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Optimum sampling interval for evaluating ferromanganese nodule resources in the central Indian Ocean

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Abstract A study to estimate manganese nodule abundance (weight of nodules in kg/m^2) was carried out in a small area of the abyssal plains covering a one-degree square block in the central Indian Basin. Abundance was assessed at various intervals by progressively reducing the grid spacing. Sampling the corners of the 1° survey block (approximately110-km spacing), i.e., four stations with 5–7 free-fall operations (sampling locations) in each case, indicated a nodule abundance of 3.50 kg/m^2. By reducing the sampling spacing to four grid units (0.5° survey blocks) and sampling the entire block at eight stations (25 locations), the average abundance of the block was 3.36 kg/m^2. Further reduction of the grid to 0.25° survey blocks and sampling in 16 grid units (70 sampling locations) increased the abundance to 4.41 kg/m^2. For 64 grid units in the one-degree block (sampling in 0.125° survey blocks), a substantially higher value was recorded, i.e., 5.31 kg/m^2 or about 1.5 times the abundance obtained at a 1° spacing. Adding 25 more stations in 0.0625° survey blocks (intervals of sampling locations approximately 500 m) resulted in a negligible change in abundance, the average value of the one-degree block being 5.23 kg/m^2. These data demonstrate that, for estimating nodule resources in the region, it is important to adopt a close-grid sampling strategy, so that areas with lower abundance can be relinquished and areas with higher abundance can be confidently identified. To ascertain exact nodule abundance for mine-track selection, it may be sufficient to restrict detailed grid surveys to areas with marked variations in topography and nodule abundance, rather than carrying out such detailed (albeit less cost effective) surveys at a very narrow spacing (0.0625°) over the entire pioneer area.

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Introduction

Estimating nodule abundance is an important prerequisite in defining ocean mining sites. Published data show abundance to sometimes vary considerably over distances of a kilometer or less (e.g., Bastien-Thiry et al. 1977). This poses difficulties in deciding the sample spacing to measure abundance. The standard procedure for estimating nodule abundance is to obtain bottom samples at a relatively wide grid spacing initially, and to then progressively narrow the grid spacing in promising areas.

To estimate the abundance, grade and resources of manganese nodules in the central Indian Ocean Basin (CIOB), the above procedure was adopted in reconnaissance sampling in a one-degree square block during the 1980s by the National Institute of Oceanography (NIO), India (Qasim and Nair 1988). Sampling was narrowed down progressively to half- and quarter-degree survey blocks. Areas containing sufficient ferromanganese nodules to define potential mine sites were identified in this way (Mudholkar et al. 1988). Subsequently, the entire Indian mine site, registered with the International Seabed Authority (ISBA), was sampled by free-fall grabs at 0.125° grid spacing (NIO internal reports). Half of this area had to be surrendered in phases to the ISBA. Ten and 20% of the mine-site area were relinquished to the ISBA already in 1994 and 1997, respectively, as stipulated in Resolution II of the 3rd United Nations Convention on the Law of the Sea (UNCLOS III). Another 20% of the area has to be surrendered by the end of 2001 and, to accomplish this, the remaining area has to be resurveyed to acquire more data.

Muthunayagam and Das (1999) hypothesized that a narrow spacing of 5×5 km (0.0625° survey blocks) would be essential to survey the area for the purpose of relinquishment . To test this hypothesis, we conducted surveys in a small section of the one-degree block defined by latitudes 11.5°S and 12.5°S, and longitudes

75.5°E and 76.5°E, using a narrow grid spacing of 0.0625°. Our main aim was to evaluate the amount of information obtained through such additional data collection. In the present study we present the results of these surveys.

