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Distribution of Manganese Nodules, Rocks and Sediments in the Central Indian Ocean Basin: Factors Influencing Performance of Mining System

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ABSTRACT

Manganese nodule abundances in the Central Indian Ocean Basin (CIOB) as noted from seabed photographs (nil to 18.4 kg/m^2) and grabs (nil to 21.5 kg/m^2) are variable. The relative abundance varies from zero to infinity, suggesting variable depth of burial at different locations. Rock exposures, as observed in the photographs, have 6-100% coverage on the seafloor. Morphologically, the CIOB comprises abyssal hills and seamounts, as well as valleys and abyssal plains. The topographic highs, which are situated in the vicinity of three major fracture zones, are composed of hard, massive basalts occurring at the crests along the slopes and at the foothills as talus deposits. These parameters together with geotechnical properties of the host sediment, which are likely to influence the design and performance of the nodule mining system, have been evaluated in this study. Design considerations suggested for an efficient mining system include; (i) crushing of the manganese nodules in the collector system, (ii) use of water jets to dislodge the nodules from the seafloor, and (iii) designing the collector in such a manner as to negotiate barren areas and rock outcrops. Burial of nodules in the sediment-water interface and the shear strength of the sediment may also influence the efficiency and manoeuvrability of the system and suitable mechanisms may have to be provided.

INTRODUCTION

Deep-sea manganese nodule deposits have attracted considerable commercial interest in recent years, as large deposits of manganese nodules have been identified in the world oceans. Nodules are spherical, earthy and black coloured, and enriched in various metals like Mn, Fe, Cu, Ni and Co [7]. These may partly or wholly act as an alternative source of metals due to the depletion of land resources

[2]. Nodules are reported to occur in all basins of the Indian Ocean, whereas one of the highest concentrations is in the Central Indian Ocean Basin (CIOB) [4].

As a result of the extensive surveys for manganese nodules in the CIOB, India has become the first Pioneer investor to have been allocated an area of 1,50,000 km² for demarcating potential mining areas. Several factors determine the selection of an area for mining manganese nodule deposits. These include an average abundance of 5 kg/m² and an average grade of 1.8% of Cu + Ni [2]. Favourable seafloor topography and sediment characteristics (high shear strength) are the other important requirements for delineating mineable areas [2].

The present study aims at analysing the seafloor features (morphological and lithological) and the distribution of manganese nodules and their possible influence on the performance of the mining system. Such a study would provide inputs while considering the design parameters for development of a suitable mining system.

METHODS

Bathymetric map (Fig.1) was prepared using single-beam (3.5 and 12 kHz) echosounder data and detailed surveys in some areas were carried out using multibeam (15.5 kHz) swath bathymetry system. Position fixing was carried out using satellite navigation and global positioning systems. Nodule abundance data were computed from grab samples [26,27] and potential areas were demarcated (Fig.1). Photography data was used for studying the distribution of nodules and associated features on the seafloor. The percentage of agreement between the photo-abundance and grab- abundance (i.e., relative abundance, R) was calculated. The R factor reveals the extent of burial of manganese nodules; the photograph records only the exposed manganese nodules, whereas the grab collects the buried manganese nodules [23]. The distribution of other seafloor features (such as sediments, rock exposures) and their relation with nodules in different morphological settings was also studied from seabed photographs [25]. Data on rock samples collected using grabs and dredges [9], and their relationship with the distribution of manganese nodules and sediments [10] were also used in this study.

RESULTS AND DISCUSSION

Morphology of the seafloor

CIOB is made up of a number of structural features, such as abyssal hills, seamounts and fracture zones (Fig.2). Sharma and Kodagali [24] have classified the seafloor into four morphological divisions: crests of seamounts and abyssal hills, their slopes, abyssal plains and valleys. Mukhopadhyay and Khadge [18] reported 18 seamounts and more than 100 abyssal hills of varying dimensions in the basin. Kodagali [15] reported a large seamount at 12°35'S/76° 16'E with a

