

OCEANIC FERROMANGANESE DEPOSITS: FUTURE RESOURCES AND PAST-OCEAN* RECORDERS

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ABSTRACT

Although ferromanganese nodules on the deep-ocean floor were discovered in 1873 during voyages of HMS Challenger, their economic potential came to light only in 1965. By now, the 1970's "Nodule Rush" has almost come to an end. Most of the pioneer countries in this field have realized that the present techno-economic situation is not in favor of nodule mining. Therefore, the UN registered Pioneer Investors appear to have preserved the demarcated nodule mine sites for future use. As a spin-off of that Nodule Rush, foreign and Indian scientists explaining the mystery of nodule carpets on the sea-floor have published several research papers. In this paper we attempt to discuss the chemistry, mineralogy, morphology and allied features of the oceanic ferromanganese deposits in relation to their genesis and growth. We also discuss in brief the importance of seamount ferromanganese crusts both as resources and as recorders of the paleoceanographic events.

Oceanic ferromanganese deposits occur mainly in two forms, as nodules and as encrustations; while the nodules form a carpet on the deep-sea abyssal plains, encrustations occur as caps on seamounts. The genesis of nodules has been attributed to multiple processes such as hydrogenetic, diagenetic and mixed, but encrustations are generally believed to be of hydrogenetic origin. It has been estimated that, nearly 43 million km² of the world's sea-floor area is covered with ferromanganese nodules, totaling to a considerable 1.7 to 3 trillion tons. On the other hand, encrustations have been found on most of the seamounts underlying high productive surface waters. Ferromanganese nodules are known for the enrichment of Copper and Nickel, while encrustations are enriched in cobalt. Their ubiquitous occurrence in almost all the ocean basins make them a potential future multi-metal resource.

As encrustation form due to hydrogenetic precipitation of metal hydroxides from the ambient water, they are best suited to trace the contemporary oceanic environment prevalent during their growth period. Several workers have demonstrated that ferromanganese encrustations are the condensed repositories of past-ocean conditions. Exploiting this potential, researchers world over have demonstrated that, Quaternary climatic fluctuations, deep-water circulation changes, major erosional episodes and similar events have left behind unambiguous records in the encrustations.

Thus the oceanic ferromanganese deposits not only are important as potential resources, but because they also host valuable records of paleocean environment.

INTRODUCTION

The ferromanganese nodules from the sea-floor were recovered for the first time during 1873 onboard HMS Challenger (Murray and Renard, 1891). Until nearly a century

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later, the nodules were the subject of only academic interest. Only during 1965, world economists, policy makers and industrialists began to look at them as a potential natural resource when Mero (1965) published a book titled "The Mineralogical Resources of the Sea (Elsevier, Amsterdam)". Two decades following the Mero's publication witnessed global "Nodule Rush". The technological leaders of those years like US, Germany, Japan, France, New-Zealand, and USSR have conducted major scientific expeditions to the Central Pacific to map the distribution of nodules. United States undertook a major exploration program funded by NSF. Several consortia were formed to explore and exploit the nodule resources. Exploration of and Research on ferromanganese nodules (Manganese nodules or polymetallic nodules: hereafter referred only as nodules) were thus picked-up the momentum. As a result of those works, several hypotheses were put forward to explain the genesis and formation of nodules.

Though the aim of initial expeditions was to identify the ore grade nodule deposits, the resultant spin-offs were in the form of large published literature describing, the nodule morphology (Mero, 1962), internal structures (Sorem, 1967), chemical composition (Cronan, 1972); Mineralogy (Glasby, 1972); growth rates (Petterson, 1943), and genetic aspects (Goldberg and Arhenius, 1958; Petterson, 1945) and several other aspects.

The gist of earlier hypotheses explaining the formation of nodules is as follows:

- a) Decomposition of ultrabasic rocks on the seafloor releases the Mn and Fe to the bottom waters. Further transformation of Mn and Fe in to carbonates and subsequently in to oxides form nodules.
- b) The organic matter decomposition on the seafloor reduces sulfates to form Mn and Fe sulfides. Subsequently the Mn-Fe sulphides oxidize to form nodules.
- c) Precipitation of Mn and Fe oxides released from the submarine springs (hydrothermal solutions) accumulate to form nodules at the seafloor.
- d) Precipitation of dissolved manganese first as bicarbonates subsequently transform in to oxides at seafloor to form nodules.