Methods

In August 1998 a small section (ca. 42×42 km) of the one-degree square reconnaissance block (Fig. 1) was sampled from aboard the ORV Sagar Kanya (cruise SK-136). At each of 25 stations in a grid of 0.0625° spacing, material was collected by deploying 4–7 free-fall grabs (99 sampling locations in all), and these data were used to calculate average abundance. Sampling followed a hexagonal pattern at each station, with intervals of approximately 500 m between locations. Abundance values thus obtained were combined with existing data sets (Qasim and Nair 1988; Mudholkar et al. 1988; Muthunayagam and Das 1999; NIO internal reports), and new averages for the one-degree block

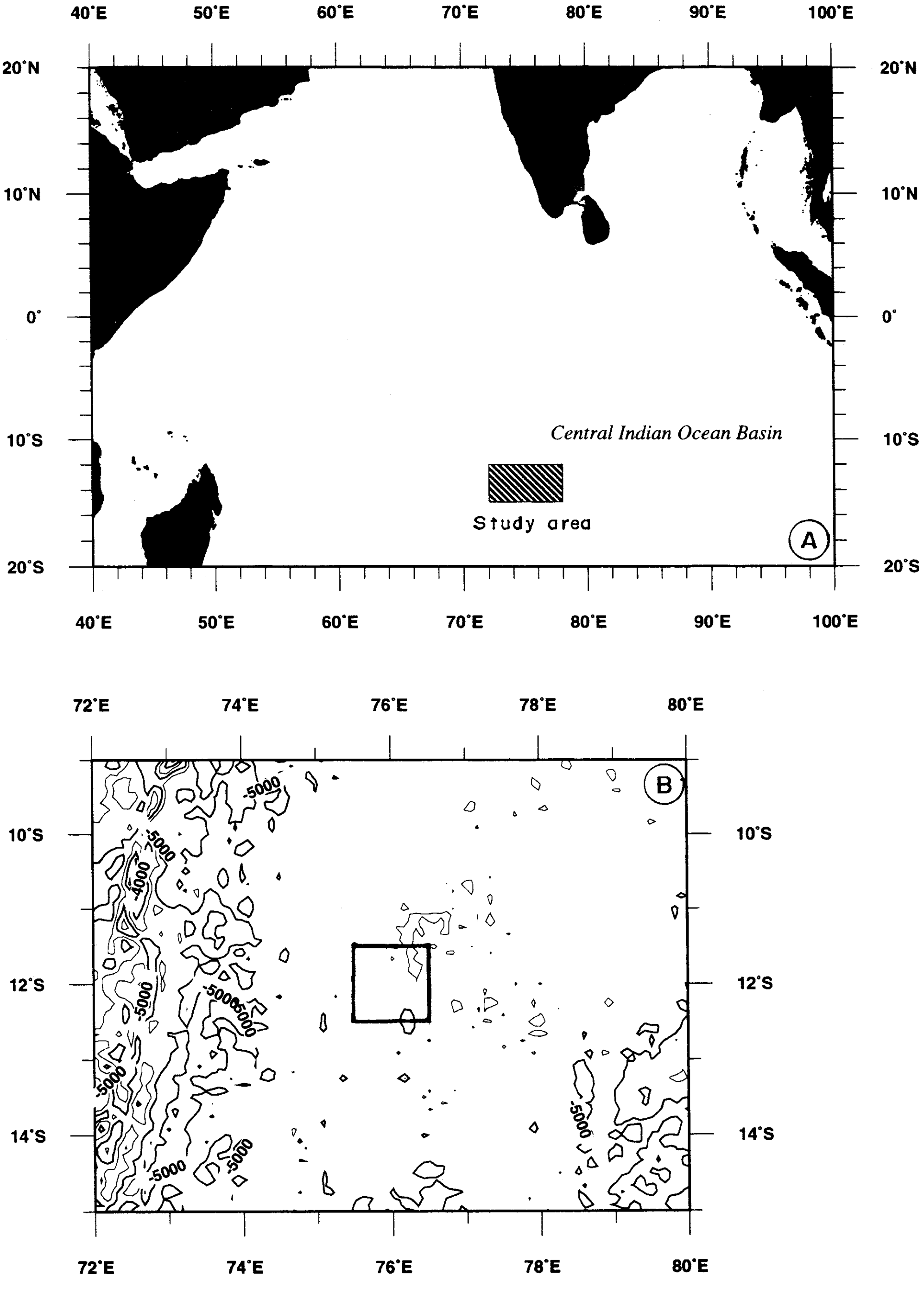

Fig. 1 **A** Location of the general study area in the central Indian Ocean Basin. **B** Location of the one-degree survey block in the study area. Depth contours are in m

were obtained at 1, 0.5, 0.25, 0.125 and 0.0625° grid spacings. In this way variations in ferromanganese nodule abundance and resources were determined for the area.

