

Distribution of nodules and associated features in the Central Indian Basin : observations from seabed photographs

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Abstract- Observations from more than one thousand seabed photos, have brought out various factors which influence the distribution of nodules, sediments and rocks and as a result six different phases have been identified for their distribution with respect to different topographic domains. The rock exposures associated with nodules are products of volcanic eruptions which have given rise to the present day seamounts and abyssal hills. Coating of Fe-Mn oxide on these exposures, results in encrustations. The transported fragments of rocks, which act as nuclei, enable accumulation of nodules along the lower slopes of abyssal hills, whereas in the basins, nodules are generally buried under thick sediment cover. The effect of the sediment-water interface layer on burial of nodules leads to an under-estimation of nodule abundance.

Empirical relationships have been developed for nodule abundance estimation. Digitization of photos was carried out using a specially designed interactive software (PHDIC) and the results were catalogued in standard format (SPHINCS) developed for photography data in dBASE III+. The photographic observations have helped in classifying the seafloor, as nodule dominant, sediment dominant and rock dominant, based on the coverage and abundance data; which will be useful in selection of the mine-site as well as a suitable mining system.

INTRODUCTION

Although deepsea nodules have been known for more than a century, these ferromanganese deposits have acquired greater importance in the recent years as large deposits have been identified in all the oceans of the world (ANONYMOUS, 1982). These earthy, black coloured potato shaped, spherical minerals are rich in various metals such as Mn, Fe, Cu, Ni and Co and are expected to be the alternative source of these metals, when the land resources get depleted (GLASBY, 1977). Presently, a number of countries and consortia are concentrating on exploration of the most potential areas for mining in the future (ANONYMOUS, 1984). India has been recognised as a 'Pioneer Investor' and also been given exclusive rights for detailed exploration in an area of 1,50,000 sq. km in the Central Indian Ocean.

The underwater photography systems have been extensively used for exploring these deposits as they are time saving and economical. Moreover, they have an advantage over other survey systems as they enable visual observation of nodules on the seafloor (Fig. 1) and provide a variety of data on the associated features. The objective of this paper is to evaluate the nodule resources as well as understand the environment of occurrence of nodules in the Central Indian Basin from seabed photography data.

MATERIALS AND METHODS

Data acquisition and cataloguing

Photographic data on nodules is collected using cameras attached to free-fall grabs or those lowered on a tow body along with flash unit, battery packs, pingers and altimeters. The grab mounted cameras are used in single-shot operations for photographing the seafloor on standard 35mm black & white or colour films, just before sampling

which serves as a ground truth. The towed camera systems can take a few hundred photos at regular intervals (either remotely controlled or trigger operated), on 100 ft., 35mm black & white films, or continuously record the seabed features on a video film.

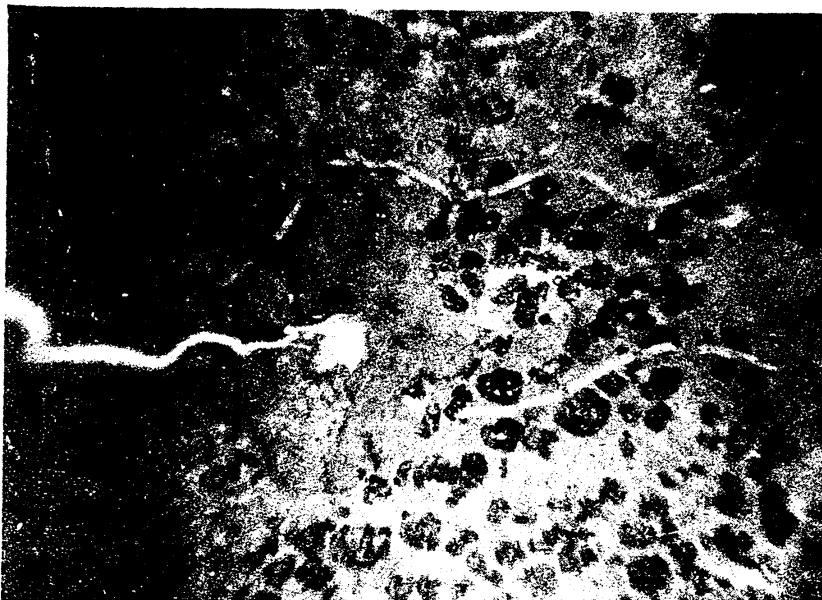


Fig. 1. Nodules with associated sediment and traces of biological activity (fecal casts, pellets and reworked sediment surface) on seafloor at 4815 m depth. Nodule coverage, 30% area of photograph 59 cm x 89 cm, some of the nodules are partly covered by sediments.