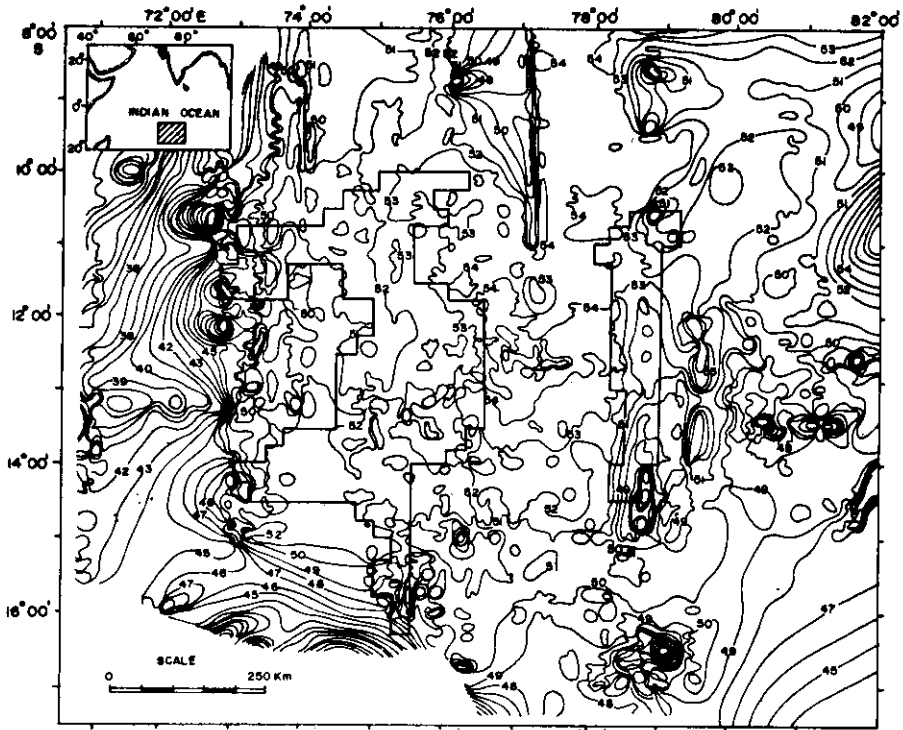


Fig. 1 - Bathymetry map of the Central Indian Ocean Basin [after Ref. 17] and nodule areas (within solid lines) demarcated in the basin

cratered summit. In addition to these, there are three major fracture zones at 73°E, 75°45'E and 79°E in the study area and recent multibeam studies have revealed the presence of 14 seamounts at the southern end of the 79°E fracture zone [12].

Manganese nodule distribution

CIOB is the most promising area for the exploration of paramarginal ore grade ($\text{Co}+\text{Cu}+\text{Ni} > 2.47\%$) and economically potential deposits (5 kg/m^2) of manganese nodules compared to the other basins of the Indian Ocean [4.6].

Nodules having $> 5 \text{ kg/m}^2$ abundance and $> 2\%$ grade are common between 10°S and 16°S. These nodules are underlain mostly by siliceous sediments [27,28], where diagenetic processes are predominant, leading to high trace metal incorporation into nodules. To the north of this region (north of 10°S), there are siliceous sediments influenced by the terrigenous input, where paucity of nodules is observed. Further north, there is terrigenous input from the Ganges-Brahmaputra river influence, a region totally devoid of nodules. To the west, there are

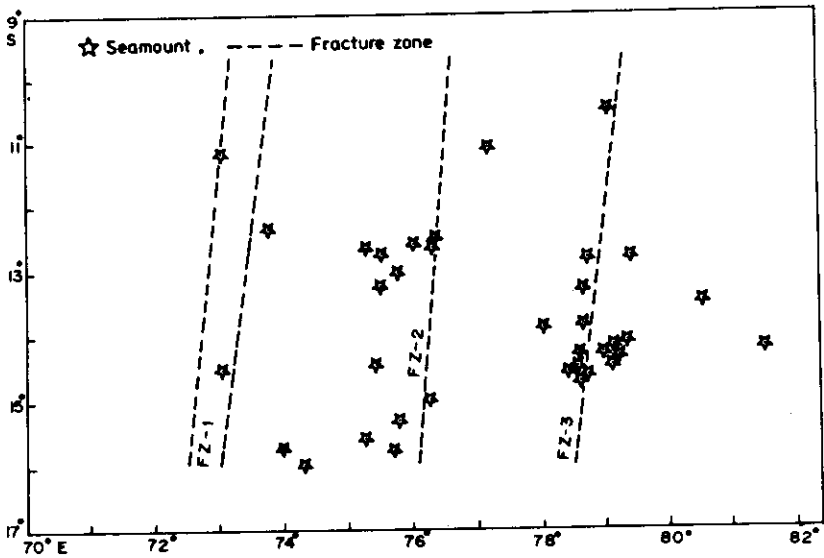


Fig.2 - Distribution of seamounts and fracture zones reported in the Central Indian Ocean Basin