Results

The results for the 25 stations (99 locations) covered during the SK-136 cruise are indicated in Table 1. The data show that, for a grid spacing of 0.0625°, average nodule abundance varied from zero to ca. 10 kg/m^2 within this area.

Variations in abundance at larger sampling intervals were quantified for 1, 0.5, 0.25 and 0.125° square grid intervals (Tables 2 and 3, Fig. 2). Sampling in the 1° grid was carried out at the corners, covering four stations (25 sampling locations) with free-fall grabs (Fig. 2a). The average abundance thus obtained for the block at a 1° spacing was 3.50 kg/m^2 (Table 2). This main block was subdivided into four square grid units, and sampling in these 0.5° survey blocks was carried out at the eight stations (25 locations) indicated in Fig. 2b. Increasing the number of stations showed that the average abundance of the entire block was 3.36 kg/m^2, only 0.14 kg/m^2 less than the value estimated at 1° (Table 2).

Each of the 0.5° grid units was subdivided further into 0.25° survey blocks, resulting in 16 grid units (70 sampling locations) within the one-degree square block (Fig. 2c). With these additional data, the average abundance for the entire one-degree square grid area increased marginally to 4.41 kg/m^2 (Table 2).

To estimate nodule abundance at a 0.125° grid spacing, a further subdivision of the 0.25° survey blocks was carried out, resulting in 64 grid units with 64 stations (Fig. 2d). Values for average abundance and standard deviation for each subunit are indicated in Table 3. Comparing the average abundance obtained at a 1° grid spacing to the value obtained at a 0.125° grid spacing showed a substantial increase in abundance from 3.50 to 5.31 kg/m^2. This indicates the necessity for a closer grid sampling for estimating nodule resources, so that areas with lower abundance of nodules can be confidently relinquished and those with higher abundance can be retained.

The results of 0.0625° grid sampling survey (Table 1) are representative for only a limited area within the main block which was selected as a case study (Fig. 2e). Twenty-five stations were selected, with an average of four free-fall grabs at each station. Thus, the total number of sampling stations in the one-degree block increased from four stations at the 1° spacing (Fig. 2a) to 89 stations for the combined 0.125°/0.0625° data sets (Fig. 2e). Comparison of average values for the 0.125° and 0.125°/0.0625° data sets within each of 14 grid units (Table 3) showed no marked differences in the abundance of nodules between the 0.125° and 0.0625° grid spacings. In addition, adding 25 more stations in 0.0625° survey blocks resulted in a negligible change in abundance for the one-degree block as a whole, average nodule abundance being 5.23 kg/m^2.

Table 1 Results for 25 stations sampled at 0.0625° grid intervals during cruise SK-136