Though none of these hypotheses could explain independently the complex process of nodule formation, however, were continuously refined to provide more plausible hypothesis. In spite of several well-known mechanisms responsible for removal of trace metals from sea- water, their relative importance in explaining nodule formation by and large remained inconclusive. Vinogradov (1953) observed a significant concentration of several minor metals in planktonic assemblage. Kuenzler (1965) has estimated that more than 90% of the Fe flux to deep waters occurs through sinking fecal pellets. Revelle, et. al., (1955) found striking association between Ba concentrations with siliceous ooze sediment. Graham and Cooper (1959) observed the colonization of many bacterial community on Mn-nodules. The associations of trace metals with sinking biological particles and microbial community with nodules were used as evidences to propose biologically mediated precipitation of Fe-Mn oxide leading to the formation of nodules. But the co-existence of oxidizing and

reducing bacteria and overwhelming majority of reducing bacteria in deep-sea environment rendered the role of biological processes in the formation of nodules a highly complex issue. Therefore, the exact role of biological activity in the formation of nodules could not be explained convincingly by those workers who proposed the hypothesis invoking biological origin.

Bonatti and Nayudu (1965) have proposed submarine volcanism as the metal source for formation of nodules. They suggested that, the strong interaction between lavas and seawater takes place in many submarine volcanic effusions. As a result, large quantity of Fe, Mn and other trace metals are leached out of the lava. Thus leached metals subsequently precipitate on the seafloor forming the nodules. This hypothesis could explain the nodules in the vicinity of effusive centers but failed to explain the formation at abyssal areas far removed from the centers of submarine volcanism. In addition, the composition of nodules formed due to volcanically sourced metals is quite different from those formed in non-volcanic areas.

Based on a strong linear relationship between Mn and other trace metals in manganese nodules Glasby (1974) concluded that adsorption of trace metals on settling particles in the water column was a dominant process of extracting Fe, Mn and other trace metals from sea water into nodules. Later, several workers demonstrated various inorganic mechanisms to explain the process of nodule formation. This concept finally laid the foundation for widely accepted mechanism of nodule formation which hinges solely on inorganic precipitation of metal oxides. According to this hypothesis the nodule accretion takes place due mainly to hydrogenetic and or diagenetic processes. In hydrogenetic process, the source of the metals is the sea-water, while in diagenetic process the main source of metals is the interstitial water trapped within the sediment column. Bonatti et al., (1972) for the first time proposed a triangular diagram to classify the different genetic types. The nodules falling in the hydrogenetic field invariably have low Mn/Fe ratios (< 2.5) and those accreted due to diagenetic process have Mn/Fe ratio > 2.5 . This ternary diagram was later refined by Halbach et. al., (1981) to clearly depict the varying relative influence of hydrogenetic and diagenetic end members (Fig. 1).

Prior to 1980, bulk of the nodule literature was concerned with Pacific Ocean deposits. Subsequent to launching of the Polymetallic Nodules program by the National Institute of Oceanography in 1980, several interesting research articles dealing with Indian Ocean deposits have appeared. It is worth mentioning here that, the first nodules were collected onboard R.V. Gaveshani, which paved the way for launching a major exploration program funded by the Department of Ocean Development. The sustained efforts of several scientists and engineers of the National Institute of Oceanography with the financial support of the Department of Ocean Development enabled India to register her exclusive rights on 17th August 1987 for development of a nodule mine site in international waters.

This paper presents a brief account of the characteristic features of Fe-Mn oxide deposits (nodules and encrustations) and their implication in the paleoceanographic studies.

