

**Significance of size in occurrence, distribution, morphological characteristics, abundance and resource evaluation of polymetallic nodules**

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**Abstract**

About 13000 different sized nodules from 249 locations covering 75000 km<sup>2</sup> relinquished Pioneer area in the Central Indian Basin (CIB) have been studied by assorting them in groups of 1 cm size intervals. The study shows systematic variation, and inverse relationship of nodule size with the occurrence, distribution, grade, abundance, and Mn/Fe ratios. The study indicates that only 3-4 cm sized nodules in the first generation mine (FGM) site area are resourceful and have highest economical potential. The different sized nodules probably represent their formation under different environmental conditions existed in the CIB.

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## 1. Introduction

The deep-sea surficial deposits of polymetallic nodules (PMN; also known as ferromanganese nodules) are reported from many parts of the world. The nodules cover large field in the Pacific Ocean than in the Indian and Atlantic Ocean. Initial studies on nodules from the Clarion and Clipperton fracture zones (FZ) generated much information on the distribution, composition, and their formation process (Calvert and Price 1977; Bischoff and Piper 1979). In the Indian Ocean, PMN are reported from eight major deep-sea basins, but only those from the Central Indian Basin (CIB) having high abundance ( $\sim 5 \text{ kg/m}^2$ ) and paramarginal grade ( $\text{Cu}+\text{Ni}+\text{Co}= 2.5\%$ ) are considered economically important (Frazer and Wilson 1980; Cronan and Moorby 1981; Siddiquie et al. 1984). The CIB is centrally located isolated basin, bordered by an active Central Indian ridge (CIR) system in the west, south-east Indian ridge (SEIR) in the south,  $90^\circ \text{ E}$  aseismic ridge in the east, and India-Sri Lanka sub-continent in the north, with an average water depth of 5100 m (Kodagali et al. 1992).

Previous work on the CIB nodules showed that they vary in size [from micro (75 to 1000  $\mu\text{m}$ ; Pattan 1993) to  $>10 \text{ cm}$  (Valsangkar and Khadge 1989)], in shape and surface texture (Valsangkar and Khadge 1989), in the grade and abundance (Sudhakar 1988), and in the accretion rate (1 to 5 mm/Ma; Banakar 1990). The average concentrations of the CIB nodules are found to be quite comparable to those from the Pacific Ocean (Siddiquie et al. 1984; Valsangkar and Khadge 1989).

Earlier studies on the CIB nodules showed that their formation is controlled by various parameters, such as the sea floor topography (Kodagali 1988), sediment types (Jauhari 1987), surface productivity, bottom currents (Vineesh et al. 2009), and source and mechanism of accretion (Valsangkar and Khadge 1989; Valsangkar and Karisiddaiah 1993; Vineesh et al. 2009; Mukhopadhyay and Gosh 2010). It therefore appears that not only one but combination of all these parameters are responsible for the formation of the CIB nodules. The main objective of the present study is to demonstrate yet another controlling parameter responsible for the formation of the CIB nodules, and to show the exact relationship of the nodule size with occurrence, distribution, morphology, grade, and abundance on the spatial and region scale. The study further reveals that 'nodule size' can be a reliable indicator and independent parameter. Factors liable for the formation of different sized nodules are discussed, and an environmental model responsible for formation of different sized nodule is proposed. The data set represents the largest systematic study in the CIB on different sized nodule's morphology, grade and abundance.

The National Institute of Oceanography (NIO), Goa, carried out systematic exploration in the CIB since 1982, and over  $4 \times 10^6 \text{ km}^2$  area was sampled for PMN using free fall and Okean grab sampling methods (Valsangkar 2003). Initially, 100 km grid pattern was used for PMN sampling in the entire

Pioneer Area. Based upon the application submitted by the Indian Government, the International Seabed Authority (ISBA) allocated 150000 km<sup>2</sup> Pioneer Area in 1987 (P<sub>1</sub> and P<sub>2</sub>; Figure 1). Later, the Pioneer Area was relinquished to 50 % in phases by sampling at 50, 25, 12.5, and 6.25 km grid to identify the first generation mine (FGM) site. Accordingly, the Indian mine site was registered in 1987. It is estimated that, the P<sub>1</sub> area has ~380 million metric tons (MMT) of nodules (Shyam Prasad 2007).

### **3. Materials and methods**

Large amount of morphological and abundance data obtained during 11 cruises in the CIB by 3 research vessels has been compiled and used here for various comparison. The data set includes examination of ~13000 nodules from 249 stations and 384 sub-stations (Table 1). The sampling locations include four sub- areas (P<sub>1</sub>, P<sub>2</sub>, relinquished, and FGM) of the Pioneer Area in the CIB (Figure 1). The nodules were obtained by Okean grab, and free fall grabs having sampling area of 0.24 m<sup>2</sup> and 0.13 m<sup>2</sup> respectively. The sampling of PMN by free fall (boomerang) grab was restricted to only to SK-136 cruise. The number of grab operations at each station ranged from minimum two (sub-station A and B) to maximum six (by free fall). The nodules obtained at each sub-station varied in size, shape and abundance (kg/m<sup>2</sup>). Nodules from each sub-station were washed to remove the sediments, air dried, and sorted (or grouped) at 1 cm size (long axis) interval using a scale. Accordingly, there were maximum 14 groups (size classes) of nodules possible (Table 2). The station averages were calculated for the recovery, occurrence, and abundance, and used for comparison. The morphological characteristics and abundance were determined for each size group of every sub-station. Similarly, the average Mn, Fe, Cu, Ni, and Co concentrations of each size group were determined from 1588 published chemical analysis that represented 436 locations in the CIB (Valsangkar and Khadge 1989, Valsangkar and Karisiddaiah 1993, Valsangkar and Ambre 1994, Valsangkar 1995) and used for comparison and interpretation.

## **4. Results**

### **4.1 Nodule Size**

The long axis of different sized nodules shows variation with respect to four areas in the CIB. It is found that the nodule long axis has maximum range in the Pioneer Area P<sub>1</sub> (<1 to 14 cm), followed by both relinquished and FGM area (<1 to 12 cm), and comparatively smaller range in the Pioneer Area P<sub>2</sub>, (<1 to 10 cm; Table 3 to 6).

### **4.2 Number of nodules**

It is observed that the recovery of different sized nodules vary largely in the CIB. Therefore, the total number of different sized nodules also varied at the each sub-station. The recovery status of 14 size

classes (groups) of nodules from 249 stations covering four areas in the CIB is given in Table 3. The significant features and morphological characteristics of each size class (group) are highlighted below.

**<1 cm:** Nodules of this size class were found to occur only at few locations in the CIB. Hence, their occurrence was noticeably low per station (9.6 % total, Table 3) and in the CIB (0.7 % total, Table 6; Figure 2). These nodules are mostly rounded to ellipsoidal with rough surface texture (Table 4). However, the P<sub>1</sub> area showed presence of 3 % smooth textured nodules. Although these nodules could be divided in to maximum seven types, it is found the FGM area has single nodule type (Table 4).

**1-2 cm:** Nodules of this class showed better recovery (67 % total, Table 3) at every station and for the CIB (Figure 2). Their population is higher in the FGM area and further south. The nodules are mostly rounded, ellipsoidal and botryoidal with rough and gritty surface texture, but 21% nodules from P<sub>2</sub> area also have smooth texture. The number of nodule types varies with respect to the area. When the relinquished area has 12 and the P<sub>1</sub> area has 10 nodule types, the P<sub>2</sub> and FGM area have 6 and 5 types respectively (Table 4).

**2-3 cm:** These nodules appear to be most common in the CIB as their recovery reached to 90 % per stations (Table 3, Figure 2). The maximum recovery (33 %, Table 5) was reported from the FGM area and at the locations 1° east of the FGM. It is observed that, 2-3 cm sized nodules are always present in the highest number at every station (Table 5), and comparatively, the relinquished area has highest occurrence (17 %, Table 6). The nodules are dominantly rounded to sub-rounded, ellipsoidal and botryoidal with rough surface texture. The number of nodule types appears to be highest in relinquished area (12), followed by the FGM (9), and the P<sub>2</sub> area (6). Nearly 30 % nodules in the P<sub>2</sub> area have smooth texture (Table 4).

**3-4 cm:** The nodules belonging to this size class are most abundant in the CIB (92 % total, Table 3, Figure 2). The nodules are mostly rounded and ellipsoidal with rough and gritty texture. These nodules have 2<sup>nd</sup> largest occurrence in the CIB (30 % total, Table 5), and 15 % in the relinquished area (Table 6). The P<sub>2</sub> area has 6 different nodule types and 39 % smooth textured nodules (Table 4).

