

Indian exploration for polymetallic nodules in the Central Indian Ocean

M. Shyam Prasad

National Institute of Oceanography Dona Paula, Goa-403004

shyam@nio.org

Abstract

The recovery of manganese nodules for the first time in 1981 by Indian scientists heralded an era of deepsea exploration and research in India. The exploration for polymetallic nodules in the Central Indian Ocean was formally launched in 1982. The country was also recognized as a Pioneer Investor in 1982. Massive exploration efforts encompassing over 4 million km² of the deep sea floor were undertaken over the last two decades. This involved systematic grid sampling, detailed chemical analysis for resource evaluation and deciphering the topography of the Central Indian Ocean. These efforts led to the allocation of a Pioneer Area in 1987 and also enabled subsequent phase wise relinquishment of the area. Having relinquished 50% of the allocated area, as per the UNCLOS resolution, by the year 2002 India was left with 75,000 km² of nodule-rich area of the Indian Ocean. The efforts from then on have been to identify a first generation mine site for nodules within the retained area. An area measuring 18,400 km² has been earmarked for this purpose wherein close-grid sampling, detailed resource evaluation, and high resolution mapping is being carried out. While the abundance of nodules and grades are now known in all the allocated areas of the world, future exploration necessitates a closer view at the seafloor and the subbottom using remotely operated vehicles. Exploitation of the nodules involves broad industrial development, and extracting many more metals that nodules can offer by innovative metallurgy. Further, the exploration by dedicated manpower has led to several important spin offs : understanding of the operative processes in the deep sea areas which have resulted in over 200 scientific publications, launching other major exploration projects, and also, capability for exploring the waters surrounding other Indian Ocean countries.

Introduction and initial surveys

Polymetallic nodules carpet practically ~70% of the deep sea floor. They were discovered about 135 years ago by the Glomar Challenger expedition. The nodules were christened 'manganese nodules' in view of the largest component being manganese. However, since it was discovered that they contain many more important metals (although in lower percentages) the term currently in use is 'polymetallic nodules'. By all estimates the total quantity of

polymetallic nodules on the seafloor is ~500 billion tons. The possible economic importance of these deposits was highlighted by Mero (1965), who was able to convince some major industrial houses and governments to launch exploratory efforts in estimating the reserves. While, most of the earlier efforts were concentrated in the north central Pacific Ocean between the prolific Clarion and Clipperton fracture zones, there had been scanty data regarding the occurrence and distribution of nodules in the Indian Ocean. The Indian Ocean contains several deep sea basins which intrinsically provide the base conditions for nodule formation (Fig.1) : seawater depths between 4000 – 6000 metres, low rates of sedimentation, source supply of metals.

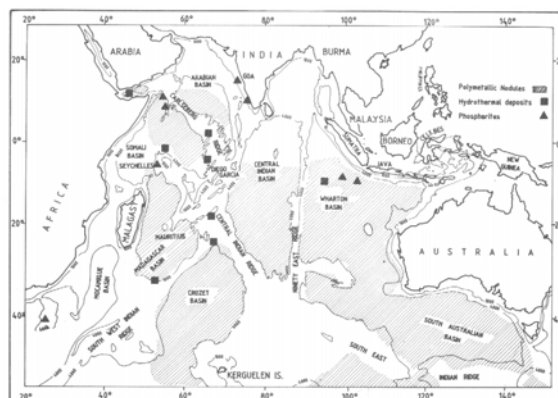


Fig. 1. Various ocean basins in the Indian Ocean which show presence of manganese nodules. Of these, the Central Indian Ocean Basin has proved to be the best for nodule density.

India has been the only country to have taken up large scale exploration for nodules in the Indian Ocean. The recovery of manganese nodules for the first time in 1981 by Indian scientists marked the beginning of an era of deep sea exploration in the country. The exploration for polymetallic nodules in the Central Indian Ocean was formally launched in 1982. The National Institute of Oceanography (Goa, India) was entrusted with the massive task of identifying such deposits. Based on the existing information through available literature it was determined that the Central Indian Ocean Basin (CIOB) could be most