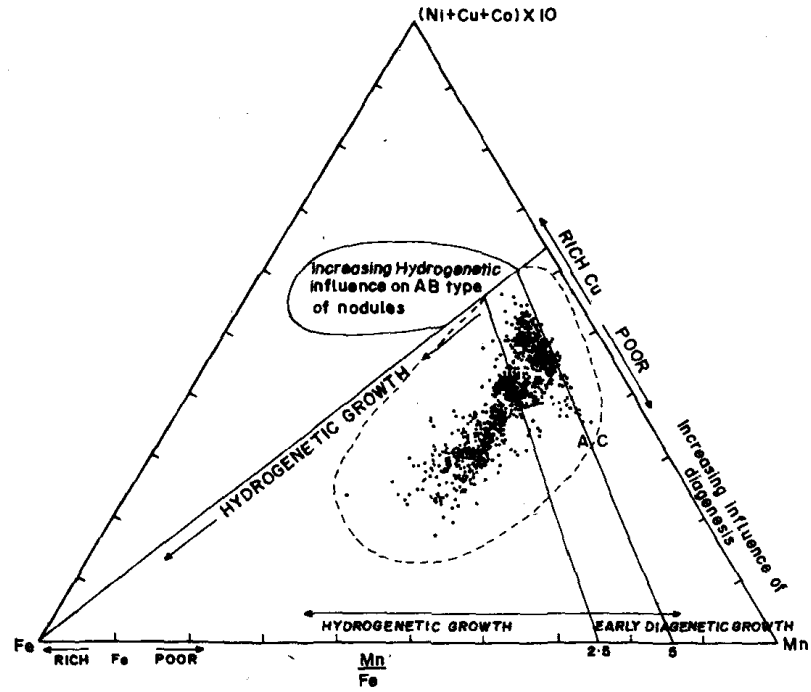
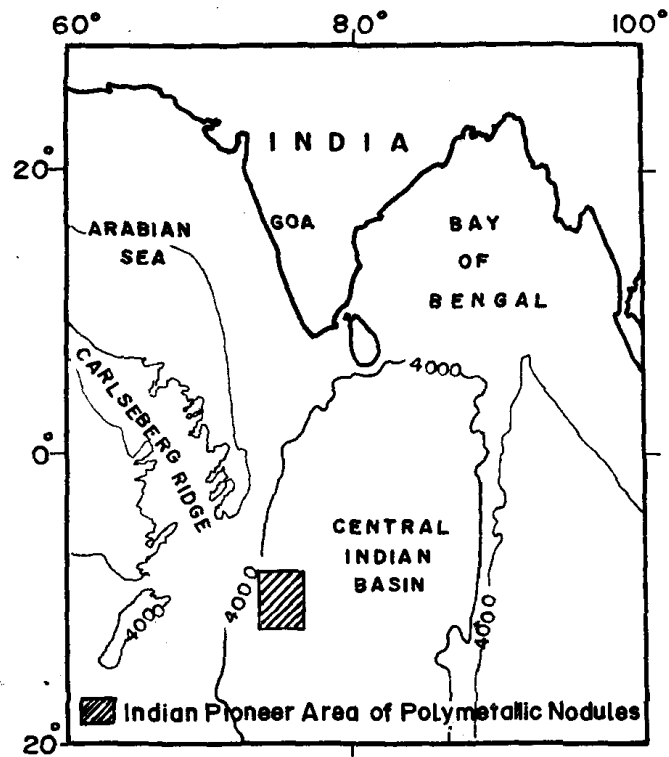


Fig. 1: Three-component diagram showing the relationship between Fe-Mn-(Cu+Ni+Co) in ferromanganese deposits from the Central Indian Ocean (Source: Jauhari, 1987).



DISTRIBUTION

The nodules occur invariably in almost all the deep-sea basins witnessing low sedimentation rates. But abundant ore grade deposits are limited to Equatorial North Pacific (Clarion-Clipperton fracture Zone), Cooks Island and Central Indian Basin. In Pacific the nodule deposits occur also in South-Western Pacific Basin, Peru basin, Chile basin, Tasman basin and Tahiti basin. In the Indian Ocean, the nodule occurrence was also reported from Crozet basin and Western Australian basin. Whereas in Atlantic, the nodule deposits are scanty probably due to high input of terrigenous sediment relative to its small size, hindering growth of nodules. During 1965, Mero, for the first time gave approximate resource estimates for Pacific nodules as around 1.6 trillion tons. Subsequent exploration and surveys by various agencies suggested that the nodule deposit of the world oceans is between 1.7 to 3 trillion tons.