**4-5 cm:** These nodules occupy 3<sup>rd</sup> position in the recovery per station (89 %, Table 3), and total occurrence in the CIB (17 %, Table 6). Their occurrence is comparatively more in the north and south of the FGM area (Figure 3). The nodules are mostly rounded, ellipsoidal, bulged and discoidal, and bear rough and gritty texture. The relinquished area has 14 types of nodules (Table 4), whereas the P<sub>2</sub> area holds higher percentage of smooth textured nodules (47 %, Table 4).

**5-6 cm:** This size class of nodules have lower presence per station (58 %; Table 3), and only 6 % total occurrence in the CIB (Table 6; Figure 3). The relinquished area has maximum occurrence followed by

the P<sub>1</sub> area (Table 3). The rough and gritty surface texture dominates. The P<sub>1</sub> and relinquished area showed presence of as much as 10 to 12 nodule types. Conversely, the P<sub>2</sub> area resulted in only 4 nodule types, 35 % of which were smooth, discoidal, tabular and botryoidal (Table 4).

**6-7 cm:** These nodules have 43 % presence per station (Table 3), but only 2 % occurrence in the CIB (Table 6). Although nodules are mostly rough and gritty (Figure 3), the P<sub>2</sub> area contain 25 % smooth textured nodules. The FGM and relinquished area mostly have rounded nodules, whereas polynucleated and ellipsoidal nodules are abundant in the P<sub>1</sub> and P<sub>2</sub> area (Table 4).

**7-8 cm:** These nodules have very low occurrence in the CIB (22 %, Table 3), hence their recovery per station is also found to be very low (Figure 3). This is also reflected in their poor occurrence (<1 %) in the CIB (Table 6). The nodules are mostly rounded and botryoidal, rough and gritty. Comparatively, the P<sub>1</sub> area found to contain 5 % smooth textured nodules (Table 4). Nodules from the relinquished and P<sub>1</sub> area have more than 10 types, the FGM area has 5 types, and the P<sub>2</sub> area showed only 2 types (Table 4).

**8-9 cm:** Nodules of this size class are scarce in the CIB (7 % total, Table 3; Figure 4) and their total occurrence in the CIB is very poor or negligible (0.26 %, Table 6). The nodules are mostly rounded, ellipsoidal, botryoidal and polynucleated, and have rough surface texture. The relinquished area also found to contain 10 % smooth textured nodules (Table 4).

**9-14 cm:** Nodules larger than 9 cm size are typically rare in the CIB (Table 3, 5 & 6; Figure 4 & 5), and they have <0.1 % occurrence (Table 6). The FGM area has nodules maximum up to 12 cm size (Table 3, 5 & 6; Figure 4), whereas those in the P<sub>2</sub> area range size maximum up to 10 cm (Table 3, 5 & 6; Figure 5). These nodules are typically bulged, botryoidal, tabular, flat, irregular, polynucleated and sometimes rounded to sub-rounded (Table 4). They commonly have rough surface texture. The 12-13 cm sized nodules are either totally absent or very rare in the CIB, because they were not recovered at any station.

#### **4.3 Occurrence of nodules**

The CIB nodules have different percentage of occurrence with respect to the size classes. The size analysis shows that the nodules of 2-3 cm size class (group) have highest occurrence (33%; Table 6). This is followed by 3-4, 4-5, 1-2 and 5-6 cm sized nodules in decreasing order from 29 to 6 %. Also, the larger sized nodules typically have meager occurrence. It is observed that the percentage of occurrence of nodules decrease with increase in nodule size, and that 2-3 and 3-4 cm sized nodules have nearly similar percentage of occurrence in the CIB (Table 6).

#### **4.4 Shape and types of nodules**

Nodules up to 9 cm size in Area P<sub>1</sub> and up to 5 cm size in Area P<sub>2</sub> are rounded to sub-rounded, and ellipsoidal (Table 4). Similarly, small and large sized nodules in the FGM area are rounded to sub-rounded, but 2-3 and 4-6 cm sized nodules are ellipsoidal. Nodules in the relinquished area are mostly rounded to sub-rounded, whereas the ellipsoidal shape typically decreases and botryoidal dominates with increase in the nodule size from 7 cm onwards (Table 4). Morphological studies further show that the number of nodule types also varies with respect to the area. Accordingly, the relinquished area has maximum 14 types, followed by the Area P<sub>1</sub> (13 types), FGM (9 types), and Area P<sub>2</sub> (6 types; Figure 6 a). It is further noticed that, the maximum number of nodule types are associated to a particular size group. Accordingly, 4-5 cm sized nodules from the relinquished and the P<sub>1</sub> area, 2-3 cm sized nodules from the FGM area, and 2-4 cm sized nodules from the P<sub>2</sub> area have maximum number of nodule types (Figure 6 a). In general, the number of nodule types decrease with increase in nodule size (especially from 6 cm onwards).

#### **4.5 Surface texture**

Most nodules in the CIB have rough and gritty surface texture (Figure 7), and in the few areas particular size group of nodules have smooth surface texture. Accordingly, 40 % of <1 cm nodules from the P<sub>1</sub> area and 47 % of 4-5 cm sized nodules from the P<sub>2</sub> area have smooth surface texture (Figure 6 b). Nodules from Area P<sub>2</sub> display mixed (smooth and rough) surface texture but lack gritty surface texture. Similarly, nodules from the FGM area are rough and gritty, and lack smooth surface texture (Table 4). It is observed that, mixed surface textured nodules typically belong to <2 cm size class in Area P<sub>1</sub>. However, in Area P<sub>1</sub>, the mixed surface textured nodules are associated with size classes from 1 to 7 cm, and those in the relinquished area belong to <1 to 4 cm size classes. Nodules from the FGM area lack smooth- or mixed- surface texture (Table 4). It is further observed that, the nodules with smooth surface texture have very wide size range (1-7 cm) in Area P<sub>2</sub>, and very small size range (<2 cm) in Area P<sub>1</sub>.

#### **4.6 Nodule abundance**

The nodule abundance (kg/m<sup>2</sup>) implies weight of nodules per square meter area. It is observed that the nodule abundance in the CIB vary significantly with respect to nodule size class, and 14 size classes of nodules have different abundance value (kg/m<sup>2</sup>). Further, the average abundance of 3-4 and 4-5 cm sized nodules signify the average abundance of all sized nodules in the CIB (4 kg/m<sup>2</sup>; Table 7). In fact, the 3-4 and 4-5 cm sized nodules in the CIB have the highest abundance (>4.0 kg/m<sup>2</sup>, Table 7), and 2-3 and 5-6 sized nodules have comparatively much lower abundance (Av. 2.3 kg/m<sup>2</sup>, Table 7).

Interestingly, the nodule abundance in the CIB display systematic decrease towards increase of nodule size, and thereby exhibits an inverse relationship (Table 7; Figure 8). The 6-7 cm sized nodules have very low abundance ( $1.4 \text{ kg/m}^2$ , Table 7), and the abundance of nodules larger than 7 cm sizes decrease down systematically from 0.6 to  $0.01 \text{ kg/m}^2$  (Table 7).

Comparatively, all sized nodules in the FGM area has highest average abundance ( $6 \text{ kg/m}^2$ , Table 7; Figure 8) and  $P_2$  area has lower abundance  $4.3 \text{ kg/m}^2$  (Table 7; Figure 8). The size analysis further shows that 2-3, 3-4 and 4-5 cm sized nodules in the FGM area have maximum abundance in the range from 1.1 to  $1.5 \text{ kg/m}^2$  (Table 7). Similarly, 3-4 and 4-5 cm sized nodules in  $P_2$  area have maximum abundance 1.2 to  $1.1 \text{ kg/m}^2$  respectively; (Table 7).

## **5. Discussion**

Although nodule size is a physical property it is surprisingly seen related to many other physical (occurrence, abundance, etc.) and chemical parameters (grade, Mn/Fe ratio, etc.). Therefore, nodule size appears to be a reliable indicator while selecting the high grade nodules. Probable reasons of association of different parameters with nodule size are discussed below.

