

Development of manganese nodule resources in the Central Indian Ocean

Rahul Sharma

National Institute of Oceanography
Dona Paula, Goa 403004, India.

Abstract

Occurrences of large reserves of the manganese nodules in the abyssal basin of Central Indian Ocean are envisaged as alternative source of strategic metals such as copper, nickel and cobalt, in the future. India, as one of the 'Pioneer Investors' embarked on a national project of exploration for manganese nodules in 1981, and was registered, in 1987, as the first country to claim an area in the international waters, under the UNLOS. Extensive surveys were carried out from about 2,000 ships days, 54 cruises and sampling at about 9,000 locations, as well as collection of 400,000 line kilometers of bathymetric, 280,000 line kilometers of magnetic, and 300,000 sq. km. of multibeam data, by about 60 scientists and technicians belonging to various disciplines, the findings of which have been published in more than 200 research papers, more than half of which are in international journals and symposia.

Resource evaluation on grade and abundance of nodules using statistical methods for grab samples and photography data, combined with bathymetric and structural mapping, were carried out for delineation of the potential area. Results show that distribution of nodules is patchy (1 to 20 kg/sqm. abundance and 1 to 75% coverage), sizes are variable (<1 to 10 cm), and the burial is differential (0 to 100%), which are influenced by the seabed morphology and distribution of associated features, such as the sediments and rock exposures, on the seafloor.

Geochemical, petrological, mineralogical and geochronological studies on nodules and the associated sediments have resulted in understanding the formation process of the deposits. Occurrence of megabenthic organisms (6 individuals /100sq.m.) and their activities in nodule areas (4-12 traces/sq.m.), as well as geotechnical properties of the seafloor sediments have been evaluated. Studies on characterization of seabed from backscatter of multibeam data are underway. Time-series measurements on various oceanographic parameters in the claim area, have also been undertaken for collection of baseline information to evaluate the effects of mining during test and commercial mining operations.

The requirements of specific data parameters have resulted in development of newer sampling methods, such as, corers with cameras and modified dredges, evolve techniques for data processing and cataloguing, as well as efforts at fabricating a multipurpose bottom lander equipment.

The variety of data parameters collected are useful for designing the future mining system. Future program is aimed at dredging large quantities of nodules for testing of the metallurgical processing plant, detailed bathymetric mapping of potential mine-sites, geotechnical investigations and bottom photography with deep-towed TV system.

Introduction

The long coastline of about 7,500 km, large EEZ of 2 million sq.km, as well as proximity to the vast seas on 3 of its sides, justifies India's position as one of the leading countries involved in exploration and exploitation of marine mineral resources. Having tapped the offshore oil and gas as well as mapped the occurrences of placers on the continental shelf, the focus was shifted to deep-sea minerals in 1981; and in 1982, India became a 'Pioneer Investor' under the law of the sea. The state of art technology was employed for exploration of manganese nodules and in August 1987, India became the first country to have been allotted an area of 150,000 sq. km in the Central Indian Basin (Fig. 1) by the

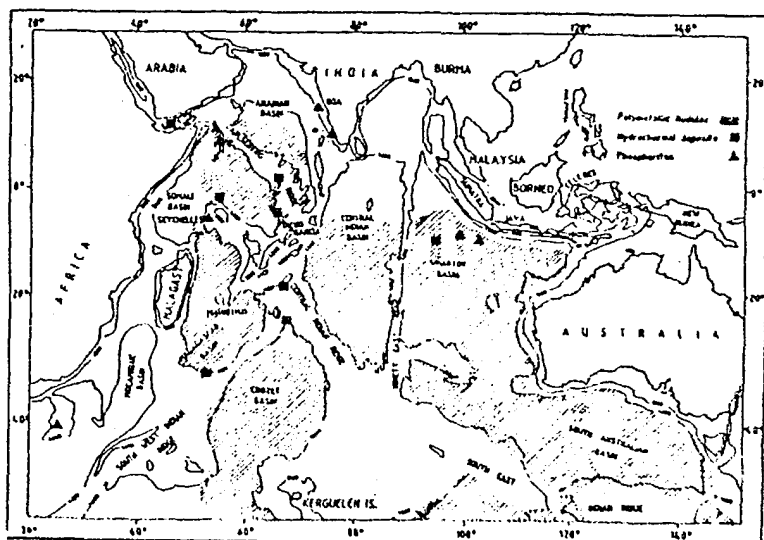


Fig 1 Deepsea minerals in the Indian Ocean

UN, with exclusive rights to carry out further surveys for identification of potential mine-sites.