The distribution and abundance of nodules is governed by rate of sedimentation, the length of time available for their accretion and availability of nucleating material. In general the low sedimentation rates lead to higher abundance of nodules (Ewing et al., 1971). Therefore, the areas receiving low sediment input of the order of 1-5 mm kyr⁻¹ (Opdyke and Foster, 1970) are enriched with abundant nodules. In addition, Banakar et al., (1991) related the erosion of younger sediment in the Central Indian Basin to the occurrence of abundant nodules. They suggested that the sediment erosion activity probably keeps the nodules at sediment water interface facilitating their growth process. It should be noted here that, once buried, the nodules cease to accrete as evidenced by their thorium-²³⁰ isotopic inventories and radiolarian bio-stratigraphy (Banakar and Gupta, 1998). Krishnaswami et al., (1972) have suggested that, nodules grow only 10% of their life-time. In such a situation, the majority of nodules should be found buried or exhibit growth discontinuity. However, it is hard to assess the total time period of their growth because, some nodules remain unaffected at the sediment surface for over millions of years but exhibit structural variations within. The third important factor controlling the nodule abundance is the availability of suitable nucleating material. Almost all nodules accrete around hard foreign objects like rock fragments, sediment lump, shark teeth, pumice etc. Therefore, relatively high concentration of nodules in the areas of submarine volcanic activity was related to the abundant nucleating material (Murray and Renard, 1891). Glasby (1977a) proposed that benthic biological activity and bottom water currents maintain the nodules at sediment-water interface. McCave (1988) demonstrated that the upward forces exerted by the benthic wormiforms hold the nodules at sediment surface. Piper and Fowler (1980) suggested that, the shear strength of underlying sediment increases downwards and hence the force required to push the nodule downward into sediment is greater than to push it upwards. In other words, the distribution and abundance of nodules not only depend upon the sedimentation rate or availability of nucleating material but also largely depend upon cumulative effect of many other physical processes active at sediment-water interface. Under the influence of above mentioned forces, nodules generally do not remain stationary at the sediment surface but are continuously subjected to turnover (Krishnaswami and Cochran, 1978; Moore et al., 1981; Banakar, 1990). In general the distribution of nodules varies from traces to high abundance to the order of 25 kg m² in a

given area (Plate I, Fig. 2 inset). Therefore, the local processes appear to play an important role controlling the distribution and abundance of nodules at sediment-water interface.

MORPHOLOGY AND COMPOSITION

A detailed account of the morphological description of nodules is available in Raab and Meylan (1977). Based on the Challenger Expedition samples, Murray and Renard (1891) recognized three morphological types, a) pyramidal, b) spheroidal/ellipsoidal and c) mammillated. Later, Heezen and Hollister (1971) utilized highly descriptive terminology as cannonball, potato, grape and slab to describe nodules. Meylan (1974) gave first systematic field classification guidelines for describing nodule morphology. He suggested mainly two parameters, the shape and size to classify the nodules. Primary morphology (shape) constitutes the shapes like spheroid (S), ellipsoid (E), discoid (D), poly-nucleate (P), biological nucleus (B), tabular (T), faceted (F). These primary categories are pre-fixed by size parameters such as "s" (small nodules, < 3 cm in diameter), "m" (medium nodules, 3-6 cm diameter), and "l" (large nodules, > 6 cm diameter). On the other hand, Valsangkar and Khadge (1989) used six size classes with a constant size difference of 2 cm to describe the Central Indian Ocean nodules. Several workers use the Meylan (1974) classification with marginal modification. Certain modification to any classification pattern appears necessary as the nodule shapes and size have a wide range of variation. During the initial stages of accretion the shape of nodule generally follows the shape of nucleating material, but on continued growth the shape smoothes out to a nearest spheroid or discoid (Fig. 3 Plate 1,1 to 11).

