grade map based on relatively few samples from the CIB reveals that the area between 10°S and 15°S latitudes is the potential zone of ore grade nodules. It has been observed that the surfaces having grades < 1.75 percent appear below 15°S. This is well supported by the sediment distribution maps (Udinstev 1975), which show a boundary between siliceous sediments to the north and the red clays toward the south at 15°S.

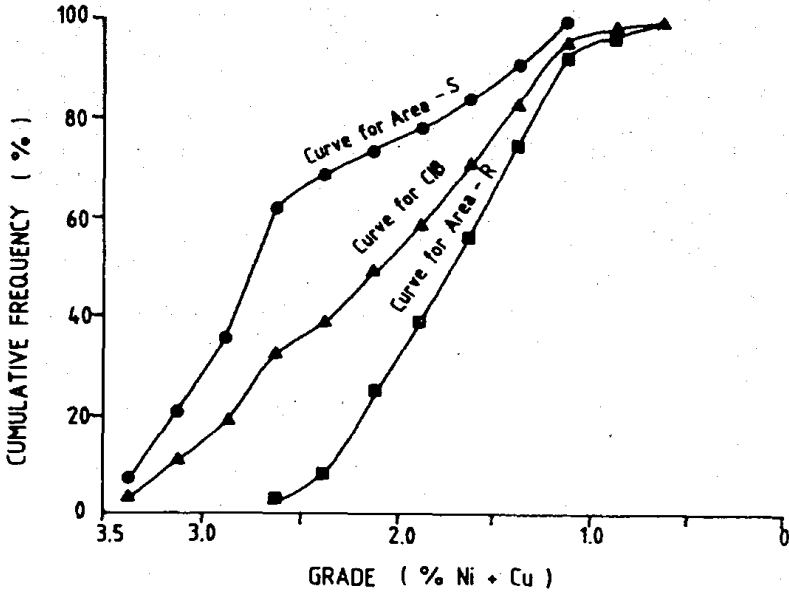


Figure 4. Plot of cumulative frequency of manganese nodules by grade (% Ni + Cu) in the CIB.

Figure 6 shows the Pioneer Area allocated to India by the UN (Anon 1987). It is evident that more than 95 percent of the area (150,000 sq. km.) allocated encompasses the region between the latitudes 10° to 15°S where the sediment is mostly siliceous in nature and the Ni and Cu concentrations are very high. The average grade (percent Ni + Cu + Co) is 2.55 percent, similar to the grades reported in the north equatorial Pacific between the Clarion and Clipperton fracture zones, wherein all the potential mine-sites are demarcated. Paramarginal resources between 10°-15°S in the CIB could not be ascertained by the previous workers (Frazer and Wilson 1980; Cronan and Moorby 1981), because of the low nodule abundance reported. The present investigation reports a mean nodule abundance of 7.48 kg/m² in Area S and 4.68 kg/m² in Area R. The present study therefore reveals that the area comprised of siliceous sediment in the CIB appears to be the only promising paramarginal zone. A detailed exploration may provide additional

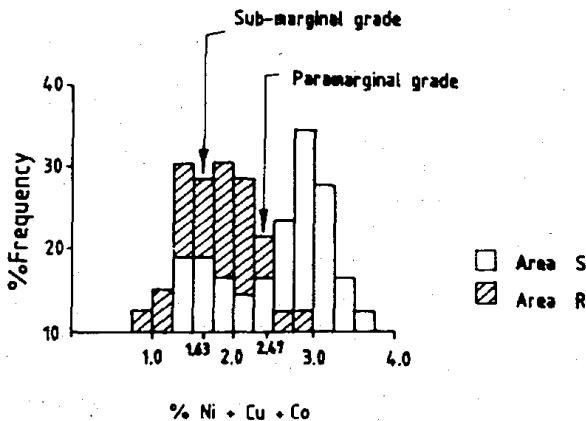


Figure 5. Frequency distribution of % Ni + Cu + Co for CIB nodule stations.

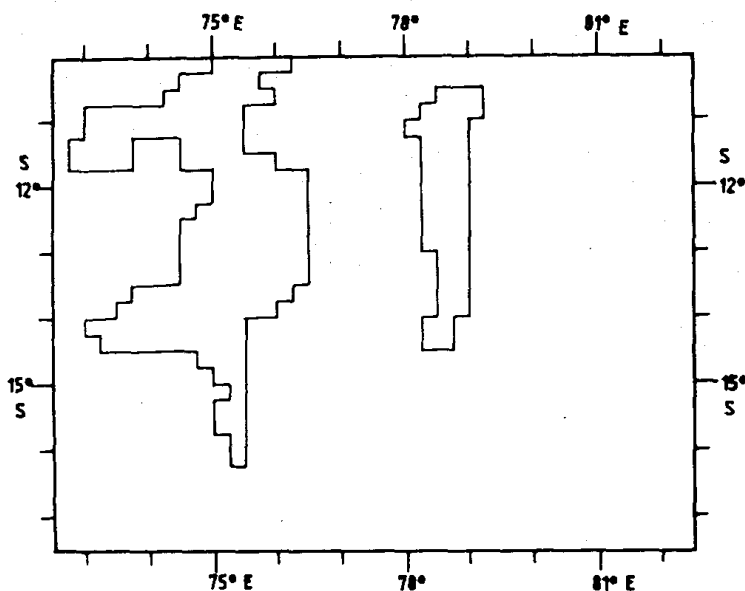


Figure 6. Map showing the Pioneer Area allocated to India in the CIB.

data on the locations of first generation mine-sites that are on a par with those found in the Clarion-Clipperton zone in the Pacific. It may also unravel the mysteries about the nodule growth processes.

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