### ***5.1 Nodule size, morphology and growth***

It is known that nodule grows due to deposition of oxide layers around nucleus. In fact, the nodule growth depends upon the diagenetic and hydrogenetic accretionary processes, availability of metal concentration, calcite compensation depth (CCD), primary productivity, and rate of sedimentation in the area (Cronan and Hodkinson 1994). Further, existence of bottom water currents thought to be responsible for different the morphological and textural characteristic (Vineesh et al. 2009). However, present study deviates from the above views. It may be pointed that, the different sized nodules were collected from a narrow depth range (5100 to 5200 m), and well below the carbonate compensation depth (CCD) in the CIB ( $\sim 5000 \text{ m}$ , Belyaeva and Burmistrova 1985). Therefore, the influence of CCD in an area during the formation and growth of different sized nodules should have been similar. But, the fact that, the different sized nodule group in the CIB have distinct morphological properties (Table 4). Secondly, the smooth surface textured nodules in  $P_1$ , FGM and relinquished area have small occurrence, whereas those in  $P_2$  area show systematic increase in the smooth surface texture with respect to the nodule size (from 3% for  $<1 \text{ cm}$  nodules to 47% for 4-5 cm nodules, and a decrease up to 10% for 8-9 cm nodules; Table 4). Hence, increase and decrease of smooth textured nodules in  $P_2$  area is size related, and clearly suggest a topographic control rather than the influence of bottom water or Antarctic Bottom Water (AABW) currents in the CIB. Thus, the present study points at negligible role

and/ or influence of the bottom water currents in the CIB towards the growth and development of morphological features of nodules.

The size analysis of different sized nodules from the CIB show that the occurrence of <1-8 cm sized nodules are more common (Table 2), and 12-13 cm sized nodules are absent or very rare (Table 3 to 7). It is also revealed that >90 % of nodules belong to 2-3, 3-4 and 4-5 cm size classes (Table 3), and their presence is more in relinquished area followed by Area P<sub>1</sub>, FGM and Area P<sub>2</sub> (Table 5). Conversely, nodules larger than 5 cm size have diminishing presence in the CIB. The 2-3 and 3-4 cm sized nodules usually have 30-33 % of occurrence and is highest in comparison with the other size classes, whereas >6 cm sized nodules have decreasing occurrence from 2 to 0.01 % (Table 6). Particularly lower percentage of occurrence of larger sized nodules therefore suggests that the smaller sized nodules have not grown to the bigger or larger sizes. This view is further supported by the observation that the percentage of occurrence of bigger and larger sized nodules in the CIB is always lower than those of the smaller sized nodules (Table 6). Therefore, the perception that 'nodules grow' appears doubtful at least for the areas in the CIB. Instead, there appears strong possibility of formation of particular size group of nodules under particular physico-chemical environmental conditions existed in the CIB. Consequently, the different size group of nodules represents variable physico-chemical environmental conditions existed in the CIB.

Considering that the oxide forming process by accretion was initiated at the nucleus of the nodule, the nodules obtained from the small sampling area should have been of similar sizes. In fact, the sampling device brought varying percentages of different sized nodules from each location and sub-station (Table 3 to 7). It is also observed that the CIB nodules generally have hard sediment as nucleus. Previous measurements have shown that the nucleus size has positive relationship with the nodule size (Valsangkar and Ambre 1994). This observation therefore suggests that, the variation in the nodule size is mainly due to the variation in the nucleus size, over which the oxides deposited took place later (growth). Thus, assuming similar rate of deposition of oxide layers in the area, the incorporation of different nucleus sizes should result in the formation of different sized nodules. The closely occurring smaller sized nodules can also coalesce to form the bigger or larger sized nodules. Such nodules are typically polynucleated and botryoidal, and indicate limited growth around the nucleus.

## **5.2 Nodule size and surface texture**

The textural study shows that smooth textured nodules have poor occurrence and mostly isolated in the CIB (Figure 7). The smooth textured nodules are generally the product of hydrogenous deposition. They usually have higher Fe content and thereby indicate their formation on the seamount tops where high Fe maxima exists (Valsangkar and Khadge 1989). The diagenetic process are absent on the



seamount due to lack of sedimentation. Hence, the nodule formation on the seamount is governed by the hydrogenetic process and thereby facilitates enrichment of Fe and Co phases (Usai et al., 1987, Valsangkar and Khadge, 1989). In the present study, the nodules from FGM area are characteristically rough and granular, and devoid of smooth texture (Table 4). The measured phase- mean current velocity rarely exceeded  $>2.0$  cm/s in the CIB (Murty et al.1999) also points towards existence of weak bottom water currents and supports the above view. Such weak currents are incapable to cause the sediment erosion and rolling movements of surface nodules and thereby rules out the possibility of formation of smooth textured nodules in the CIB. The abyssal hills and seamounts in the CIB probably act as obstruction and hinder the bottom water currents (Muhkopadhyay et al. 2002). Therefore, isolated occurrence of smooth textured nodules (along  $14.4^{\circ}$  S latitude; Figure 7) in the CIB suggests topographic control rather than mere speculation that Antarctic Bottom Water (AABW) currents control formation of smooth surface texture (Vineesh et al. 2009). Similarly, higher percentage of occurrence of smooth textured nodules for wide range of nodule size in Area P<sub>2</sub> (1 to 7 cm) than in Area P<sub>1</sub> ( $<1$  and 2-4 cm, Table 4) indicates topographic control.

### **5.3 Relation between nodule size and abundance**

Previous studies have attempted correlation of nodule abundance with topography (Kodagali 1988; Pattan and Kodagali 1988) and showed that the high relief areas [hilltops ( $5.81$  kg/m<sup>2</sup>), seamounts, slopes ( $4.3$  kg/m<sup>2</sup>) and valleys ( $6.94$  kg/m<sup>2</sup>)] have highest nodule abundance against plain areas in the basin ( $2.72$  kg/m<sup>2</sup>; Kodagali and Sudhakar 1993). It has been earlier pointed that the higher nodule abundance on the high relief areas is facilitated mainly due to the presence of more nucleating material as a result of volcanic activity around abyssal hills and seamounts or fragmentation of basaltic rocks by weathering processes (Horn et al. 1973; Glasby 1973). This observation further implies that, the nodules from the high relief areas contain fragmented basaltic rock as nucleus.

However, our studies on 12938 nodules from 266 locations covering very large area in the CIB show very good relation of abundance with the nodule size rather than the topographic variations in the basin (CIB) and that majority of nodules contain sediment as nucleus. Although, different sized nodules occur in variety topographic environment in the basin, it is pointed here that the nodule abundance characteristically decreases with increase in the nodule size (Figure 8, Table 7). As the nodule abundance depends upon the real presence of nodules, it is clear that the observed decrease in abundance with respect to nodule size is mainly because of the poor occurrence of bigger and larger sized nodules in the CIB. It is further observed that out of 14 size classes, only 3-4 and 4-5 cm sized nodules have the highest abundance in the CIB ( $4.3$  and  $4.0$  kg/m<sup>2</sup> respectively; Table 7). This observation further indicates that, irrespective of the topographic variations and growth of

ferromanganese oxides around the nucleus, the 3-4 and 4-5 cm sized nodules occur in large quantity as compared to 2-3, and 5-6 cm sized nodules in the CIB (Table 3 and 7). It may be noted that, the topography in the FGM area is reasonably plain as compared to other areas in the CIB, and the different sized nodules have highest total abundance (5.99 kg/m<sup>2</sup>, Table 7) against that for the average entire CIB (4.09 kg/m<sup>2</sup>; Table 7). Therefore, there exists no relation of nodule abundance with the topography (high and low relief areas) in the CIB. The highest abundance observed for different sized nodules particularly in the FGM area therefore suggests existence of most favorable conditions for formation of different sized nodules in the FGM as compared other areas in the CIB.

#### **5.4 Relation between nodule size and grade**

Earlier studies have reported inverse relationship between nodule grade (Cu+Ni+Co %) and nodule abundance for the nodule areas in the Pacific Ocean (Menard and Frazer 1978) and in the CIB (Sudhakar 1988). But, later studies on 613 different sized nodules from 150 locations in the CIB showed an inverse relationship between the nodule size and grade (Valsangkar et al. 1992). They have also pointed that only medium sized (2-4 cm) nodules in the CIB have the highest occurrence and high concentration of Mn, Cu, Ni and Zn, whereas that the Fe enrichment (7.8 %) occurs in the larger (6-8 cm) sized nodules. In their study, it was observed that the Mn/ Fe ratios decreased from 5.6 (smaller, <2 cm) to 3 (larger, >10 cm) sized nodules due to variations in the accretionary processes (Valsangkar and Karisiddaiah 1993). Previously, it was suggested that the moderate biological productivity the CIB could release divalent metal ions of Mn, Cu, Ni and Zn in the sediments enhancing the formation of todorokite in nodules to form high grade nodule deposits (Glasby and Thijssen 1982). However, the surface and chlorophyll a estimates showed low biomass level, suggesting low rates of average primary productivity (3.72 mg C m<sup>-3</sup> d<sup>-1</sup>) in the CIB (Matondkar, et al. 2005). Therefore, incorporation of transition metals appears to be controlled by 10<sup>0</sup> manganite (todorokite) phase which associates Cu and Ni divalent metal ions (Usui 1979), whereas the supply of divalent trace metal ions during diagenesis controls the formation of todorokite and the nodule composition (Glasby and Thijssen 1982). Consequently, medium (2-4 cm) and intermediate (4-6 cm) sized nodules having higher concentrations of Mn, Cu and Ni indicate their formation by diagenetic process and incorporation of todorokite, whereas the bigger (6-8 cm) and larger (8-10 cm) sized nodules indicate their formation by hydrogenetic process in absence of todorokite. The progressively decreasing peak height and crystallinity of todorokite from smaller to bigger and larger sized nodules (Valsangkar and Karisiddaiah 1993) also supports the above view.