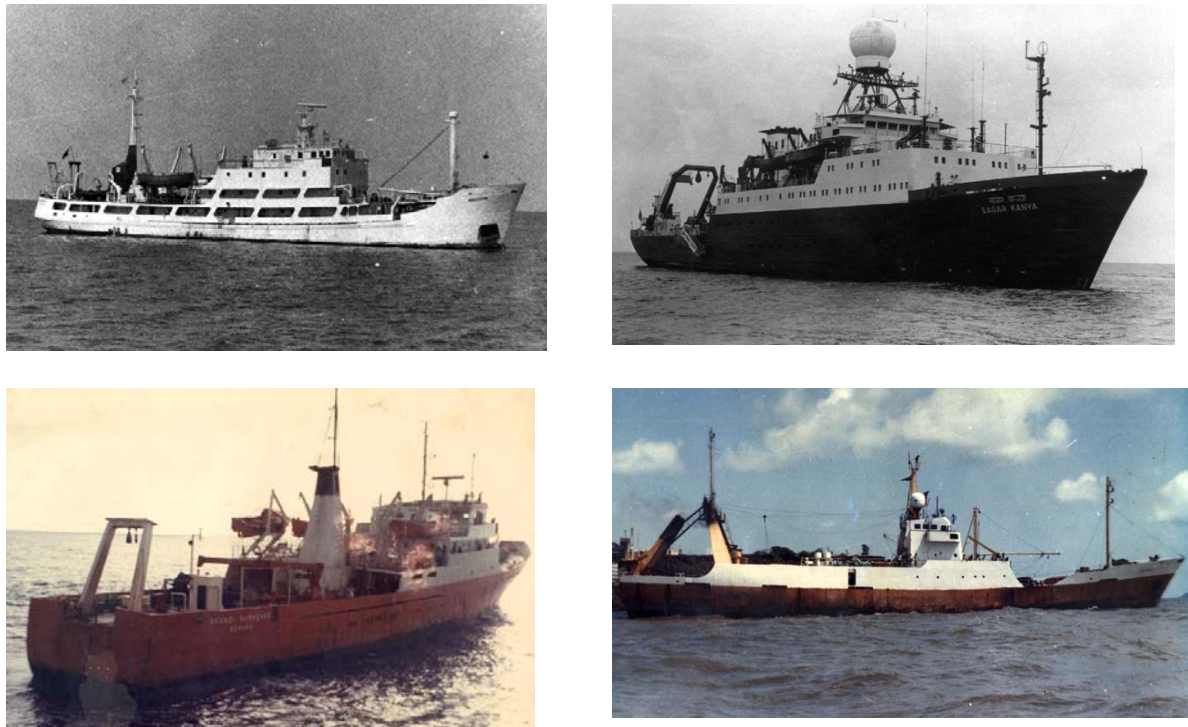


Fig. 2 Some of the research vessels used extensively in the nodule exploration program, clockwise : (A) RV Gaveshani, NIO's research vessel having endurance of 22 days; (B) ORV Sagar Kanya, Research vessel of the Govt. of India has an endurance up to 50 days (C) ORV Skandi Surveyor, a research vessel chartered from Norway ; (D) MV Farnella, a research vessel chartered from U.K.

potential basin for large scale concentration of nodules. The main resource available with the NIO in 1982 was the research vessel *RV Gaveshani* (Fig. 2). This vessel was a hopper barge converted into a research vessel – this vessel in fact did 238 multidisciplinary oceanographic cruises between 1976-1992 and was practically the harbinger of oceanographic research in India. *RV Gaveshani* had an endurance of about 22 days, considering that the CIOB was about 7 days of ship time away from Goa, one would get only a week's time in the CIOB using this vessel. After few initial cruises with this vessel, other research vessels having larger endurance were hired to expedite the exploration work. More importantly, large numbers of scientific and technical manpower was recruited for the project. From 1982 till date, 8 research vessels have been operated in the CIOB area which have generated enormous data to enable the country to identify a Pioneer Area, achieve the difficult task of relinquishment and are currently looking forward to identify a First generation mine site in the CIOB using sophisticated techniques.

The last two and half decades of nodule exploration has seen many milestones for the country a few of which are presented in Table 1. In addition, nodule exploration has also paved the way for carrying out vibrant research on various aspects of science on the deep sea regions of the Indian Ocean. In addition, this experience has accorded the confidence to explore for other mineral deposits, areas of research such as the mid-oceanic ridges, and to explore the waters of Indian Ocean countries. While it needs to be appreciated that, in addition to nodule exploration the country also has an active programme for extraction of metals from nodules involving several national labs, development of a mining system and the environmental impact of nodule mining. These three other activities have made important inroads in their respective areas. In this paper, a succinct account of the nodule exploration efforts of the country is presented.

Table 1. Milestones in India's nodule exploration programme

Event	Date
First nodule sample collected by Indian scientists	26 Jan.1981
India recognised as Pioneer Investor	April, 1982
India Signed UNCLOS III	December, 1982
First metal from nodules extracted and 3 million Sq.km area explored	August 1983
Pioneer Area Allocated (150,000 sq.km)	August 1987
India Registered as Pioneer Investor	December 1987
20% area relinquished	July 1994
India Ratified UNCLOS III	June 1995
10% area relinquished.	October 1996
Final 20% of area relinquished to the International Seabed Authority	April, 2002
Current activity	Identification of a First generation Mine Site in the Retained Area

Identification of pioneer area

Since the information available on nodule deposits of the CIOB was scanty, the country literally had to start from a scratch, explore almost the entire basin to get an understanding of the quality and the quantity of nodules. In this process, enormous data in the domains of geology (sampling using spot samplers, bulk sampling using dredges, various types of sediment cores etc.) and geophysical (gravity, magnetic), had been generated over the last two decades. Further, evaluation of the mine site is being carried out and data collection therefore, is an ongoing process.