The need for exploring these deposits was recognized from the fact that, India's copper reserves are depleting very fast, nickel reserves are not economically viable and there are no cobalt deposits in the country. The area claimed by India (150,000 sq.km.) is estimated to contain 650 million tonnes of manganese nodules. The national project on 'Surveys for polymetallic nodules', sponsored by Department of Ocean Development (Government of India), was taken up mainly by three of the research Institutes under the Council of Scientific and Industrial Research. The exploration and resource evaluation for identification of potential areas was undertaken by the National Institute of Oceanography (Goa), whereas the development of mining system and metallurgical processing are being done at Central Mechanical Engineering Research Institute (Durgapur) and Regional Research Laboratory (Bhubaneswar) respectively, with the support of various laboratories, universities and companies more than 15 million US\$ have been incurred over the period of 12 years for the project.

This paper describes the distribution of nodules and various seabed features in the Central Indian Ocean, and their influence on exploitation of these deposits.

Distribution characteristics of nodules

The collection of data on distribution of nodules was carried out in a phased pattern, in order to achieve the time targets and optimise the efforts, such as:

Regional surveys - 1981 to 1984

Close grid surveys - 1984 to 1987

Detailed bathymetric - 1989 to 1991

Environmental data - 1991 to 1994

Bulk sampling and geotechnical data collection - 1994 onwards.

More than 50 cruises of 7 research vessels have been undertaken to collect the large quantum of data (Qasim and Nair, 1989), as follows:

No. of stations covered : 2,000

Freefall grabs operated : 7,200

Photograbs operated : 1,700

Corers operated : 44

Grabs operated : 248

Quantity of nodules collected : 55 tons

Chemical analysis on nodules : 10,000

Echosounding : 400,000 line km

Magnetic surveys : 280,000 line km

Multibeam data collection : 300,000 sq km.

The data thus collected were analysed in the Institute for resource evaluation and the potential areas above the cut off abundance (5 kg/sq m) and cut off grade (Cu+Ni=2.0%) and suitable topography were identified for the claim, based on geostatistical analysis (Sudhakar, 1993). High abundance and paramarginal grade nodules were located between 12 and 16 degrees south latitudes, the highest being 28 kg/sqm (Sudhakar, 1989). These occur at a great distance from the major source of terrigenous sedimentation and at depths

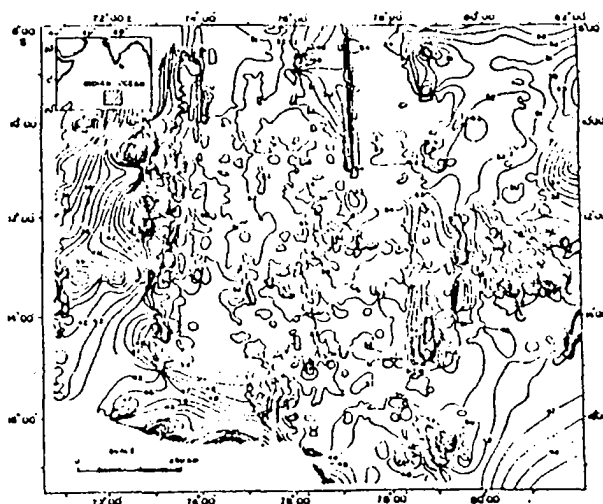


Fig 2 Bathymetry of the Central Indian Basin
(depths are $\times 100$)

below the CCD.

Narrow beam echosounding data along numerous tracks were digitized to map the bathymetric contours of the survey area (Fig.2) (Kodagali et al, 1992).