calcareous sediments, where shallower depths are encountered (near the mid-oceanic ridge) and the nodule grade and abundance in this region is low compared to the other parts of the basin. To the south of siliceous sediment domain, red clays predominate the seafloor, where nodules exhibiting < 2% grade and moderate abundances are reported. On a regional scale, nodule abundance and grade are inversely related [26].

The manganese nodules are mostly spherical to sub-rounded in shape, with sizes ranging from 2 to 8 cm. The dominant size ranges are 2-4 cm and 4-6 cm. These size ranges also have high Mn/Fe ratios and high trace metal incorporation, thereby giving high grades. Larger nodule sizes of > 6 cm are not uncommon, but these sizes do not possess the requisite economic grade.

The rough textured manganese nodules are dominated by the presence of well-crystallized todorokite, high Mn/Fe (4.75) quotients and high enrichment of Ni and Cu (1.23 % and 1.27 %). Gritty and granular surfaced nodules show the presence of pumice clasts as nucleus material. This suggests that pumice could decide the shape and size of manganese nodules [29].

Such deposits were further explored extensively by the National Institute of Oceanography (Goa, India) and more than 10,000 samples were collected from the entire basin. These deposits occur in deeper parts of the basin where the depths encountered are more than 5000 m. Based on such a vast database, areas contain-

ing economically viable deposits were demarcated in the region. High abundance and paramarginal grade nodules were located particularly in the belt between 12°S and 16°S. The maximum abundance and grade recorded so far are 28 kg/m² and 3.82 (% dry weight), respectively [19].

These nodule deposits take a near N-S orientation closely following the trends of the three major fracture zone running parallel in the basin; hence, a tectonic control is envisaged.

Comparison of nodule distribution

Abundance data from 961 locations was computed from photographs and compared with that of the grabs. Nodule abundances are highly variable both in photographs (0-18.4 kg/m²) and grabs (0-21.54 kg/m²). The data for photographs and grab samples match at 65 % of the locations : either manganese nodules are recorded in both (44%) or in none (21 %), whereas at the remaining locations there is a mismatch: a majority (29 %) of them show manganese nodules only in grabs and very few (6 %) show the nodules in photographs only.

At many locations, the abundance in photographs is lower than in the grabs, which may be due to the burial of nodules in the sediment layer. The R factor varies from 0% (nodule in grab only) to as high as 100 % (and also infinity in some cases). The locations with R=0% may be due to buried nodules, whereas R=100 % is found either at locations with no nodules recorded in both grab and photograph or when both record an equal quantity of nodules. Locations with R 100 % (more nodules in photographs) and infinity (nodules in photographs only) imply either mechanical failure of grab to collect the nodules or the presence of very few nodules on seafloor which the grabs failed to collect due either to obstacles on the seafloor or mechanical failure of the grab. Many of the locations at which only grabs have collected the nodules have low nodule population (< 1 kg/m²). When manganese nodules are recorded in both, the R values have a wide range (8 - 100 %), suggesting non-uniformity in the burial of manganese nodules at different locations, depending upon the seabed conditions.

Distribution of substrates and relation with manganese nodules

Substrates, such as rock exposures and sediments, occur as hosts for manganese nodules and crusts on the seafloor. Rock exposures are observed in about 40 locations in the entire CIOB. These exposures vary in their areal extent from 6 to 100 % coverage and range in depth from 4200 m to as deep as 5400 m, but a large number of them (21/40) are located along crests of seamounts and abyssal hills (water depth < 5000 m). Grabs and photographs at locations with high coverage of rock outcrops show nil or traces (< 1 kg/m²) of nodule abundance, whereas high nodule abundance (6.23 kg/m² in photographs and 15 kg/m² nodules in grab) occurs where rock coverage is low (6-20%).