Position data was obtained with highly sophisticated navigation systems which operate in conjunction with various satellites and locations were plotted on International Hydrographic Charts. The depth data is recorded with deep-sea echosounders which transmit sound pulses at 3.5 or 12 KHz, and compute the travel time of the pulse reflected from the seafloor, which is then converted into two-way distance.

The interpretation and cataloguing of data from seabed photos was carried out as described in 'Seabed Photographs Interpretation and Cataloguing System (SPHINCS) (SHARMA and KODAGALI, 1990).

Measurement of size, coverage and abundance

For the measurement of dimensions of nodules, from vertical photographs, the magnification factor (Mf) is calculated as:

$$Mf = (A_p/a_p)^{1/2} \quad (1)$$

where A_p = Area photographed on the seabed,
 a_p = Area of the photograph.

Coverage of nodules (C) refers to the area covered by them on the seabed (in percent). Hence,

$$C = (A_t/a_p) \times 100 \quad (2)$$

where A_t = total area covered by nodules.

An interactive software program (PHDIG) which has been developed in ANSI 77 FORTRAN (RAMPRASAD and SHARMA, 1989), was used to compute the nodule coverage based on the nodule boundaries defined by the operator. For 'n' number of points on the circumference, the area of a nodule is given by the following equation:

$$AN = \left(\sum_{i=2}^{n-1} \Delta_{1,i,i+1} \right) + \Delta_{1,n,2} \quad (3)$$

where AN = Area of nodule 'N'

Δ = represents area of the triangle defined by corners at the suffix

Areas of all nodules are added up and compared with area of the photograph to compute coverage.

For estimation of nodule abundance from photos, different workers have proposed different methods (FRAZER et al., 1978; BASTEIN- THIRY, 1979; FEWKES et al., 1979). However, nodule abundance can be calculated directly with the equation suggested by HANDA and TSURUSAKI (1981), as it uses data from photos alone, as follows:

$$\text{Abun (photo)} = 7.7 * D * C / 100 \quad (4)$$

where Abun(photo) = Abundance in photograph (kg/sq.m.)

D = Average nodule diameter (cm)

C = Nodule coverage (%)

Abundance from grab, Abun(grab), is calculated by dividing weight of nodules recovered by the area of the grab. A comparison of results obtained from grabs and photos can be made using the relative abundance (R), which is expressed in percent, as:

$$R = \{ \text{Abun(photo)} / \text{Abun(grab)} \} * 100 \quad (5)$$

This gives the percentage of agreement between photo-data and grab-data. Generally, the photo-data is less than that of grab, because some of the nodules are buried. The extent of burial (B), in percent, can be estimated as:

$$B = 100 - R \quad (6)$$

The distribution of nodules was evaluated with respect to the regional as well as local topography and the distribution of rock exposures, sediment type etc.

RESULTS

Distribution of nodules

Observations from seabed photographs include estimation of nodule abundance as well as delineation of their environment. The average nodule diameter and coverage estimated from these photos are used to compute nodule abundance at each location. Out of the 1034 stations sampled, 82% stations have nodule coverage ranging from 0-5 %, the remaining 18% accounting for all the other coverage ranges from 5 % to 90 %. Similarly, almost 75 % of the observations account for nodule abundance between zero and 5 kg/sq.m., with a steady decline in number of observations towards higher nodule abundance.

The regional distribution of nodule coverage and abundance in the area is obtained by computing the average of all the station values in every one degree grid. Of the 59 blocks investigated, 56 % have less than 5 % average nodule coverage, with a decrease in higher nodule coverages. Similarly, 78 % of the 59 blocks have average nodule abundance of 0-5 kg/sq.m., followed by 5-10 kg/sq.m. in 22 % of the area.