Station no.	Longitude (°E)	Latitude (°S)	Depth (m)	No. of buoys	No. successful hauls	Total weight (kg)	Average weight (kg)	Average abundance (kg/m^2)
1	76.1250	11.8125	5,375	4	2	0.0	0.0	0.0
2	76.1850	11.875	5,280	4	4	1.69	0.42	3.25
3	76.2466	11.875	5,310	4	4	4.20	1.05	8.08
4	76.1875	11.875	5,290	4	3	3.85	1.28	9.87
5	76.1766	11.99	5,200	4	4	3.55	0.89	6.82
6	76.1833	12.06	5,280	4	0	1 nodule	0	Traces
7	76.2458	12.06	5,200	4	3	1.05	0.35	2.70
8	76.1791	12.125	5,210	4	4	2.45	0.61	4.72
9	76.1850	12.186	5,200	4	4	1.05	0.26	2.01
10	76.2420	12.185	5,250	4	4	4.40	1.10	8.46
11	76.1790	12.247	5,150	4	4	5.22	1.30	10.03
12	76.1200	12.1833	5,240	7	3	2.02	0.67	5.18
13	76.0790	12.25	5,200	3	3	2.20	0.73	5.64
14	76.0550	12.19	5,240	4	4	2.25	0.56	4.33
15	76.0583	12.125	5,200	4	4	3.36	0.84	6.46
16	76.1170	12.062	5,250	4	3	0.97	0.32	2.49
17	76.0625	12.0625	5,245	4	4	2.65	0.66	5.1
18	76.0625	11.9966	5,250	4	4	2.24	0.56	4.3
19	76.1183	11.9366	5,270	4	4	5.30	1.32	10.19
20	76.0533	11.9383	5,300	4	4	3.40	0.85	6.54
21	76.0583	11.874	5,430	4	3	0	0	0
22	76.0000	11.9375	5,275	3	3	3.10	1.03	7.95
23	75.9330	11.99	5,195	4	4	2.80	0.70	5.38
24	75.9416	12.0617	5,190	3	3	1.00	0.33	2.56
25	75.9900	12.0617	5,200	3	3	1.95	0.65	5.00
Total						59.68	0.67	5.15

Table 2 Average abundance values, standard deviations (SD) and block areas in the one-degree square block, for 1, 0.5, and 0.25° grid spacings (1, 4, and 16 survey blocks, respectively; cf. Fig. 2A–C)

Grid spacing	Block number	No. of locations (n)	Average abundance (kg/m^2)	SD	Block area (km^2)
1°	1	4	3.50	2.926	12046.911
			3.50 Grid average		
0.5°	1	6	3.42	1.944	3014.449
	2	8	3.17	2.169	3014.449
	3	7	4.24	2.052	3009.006
	4	4	2.62	1.654	3009.006
			3.36 Grid average		
0.25°	1	4	4.51	2.834	753.946
	2	4	3.98	3.334	753.946
	3	4	3.15	2.382	753.946
	4	3	1.60	0.645	753.946
	5	5	4.32	2.823	753.279
	6	6	4.80	2.037	753.279
	7	6	5.27	1.589	753.279
	8	4	4.43	2.319	753.279
	9	4	3.63	2.330	752.599
	10	6	3.38	1.429	752.599
	11	6	4.40	1.938	752.599
	12	5	4.98	2.628	752.599
	13	3	6.76	1.283	751.904
	14	3	5.18	2.871	751.904
	15	3	5.11	4.936	751.904
	16	4	5.19	4.574	751.904
			4.41 Grid average		

Discussion

The results demonstrate that none of the 0.125° grid stations showed substantial changes in average nodule abundance upon incorporation of additional data from a 0.0625° sampling strategy. Most earlier investigators agreed that variations in abundance are generally high, but no scientific theory has been put forward to explain their distribution patterns satisfactorily. Andrews and Friedrich (1979) reported abundance to vary even over tens of meters.

Determining nodule abundance on the seafloor from grab samples or photographs can have an error margin of 20–25% (Bastien-Thiry et al. 1977). Seeing that the data from public sources are often limited, in order to make accurate estimates of nodule resources more detailed assessments of nodule concentration are needed (Frazer 1977). During the late 1970s, a few available publications on nodules from the central Indian Ocean Basin indicated the radiolarian ooze areas south of the equator to contain higher grade nodules (Archer 1976; Holser 1976; Frazer et al. 1978; Cronan 1980). There has been considerable improvements in our knowledge of various aspects of nodules in the CIOB since then (e.g., Jauhari and Pattan 2000).

The results of the present study, in a small area on the abyssal plains of the CIOB, indicate that extensive sampling at a 0.125° grid spacing substantially modified existing data sets of nodule resources based on larger grid spacings. However, by further reducing the sampling interval to a 0.0625° spacing (and having established that abundance had been assessed by means of the same sampling device in the various surveys) did not add much information for the present study site. This may not always be the case at other sites. For one, bathymetry is an important factor in nodule distribution (Kodagali 1988; Kodagali and Sudhakar 1994). Johnson (1972) and Moore and Heath (1966) have shown that sediment thickness, which is related to nodule abundance, varies over even short distances and, in turn, is related to the bathymetry of the region. Therefore, to ascertain exact nodule abundance for mine-track selecting, it may be necessary to carry out detailed closer grid surveys in areas with marked topographic variations and fields with highly variable nodule abundance. However, the results of the present study argue against the need to automatically carry out such detailed surveys in the entire pioneer area.