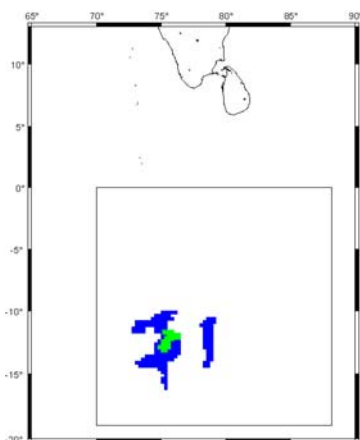


Fig. 3 : Comparative dimensions of the area surveyed and the Pioneer Area allocated. The large square shows the total area of the CIOB Surveyed (>4 m km²) and the blue coloured portion inside is the Pioneer Area (150,000 km²). The green coloured

portion inside the Pioneer area could form the nucleus for a First generation mine site for nodules in the Indian Ocean.

The area initially chosen for exploration involved a large area between 72° and 89° E and 0° – 19° S, which is a massive >4 million km² (Fig. 3). Several research vessels simultaneously explored the deep seabed within the above co-ordinates. The initial methods of sampling involved using grab samples and single beam echosounding for deciphering the topography. The grabs used extensively were free fall grabs (Fig 4), these sample a specific spot of the seafloor hence the total quantity of nodules recovered in each of these grabs for a specific area helped estimate the abundance to be used for extrapolation of the total resource available by weight. The nodules were subsequently analyzed in the lab for their metal contents : most primarily Mn, Co, Ni, Cu and Fe. Of these, for grade estimation Ni + Co + Cu weight percentages were used. Average duration of each cruise was 45 days. To cover the entire area, initial grid used for sampling was 100 km, subsequently, based on the results obtained this was narrowed down to a 50 km grid. The data obtained from these two grid intervals in addition to the topographic data obtained by using a single beam echosounder enabled to identify two areas : a Pioneer Area and a Reserve Area each of which measured 150,000 km² in the CIOB (Fig. 3). Both of which having equal grade, abundance and of similar topography. On the 17th August, 1987 the ISBA and International Tribunal for the Law of the Sea (PrepCom) granted exclusive rights for exploration for seabed resources in the Pioneer Area.

Phased relinquishment of pioneer area

The allocation of a Pioneer Area by the ISBA however came with a rider that, it was the obligation of the Pioneer Investor to relinquish 50% of the allocated area in accordance with the resolution II, Para 1 (e) of the UNCLOS III. This was to be achieved in a phased manner :20% of the area by the end of the third year from the date of allocation, an additional 10%, followed by 20% during the third phase of relinquishment. Therefore, the target years for the three phases of relinquishment were 1994, 1996 and 2002 respectively.

Relinquishment Phase I: Having identified the Pioneer Area (Fig. 3) in the CIOB admeasuring 150,000 km², the exploration team set about the task of the first phase of relinquishment. Sampling at a grid of ~25 km (1/4 degree) was undertaken accompanied by consistent resource evaluation, which was further narrowed down to ~12.5 km grid (1/8 of a degree). The total quantum of data acquired from 45 cruises, carried out onboard five research vessels and including abundance estimates from 893 sampling stations was utilized in order to carry out the 1st phase of 20% relinquishment of the Pioneer Area.



Fig. 4 Various sampling equipments used, clockwise: A : Free fall grab or a boomerang grab; B: Space corer; C: A gravity corer; D : Deep towed camera system; E : Dredge used for bulk sampling of nodules

More importantly, a seafloor mapping system was acquired by the country. This jump in technology threw up many features of the seafloor undetected before (please see the appendix references on seabed topography etc.). Some very interesting features, such as fracture zones, hitherto uncharted seamounts, crenulations on the seafloor etc. were discovered. These features although would be eventual impediments for carrying out mining activities, but are of great interest from scientific standpoint clarifying certain issues on plate tectonics. In addition, multibeam swath bathymetric data also enabled to calculate slope angles of the area in an efficient manner.

Relinquishment Phase II : Ten percent of the Pioneer Area (15,000 km²) was to be surrendered to the ISBA during this phase. This exercise was undertaken in the remaining 110,000 km² area with the country. With the continuous generation of data from the Pioneer Area, the total data available at this stage was : sampling data from

1026 stations, at a grid spacing of 0.125° grid, 776 chemical analyses and multibeam bathymetric mapping data from the Pioneer Area. Blockwise estimates were made and an area measuring 15000 km² was identified and finally relinquished in October, 1996.