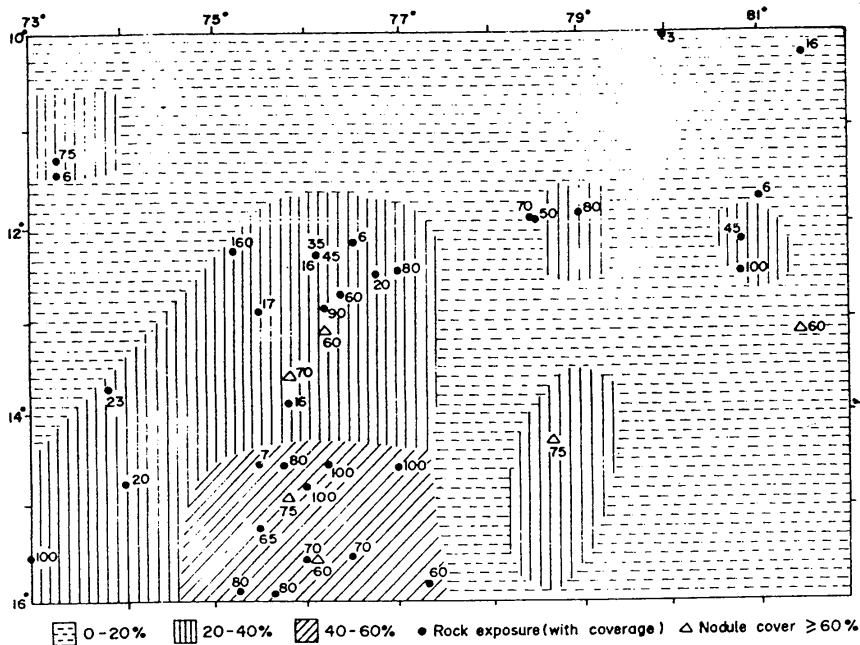


Fig. 2. Regional distribution of nodule populations (coverage) in CIB and locations of rock exposures (with coverage).

The average values for nodule coverage were then hatched to observe the nodule distribution pattern (Fig. 2). Nodule distribution can be divided into zones of varying nodule population. The low nodule population zones (0-20 %) are in the northern part, whereas southern part has areas of higher nodule population (20-40, 40-60 %, and >60%).

Evaluation of associated seafloor features

Photographic observations show a variety of features due to animal activities associated with rock exposures and sediments in different nodule populations, having a mutual influence on one another. These are evaluated in the following paras :

(i) Rock exposures : Massive rock outcrops are observed in seabed photos as hard, dark-coloured substrates, marked by no penetration of the camera counterweight, as they have very less sediment cover, generally trapped in the micro- relief of the rock surface. The rocks are basalts with typical flow textures, which are products of volcanic eruptions, represented by the present day seamounts and abyssal hills. These rock exposures are found on the summits of the seamounts and abyssal hills, their coverage varying from 6% to 100%. Nodules are generally absent in the areas of rock exposures.

(ii) Sediment cover: Siliceous ooze is the dominant sediment type in the study area, with a thin strip of calcareous ooze in the west and red clays to the south (UDINTSEV, 1975). The thin, fluffy, sediment-water interface boundary (SWIB) layer (SOREM et al., 1979) is known to bury nodules and obscure them from camera view (FEWKES et al, 1979). The extent of burial depends upon the size and shape of nodules (FELIX, 1980). This burial causes 'fractionation effect' due to which nodules appear

smaller or fractionated, resulting in a lower average nodule diameter. The abundance estimates of the partially or fully buried nodules tend to be lower and erroneous (SHARMA, 1989a).

(iii) Biogenic activity : Widespread megabenthic activity is observed in the photographs, implying the population density of 7 individuals / 100 sq m (SHARMA and RAO, 1992a). A large number of organisms (88 %) and their activities such as casts, burrows, tracks etc. (85-100 %) are associated with sediments. Similarly, many organisms (66 %) and their burrows, tubes, casts and tracks, (43-75 %) are also observed in nodule areas, having a fairly close association of megabenthic activity (4-8 & 8-12 traces/sq.m.) with all nodule coverage ranges. Rocky areas seem to inhibit widespread megabenthic activity, except in the sediment patches on and around them (SHARMA and RAO, 1992b).

(iv) Micro-relief features: Although micro-relief generally implies a ripple or scour mark as a result of current action, these are seldom observed in the nodule areas of the CIB, indicating feeble ocean-bottom currents. However, animal activities, rock exposures and nodule deposits do bring about minor variations in the topography of the seafloor.