Correlation of nodule abundance with seamounts, abyssal hills and valleys with intervening plains, shows that average nodule populations are higher in rugged, uneven and undulating topography (Kodagali, 1988; Mukhopadhyay and Nagendranath, 1988; Sharma and Kodagali, 1993). The flanks of hills and seamounts have the highest concentration of nodules (15.3% coverage, 4-6.7 kg/sq.m. abundance), followed by crests (12.3% coverage, 3.5-5.5 kg/sq.m. abundance) and the least in valleys (0.3% coverage, 0.2-2.0 kg/sq.m. abundance) and the plains (14% coverage, 0.8-3.6 kg/sq.m. abundance).

Multibeam studies have shown the presence of large number of tectonic features, such as seamounts, fracture zones and lineaments on the seafloor. Detailed morphology of the 79 degree East fracture zone, its southern extension and the variable downthrow of 150m to 450m was recognised (Kamesh Raju et al, 1993). Numerous seamounts with flat tops, pointed cones and craters have been reported from the area, suggesting volcanic origin (Kamesh Raju et al, 1993) as well as indicators of Indian plate movement (Mukhopadhyay and Khudje, 1990). East-west trending lineaments of alternating 100-150m highs and lows are identified, indicating evolution history of the seafloor.

Evaluation of seabed photographs has revealed significant relationship of nodule distribution with respect to the associated parameters (Fig.3).

Methods for interpretation and cataloguing of various seabed parameters were evolved. These include the scale factor for measurement of dimensions, coverage for surface concentrations, a digitization software for area measurement and abundance estimation, relative abundance for accuracy of data and the burial ratio for extent of burial of nodules (Sharma and Kodagali, 1990).



Fig 3 Seabed photographs showing nodules, sediments and rocks (Fe-Mn encrustations) on the seafloor.

The results show that although the occurrence of nodules recorded from photographs agrees with that from grabs, the abundances calculated from photographs are underestimates, because of the variable burial of nodules under the 'Sediment Water Interface Boundary' layer, resulting in 'fractionation effect' and hence lower estimates (Sharma, 1989a). The relative abundance is high (>50%) in the areas of thin sediment and it gradually becomes less in the areas of thicker sediment, because of increase in buried nodules; whereas in the areas of rock exposures the agreement with grab data is very high (90-100%) (Sharma and Kodagali, 1993). Hence, nodule estimates must be computed based upon the seabed conditions at different locations, for which a number of empirical formulae have been worked out (Table 1) (Sharma, 1989b).

Table 1. Formulae for computing nodule abundance in different seabed settings

Based on SWIB thickness					
Class	Data (n)	SWIB thickness	Trigger wt. penetration	Correlation coefficient	Relation to be used
1	9	0-3 cm	Nil	0.83	$Y=6.18X+2.04$
2	11	3-6 cm	Very less	0.83	$Y=6.80X+4.62$
3	24	6-9 cm	Inter-mediate	0.75	$Y=6.97X+4.97$
4	23	9-12 cm	High	0.84	$Y=7.14X+2.98$
5	211	12-15 cm	Complete	0.53	$Y=8.55X+1.14$
ALL	278	-	-	0.75	$Y=7.54X+3.31$

Based on nodule burial					
Class	Data (n)	SWIB thickness	RA (%)	Correlation coefficient	Relation to be used
1a	29	0-20 cm	100-80	0.99	$Y=8.41X-0.01$
2b	22	20-40 cm	80-60	0.98	$Y=10.15X+0.67$
3c	28	40-60 cm	60-40	0.99	$Y=11.91X+0.17$
4d	43	60-80 cm	40-20	0.95	$Y=21.84X+1.20$
5e	147	80-160 cm	20-00	0.69	$Y=42.51X+2.97$
ALL	269	-	-	0.75	$Y=7.74X+3.78$

Environment of occurrence of manganese nodules

This basin has a variety of sub-environments preserved in 5 different sediment types (Nath et al, 1992), which are :