In the present study, we have compiled the published data on grade (Cu+Ni+Co %) of different sized nodules from the CIB (Valsangkar and Khadge, 1989, Valsangkar and Karisiddaiah, 1993; Valsangkar

and Ambre 1994; Valsangkar 1995), and demonstrated the results for the entire range of <1-14 cm sized nodules at 1 cm size interval (Figure 9). Accordingly, the average grade (of 1588 different sized analysis from 436 locations in the CIB; published data) and average abundance (of 12938 different sized nodules from 266 locations; this study) show a positive relationship, where the graphs of both these parameters are parallel and display downward tilt towards increase of nodule size (Figure 9). The negative correlation between grade and nodule size, abundance and nodule size, and between Mn/ Fe ratios and nodules size is clearly depicted in the Figure 9, illustrating that that only 3-4 and 4-5 cm sized nodules have higher grade and higher Mn/ Fe ratios. The trend showing decrease in average grade and Mn/ Fe ratios with increase in the nodule size (Figure 9) further imply that 3-4 and 4-5 cm sized nodules are diagenetic, whereas bigger and larger sized nodules are hydrogenetic. Therefore, systematic decrease in the grade and Mn/ Fe ratios from small to large sized nodules strongly suggests formation of different sized nodules under diverse environmental conditions existed in the CIB.

#### **5.6 Relation between nodule size and resources**

The grade (Cu+Ni+Co %) and abundance (kg/m<sup>2</sup>) of nodules are important parameters for estimating the resources in the area for first generation nodule mining consideration. As discussed above, both these parameters show systematic variation with respect to different sized nodule groups in the P<sub>1</sub>, P<sub>2</sub>, relinquished and FGM areas in the CIB. In general, the 3-4 and 4-5 cm sized nodules have highest total abundance (Figure 8), and FGM area has 3.7 kg/ m<sup>2</sup> total abundance for the nodules in the size range of 2-5 cm. Present study thus demonstrates that, among the 14 different size classes of nodules in the CIB only 3-4 and 4-5 cm size group of nodules are of 'quality grade nodules', because only these among the other groups have the highest percentage of occurrence, distribution, abundance, grade (Mn, Cu and Ni %), and Mn/ Fe ratios. Therefore, the 3-4 and 4-5 cm sized nodules have high significance and should be focused during their mining and metallurgy. It can be summarized here that, the resources of different sized nodules are different at different places in the CIB.

#### **5.7 Environmental model of nodule formation**

The deep-sea accretionary processes (such as the diagenetic, hydrogenetic, and hydrothermal) are responsible for the growth of nodules in the deep-sea (Chester 1990). The ridge systems surrounding the CIB perhaps restrict in coming supply of terrigenous material. Also, the most promising FGM area in the CIB lies in between the area of two major fracture zones (FZ), i.e. between the Vishnu FZ along 73° E and Triple Junction trace on the Indian plate (TJT-In) around 76.4° E. The abyssal hills and seamounts in the CIB possibly act as barrier and obstruct the bottom water currents (Muhkopadhyay et al. 2002). Therefore, compared to other areas in the CIB, the environment in FGM appears most ideal for the formation of all sized nodules. It is further observed that the siliceous sediment is the major

sediment type in the FGM area and among the different types of sediments present in the CIB, the nodules associated with siliceous sediments have higher concentrations of Mn, Cu and Ni, those with red clay sediments have higher Fe content, whereas nodules and encrustations occurring on the seamounts have more Fe and Co content.. Therefore, besides the presence of siliceous sediments, the availability of seeds (nucleus) and metal sources appears more favorable in FGM area for the formation of high grade nodules. In other words, similar situation (like FGM) does not exist in the CIB, or the other areas probably have comparatively large topographic variations, less availability of seeds and less metal source of supply.

The nodule forming accretionary processes in the CIB appears complicated and size selective because the small and medium sized nodules (diagenetic) probably have grown at faster rates than the medium, big and large sized nodules (hydrogenetic; Valsangkar and Khadge 1989). Therefore, although favorable environment is prevailed in the CIB, the nucleus and metal supply mostly controlled the formation of different sizes of nodules. It is also possible that the different sized nodules have formed at different places under different environmental conditions (Valsangkar and Karisiddaiah 1993). However, examination of the present data suggests the formation of different sized nodules in association with different environmental conditions that varied with time and space in the basin.

According to this (environmental) model, the small and medium sized nodules (<1-5 cm) were formed at faster rates by digenetic accretionary process during short lived nodule forming conditions existed in the CIB. Therefore, these nodules essentially have todorokite mineral and smaller size nucleus surrounded by the sediments. The Mn, Cu and Ni content in the medium sized (3-4 cm) nodules enhanced due to incorporation of crystalline variety of todorokite in the FGM area under undisturbed environment. Conversely, accretion by hydrogenesis on large part of nucleus (mostly exposed to the water) resulted in the formation of bigger sized (>5 cm) nodules with lower Mn, Cu and Ni content due to paucity of crystalline todorokite. These nodules have higher Fe and Co content due to incorporation of  $\delta$ -MnO<sub>2</sub> mineral. Thus, the different size groups of nodules were formed under different environment conditions and show coexistence of different nodule size. It is more likely that, nodule size (in each group) remained unaffected after their formation.

## **6. Conclusions**

Large quantity (~13000) of different sized nodules (<1 to 14 cm) from 266 locations covering 75000 km<sup>2</sup> relinquished area in the Central Indian Basin (CIB) show systematic decrease in the percentages of occurrence, distribution, morphology, grade (Cu+Ni+Co %), abundance (kg/m<sup>2</sup>) and resources towards increase in nodule size. The study reveals that among the 14 size group of nodules, only 3-4 cm sized nodules from the FGM area have the highest economical potential. The study further emphasizes that

'nodule size' is an important factor for estimating the grade, abundance and resources, and indicates rare possibility of identification of another area in the CIB similar to that of FGM area. The study strongly suggests that different sized nodules were formed under variable environmental conditions in the basin and their sizes remained unaffected then afterwards. Therefore, the nodule size can not only act as a good indicator to know the high grade nodules, but also can be used to deduce the deep-sea environmental conditions existed in the basin.

### **Acknowledgements**

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### **Table captions**

Table 1. Details of PMN sampling cruises and total number of nodules examined.

Table 2. Range of nodule size classes (groups) examined.

Table 3. Number of stations and recovery of different sized nodules.

Table 4. Morphology of different sized nodule groups in the CIB.

Table 5. Distribution of different sized nodule groups in the CIB.

Table 6. Percentage of occurrence of different sized nodule groups in the CIB.

Table 7. Average abundance ( $\text{kg/ m}^2$ ) of different sized nodule groups in the CIB.

### **Figure captions**

Figure 1. Sampling stations of polymetallic nodules. The stations were sampled during 11 cruises which covered the Pioneer Area, P<sub>1</sub> area and P<sub>2</sub> area in the Central Indian Basin (CIB). Each sampling station included 2-5 sub-stations.

Figure 2. Distribution of <1, 1-2, 2-3, and 3-4 cm sized nodules in the CIB.

Figure 3. Distribution of 4-5, 5-6, 6-7, and 7-8 cm sized nodules in the CIB.

Figure 4. Distribution of 8-9, 9-10, 10-11, and 11-12 cm nodules in the CIB.

Figure 5. Distribution of 13-14 cm nodules in the CIB.

Figure 6. (a) Relationship between nodule size and nodule types.

(b) Relationship between nodule size and surface texture.

Figure 7. Distribution of surface texture of nodules in the CIB.