DISCUSSION

Factors controlling occurrence of nodules

The presence (or absence) as well as quantity of nodules depends upon several factors such as availability of nucleating material and sedimentation, input of various oxides and the local topographic variations. The broken fragments from the rock outcrops, get transported along the slopes and flanks, where the oxides from the hydrogenous as well as diagenetic source accrete around them. The availability of this nucleating material, in turn, depends upon the proximity of the source from which they are derived (such as rock outcrops) and the accretion of oxides around them depends upon the rate of sedimentation in the area.

a) Distribution of nucleus

The distribution and availability of rock fragments, which act as nucleating material, play a major role, in the distribution of manganese nodules. Two principal types of rocks were observed - basalt and pumice. The basalts are fresh to slightly weathered. The fresh basalts have nil or very thin veneer of Fe-Mn oxide coating in comparison to the weathered basalt. The pumice vary widely in shape, size and vesicularity. The basalts and pumice are known to have originated from the local seamounts. The basalts are fragmented due to weathering and current action, and transported in the areas surrounding the topographic highs, whereas the pumice can be transported to large distances by currents due to their porosity and low specific gravity (0.65) (YER and KARISIDDAIAH, 1988).

These rock fragments act as centres for accretion of oxide layers to form nodules. The rock outcrops (or encrustations) are restricted to seamount tops and upper slopes, whereas availability of rock fragments depends upon the dispersal due to local physical forces such as currents. Broken fragments drift downslope from the peaks, and, when exposed get coated with metal oxides. This process results in abundant distribution of nodules along the lower slopes (YER and SHARMA, 1990).

b) Nature of substrate and sedimentation rates

The nature of the nodule substrate (sediment type) seems to affect nodule population because higher nodule abundances are associated with the siliceous ooze in this area.

Because of the loose porous nature and high interstitial water content of this sediment, Ni and Cu may be able to diffuse through the interstitial waters to remain at the sediment surface where they could be incorporated into forming Fe-Mn oxides (HORN *et al.*, 1972). These elements could be supplied to the nodules not only by the dissolution of calcareous organisms at or near the sediment surface, but also by dissolution of siliceous organisms after burial.

The nodule occurrence in the Indian Ocean is associated with areas of low sedimentation rates, which are away from influx of continental detritus. In the Pacific also, the major belts of nodule occurrence are associated with regions of low sedimentation rates (GLASBY and READ, 1976).

c) Role of organisms

Since the animals are actively involved in burrowing, as well as ejecting the undigested sediments, they not only have a role in keeping the nodules on surface (SANDERSON, 1985) but also in supplying them with different metals for accretion (DUDLEY, 1979).

d) Influence of bathymetry

The bathymetry of the CIB is a combination of rugged topography with seamounts and abyssal hills as well as abyssal plains with flat topography (KODAGALI *et al.*, 1991). The distribution of rocks, sediments and nodules is controlled by these topographic variations (Table 1).

Table 1. Relationship between topography and other observed features

Physiographic region	Water depth	Observations from seabed photos			Nature of nucleus
		Sediment cover	Rocks	Nodules	
Hill tops and summits	4080 m to 5200 m	Nil	Massive outcrops exposed.	No nodules seen in any of the photos	Fresh basalt and pumice with thin veneer of oxide coating.
Slopes and flanks of hills and seamount	5200 m to 5400	Thin (cm)	Partially exposed sometimes	Many nodules seen in most of the photos (0.15.5 kg/m)	Partly weathered basalt and pumice with substantial oxide coating.
Abyssal plains	More than 5400 m	Thick (10 cm)	Not exposed, totally buried	Nil or very less nodules, totally (0-1.25 kg/m) in all photos	Pumice and highly weathered basalts as core of nodules.

There is almost no sediment cover on the hill tops, but it gradually increases towards the flanks and the deeper abyssal plains. Massive rock outcrops are observed on the summits, on which thick layer of Fe-Mn oxides can accrete to form Fe-Mn encrustations. The broken fragments from these outcrops get transported along the slopes and flanks, where they start accreting the oxides from the hydrogenous as well as diagenetic sources of these metals. As a result, large quantities of nodules are found exposed on the gentle slopes and flanks forming thick nodule fields. This confirms the 'seed' hypothesis of HORN *et al.* (1973) according to which the nodule population is controlled by the distribution of the 'seeds' or the rock fragments which act as nuclei for nodules. The distribution (and morphology) of nodules is controlled by availability

of potential nucleating agents on which oxide minerals can accrete (GLASBY, 1973). The nodule abundance is very low and distribution is patchy in the abyssal plains where the rock fragments as well as the nodules which roll downwards get buried under thick sediment cover.