- (1) terrigenous sediments from northernmost part of the basin with illite, kaolinite and chlorite;
- (2) siliceous sediments from the north central part, with no nodules due to the effect of terrigenous sedimentation (Nath et al, 1989);
- (3) siliceous sediments from the south central part with abundant nodule concentration (Sudhakar, 1989); and an average sedimentation rate of 2mm/ka (Banakar et al, 1991);
- (4) calcareous sediments from shallower areas; and
- (5) pelagic red clays from the southern part of the basin. Illite, kaolinite and chlorite contents in the sediments decrease from the north to the south, due to the proximity to continental source (Rao and Nath, 1988). Montmorillonite content is the highest in pelagic clays, being derived from weathering of ridge basalts (Rao and Nath, 1988). These sediments are considered to be of late quaternary to holocene age (Gupta, 1991).

Studies on surface textures as well as internal structures have revealed the environment and history of nodule growth (Pattan, 1988; Banerjee and Mukhopadhyay, 1991). Surface textures of nodules vary with sedimentary environment, the smooth ones dominating in the terrigenous clays (in the north) as well as pelagic / red clays (in the south) and rough ones in the siliceous sediments (central part). Nodules consist mainly of δ -MnO₂, todorokite, amorphous iron oxyhydroxides, rock forming minerals like quartz and feldspars, clay minerals (mainly smectites) and authigenic silicates (zeolites) (Rao, 1987; Nath and Sudhakar, 1992).

Relationship between morphology and composition of manganese nodules, their classification and interelemental variations have also been studied in detail (Jauhari, 1987; Valsangkar and Khadge, 1989; Jauhari, 1990). Nodule composition varies with the type of substrates. Ba, Cd, Cu, Ga, Mn, Mo, Ni, Rb, Si, Zn are enriched in nodules from siliceous sediments, unlike those from pelagic clays, which have higher Al, Ca, Co, Cr, Fe, Mg, Nb, P, Pb, Sr, Ti, V, Y, Zr and REE contents. Mn/Fe ratios and Ni+Cu in these nodules, are significantly high (3.77, 2.41%) in the former area, than in the latter (2.24, 1.61%). The highest grade (Ni+Cu+Co) recorded is 3.82% dry weight (Nath and Sudhakar, 1992).

Analyses of rocks show the presence of fresh as well as altered basalts and encrusted as well as non-encrusted pumice as nuclei for nodules and as substrates for the encrustations. Thin sections of fresh rocks show dominance of plagioclase, followed by olivine, pyroxenes and opaques, whereas the altered rocks have sericite, iddingsite and palagonite. The origin of these rocks is suggested to be from submarine volcanism. The erosion of the rock outcrops exposed over the crests and slopes, gives rise to rock fragments which act as nuclei, resulting in large population of nodules along the slopes and flanks of the abyssal hills and seamounts (Iyer and Sharma, 1990). Spilites (Nu-rich basalts) were observed near the 79 degree East fracture zone,

alongwith altered basalts indicating incipient spilitisation of basalts as a result of local hydrothermal solution (Karisiddaiah and Iyer, 1992).

Pumice occurs as small pieces of <1-180mm size and in various shapes. These are highly vesicular and composed of quartz with minor plagioclase and pyroxene. The occurrence of uncoated as well as coated pumice suggests insitu episodic volcanism from the seamounts and fracture zones (Iyer and Sudhakar, 1993a). Altered slabs of zeolites were also recovered from the fracture zones and topographic highs, indicating a process of transformation of volcanic glass to zeolites through palagonite (Iyer and Sudhakar, 1993b).

The role of rocks with respect to occurrence of Fe-Mn oxides can be summarised as:

- (1) fragments of basalts and zeolites occur as nuclei and substrates for nodules and crusts,
- (2) outcrops of basalts, occurring usually on crests, flanks and slopes of seamounts and abyssal hills, form substrates for Fe-Mn encrustations,
- (3) morphology of pumice occurring as nuclei, determines the shape and surface texture of nodules.