Relinquishment Phase III : For this exercise of relinquishing the final 20% of the Pioneer Area (30,000 km²), all the available data at a sample grid spacing of 12.5 km generated by 6 research vessels from 56 cruises was utilized. In all, 1056 sampling stations enabled to compile abundance data at 0.125° grid spacing. In addition, 25 stations were further sampled at a much smaller grid to confirm the earlier results. The abundance data derived from sampling stations, in addition to the chemical data being generated consistently for resource assessment, combined with the swath bathymetric mapping carried out in the Pioneer Area provided the essential data to enable the final relinquishment of 30,000 km² of the Pioneer Area in early April, 2002.

Current exploration activity

The country now has 75,000km² of Pioneer Area in the CIOB for carrying out its exploration activities , this now becomes the Retained Area after the completion of the relinquishment activities. The approximate reserves of nodules present in this area are about 380 million metric tons of nodules having high grade and abundance. The actual tonnage of metals that remains with the country after carrying out the relinquishment exercise is given below in Table 3

Table 3 : Tonnage of metals in the retained area (calculated for 382 million tons of dry nodules)

METAL	TONNAGE (mmt)
Manganese	95.17
Nickel	4.509
Cobalt	0.418
Copper	4.455

After the final relinquishment the exploration target has been to identify a first generation mine site (FGM) within the retained area. A part of the Retained Area measuring 18,400 km² has been identified for this purpose (Fig 3). The attributes of this FGM designate area are : consistently high abundance, high grade, reasonably even

topography and contiguous blocks. While grade, abundance and topography remain primary concerns, contiguity of the blocks is also very important. This part of the CIOB contains several seamounts which unfortunately, from a nodule exploration point of view, fall within the retained area and the blocks containing these seamounts have been relinquished. In order that the mining system moves unimpeded, a vast expanse of flat topographic domain is needed, therefore, the retained blocks nearest to seamounts need to be avoided.

Exploration in the FGM area involves, close-grid sampling (@ 6.25 km), resource evaluation, and high resolution mapping.

Close-grid sampling the entire area had already been sampled at a grid interval of 12.5 km earlier. The inconsistencies in nodule abundance for a given area of the seabed is well known. In addition to sampling, therefore photographic and acoustic techniques (using multifrequency echosounders) have been used by other investors in the deep seabed areas. While, acoustic techniques have not been tried, photography in particular has not been particularly successful in the CIOB. Over 50,000 photographs have been taken using a deep towed photographic instrument, however, there has always been a discrepancy between the abundance derived from sampling operations as compared with visual techniques. The nodules in the CIOB appear to be buried under a thin veneer of sediment and are therefore not visible in their entirety to photographic techniques (Please see the references on deep seabed photography in Appendix I). Therefore, in order to circumvent the uncertainties in these techniques, more ground truthing in the form of close-grid sampling was found as an option for fine tuning the resources. Close-grid sampling of a selected area is currently being carried out.

Resource evaluation : Polymetallic nodules offer more than the traditional 3 metals (4 if one includes manganese as well) : Cu, Ni, Co. Given in Table ... are the approximate contents of important metals contained in nodules. Mining activity would be primarily carried out for Ni, Co and Cu which comprise of only 2.5% of the total quantity of nodules mined. Considering that mining would take place at a scales of 2-3 million tons/year, we are looking at millions of tons of gangue material which needs to be disposed unless some alternative use is found. The current concepts therefore involve exploiting manganese (which comes in the residue after the removal of Cu, Ni and Co), also as one of the economically important metals. One option would be to have at sea processing of nodules which would redeposit the gangue material in the deep sea itself, the other alternative would be to find other elements

that could be extracted from the nodules. It would be interesting if metallurgical processes are developed keeping the 'other metals' also in consideration. Comprehensive resource evaluation of the nodule deposits in the entire Retained area is currently going on which could form an important input for the metallurgical operations.

High resolution mapping : while the entire FGM designated area has been mapped earlier using a multibeam mapping system. The technique utilized in ORV Sagar Kanya incorporates 59 beams having a narrow beam footprint of 2.3⁰ at depths of ~ 5000 m. From the operating height of >5 km (from the seafloor) this means an approximate insonified area of about 150 metres on the seafloor from which the system derives its depth information. In between these 150 metres separation between the pings, the depths are extrapolated by the system software. This resolution was good enough for identifying large scale features seamounts, abyssal hills, fracture zones, and high angle slopes etc. which went a long way in relinquishing uninhabitable areas. However, for delineating microtopographic features of smaller dimensions (eg. < 150 m) the system generates its own depths based on the total information received by it from the footprint or the insonified area – this is a best fit data and has its limitations.