Most of the rock outcrops are associated with a thin layer of sediment and have few nodules associated with them. Of the 40 locations, where the rock exposures were observed, no nodules were observed at 23 locations (57 %); < 5 kg/m² abundance was observed at 13 locations (30 %); and only 4 locations had > 5 kg/m² nodules. Due to thin sediment cover in the elevated areas, nodules are exposed and hence R is high (100 % in most cases), which suggests limited possibility of buried nodules.

The thickness of the sediment cover increases towards the abyssal plains and the valleys, with no or very few rock exposures in these regions. The crests and slopes have thinner sedimentary layers, and the thicker ones are in the valleys and plains.

The sediment cover plays an important role in the exposure of manganese nodules. The mixed layer or the sediment-water interface boundary (SWIB) layer obscures the nodules from the camera view [3]. The nodules get partially or fully buried, resulting in lower estimates of the abundance from the photographs than the grabs. If the SWIB layer is thin, there is a high ratio of agreement (i.e. R factor), because more number of nodules are exposed, whereas in the case of a thick SWIB layer, there is low agreement [21].

Rock types

At many of the locations, rock fragments and ferromanganese encrustations have been recovered. Broadly, we have identified two rock types in the study area, viz., basalt and pumice [8, 9]. The rocks collected occur as boulders, pebbles and pillow fragments in a variety of topographic settings, such as crests of seamounts, their slopes and flanks and sometimes in the abyssal plains. These rock fragments are found to act as nuclei or 'seeds' for the manganese nodules and as substrates for crusts [10]. The basaltic boulders and large fragments have fresh to palagonitised glass, with varying thickness of ferromanganese oxide deposits on their surface.

Pumice samples occur as large clasts up to about 16 cm in size, but mostly lie in the range 0-4 cm. A large field of pumice (600,000 km²) is reported in CIOB, which is also correlated to potential deposits of manganese nodules. Based on structural evidences, an *in situ* origin for the pumice has been envisaged [11].

Topography and distribution of nodules

Distribution of nodule coverage and abundance show a preferential occurrence in certain morphological domains [14]. The average as well as maximum nodule populations recorded near the crests and the slopes are much higher than those recorded in the valleys and the plains [24]. High nodule coverages (av. = 12 and 15%), as well as nodule abundances (av. = 5.53 and 6.65 kg/m²) are observed along the crests and the slopes, respectively. Nodule concentrations are much less in the valleys (av. = 0.25 % coverage and 2.03 kg/m² abundance) and the plains

(av. = 1.36% coverage 3.56 kg/m² abundance). However, locations with no nodules are also common in all the domains, which confirms the patchy distribution of these deposits in all the morphological settings of the seabed.

A distinct agreement between photographic data and grab data is observed along the slopes (av. R = 60%), which suggests that the remaining (40%) nodules are buried in these areas, and hence are not recorded in the photographs, but were collected in the grabs. This agreement decreases in the valleys (av. R = 44%) and the plains (R = 33%), as the nodules are more likely to be buried in these areas due to thick sediment cover [24].

Correlation between the occurrence of rocks and nodules suggests that the rock fragments from the large outcrops at the crests get transported downslope, act as nuclei and result in large nodule fields along the slopes and flanks and in areas of rugged topography [10].

Design considerations for the mining system

Nodules — Nodule concentration on the seabed has a direct influence on the quantity of nodules recovered by the mining system. The higher the abundance, the larger are the quantities that can be recovered in shorter duration and *vice-versa*. Considering an annual recovery of 3 million tonnes of dry nodules and their patchy distribution, the average nodule concentrations should be high (5-10 kg/m²) for a better recovery. Hence, the mining system should have a large sweep area and it should be capable of detecting zones of higher nodule concentrations, acoustically or photographically, before sweeping the seafloor.

Nodule sizes vary from < 1 to 10 cm over the entire area and the average size varies from region to region. The mining system has to be designed for an optimum nodule size for efficient recovery as well as pumping them to the surface. A crusher on the nodule collector head may be helpful in maintaining consistency in size of nodule to be lifted to the surface. Use of buffer is recommended for the nodules to be stored and pumped in fixed quantities for lower energy consumption.