Nodules are composed of intricate internal structures. Sorem and Fewkes (1977), Sorem et al., (1979) recognized four structural categories, viz., columnar, mottled, lamellar and compact. The internal microstructure of the nodules and crusts are the basic growth-units that reflect the ambient environment through time under which the ferromanganese oxide deposition has taken place (Freidrich and Weichowski, 1980). The alternate dark and light bands within a structural unit were studied for compositional variation using microprobe. The Mn-enrichment in higher reflectance bands and Fe-enrichment in lower reflectance bands suggest the relative enrichment and depletion of these metals during the growth of micro-bands (Banakar and Tarkian, 1991). The internal micro structural units are of great significance in constructing the growth history of these deposits which will be discussed later in this paper.

The nodules are not monomineralic. Instead they composed of several phases intimately intergrown leading to a complex mineral composition. The nodules contain detrital grains, Fe-Mn oxide phases, organic matter, and biogenic skeletons of microfauna. The major component is the authigenic Fe-and Mn-oxides. The acid-insoluble residue and hydrolysate fractions of the SW Pacific nodules indicated that the influence of residue fraction on the overall composition of nodules is insignificant and the hydrolysate fraction is the phase forming dominant mineral composition of the nodules (Glasby and Thijssen, 1982). In other words, the hydrolysate fraction is represented by authigenic precipitation of Fe-Mn oxides to form the nodule while residue is mainly from silicate detritus. Glasby

and Thijssen (1982) noticed significant amount of Barite in residue fraction of nodules underling equatorial high productivity belt and thus related the barite content to the productivity levels. Amongst the hydrolysate fraction, compounds of Mn and O and, Fe and O are the major minerals. Basically, the hydrolysate component of the nodule is represented by amorphous or crypto crystalline material, rendering mineral identification to extreme complexity. Buser (1959) originally termed the Mn-phase in the nodules as 10 A-Manganite, 7 A-manganite, and δ -MnO₂ by comparing the prominent reflections in X-ray powder pattern to those obtained for synthetic compounds. Subsequent studies were concentrated on identifying the true Mn-mineral phases in nodules. After several investigations and debates (see Burns and Burns, 1977), todorokite, birnessite and δ -MnO₂ terminology was accepted. However, this terminology is also not a final one as todorokite is considered as a mixture of buserite, birnessite and manganite (Burns and Burns, 1977). Some studies have also indicated that, upon removal from the ambient environment the dehydration could lead to changes in the mineralogical composition (Stevenson and Stevenson, 1970). Some workers consider δ -MnO₂ as the disordered form of Birnesite. For convenience, now it has become a practice to use todorokite for 10 A line, birnessite for 7 A line and δ -MnO₂ for broad lines around 2.4 and 1.4 A.

The Fe-bearing phase in nodules include goethite, lepidocrocite, maghamite, hematite etc. However, in most descriptions of nodules the iron bearing phase is usually described as cryptocrystalline or amorphous hydrated Fe-oxide (Crerar and Barnes, 1974; Glasby, 1972). Nodules are well known for poor quality diffractograms they produce. In most of the cases Fe-hydroxide phase is unidentifiable and in general almost all reflections are highly diffused. The X-ray behavior clearly suggests that the nodules are composed of extremely small particles of Mn and Fe oxides leading to its amorphous or cryptocrystalline nature.

The mineralogical composition of Central Indian Basin (CIB) nodules was shown to be quite similar to those of Pacific Basin (Martin-Barajas et al., 1991; Rao, 1987). The todorokite intensity in the CIB nodules was shown to decrease with increasing size of nodules, which in turn, associated with increasing δ -MnO₂ intensity. This observation was related to the intensity of diagenesis with todorokite formation (Banakar et al., 1989; Martin-Barjas et al., 1991; Valsangkar and Khadge, 1989). Irrespective of the mineralogical composition and the sediment type hosting the nodules, the Mn present in nodules is in the form of Mn (IV) oxidation state suggesting its stability in deep-water environment (Pattan and Mudholkar, 1990). Several studies have indicated that, the δ -MnO₂ mineralogy nodules (Rao, 1987; Takematsu et al., 1984; Usui, 1979). This observation explains the oxygenation condition of nodule accretionary environment wherein, δ -MnO₂, a more oxidized phase generally form under more oxic hydrogenous conditions, whereas the todorokite, a less oxidized phase precipitates under oxygen depleted diagenous conditions.