In order to delineate a FGM it is essential that a more accurate mapping system be used, because based on this information further, more close-spaced and expensive equipment would be deployed on the seafloor. Recently, another research vessel having a multibeam swath bathymetry system having 240 beams was chartered. The input for the system in this vessel is obtained from 240 beams for the same insonified area of the seafloor, resulting in increased accuracy and resolution. The system has a footprint of 1.2⁰ at 5000 m water depth and coverage is around 100 metres. This system is definitely an improvement on that used in the early nineties for mapping the Pioneer Area. Topographic information based on the surveys carried out by this vessel is being processed to generate an accurate map of the probable FGM site.

The First generation mine site would be identified by integrating the results from all the above parameters.

Exploitation

To deal with exploitation is beyond the scope of this paper. Exploitation is also a complex scenario involving demand and supply equations. One important parameter that one needs to consider is that there is no known nodule exploitation system developed on a commercial scale at the moment and also that all large nodule deposits are

beyond the EEZ of the various countries therefore involve large transport logistics. The development of the mining system would take into consideration a machine which would work for long durations underwater under hyperbaric conditions of around 500 atmospheres pressure. The development of such a system also involves several spin offs that could be utilized in other industries in a similar fashion that space technology has led to the advancement of the quality of life on earth in the form of respirimeters, sonar devices for evaluating the functioning of heart, safety spinoffs for automobiles, computer techniques etc.

Further, the shipping industry would get a huge fillip with the exploitation of nodules, in addition to harbour development, transport industry for inland transport of nodules from ports to processing plants, processing industries and their ancillaries. The scenario that emerges is that of broad industrial development.

Future exploration plans

Having determined the grades and abundances with relative accuracies and the resources identified. One would then be in a position to narrow down the area of operations considerably in identifying the FGM. It becomes now important to get observations systems close to the seafloor in order to obtain most accurate information from the seafloor, the benthic environment, and the sub-bottom so that there are no surprises in store for the mining system which could result in loss of huge investments and invaluable time.

The best of mapping technology available today offers an accuracy of about 100 metres considering that the operating depths are between 4000-6000 metres.

If one considers the possible dimensions of the mine head, it is expected to have a width of about 10-20 metres. Considering the dimensions of the mine head, one needs to have better understanding of the seafloor with much higher precision in order to facilitate its movement on the seafloor and also to derive essential input parameters for its design and development. The resolution obtained from the multibeam systems (~100 m at 5 km water depth) may fall short of expectation. Resolutions of the seafloor features at an order of magnitude higher levels are needed for this purpose. An observation system (ROV) which would be towed very close to the seafloor would be able to give the necessary information. In addition to the above, it is also essential that the engineering properties of the seabed needs to be obtained where the mining system rests – this is a key parameter.

Research on nodules and Central Indian Ocean

The scientists working in the project have carried out studies in various aspects of science such as nodule geochemistry, sediment geochemistry, paleoceanography, engineering properties, marine acoustics, benthic environment, resource evaluation, plate tectonics, volcanology and planetary geology to name a few

Few major findings of the group are given below. The relevant references are given in the appendix.

Nodule distribution, geochemistry, mineralogy, resource evaluation

Survey and exploration for polymetallic nodules (ferromanganese) in the Indian Ocean have shown that only the pelagic sediments of the Central Indian Basin (CIB) have high abundance of ore grade polymetallic nodules (PMN), and therefore they are economically important. Based upon the analysis of strategic metal content it is quite possible that the first generation mine site be located within CIB.

The CIB has different topographical features such as fracture zones (FZ) and seamount chains. The nodules associated with different topographical features have different morphological and chemical characteristics. The nodules have different shape, size, texture, and vary in diameter from <1 to 10 cm. Valsangkar et al. (1992 a, b) identified >13 types of nodules in CIB. Study of 850 nodules from 234 sites showed inverse relationship between nodule size and grade (Cu+Ni+Co %), and among the different sizes, only small to medium sized nodules have high grade of 2.5 to 2.6 % of combined Cu+Ni+Co (Valsangkar, 1995). In order to minimize the ecological and environmental impacts due to deep-sea mining, Valsangkar (1995) suggested to design proper mining device so that the required size of the nodules would be screened on the sea floor itself.

The studies taken up on morphology, geochemistry, mineralogy and distribution pattern of manganese nodules from Indian Ocean have revealed several interesting findings. The detailed internal structural analyses indicated that these nodules never grew continuously during their growth process and neither they have any unique mineralogy-texture relationship as conceived earlier on nodules from other world oceans (Banerjee et al., 1993, 1999). It was interesting to note that the trace metal content of the nodules were typical on specific sediment types and it also show some relationship with their morphology (Banerjee and Mukhopadhyay , 1991). The buried nodules interestingly indicated that they neither dissolve nor grew even after burial in siliceous sediments &

retains their pre burial characters (Banerjee et al., 1991). Significant Influence of biogenic matter was observed in the growth process of both micro and macro nodules (Banerjee and Iyer, 1991; Banerjee, 1993; Banerjee et al., 1999). It was observed that the nuclei of majority of the nodules in the CIB area are supplied by weathering of nearby seamounts (Banerjee and Miura, 1998). The distribution pattern of the CIB nodules indicated that while their grade and abundance does not have any significant relationship, their growth rate and grade have positive relation to a certain extent (Banerjee and Miura, 2001). In addition to their high Cu, Ni and Co content of mineable quantity, the nodules from CIB could be a potential resource for PGEs as well (Banerjee, 2004).