Frazer (1977) utilized the data on nodules stored in the sediment data bank of Scripps Institute of Oceanography, including 3,100 nodule assays from about 1,500 sampling sites. Despite a much larger database and a different approach, this author's estimate for the Clarion-Clipperton zone was about the same as those of previous authors. Mero (1965) for the first time forwarded the idea of commercial mining of ferromanganese nodules, based only on 54 nodule assays, 29 seafloor photographs, 10 grab samples and 62 cores for the entire Pacific Ocean. This author's observations about where nodules are likely to be abundant, and where they are enriched in certain elements, were remarkably accurate, considering the small amount of data available. On the contrary, Frazer and Wilson (1980), using limited data for CIOB nodules, concluded that, although the basin has the highest grade nodule deposit yet found outside the Clarion-Clipperton zone, nodule abundance in the region is not sufficient for

Table 3 Average abundance values, standard deviations (SD) and block areas in the one-degree square block, for the 0.125° grid spacing (64 survey blocks; cf. Fig. 2D–E). * Values including additional data from the 25 stations in the 0.0625° grid

Grid spacing	Block number	No. of locations (n)	Average abundance (kg/m^2)	SD	Block area (km^2)
0.125°	1	2	4.05	2.205	188.527
	2	2	2.30	2.127	188.527
	3	4	3.39	1.687	188.527
	4	3	3.14	3.805	188.527
	5	3	4.46	3.453	188.527
	6	3	4.90	0.68	188.527
	7	2	2.58	0.000	188.527
	8	1	0.70	0.000	188.445
	9	1	1.31	0.797	188.445
	10	3	2.25	3.036	188.445
	11	5	4.01	3.551	188.445
	12	4	5.12	2.064	188.445
	13	3	5.12	1.165	188.445
	14	3	5.89	1.258	188.445
	15	3	6.26	2.219	188.445
	16	3	4.16	1.875	188.362
	17	2	5.07	1.880	188.362
	18	4	5.28	2.719	188.362
	19	4	6.37	2.264	188.362
	20	4	6.96	4.252	188.362
	21	4 (5*)	6.88 (5.5*)	4.303	188.362
	22	5 (8*)	5.38 (6.01*)	5.627	188.362
	23	4 (6*)	6.47 (6.27*)	6.205	188.362
	24	3	6.83	4.699	188.278
	25	6	6.31	3.622	188.278
	26	4 (5*)	9.25 (9.01*)	2.552	188.278
	27	4 (9*)	8.67 (8.1*)	3.529	188.278
	28	5 (11*)	6.62 (6.08*)	2.581	188.278
	29	5 (8*)	6.06 (6.06*)	2.490	188.278
	30	4	6.58	0.811	188.278
	31	4	4.01	1.238	188.278
	32	3	2.68	1.525	188.192
	33	2	5.40	1.752	188.192
	34	4	4.58	1.718	188.192
	35	4	4.79	2.116	188.192
	36	5 (9*)	5.46 (5.0*)	2.723	188.192
	37	6 (11*)	6.37 (5.59*)	1.985	188.192
	38	4 (8*)	7.64 (5.91*)	0.943	188.192
	39	4 (5*)	6.51 (5.75*)	2.545	188.192
	40	5	4.98	0.500	188.107
	41	2	6.78	0.824	188.107
	42	4 (5*)	6.05 (6.53*)	2.584	188.107
	43	5 (10*)	5.74 (5.91*)	3.472	188.107
	44	5 (9*)	5.68 (5.55*)	2.734	188.107
	45	4	4.48	1.107	188.107
	46	4	2.88	2.375	188.107
	47	4	2.91	2.799	188.107
	48	3	4.72	2.828	188.020
	49	3	4.76	2.435	188.020
	50	4	3.46	0.918	188.020
	51	4	3.04	1.357	188.020
	52	4	3.23	4.999	188.020
	53	5	5.98	4.458	188.020
	54	5	7.11	1.704	188.020
	55	4	7.49	3.744	188.020
	56	3	6.23	3.679	187.932
	57	3	5.89	3.880	187.932
	58	4	6.43	3.781	187.932
	59	3	10.39	5.175	187.932
	60	2	10.49	1.080	187.932
	61	2	4.23	3.967	187.932
	62	3	6.52	3.181	187.932
	63	4	6.93	2.698	187.932
	64	3	3.92		
			5.31 Grid average		