The compositional heterogeneity in nodule deposits is well known (see Glasby, 1977). Within a basin nodules exhibit a wide range of composition. The inter-and intra-nodular compositional differences are also quite common (Banakar, 1990; Roy, 1990).

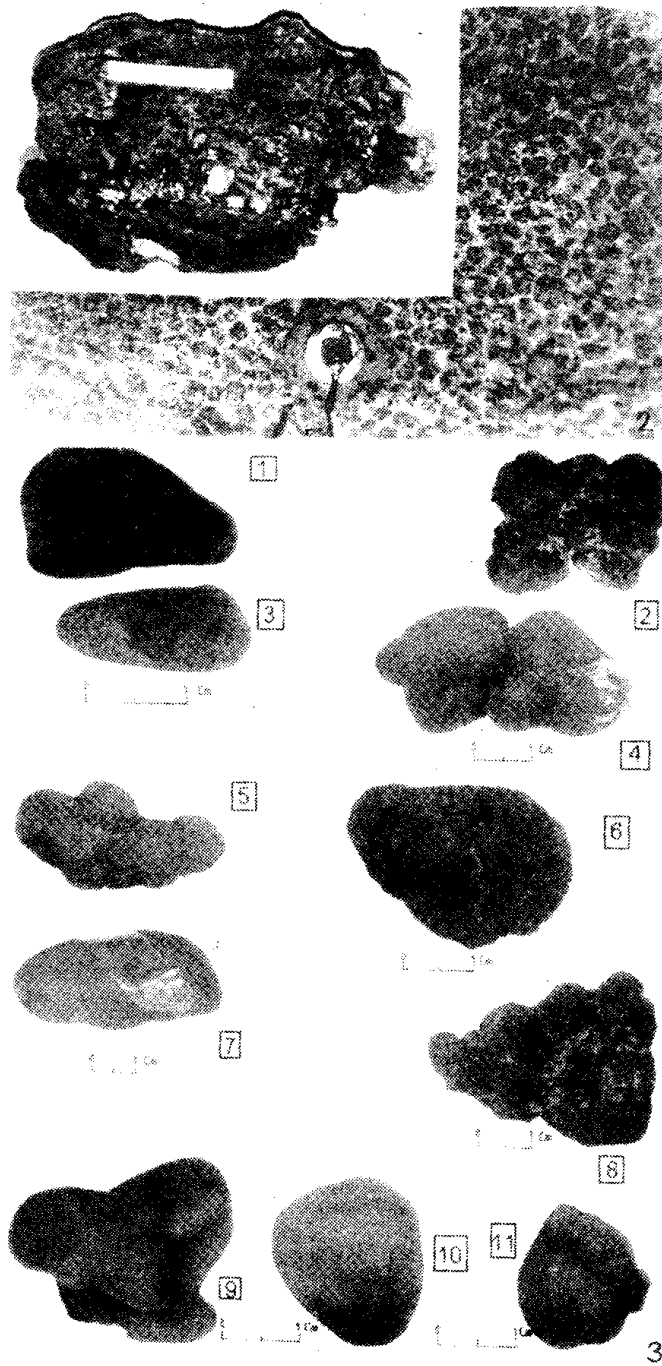
Even the microscopic counter parts of nodules known as micronodules do have inter-nodular compositional differences (Pattan, 1993). The first important aspect which controls the general composition is the underlying sediment type. In the CIB, the nodules sitting on siliceous sediment are generally exhibit-increased influence of diagenesis. As a result of diagenetic immobilization of Mn in the upper sediment column, the diagenetic nodules generally enrich Mn compared to Fe (Jauhari, 1987; Roy, et al, 1990; Valshangkar and Khadge, 1989; Banakar and Jauhari 1994; Martin-Barajas et al., 1991; Banakar et al., 1989; Mukhhopadhyaya, 1987; Rao, 1987; Nath and Mudholkar, 1989 and references therein). The nodules, occurring on red clays and carbonate sediments on the other hand exhibit more hydrogenetic influence with $-\delta\text{MnO}_2$ dominant mineralogy and low Mn/Fe ratios (See Cronan and Moorby, 1981). Despite a large compositional variation, the deep-sea nodules contain Mn and Fe as the major metals. The Si and Al in nodules are generally associated with detrital phase (Glasby and Thijssen, 1982). The influence of the substrate or nucleating material on the composition of nodular-oxide material is insignificant (Hein and Morgan, 1999) as they provide just a necessary substrate for oxide accretion without undergoing any chemical interaction with oxide material. Cronan and Moorby (1981) provide a general composition of nodules from different basins and sedimentary types of the Indian Ocean, wherein Mn varies between 15 - 21 %, Fe, between 9 - 17 %, Ni between 0.2 - 0.9 %, Cu between 0.1 - 0.8 % and Co between 0.1 - 0.4 %. Based on 600 chemical analyses data generated for PMN project, Jauhari (1987) suggested that the CIB nodules show an order of magnitude variation in their Mn/Fe ratios (0.9 to 9). The majority of nodules fall within hydrogenetic field (Mn/Fe < 2.5), followed by mixed types or early diagenetic type (Mn/Fe 2.5 - 5) and rarely of diagenetic type (Mn/Fe > 5). Thus it can be concluded that, the CIB nodules are intermediate between hydrogenetic and early diagenetic end members wherein, either overlying water column or sub-oxic upper sediment column act as the source of metals for nodule accretion. Very low abundance of purely diagenetic nodules in CIB perhaps suggests that the export production is not that significant to induce anoxia in the peneliquid sediment layer.