Sediment distribution, deep-sea volcanism and geochemistry

Different size fractions of the clays from three sediment domains (siliceous, pelagic and calcareous sediments) of the Manganese nodules field, Central Indian Basin were analysed for their mineralogy. Illite, followed by chlorite and kaolinite are the dominant minerals phases in the northern Central Indian Basin. These are detrital products transported from the Ganges and Brahmaputra river system by the turbidity currents. Two mineral phases of smectite were found in the basin. Montmorillonite, the weathering products of ridge basalts, is abundant in calcareous sediments closure to the Ridge. Fe-rich montmorillonite, an early diagenetic product between silica and iron with sea water processes at the seafloor, is abundant in siliceous and pelagic clays. It was found that the manganese nodules with distinct todorokite-rich manganese mineral phase are associated with Fe-rich montmorillonite clays of siliceous sediments. Studies on the mineralogy and geochemistry of associated sediments with the manganese nodules from CIB indicated that they could be broadly grouped into three types and their intermixtures. While the northern part of the basin have significant terrigenous input, it shows sufficient volcanogenic components in the southern part of the basin (Banerjee, 1993, 1998). It was observed that the nodule geochemistry is influenced by the diagenetic processes undergone by the associated sediments (Banerjee, 1993, 1998) Presence of ash layers in down core sections intercalated with the siliceous sediments near several sea mounts indicated possibilities of insitu volcanism as source of these ash layers, while their radiometric dates corresponded with global cooling events (Sukumaran et al., 1999). Presence of a significant numbers of animal burrows in soft as well as hard sediment substrates from different part of the CIB indicated the presence of a prolonged biogenic activity, possibly predating the formation of these nodules, is active in this basin (Banerjee, 2000).

Buried Nodules

The occurrence of buried nodules is less well known than that of surface nodules. Various processes have been suggested to explain the phenomenon of keeping manganese nodules at the sediment-water interface. However, the processes of maintaining nodules at the sediment-water interface still remain unclear. In CIOB more than 60 sediment cores were collected in different sedimentary environments. Fifty buried nodules were recovered in 12 sediment cores at different depth intervals. A maximum of 15 buried nodules were encountered in one sediment core and the deepest nodule recovered at 5.50 m below seafloor. The major, trace and rare earth element geochemistry of buried nodules were studied in detail by Pattan and Banakar (1993); Pattan and Parthiban, (2006, 2007). Approximately 80 % of the buried nodules are small in size (~2 mm in diameter) and their size decreases with sediment core depth and appears to be similar to phenomenon of Brazil Nut Effect. Buried nodules exhibit smooth and rough surface texture and are ellipsoidal, elongated, rounded, sub-rounded, irregular and polynucleated. Buried nodules from siliceous ooze area suggest their formation under hydrogenetic, early diagenetic and diagenetic processes whereas those from red clay are of hydrogenetic origin. (Pattan and Parthiban, 2007). The mode of incorporation of Rare earth elements into the buried nodules is by a single authigenic phase comprising of Fe-Ti-P. The shale normalized REE pattern suggests that they are formed in an oxidising environment. Chemical composition, morphology, surface texture of buried and surface nodules from CIOB is similar. Buried nodules in CIOB does not exhibit any composition change with core depth suggesting that they neither grow nor dissolve after their burial in the sediment column (Pattan and Parthiban, 2007).

Manganese micronodules

Manganese micronodules are small counterparts of manganese nodules and occur in both surface and subsurface sediment. The large difference in size between micronodules (< 1 mm) and macronodules (2-10 cm in diameter) suggests that the former cannot grow into latter. In CIOB number of sediment cores and surface sediments were studied for micronodules abundance, size and chemical composition (Pattan, 1993; Pattan et al., 1994). Micronodule abundance (number of micronodules per g of dried sediment) and their size is higher the sediment core top and less at intermediate depth and again increases with core depth. Micronodules are formed by diagenetic process. Major, trace and REE content of micronodules are similar to that of surface nodules from the same basin.

Oxidation state of Mn and Fe in the nodules

Ferromanganese nodules from CIOB contain about 73 to 81 % of Mn in the form of Mn (IV). Mn (II) is detected qualitatively by electron spin resonance spectra (Pattan and Mudholkar, 1990). Mossbauer studies showed that iron is present solely as Fe (III) in paramagnetic or super paramagnetic phase (Pattan and Mudholkar, 1991).