first-generation mining. However, detailed exploration within this area by India has established two mine-sites of first generation.

Although the polymetallic nodules in the Indian Ocean cover an area of 10–15×10^6 km^2, the local requirements for metals (especially Mn, Ni, Cu and Co) are not high due to the low level of industrial activity in the region (Siddiquie et al. 1984). Siddiquie and Rao (1988) anticipated a rise in the demand for these metals in future with increased industrialization, and even the onland Mn deposit to deplete within a period of 20 years. Shyam (1982) predicted that, even with a modest increase in consumption, India will have to make large outlays of foreign exchange in order to purchase non-ferrous metals. Such predictions have not turned out to be true with time. Thus, there has not been any major change in the consumption of these metals in the last one and half decades.

The commercial mining of nodules was anticipated to start by the end of the 1980s but, at the beginning of the 21st century, the future of commercial mining remains uncertain worldwide, with most countries playing a low key (Chung and Sharma 1999). Even the areas surrendered by India and other countries to the ISBA for further development have remained shelved after more than a decade or so. The interest of countries other than Korea and India in manganese nodule mining is largely fading (Winterhalter 1999, personal communication). Although the prospects of commercial mining of marine minerals have improved after the UNCLOS came into force in 1994, considering the present international scenario on metal demand and mining technology, their mining is not likely to take place in the immediate future. Seeing that the daily costs of running a ship and obtaining data by free-fall grabs (3–4 stations per day) are exorbitant, and that additional data at 0.0625° (approximately 5–6 km) grid spacing have not improved the existing information significantly for the CIOB, it is recommended to carry out detailed grid surveys only in areas with highly variable topography and nodule abundance, instead of detailed surveys at a very narrow spacing (0.0625°) over the entire pioneer area.

Fig. 2A–E One-degree survey block with various grid spacings. **A** 1° survey block; **B** 0.5° survey blocks; **C** 0.25° survey blocks; **D** 0.125° survey blocks; **E** 0.125°/0.0625° survey blocks. *Filled circles* Sampling stations (5–7 free-fall grab operations in each case)