Figure 8. Relationship of nodule size and abundance in the P<sub>1</sub>, P<sub>2</sub>, relinquished and FGM area.

Figure 9. Comparison of average abundance ( $\text{kg/ m}^2$ ) of 12938 different sized nodules from 266 locations (this study), and average grade (Cu+Ni+Co %) and Mn/ Fe ratio of 1588 different sized nodules from 436 locations in the CIB (Valsangkar and Khadge, 1989, Valsangkar and Karisiddaiah, 1993, Valsangkar and Ambre, 1994, and Valsangkar, 1995).



Table 1.

Sr. No.	Cruise No.	Year	Area	Total no. of stations	Total no. of sub-stations	Total no. of nodules examined	Averages of total no. of nodules
1	AAS-12	1995	CIB	14	26	749	357 (3)*
2	AAS-13	1995	CIB	30	40	1050	563 (2)*
3	AAS-14	1995	CIB	33	66	3202	1653 (2)*
4	AAS-15	1995	CIB	36	43	1731	1462 (2 at 7 stations)*
5	AAS-36	2001	CIB	10	10	391	391
6	AAS-37	2001	CIB	10	10	519	519
7	AAS-40	2001-2	CIB	45	45	2563	2563
8	AAS-62	2003	CIB	34	34	852	852
9	SK-136	1998	CIB	21	90	1463	434 (4)*
10	ABP-26	2006-7	CIB	13	13	342	342
11	ABP-38	2009	CIB	03	07	76	22 (6)*
Total	11	8	CIB	249	384	12938	9158**

CIB – Central Indian Basin.

( )\* - Number of operations used for determining the station averages.

\*\* - 3 Stations (totaling 82 nodules) were outside the Pioneer Area.

Table 2.

Sr. No.	Cruise No.	Nodule size class (group)		Total no. of size classes examined
		present (cm)	absent (cm)	
1	AAS-12	<1 - 11	9 - 10	10
2	AAS-13	<1 - 11	8 - 10	9
3	AAS-14	<1 - 14	12 - 13	13
4	AAS-15	<1 - 12	---	12
5	AAS-36	<1 - 10	8 - 9	9
6	AAS-37	<1 - 10	---	10
7	AAS-40	<1 - 11	9 - 10	10
8	AAS-62	<1 - 10	---	10
9	SK-136	<1 - 10	---	10
10	ABP-26	1 - 12	8 - 9	10
11	ABP-38	1 - 10	8 - 9	8

Table 3.

Area	Nodule size (cm)/ group													
	<1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-13	13-14
P <sub>1</sub>	6	52	70	72	71	24	31	15	5	4	2	2	0	1
P <sub>2</sub>	1	9	10	9	8	7	6	5	1	2	0	0	0	0
Relinquished	14	90	127	131	127	102	61	30	10	8	1	2	0	0
FGM	3	17	18	18	17	13	10	5	2	0	3	1	0	0
Total CIB	24	168	225	230	223	146	108	55	18	14	6	5	0	1
Av. % of recovery/ presence*	9.64	67.47	90.36	92.37	89.56	58.63	43.37	22.09	7.23	5.62	2.41	2.01	0.00	0.40

\*= Out of 249 stations

Table 4.

Area	Nodule size (cm)/ group													
	<1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-13	13-14
P <sub>1</sub>	r g s- 40%	r g s- 3%	r g	r g	r g	r g	r g	r s-5%	r g	r	r g	r g	-	r g
	R b p (3)	Rep b f el t t r j i p (10)	Rep b p b i f e l t t r j i (11)	Rep b b l f e l t j p b i (10)	Rep d s b b l f e l t t r j p i b i (13)	Rep b l f e l t r j p i b i (10)	p e p b l e l t j l (7)	R b b l p j f e l t r i b i (10)	R b b l f e l t j p l b i (10)	b b l e l t j p (6)	b f t j i (5)	b p e p t b i (5)	-	R f p l (4)
P <sub>2</sub>	r	r s- 21%	r s-30%	r s-39%	r s-47%	r s-35%	r s-25%	r	r	r	-	-	-	-
	b e p d s (3)	Rep b d s t b i (6)	Rep d s t b p (6)	Rep d s b t p (6)	e p d s b t p (5)	d s t b p (4)	b p (2)	b p (2)	e p b p (3)	b t p (3)	-	-	-	-
Relin- quished	r g s - 3%	r g	r s- 2%	r s-4%	r g	r g	r g	r g	r s-10%	r g	r g	r g	-	-
	R b f e l e p i b i (7)	Rep d s b f e l t t r j p i b i (12)	Rep d s b b l f e l t j p i b i (12)	Rep d s b b l f j Δ- e l t j p b i (13)	Rep d s b b l f e l t t r j f p i b i (14)	Rep b e l f t t r- b l j p i b i (12)	Rep d s b b l f t e l j p i b i (12)	R b b l f e l t t r j p i b i (11)	Rep b b l f e l t j p i b i (11)	R b f e l j p i b i (8)	i b i (3)	R b b l p b i (5)	-	-
FGM	r g	r g	r g	r g	r g	r g	r g	r g	r g	-	r	r	-	-
	R (1)	R b p i b i (5)	Rep b b l f e l p i b i (9)	R b l f e l t t r i b i (8)	Rep b b l p f e l b i (8)	Rep b b l p e l i b i (8)	R b b l f e l p i b i (8)	R f e l p b i (5)	R p b i (3)	-	b b l p b i (4)	R b b l b i (4)	-	-

( ): Total number of nodule types present

Texture: r-rough, g- gritty, s- smooth

Shape: R- rounded, ep-ellipsoidal/ elliptical, ds-discoidal, b- botryoidal, bl- bulged, f-flat, el-elongated, t-tabular, r-triangular/pyramidal, j- jointed, p- polynucleated, i- irregular, br-broken, bi-biological.

Table 5.

Area	Nodule size (cm)/ group														Total
	<1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-13	13-14	
P <sub>1</sub>	12	331	724	802	468	158	42	18	7	4	2	2	0	1	2571
P <sub>2</sub>	2	47	129	192	94	34	12	5	2	2	0	0	0	0	519
Relin- quished	31	347	1521	1398	897	321	115	37	10	8	1	2	0	0	4688
FGM	15	151	635	309	110	41	22	7	3	0	3	2	0	0	1298
Total	60	876	3009	2701	1569	554	191	67	22	14	6	6	0	1	9076
Total % of occurrence*	0.66	9.65	33.15	29.76	17.29	6.10	2.10	0.74	0.24	0.15	0.07	0.07	0.00	0.01	

\*= Out of 9076 nodules

Table 6.

Area	Nodule size (cm)/ group													
	<1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-13	13-14
P <sub>1</sub>	0.14	3.65	7.98	8.84	5.16	1.75	0.47	0.20	0.08	0.05	0.03	0.03	0.00	0.02
P <sub>2</sub>	0.03	0.52	1.43	2.12	1.04	0.38	0.14	0.06	0.02	0.03	0.00	0.00	0.00	0.00
Relin- quished	0.35	3.83	16.76	15.41	9.89	3.54	1.27	0.41	0.12	0.09	0.02	0.03	0.00	0.00
FGM	0.17	1.67	7	3.41	1.22	0.46	0.25	0.08	0.04	0.00	0.04	0.03	0.00	0.00
Total %	0.69	9.67	33.17	29.78	17.31	6.13	2.13	0.75	0.26	0.17	0.09	0.09	0.00	0.02
Average	0.17	2.42	8.29	7.45	4.33	1.53	0.53	0.19	0.07	0.04	0.02	0.02	0.00	0.01

\*= Out of 9076 nodules

Table 7.