Paleoceanography

Using nanofossil assemblages, the first report of biostratigraphic age of the calcareous substrate of a ferromanganese crust, from the adjacent Vityaz fracture zone, CIR, indicated that the growth of ferromanganese material at this part of the ocean is not older than Upper Miocene (6.5 million years) (Guptha et al., 2002). As most of the central Indian Ocean basin is below CCD, only microfossil useful in assigning the biostratigraphic datum and paleoclimatic and oceanographic proxy are the radiolarian (Gupta et al., 1996, 2002, Gupta, 2002, 2003). Radiolarian studies from sediment core tops and down the core have suggested well preserved late Pliocene to Holocene climatic record in terms of faunal assemblages, sea surface temperature and salinity changes in the equatorial Indian Ocean. These paleoceanographic studies exhibited cyclic changes at the Earth's orbital eccentricity (400-, 126, and 95k), axial tilt (54-, and 41k) and precession of equinoxes (23-, 19-, and 17k), besides the sub-orbital cycles (15- and 13k) in the strength of the Indian summer monsoon (Gupta et al., 1996, 2002, Gupta, 2002, 2003).

Analyses of underwater photographic data for distribution characteristics of ferro-manganese deposits and their applications to mining

i) Distribution characteristics in relation to topography

Influence of seabed topography on the distribution of manganese nodules and inter-relation between the distribution of nodules, sediment and rocks in different topographic domains (seamount peaks, slopes, valleys and plains). This information is very useful in delineating potential areas for detailed surveys and mining.

ii) Quantitative estimation of nodule parameters

Development of empirical formulae for quantitative estimation of area coverage, size, abundance and burial of nodules from seabed photography data. The study also evaluates the effect of sediment cover in partial exposure of nodule, leading to under-estimation of nodule abundance and methods to apply a 'correction factor' to photo data for improving the accuracy of this technique for demarcation of potential areas for future sampling.

iii) Application of nodule parameters and seafloor features for mining

Evaluation of nodule distribution characteristics with associated seafloor features, such as sediment, rocks and topography in relation to mine-ability of the deposits. The study also evaluates the potential interaction of the different subsystems and suggests design considerations for developing an efficient and environment friendly mining system.

iv) Development of a method for 2 dimensional and 3 dimensional analyses of photographic data for quantitative evaluation of crust deposits

Methods for estimation of coverage and size classes of nodules using image analysis software, microtopographic analysis using photographic technique, and estimation of water depth using CTD and photogrammetric techniques, were developed for two- and three- dimensional analyses of co-rich manganese deposits, which are important inputs for resource evaluation of the mineral resource.

vi) Analysis of distribution characteristics of Co-rich deposits for identification of test mine site

Detailed analyses of distribution of nodules and crusts along a transect of 4.4 nautical miles on a flank of a seamount in the Central Pacific Ocean. This data was finally used for selection of test mine site for operation of a deep-sea mining system.

vii) Evaluation of seafloor morphology and slope angles for design considerations of future mining system

Evaluation of physical parameters, such as coverages, sizes, burial, association with rock outcrops, micro-relief of co-rich deposits with respect to seabed morphology and slope angles, has resulted in generation of critical information, for design of the future mining systems for these deposits.

viii) Impact assessment of benthic disturbance experiment

Evaluation of changes in seafloor features, extent of physical disturbance, correlation with sediment plume data and core sections before and after disturbance, have led to estimation of vertical mixing and lateral movement of resuspended sediment, which causes environmental impact on the seafloor.

Geotechnical properties of sediments

Sediment properties play a critical role during technological development of Deep-sea mining system. Nodule mining could be an outcome of the survey and research carried out worldwide for polymetallic nodules.

Sediments from the Indian Ocean associated with nodules studied for geotechnical properties (Khadge, 1995, 2005) are cohesive within short core depths. They are silty clays, rich in smectite and illite leading to high water content and low wet density (Khadge, 1998). Shear strength of these sediments vary from 0 kPa at surface layer to 14.7kPa at 30cm depth. Bioturbated layers show reduction in sediment cohesiveness. This parameter is critical for design of nodule miner due to variable cohesiveness of soft sediments with depth. Sediments are slowly deposited and highly porous. The properties are also useful for assessment of environmental impact of mining (1999a, 2002) on change in sediment characteristics (Khadge, 1999b). Physical properties of sediments are also determined for gas hydrate exploration off the Indian Coast (Pattan et al., 2007).