The Indian mine-site that is located between 10°-16° latitudes and 72°-76° longitudes exhibits an average abundance of nodules upto 7.5 kg m⁻² in siliceous-ooze area, and up to 5 kg m⁻² in red clay area. The combined copper, nickel and cobalt content generally is above 2.0 % (Sudhakar, 1989). Based on these values, an approximated estimate yields around 300 million tons of nodules containing over Rs. 100,000 crores worth of metals in the first generation mine-site (75,000 km²) (Banakar, 1996).

EXPLANATION OF PLATE-1

Fig. 2: Seabed photograph from the Indian registered Pioneer Area showing the very high abundance of nodules (-23 kg/m²) (Source: AA. Sidorenko Cruise 13, Report).

Various size and shapes of die Central Indian Ocean polymetallic nodules (Source: S.Z.Quasim & R.R.Nair, editors, 1988).



V. K. BANAKAR AND OTHERS'
OCEAN FERROMANGANESE DEPOSITS

FERROMANGANESE CRUSTS

Ferromanganese crusts (hereafter referred as crusts) have been reported from almost all the oceanic seamounts and topographic highs. The crusts are formed due to a slow accumulation of ferromanganese oxy-hydroxides on the exposed hard substrates. They generally are enriched with cobalt compared to nodules and are mainly of hydrogenetic origin (Banakar, 1997; 1991; Halbach and Putanus 1984; Hein, et. al., 1992; Usui and Someya, 1997 and references therein). In addition to Co, the Central Pacific crusts have been shown to enrich Pt upto 0.9 ppm (Halbach et al, 1989, 1984). The Afanasiy-Nikitin seamount in the Equatorial Indian Ocean has been sampled recently for Co-enriched crusts and, the study has indicated Co concentration up to 0.8% (Banakar, et. al., 1997; Parthiban and Banakar 1998). A detailed analysis of Pacific crust data-base pooled from various published and unpublished works has suggested that the crusts capping Cretaceous seamounts are generally enriched with Co, while the crust occurrence is sparse on Neogene seamounts (Usui and Someya, 1997). These authors also suggested that, the hydrothermal crusts can easily be distinguished from hydrogenetic crusts by their extremely high Mn content wherein most of the hydrothermal crust chemical data plots close to Mn end on the ternary diagram. The cobalt-rich crusts in the Pacific occur in the EEZ of Tavalu, Marshall, Hawaii, Pamyra, Kiribati, Jarvis, Baker islands in the Central Pacific. Most of the seamounts in the Indian Nodule Mine Site have low relief (maximum up to 1000 m, Kodagali et al., 1992) and were emplaced during the Tertiary due to Indian plate tectonics (Mukhopadhyaya and Khadge 1990). These seamounts are below or very close to CCD. Therefore, the crusts from the CIB are neither cobalt-rich nor Co content is very different from abyssal nodules (up to 0.3 %: Banakar and Borole, 1991; Frank et al., 1999; Banakar and Hein, 2000).