Area	Nodule size (cm)/ group														All sizes	Average
	<1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-13	13-14		
P <sub>1</sub>	Tr	0.11	0.32	0.77	0.77	0.39	0.17	0.09	0.06	0.04	0.01	0.05	0.00	0.01	2.79	
P <sub>2</sub>	Tr	0.03	0.40	1.21	1.13	0.67	0.43	0.22	0.06	0.14	0.00	0.00	0.00	0.00	4.29	
Relinquished	Tr	0.04	0.38	0.88	1.01	0.53	0.26	0.11	0.03	0.04	0.01	0.02	0.00	0.00	3.31	
FGM	Tr	0.19	1.12	1.48	1.1	0.78	0.54	0.21	0.19	0.00	0.25	0.13	0.00	0.00	5.99	
Total (CIB)	Tr	0.37	2.22	4.34	4.01	2.37	1.4	0.63	0.34	0.22	0.27	0.20	0.00	0.01	16.38	4.09 (Av. CIB)

Tr = Traces (< 100 gm), Av= average

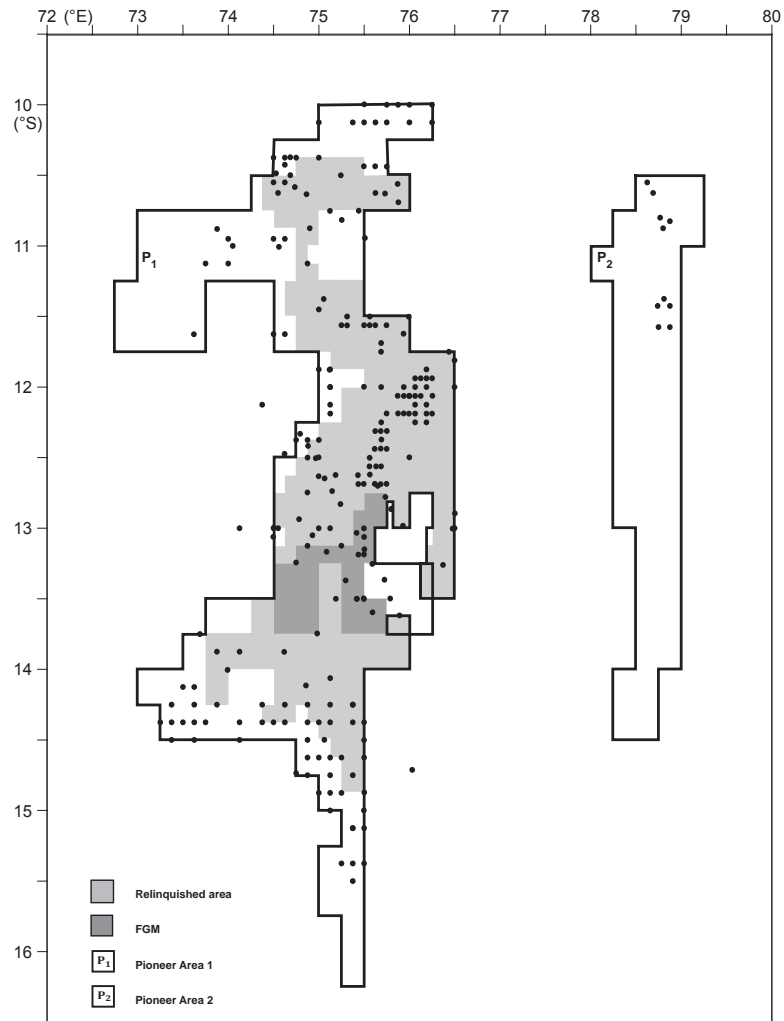


Fig. 1

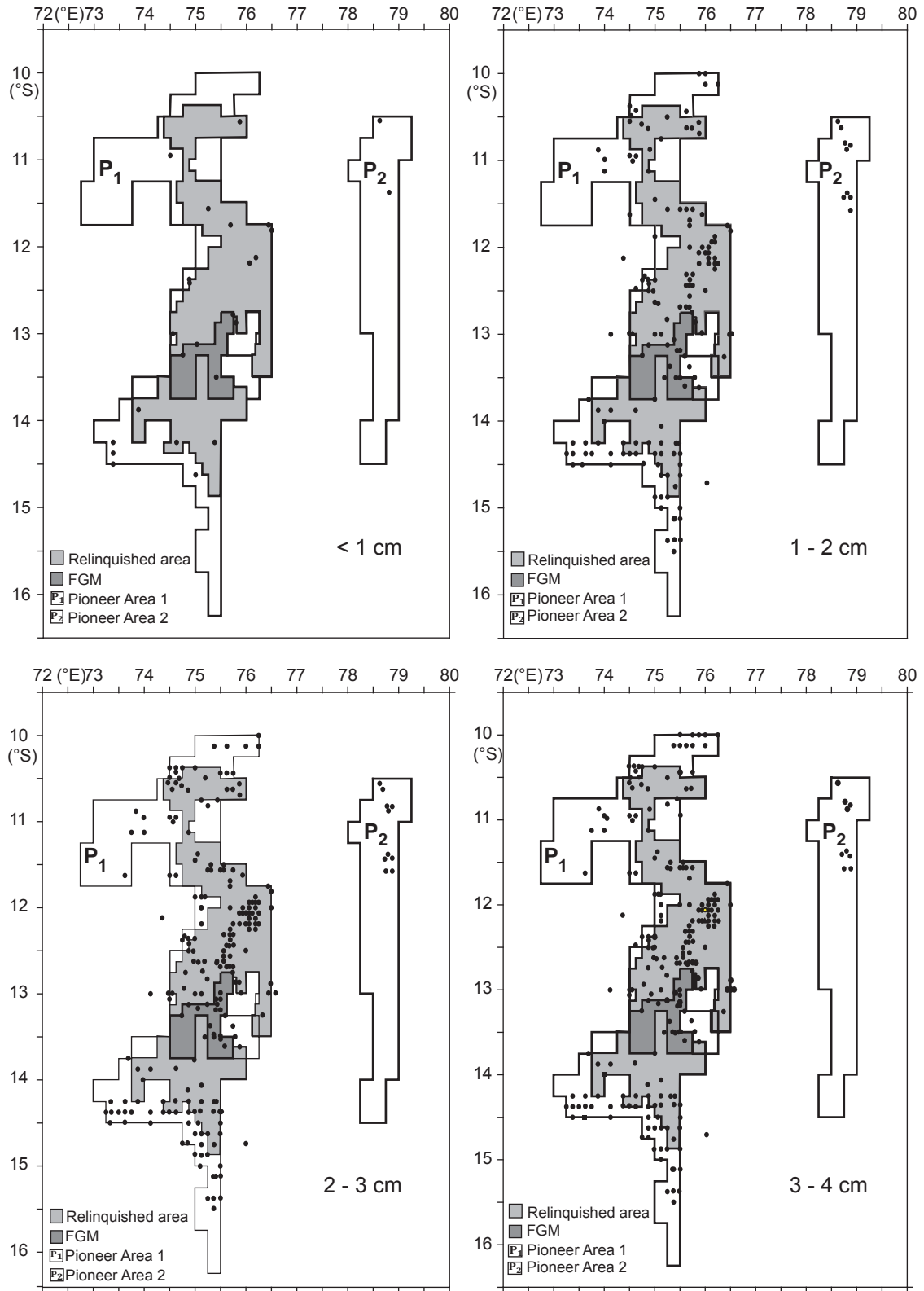


Fig. 2

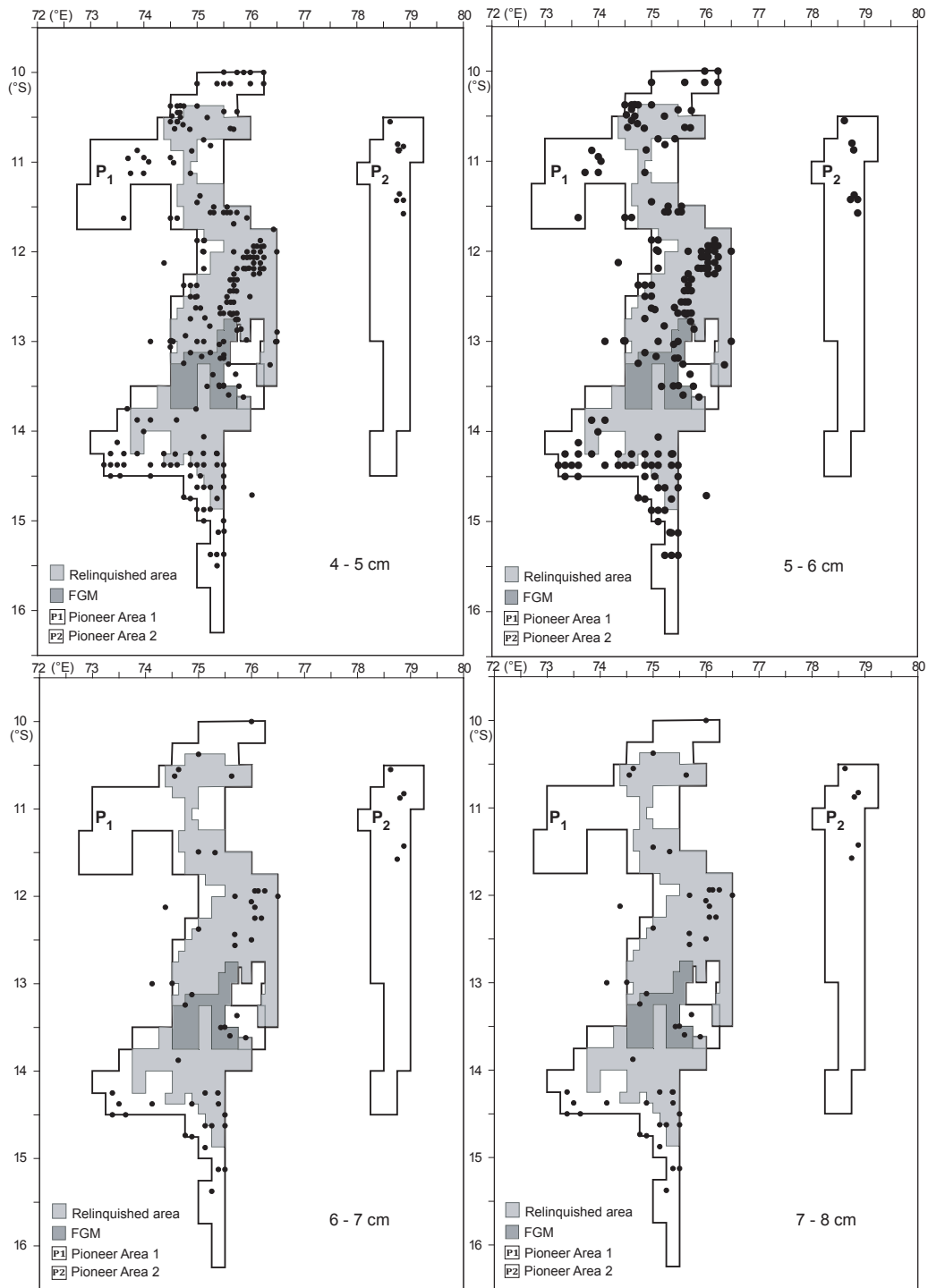


Fig. 3



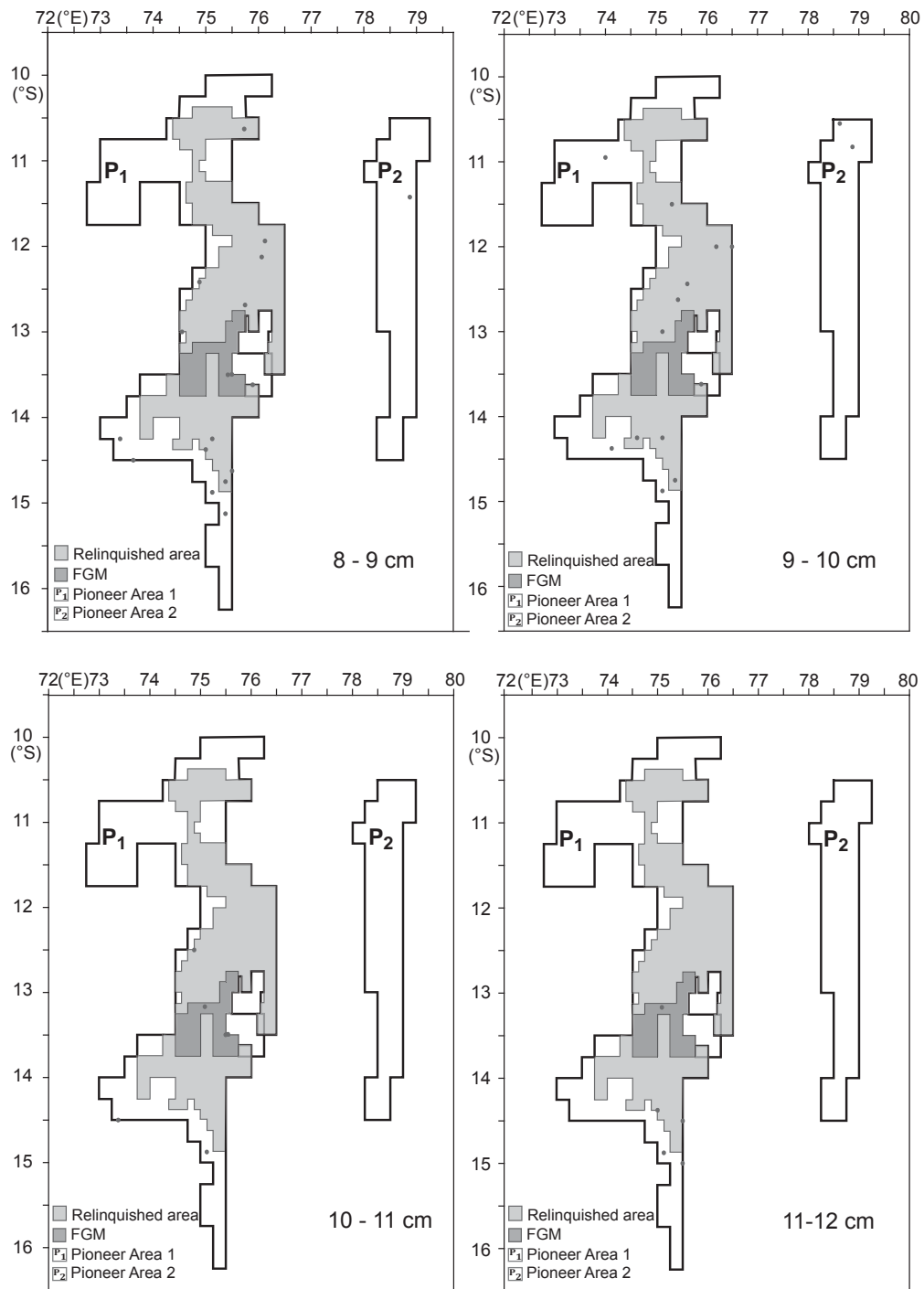
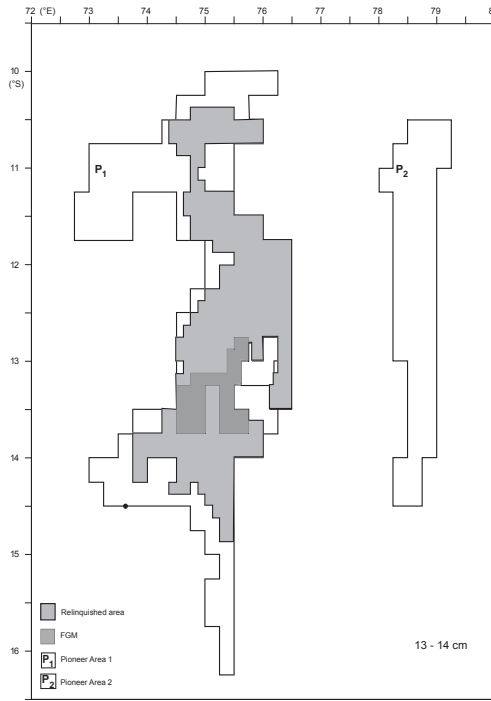