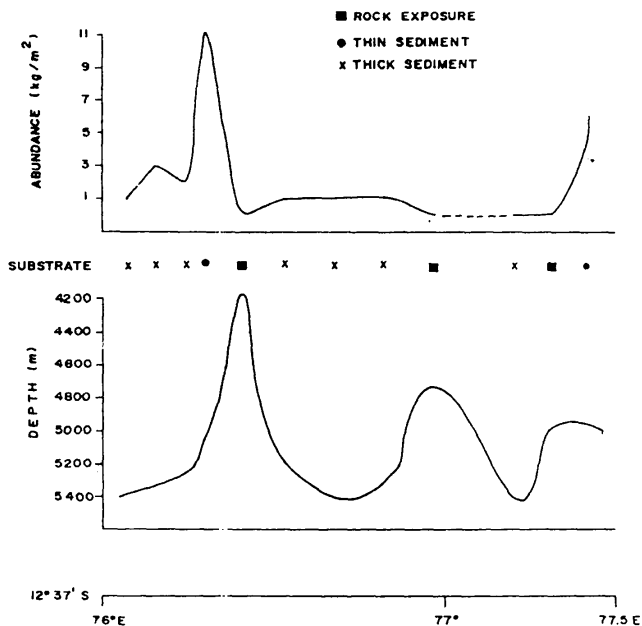


Fig. 3. Distribution of nodules (abundance) and substrates (sediments and rocks) along a cross section of seafloor topography.

The distribution of various features in relation to topography can be seen in the cross-section (Fig. 3) which cuts across all types of topographic domains. The slopes of the abyssal hills have higher nodule concentrations than the summits, where only the rock exposures are observed, and the valleys where very low nodule abundance is recorded.

Based on the observations of various seabed photographs, the following six zones of distribution of rocks, nodules and sediment thickness with respect to topography can be identified :

1. rock exposures at the summits with no sediment cover and no nodules associated with them;
2. transition zone between rock outcrops/encrustations and thin sediment cover with nodules;
3. nodule fields with thin sediment cover on the flanks;
4. gradational zone between thin sediment cover and thick sediment cover at the foot of the hills and seamounts;
5. partial burial of nodules due to increasing thickness of sediment cover; and
6. complete burial of nodules due to thick sediment cover in the abyssal plains.