Volcanic activity in the Central Indian Ocean

About 200 seamounts (height >100 m) occur either as isolated volcanoes or are arranged along eight parallel chains. The formation of these features is related to the episodes of plate re-organisation and variable rate of sea-floor spreading (Das et al., 2005). The rocks recovered from the CIOB are: Normal-Mid-Ocean Ridge Basalts (Nath and Iyer, 1989; Iyer and Karisiddaiah, 1990; Mukhopadhyay et al., 1995; Mislankar and Iyer, 2001) Ferrobasalts (Iyer et al., 1999a), Spilites (Karisiddaiah and Iyer, 1992), Rhyolitic volcanics (pumice, glass shards) transported either from the 75 ka ago Toba eruption or from the 1883 Krakatoa eruption, or formed through in situ eruptions (Iyer and Karisiddaiah, 1988; Iyer and Sudhakar, 1993). Besides these, volcanogenic - hydrothermal materials (Si-Fe sediments and volcanic magnetite spherules derived from in situ events) have also been recovered from the CIOB. (Iyer et al., 1997a, b; Iyer et al., 1999b). The volcanics form nuclei for the nodules and crusts (Iyer and Sharma, 1990; Iyer, 1991; Iyer, 1999a). The constant interaction between the CIOB basalts (glass and whole rock) and seawater has resulted in the alteration of the former and formation of clay minerals, palagonite and zeolites (phillipsite) (Iyer and Sudhakar 1993; Iyer, 1999b). Considering several parameters, the existence of a large volcanic province has been shown (Iyer and Sudhakar, 1995; Mukherjee and Iyer, 1999). The above studies resulted in a model that accounts for the formation and abundance of nodules in the CIOB. (Mukhopadhyay et al., 2002). It is vital to know the distribution of rock outcrops because once mining for nodule commences the underwater collecting device has to be deftly maneuvered to better recover nodules, avoid damages and loss of collecting time (Sharma et al., 1994).

Plate tectonics

i) Magnetic lineations, spreading rates and fracture zones:

Identification of magnetic lineations, fracture zones and spreading rates provided age estimates and the kinematics of the Indian plate during the past 48-60 million years period. Evolution of the Indian Ocean triple junction and the reorientation of Southeast Indian Ridge resulting in major spreading rate and direction changes in the Central Indian Basin are the major tectonic processes that controlled the evolution. The sudden decrease in the spreading rate at anomaly 23 (53 Ma) indicates the onset of collision between Indian plate and Eurasian plates (Kamesh Raju and Ramprasad, 1989; Kamesh Raju 1990).

ii) Multibeam swath bathymetric investigations across the 79°E fracture zone

Detailed multibeam bathymetric studies over 79°E fracture zone provided unmistakable bathymetric evidence of the southern extension of the fracture zone. Strong and weak shear coupling at the ridge transform intersection during various stages of evolution of the fracture zone modulated the bathymetric lineations. Lithosphere at the fracture zone flexes to maintain the ridge trough topography. The flexure is driven by the age contrast between the two lithospheric sections in contact at the fracture zone. Thermal structure of the lithosphere has been evaluated at the 79°E fracture zone taking into consideration the age contrast at the FZ (Kamesh Raju et al., 1993).

iii) Implications of Seamount distribution:

Several seamounts have been identified during the present studies. The distribution of seamounts in the study area, examined in the light of the hotspot traces and the broad low velocity zones as indicated by the seismic tomographic image of the Indian Plate, suggest that these seamounts represent smaller chains of major hotspot. It is suggested that the distribution of these seamounts is partly controlled by the fracture zones (Kamesh Raju, 1993).

The Law of the Sea

The law of the sea and marine policy aspects of manganese nodules as a common heritage resource were evaluated to put in perspective the Indian manganese nodules programme within the framework of UNCLOS [United Nations Convention on the Law of the Sea] (Vijay Kumar, 2004; Vijay Kumar 1999). The United States refusal to ratify UNCLOS and the Kyoto Protocol of the UN Framework Convention on Climate Change [UNFCCC] due to perceived economic losses was the subject of discussion in a brief note published in Current Science [Vijay Kumar, 2004]. The UNCLOS enabled changes and empowerment brought about by the introduction of new maritime zones and obligations were assessed in a

publication [Sudhakar and Vijay Kumar, 1996] that came about in the wake of the Convention coming into force on 16 November 1994.

Planetary geology

In hundred years of tektite research, only two Australasian tektites have been found in the Indian Ocean (Prasad and Rao, 1990; Prasad et al., 1998), these findings have suggested an oceanic extension of the australite sub-strewn field, and a broad unification of the entire tektite strewn field. In addition, microtektites from the Central Indian Ocean contain microimpact features which have an uncanny resemblance to those found on Lunar surface materials - these features have not only revealed unknown collisional processes that take place in the ejecta plume of a major meteorite impact, but also, suggest that the cosmic dust flux estimates based on microcrater counts on lunar materials could lead to an overestimation (Prasad and Sudhakar, 1996; 1998; Prasad and Khedekar, 2003).

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