Sediments — Pumping of large quantities of sediment hosting manganese nodules will not only increase the energy consumption, but will also cause the major problem of disposal of debris at the surface, which, in turn, will have an impact on the ecosystem of the entire water column [1]. There should be a mechanism to wash out the associated sediment to ensure pumping of nodules only. The influence of sediment cover on the burial of nodules [5] can pose another problem in nodule recovery. As observed from our results, manganese nodules are buried at many of the locations and the extent of burial estimated by comparison of photography and grab data varies from 0 to 100% [22]. Hence, the nodule collector should penetrate within the sediments to collect the buried nodules.

Detailed studies on siliceous sediments need to be carried out with respect to their geotechnical properties, because most of the 'target' area falls in this

sediment type. These sediments have medium to high plastic values (103 %) [13], with water content varying from 50 to 200 % and a variable consistency. Hence, the mining system may have to be so designed that it does not sink through the sediment, but penetrates just enough to recover the nodules. The binding strength of nodules to the sediment will also form an important factor in the design of the nodule collector. Use of water jets should also be considered to dislodge the manganese nodules from the seabed.

Rock outcrops — Rock outcrops are observed in the nodule areas, which may act as an obstruction to the collector. These extend laterally up to a few tens of metres on the seabed. Many of these are coated with ferromanganese oxides [10]. The collector must have a device to scrap the upper layers of such outcrops, which can be profitably processed for different metals. Alternatively, the collector will have to be either 'driven' around or 'flown' over these outcrops, which may be time-consuming and energy-intensive. With the help of high resolution techniques, mapping of the seafloor for rock exposures and high angled features is recommended so as to negotiate these areas while mining.

Topography — The seafloor comprises abyssal hills (> 200 m relief), seamounts (< 1000 m) as well as abyssal plains and valleys in the area [17]. These morphological variations of the seafloor also play a role in the performance of the mining system. The collector may be designed to negotiate certain gradients, but steeper areas and those with more frequent undulations may pose problems in smooth operation of the mining system. Morphometric analyses in a part of CIOB showed that a majority (92%) of the area has 0°- 3° slopes, with very high (15°) slope angles in certain areas [16]. Even a micro-relief of 1 m along the width of the nodule collector may cause problem in the proper functioning of the system. Moreover, nodule concentrations are known to be higher in areas of rugged topography and along the slopes of hills and seamounts. Hence, the system must be adaptable to changes in seabed characteristics in terms of different reliefs, substrates and nodule concentrations. The collector should be a self-propelled system which can negotiate different terrains. It should also be equipped with obstacle avoidance sonars and TV cameras for navigation as well as selective mining in promising areas. Use of a flexible pipe between the riser and the nodule collector will facilitate free movement of the collector on the seabed. It should also have a broad base and a low centre of gravity for climbing slopy areas.

Benthic activity — Different studies have also shown the presence of a variety of benthic organisms populating in the abyssal depths [20], which indicate the need to ensure environmentally safe mining systems. Association of 66% of benthic organisms (observed in photographs) with the nodules [25] suggests the need to reduce the possible damage to the seabed to ensure the conservation of these little known and low concentration species. Different oceanographic parameters should be studied in a specific area ('pilot site') which will be used as a reference to evaluate the impact of mining on the seabed. Separation of sediments near the seabed reduces the chances of horizontal migration and disturb

only a few metres near the seafloor. Similarly, strip mining helps in leaving unmined areas for rehabilitation by benthic organisms from the adjacent areas.

CONCLUSION

The variations in nodule abundance, their sizes, coverage and burial, undulations in seafloor morphology and slopes as well as the properties of the seafloor sediments and the presence of rock outcrops are some of the important factors which influence the performance of the mining system. The collection of continuous data on distribution of manganese nodules, association of the nodules with rock outcrops and their extent of burial using the deep tow system, and sediment characteristics using subbottom profilers and geotechnical studies, provide necessary input in designing an efficient nodule mining system.

ACKNOWLEDGEMENT

Authors thank the Director, for the facilities provided and Mr. R.R. Nair, Head, Geological Oceanographic Division for encouragement and discussion. This study was carried out under the project 'Surveys for polymetallic nodules' funded by the Department of Ocean Development, Government of India.

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