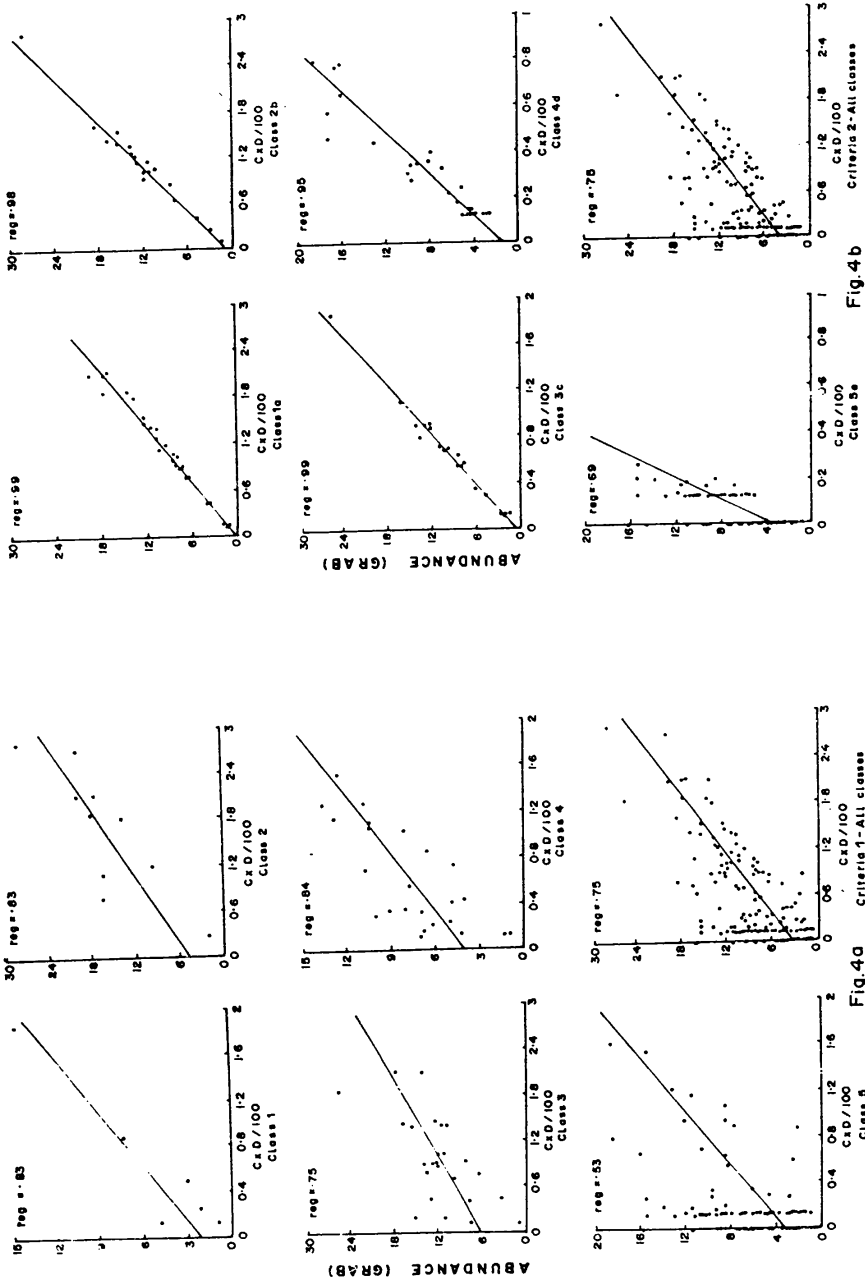


Fig. 4a Scatter diagrams for classes based on S/WIB thickness

Fig. 4b Scatter diagrams for classes based on nodule burial

Fig. 4 Scatter diagrams of nodule coverage x diameter (in photo) v/s nodule abundance (in grab).

Table 2. Formulae for computing nodule abundance in different seabed settings

<i>Based on SWIB thickness</i>					
Class	Data (n)	SWIB thickness	Trigger wt. penetration	Correlation coefficient	Relation to be used
1	9	0 - 3 cm	Nil	0.83	$y = 6.18 x + 2.04$
2	11	3 - 6 cm	Very less	0.83	$y = 6.80 x + 4.62$
3	24	6 - 9 cm	Intermediate	0.75	$y = 6.97 x + 4.97$
4	23	9 - 12 cm	High	0.84	$y = 7.14 x + 2.98$
5	211	12 - 15 cm	Complete	0.53	$y = 8.55 x + 3.14$
All	278	-	-	0.75	$y = 7.54 x + 3.31$

<i>Based on nodule burial</i>					
Class	Data (n)	Nodule burial (%)	RA (%)	Correlation coefficient	Relation to be used
1a	29	0 - 20	100-80	0.99	$y = 8.41 x - 0.01$
2b	22	20 - 40	80-60	0.98	$y = 10.15 x + 0.67$
3c	28	40 - 60	60-40	0.99	$y = 13.91 x + 0.37$
4d	43	60 - 80	40-20	0.95	$y = 21.84 x + 1.20$
5e	147	80 - 100	20-00	0.69	$y = 42.51 x + 2.97$
All	269	-	-	0.75	$y = 7.74 x + 3.78$

$x = C \times D / 100$, C = nodule coverage (%) in photograph, D = average nodule diameter in photograph, y = Abundance (kg/sq.m.)