Fig. 4



Fig, 5

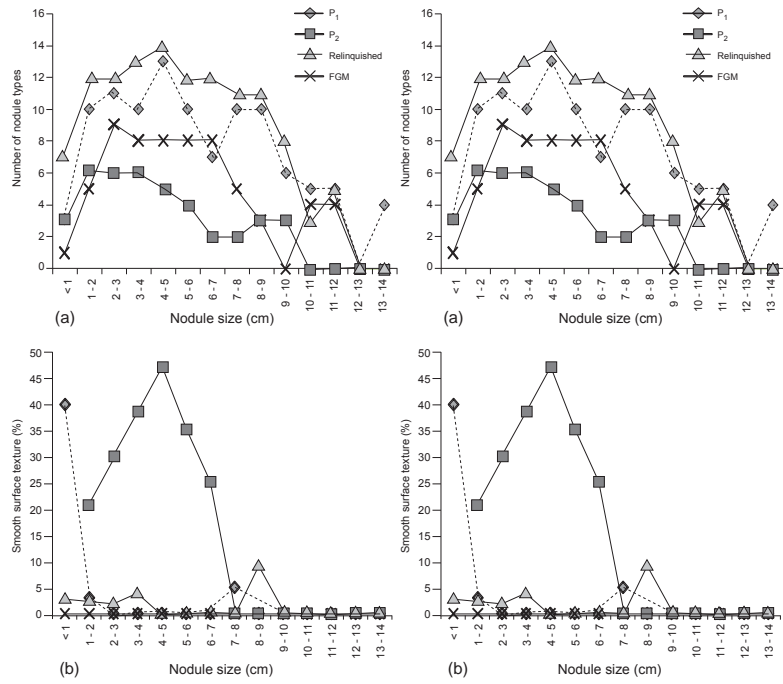


Fig. 6

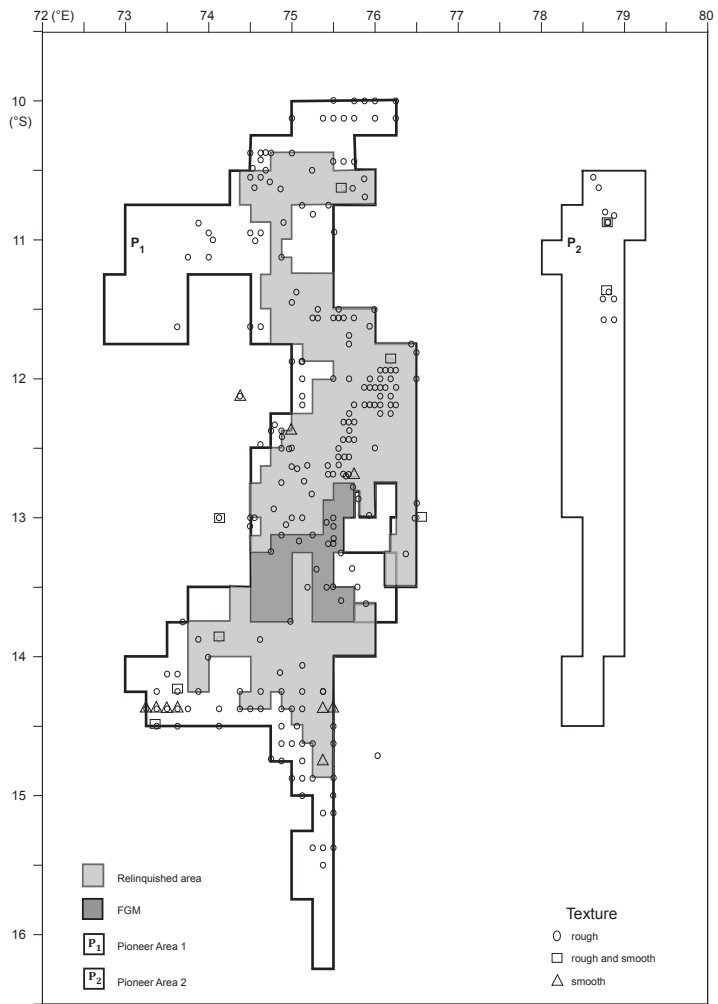


Fig. 7

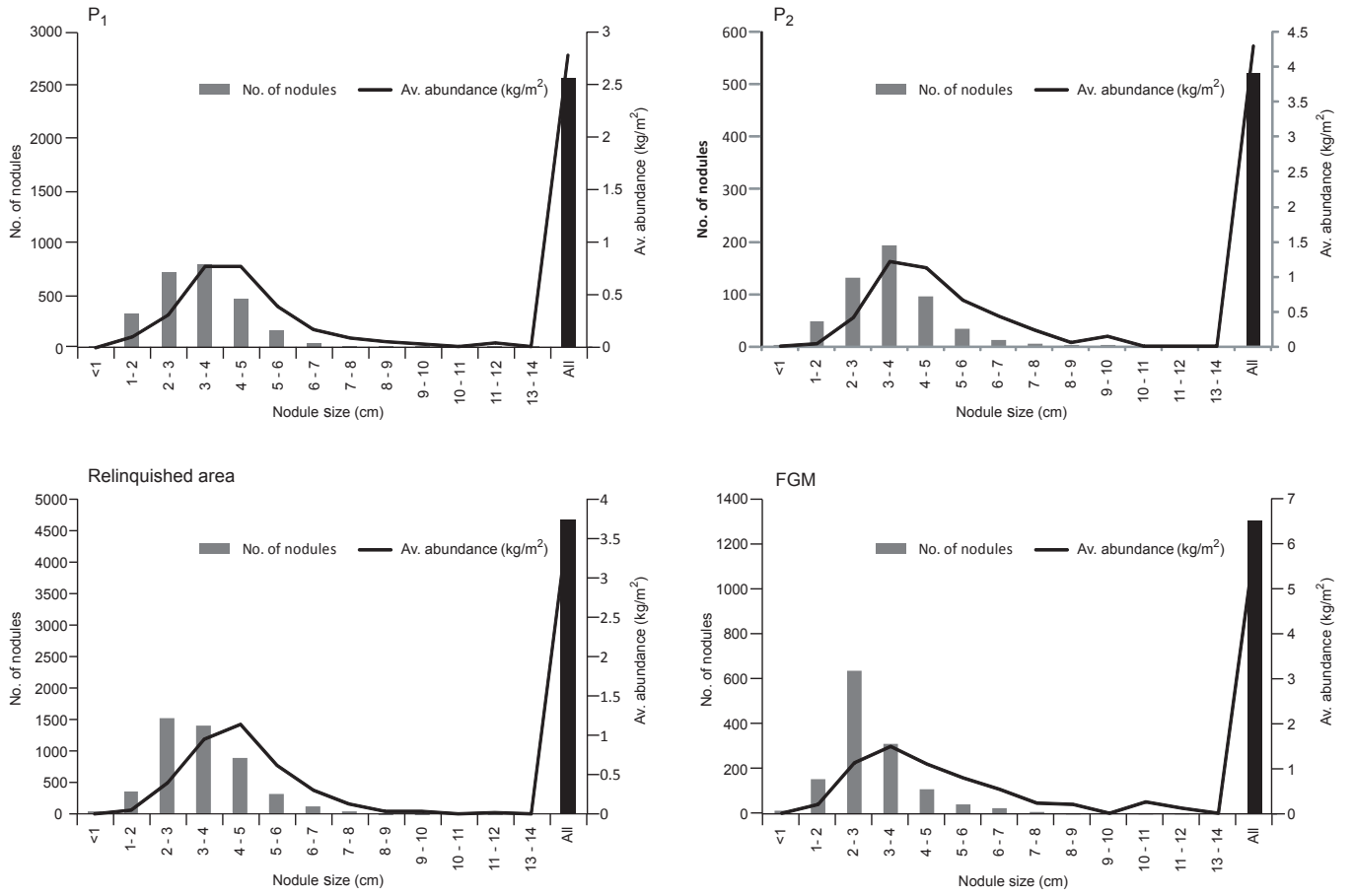


Fig. 8

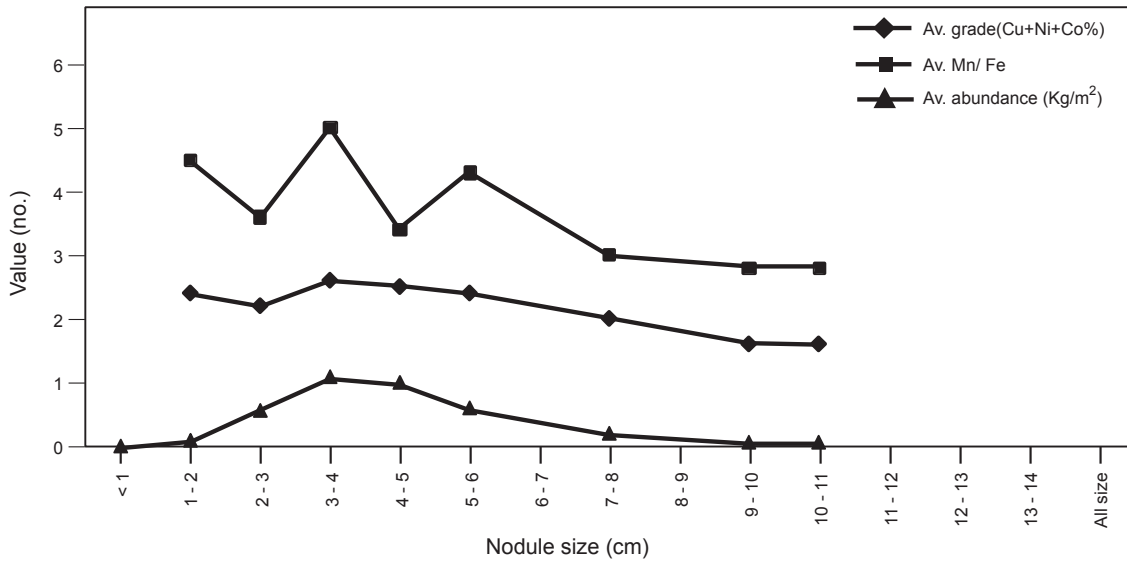


Fig. 9