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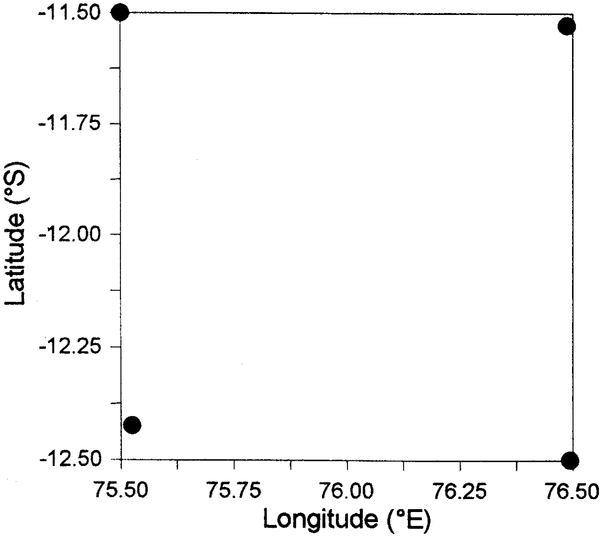
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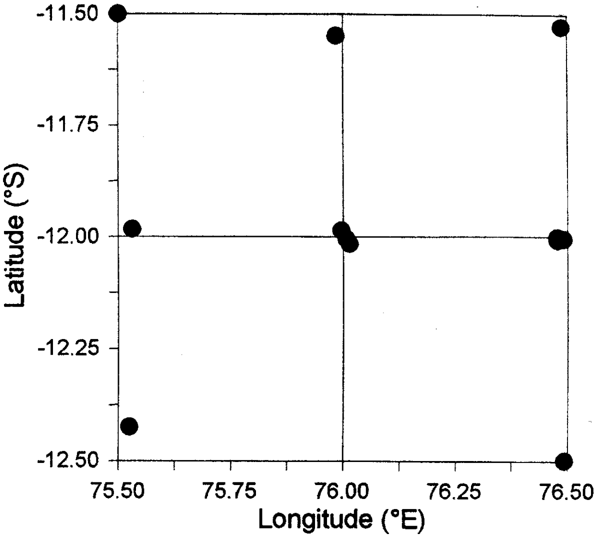
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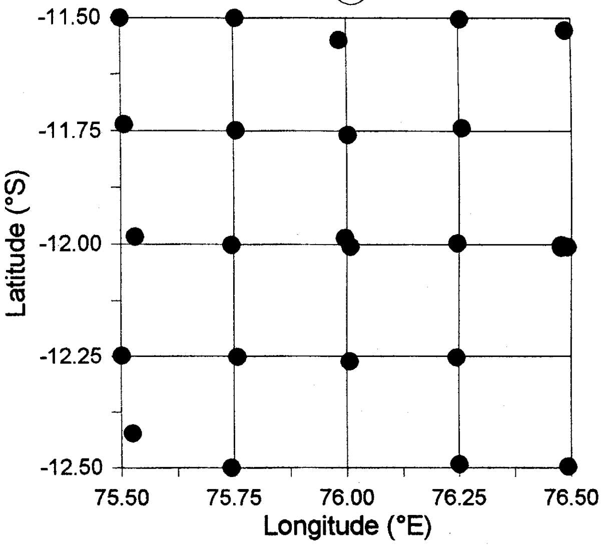
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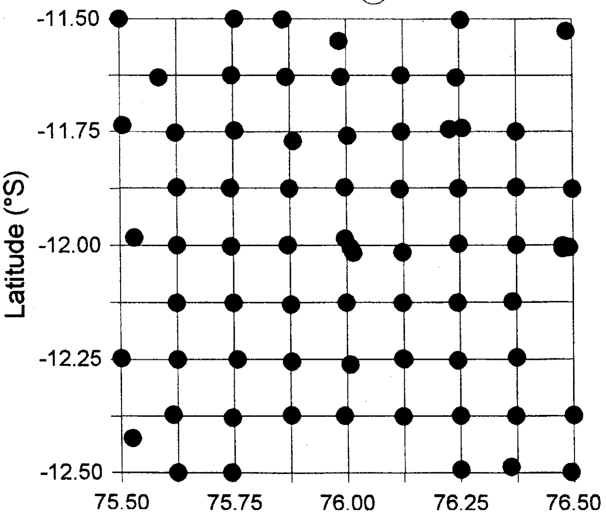
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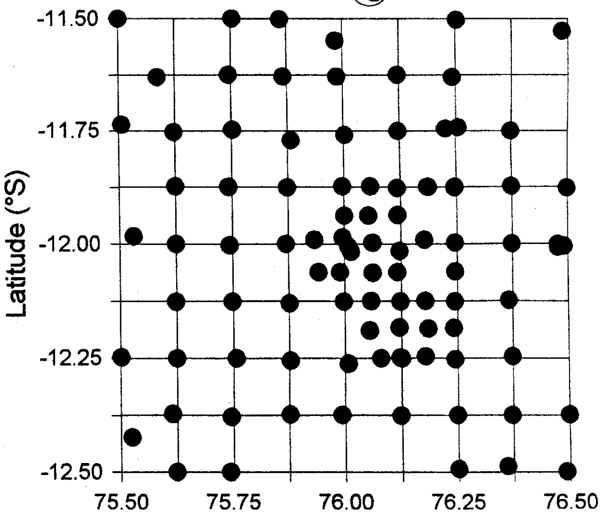
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Conclusions