In addition to their importance as potential cobalt resource, the crusts have been demonstrated as the condensed repositories of long-time scale paleoceanographic events. The advent of isotopic techniques for dating oceanic ferromanganese deposits made it possible to utilize these deposits as paleocean tracers. U-Th isotope disequilibrium has been used by several workers to date the crusts and nodules for shorter time periods of < 1 my (Ku and Broecker, 1967; Moore et al., 1981; Banakar et al., 1993 and references therein). Using ^{230}Th decay in a high-resolution depth profile of a crust, Eisenhauer et al., (1992) constructed the Late-Quaternary climatic variations in Pacific. As the hydrogenous nodules and crusts accrete at a slow rate of the order of few mm per million years, the U-Th isotopic dating can not be applied for deeper parts of the specimen. Therefore, an alternate method, which could cover few cm thick oxide-layer, became a necessity. The ^{10}Be dating on nodules (Somayajulu, 1967) which covers atleast 10-12 Ma of growth history is considered to be an excellent method available till date. Few workers have utilized the Sr isotopic ratios to construct the growth history of crusts (Hein et al., 1992; Ingram et. al., 1990; and references therein). The utility of Fe-Mn oxide deposits as paleocean recorders solely depends on their ability to pick-up the contemporary oceanographic condition without post-depositional mobility or chemical exchange of the isotopes or metals. Many marine scientists in regard to this ability of the crusts expressed reservations. A recent study of Chabaux et al. (1997)

unambiguously demonstrated that the crusts act as a close-system. This study was able to resolve and settle the doubts about isotopic-dating and all the previous crust chronology and growth history aspects therefore stand valid. The empirical models using cobalt, manganese and iron contents of the crusts have been developed as an alternative for expensive isotopic dating tools (Manheim and Lane-Bostwich, 1988; Puteanus and Halbach, 1988; Frank et al., 1999).

As mentioned earlier, the compositional, mineralogical and, structural variations in the crusts are nothing but the responses to the changes in accretionary environment or ambient water over the growth period (Segl et al., 1984; Mangini et al., 1990; DeCarlo, 1991; Banakar et al., 1997; Frank and O'Nions, 1998; Frank et al., 1999). Utilizing the above fact, Quater Mary climatic fluctuations (Eisenhaeur, et. al., 1992), Earth orbital forcing (Hein, et. al., 1992), Erosion episodes (Frank and O'Nions, 1998), Evolution of AABW (Banakar and Borole, 1991; Banakar and Hein, 1999), Paleochemistry (Frank, et al., 1999; Abouchami et. al., 1999), Messinian salinity crisis (Koschinsky, et al., 1996), Deep-water circulation changes (Mangini, et. al., 1990; Von Blanckenberg, et. al., 1996), paleo-OMZ variation (Banakar, et. al., 1997) etc. have been shown to leave their distinct signatures in the crusts. Most of these studies have demonstrated a remarkable consistency with respect to bottom water evolution and changes in flow pattern on global scale. However, local depositional environments do play a significant role during the growth of oceanic Fe-Mn crusts, which can be used to explain the local paleoenvironment.

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