Occurrence of an australite button (tektite) in the surface sediments not only extends the australite sub-strewn field to the Central Indian Basin, but also highlights the age paradox problem of tektites (Prasad and Rao, 1990). Further, the surficial occurrence of Australasian microtektites suggest bioturbation and removal of sediments by bottom currents (Prasad, 1994a). The finding of microtektites (of 0.77 Ma) in the substrate of the Fe-Mn crust, have also indicated unusually fast Fe-Mn growth rates (7.8-22.1 nm/Ma) (Prasad, 1994b).

Environmental data collection

Observations of megabenthic activity (Fig.4) show the presence of several deepsea species of 7 different phyla, with an average population density of 6-7 individuals per 100 sq.m. on the seafloor.

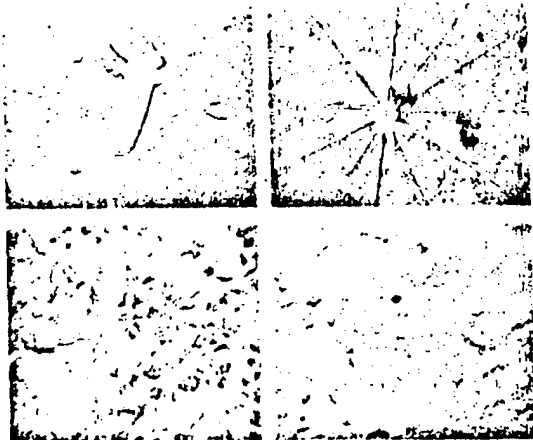


Fig.4 Seabed photographs showing benthic organism and their lebensspuren in nodule areas.

A variety of lebensspuren such as casts, tracks, burrows, mounds etc, observed in the area have a frequency of 4-12

traces/sq.m. (Sharma and Rao, 1992). These have a fairly good association with nodules, as 60% of organisms and 43-75% of different lebensspuren are observed in nodule areas. Baseline data on various environmental parameters of the water column as well as the seafloor are being collected under 'Pre-mining Environmental Assessment Studies'(PEAS, 1994). These include data on surface circulation patterns, temperature profiles, salinity, ph, oxygen, inorganic phosphate, nitrate, silicate, zooplanktons etc. at different depths in the water column.

Application of data for exploitation of nodules

Interaction of the seabed features with mining system and suggested design considerations

(1) Nodules

The local variations and patchy distribution of nodules may affect the efficiency of the collector. The higher concentration of nodules along the slopes may enhance the recovery of nodules, as compared to the low nodule concentrations in the valleys and the plains. Hence, the mining system should be capable of detecting the zones of higher nodule concentrations, acoustically or photographically, before sweeping the seafloor. Since, nodule sizes vary from <1 to 10 cm and the size distribution is inhomogenous between different locations, the mining system will have to be designed for an optimum nodule size for an efficient recovery as well as for lifting them to the surface. Use of a crusher on the nodule collector may help in maintaining the consistency in size of the nodules to be lifted to the surface, and of a buffer in storing the nodules and pumping them in fixed quantities for energy conservation.

(2) sediments

The mining head will have to encounter the associated substrate alongwith the nodules on the seafloor. Pumping of large quantities of sediments alongwith the nodules, will not only increase the energy consumption, but will also cause a major problem of disposal of debris at the surface. Hence, the sediment may have to be discharged in deeper waters below the photic zone, to reduce the impact on marine life in the water column. Preferably, there should be a mechanism to wash out the associated sediment near the seabed to enable pumping of nodules only. The nodule collector should also penetrate within the sediments to collect at least a part of the buried nodules. The binding strength of nodules to the sediment will form an important factor in the design of the nodule collector. Use of water jets may help to dislodge the manganese nodules from the seabed.

(3) Rocks

Rock outcrops, which extend upon a several tens of meters on the seabed, and at times occur in the nodule fields along the slopes as well as the abyssal plains may act as obstruction to the nodule collector. The collector should be capable of being either 'driven' around or 'flowed' over these outcrops with the help of rotors and thrusters. Such features have to be mapped using high resolution techniques, so as to avoid these areas while mining.