Based on the approach to obtain nodule samples by means of free-fall grabs and to evaluate nodule abundance at various grid spacings, viz. 1, 0.5, 0.25, 0.125 and 0.0625°, it can be concluded that, in areas devoid of major topographic variations, sampling at 0.125° is good enough to get a fair idea of average abundance in the central Indian Ocean Basin. However, in view of the fact that nodule abundance can vary over short distances, it is recommended that the applicability of this approach be confirmed in such areas. Further, considering that data collection by one and the same sampling device has own limitations, it is recommended to supplement the observations by other data sets including continuous photography of the seafloor as well as sampling with larger box grabs and Van Veen grabs. Finally, it is recommended to run echo-sounder profiles in order to investigate sediment type and thickness.

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References

Andrews JN, Friedrich GH (1979) Distribution pattern of manganese nodule deposits in the North-east Equatorial Pacific. Mar Mining 2:1–44

Archer AA (1976) Prospects for the exploration of manganese nodules: the main technical, economic and legal problems. In: Pap IDOE Worksh, 1–6 September 1976, Suva, Fiji

Bastien-Thiry H, Lenoble JP, Rogel P (1977) French exploration seeks to define mineable nodule tonnage on Pacific floor. Eng Mining J 178:86–87

Chung J, Sharma R (eds) (1999) Proceedings 3rd ISOPE Ocean Mining Symposium, NIO, 8–10 November 1999, Goa, India

Cronan DS (1980) Underwater minerals. Academic Press, London

Frazer JZ (1977) Manganese nodule resources: an updated estimate. Mar Mining 1(1/2):103–122

Frazer JZ, Wilson LL (1980) Manganese nodule resources in the Indian Ocean. Mar Mining 2(3):257–291

Frazer JZ, Fisk MB, Elliot J, White M, Wilson L (1978) Availability of copper, nickel, cobalt and manganese from ocean ferromanganese nodules. Scripps Institution of Oceanography Ref No 78-25

Holser AF (1976) Manganese nodule resources and mine site availability. Prof Staff Study, Ocean Mining Administration, US Department of Interior, Washington, DC

Jauhari P, Pattan JN (2000) Ferromanganese nodules from the central Indian Ocean Basin. In: Cronan DS (ed) Handbook of marine mineral deposits. CRC Press, Washington, pp 171–195

Johnson DA (1972) Ocean floor erosion in the equatorial Pacific. GSA Bull 83:3121–3124

Kodagali VN (1988) Influence of regional and local topography on distribution of polymetallic nodules in central Indian Basin. Geo-Mar Lett 8(3):173–178

Kodagali VN, Sudhakar M (1994) Manganese nodules distribution in different topographic domains of central Indian basin. Mar Geotech Georesour 11:293–309

Mero JL (1965) The mineral resources of the sea. Elsevier, Amsterdam

Moore TC, Heath GR (1966) Manganese nodules topography and thickness of Quaternary sediments. Nature 212:983–985

Mudholkar AV, Pattan JN, Sudhakar M (1988) Technique and results In: Qasim SZ, Nair RR (eds) From the first nodule to the first mine site: an account of the Polymetallic Nodules Project. DOD, NIO, India, pp 29–36

Muthunayagam AE, Das SK(1999) Indian Polymetallic Nodule Program. In: Chung J, Sharma R (eds) Proc 3rd ISOPE Ocean Mining Symp, 8–10 November 1999, Goa, India, pp 1–5

Qasim SZ, Nair RR (1988) From the first nodule to the first mine site. DOD, NIO, India

Shyam RM (1982) Deep seabed mining: an Indian perspective. Ocean Dev Int Law 17(940):325–349

Siddiquie HN, Rao PS (1988) Notes and comments – exploration for polymetallic nodules in the Indian Ocean. Ocean Dev Int Law 19:323–335

Siddiquie HN, Gujar AR, Hashimi NH, Valsangkar AB (1984) Surficial mineral resources of the Indian Ocean. Deep-Sea Res 31(6–8):763–812