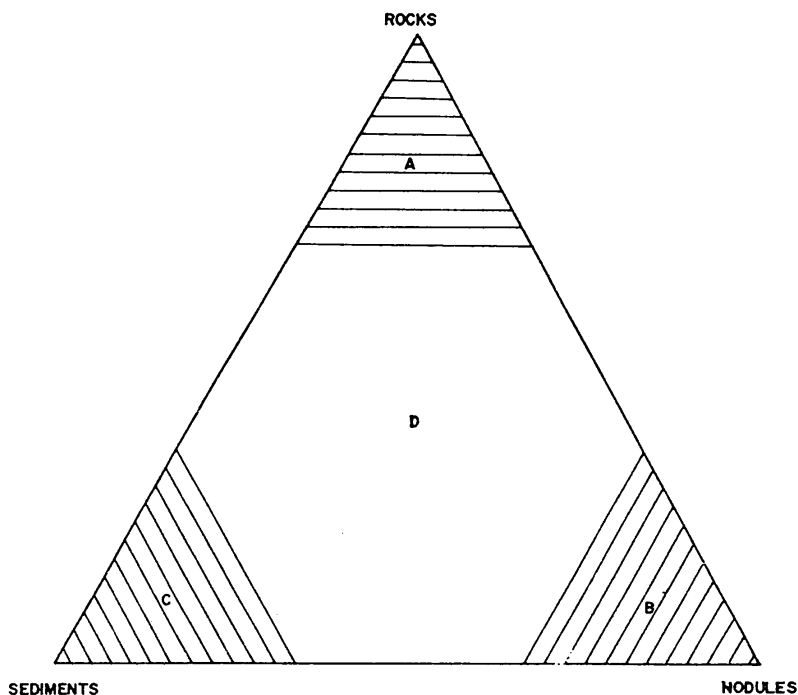


Fig. 5. Ternary diagram for delineation of different seabed environments.

Estimation of nodule abundance

Since, nodules are known to be buried to varying extents under the sediment-water-interface boundary layer, leading to an under-estimation of nodule abundance from seabed photographs (FRAZER *et al.*, 1978; BASTEIN-THIRY, 1979; ANONYMOUS, 1982); the need for a correction factor to account for buried nodules has been emphasised by various workers (FEWKES *et al.*, 1979; FELIX, 1980; ANONYMOUS, 1982). However,

no single correction factor can be applied to all estimates as the nodule burial also depends upon the varying thickness of the SWIB layer at each location (SHARMA, 1989a).

In order to overcome the effect of the SWIB layer on exposure and hence, abundance estimates of nodules, data at every location was classified into 5 classes each, on the basis of:

- i) Thickness of SWIB layer (measured from penetration of counter weight); and
- ii) Relative abundance which gives extent of burial of nodules (see equation 5).

In each class, correlation matrices were worked out for various parameters observed in photos and the nodule abundance calculated from grab sample. There was good correlation (0.75) between the product of coverage and nodule diameter from photo and the nodule abundance from grab (SHARMA, 1989b).

The data of these two parameters was plotted for each class, to arrive at empirical relation between them (Fig. 4) so as to be able to use photo data for more accurate nodule estimation depending upon different seabed conditions (Table 2).

Delineation of seafloor environment

Based on various factors associated at different locations, the seafloor can be classified for its environment. As the features of interest in nodule studies are rocks, sediments and nodules, coverage of these features at every location can be plotted on a triangular (ternary) diagram which can be subdivided into four zones, each of them corresponding to a particular seafloor setting (Fig. 5):

A: High rock exposure (66-100 %), less nodules (0-33 %), less sediment cover (0-33 %) - normally found at the summits of hills and seamounts.

B: High nodule coverage (66-100 %), less sediment cover (0-33 %), less rock exposure (0-33 %) - generally associated with slopes and flanks.

C: High sediment cover (66-100 %), less nodules (0-33 %), less rocks (0-33 %) - found in abyssal plains.

D: Low to intermediate coverage of rocks, sediments and nodules (0-66 % each) - transitions between different end members.

CONCLUSIONS

Seabed photography can be effectively used in the evaluation of nodule resources and to study the environment associated with them so as to understand the factors which influence their occurrence and concentration. The seabed can be classified into different zones depending upon percent distribution of rocks, sediments and nodules in the photos. The concentration and distribution of these deposits will determine potential mining areas. Nodules exposed on the flanks of seamounts can be recovered more easily as compared to those from the abyssal plains, where they are buried or from the summits where only encrustations are found. Hence the information collected from photography data can also be useful in delineation of minesite and also in carrying out modifications in the design of the proposed mining system depending upon local seafloor conditions.

Acknowledgements-This study was carried out under 'Polymetallic nodule project', funded by the Department of Ocean Development, Govt. of India.

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