(4) Morphology

The seafloor comprises of abyssal hills (>200m relief) seamounts (>1,000m) as well as abyssal plains and valleys (Kodagali et al., 1992). The collector will have to be designed to negotiate certain gradients, but steeper areas and those with more frequent undulations may pose some problem in smooth operation of the mining system. Morphometric analysis in a part of CIB, has shown that a majority (92%) of the area has 0-3° slope, the remaining areas having higher slopes (upon 15°) (Kodagali, 1989). Hence, the system should be a self propelled system which can negotiate changes in seabed characteristic in terms of different reliefs, substrates and nodule concentrations.

(5) Benthic activity

Close association of benthic organisms with nodules, suggests the need to reduce the possible damage to the ecosystem and ensure conservation of some of these little known species. Separation of sediments near the seabed will reduce the chances of horizontal migration of plume to large distances and disturb only few meters of water column near the seafloor. Strip mining would also help in leaving unmined areas for rehabilitation by benthic organisms from the adjacent areas.

Estimation of potential impact of nodule mining

The impact in terms of area of seabed to be disturbed and the volume of sediment to be removed due to mining operations is estimated (Sharma, 1994) as follows:

a)

(1) Mining at the rate of 3 million metric tonnes of nodules per year, for an average nodule abundance of 8 kg/sq.m., total area of seabed to be disturbed per year will be 6×10^8 sq.m. (=600sq.km).

(2) According to the equation for all the data points (Table 1, section 'a'), for an average nodule abundance of 8 kg/sq.m. and average nodule diameter of 4 cm, the average nodule coverage in the mineable area would be 16%. This implies that the remaining area of the seabed (84%) is covered with sediment.

If we consider that the depth of penetration of the nodule collector is 10 cm, the total volume of sediment (V_s) removed along with the nodules from the mining area would be: $V_s = Ad \times Dp \times Cs/100$ where,

Ad =area of seabed disturbed per year, i.e. 6×10^8 sq.m.

Dp =depth of penetration of collector head, i.e. 10 cm (or 0.1m)

Cs =sediment cover, i.e. 84%.

Hence, $V_s = 504 \times 10^7$ cubic metres per year.

b)

Similarly, for an average nodule abundance of 13 kg/sq.m., for mining 3 million metric tonnes;

(1) the area of seabed disturbed = 3×10^8 sq.m., (i.e. 300 sq.km.)

(2) average nodule coverage should be 32%, and the remaining area (i.e. 68%) is covered with sediment.

Hence, $V_s = 204 \times 10^7$ cubic metres.

The actual area of disturbance and the volume of sediment removed will be less for higher nodule abundances, as smaller area will be covered for a given yield.

Research output and achievements

After the recognition as a Pioneer Investor, India filed the claim in record time, which was the result of extensive surveys, and the analysis of data which generated a variety of information regarding the resource, not only for mining but also for scientific research. The results have been published in more than 100 scientific papers, of which 50% are in international journals, as well as presented at various symposia.

The expertise gained and facilities developed scientists and engineers of various research students of universities as well as foreign researchers involved in similar activities. Explorations for marine resources in the EEZs of different countries in the Indian Ocean were carried out as an aid to them.

The need for indigenisation and collection of variety of data has resulted in scientific innovations and newer technologies being developed for offshore exploration. Modification of sampling equipments-grabs, corers, dredges, design of underwater photography systems and deepwater mooring and sediment traps have been carried out from time to time, depending upon the requirement of the surveys. A 'bottom lander' for insitu measurement of near bottom parameters, such as pressure, temperature etc., sampling of sediment and pore waters and seabed photography is being developed for simultaneous collection of various data.

Future research plans

In order to further understand the occurrence and distribution of the resources on the seafloor, it is proposed to carry out research on:

- (1) seabed characteristics using backscatter data of multibeam sounding,
- (2) data from deep-towed TV, photography, sub-bottom profiling, CTD,
- (3) deep-sea mooring with sediment traps and time lapse photography.

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