

TECHNIQUES AND RESULTS

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EXPLORATION STRATEGY

In the early stages of exploration, it was decided to demarcate an area of at least 300,000 sq. km and to estimate the abundance, grade and reserves of nodules.

During the first phase regional reconnaissance sampling on 100 km spacing was carried out, followed by 50 km grid sampling, thus progressively narrowing down the area for detailed exploration. Regional surveys were carried out at a widely spaced but regular grid pattern to identify the most promising areas of the ocean bed. This includes collection of nodule samples to know their abundance, regional geochemistry and also the bathymetric profiles. The sampling device was chosen according to the requirements. Free fall grab samplers were the most commonly used to obtain nodule samples in addition to the photo boomerang grabs, dredge samplers and corers. Bathymetric profiles were obtained by a precision depth recorder and the nature of the sea bed by a side scan sonar. The data were studied through geostatistical methods mainly by trend surface analyses, probability tests and variogram analyses to demarcate the 'Prime Areas'.

Detailed surveys based on the results obtained from regional surveys were concentrated only in the 'Prime Areas' and the number of stations were increased at the reduced grid spacing. At every station two sets of data are collected, i.e., wet abundance of nodules, which is the average of seven sampling devices, including underwater photographs, and the grade of nodules i.e., Ni + Cu + Co content obtained mainly by Atomic Absorption Spectrophotometer and X-Ray Fluorescence Spectrophotometer.

The surveys to identify the candidate site formed the final phase of exploration. These were carried out at a close grid spacing to detail the information acquired in previous surveys. The spacing of surveys was fixed by extrapolation/interpolation of results after statistically analysing the data of previous surveys.

The candidate mine site is the area of high potential where all the conditions required for the mine sites i.e. abundance, grade and topography are satisfied. Advance stages of surveys indicated that the new abundance obtained at a closer grid pattern is higher than that obtained with a wide grid pattern, though there is little variation in the grade of the nodules.

Upto March 1982, an area of 0.304 million sq. km was surveyed with 45 stations at different sampling intervals and 10,000 line km of bathymetric and magnetic data was collected. By March, 1983, 3.5 million sq. km. area was explored with 476 sampling stations and 78,000 line km of bathymetric and 100,000 line km of magnetic data was collected. By the end of 1984, an area of 4.12 million sq. km area was surveyed with 1164 sampling stations and by the end of March 1985 over 4.24 million sq. km area was surveyed with 1283 sampling stations and 200,000 line km of bathymetry and magnetics and about 64,000 line km of gravity data. In addition, approximately 1,000 sea bottom photos were taken by different systems and a total of 30 tonnes of bulk nodules were dredged for further metallurgical work (Table 2). By the end of 1986 the Application Area was demarcated within the surveyed area of 4.4 million sq. km with 1400 stations (6700 locations), 0.35 million line km bathymetry, 0.25 million line km magnetics and 0.04 million km gravity data.

DATA PROCESSING

The main data base was created at the National Institute of Oceanography and the steps involved are schematically presented in Figure 41. Data base generation (Fig. 42) and data management further enhances resource evaluation techniques. This necessitated the involvement of Engineers India Limited (EIL) and Metallurgical and Engineering consultants

FROM THE FIRST NODULE TO THE FIRST MINE SITE

Table 2 Quantum of Work carried out by various ships from 1981-1988.

SR No	Ship/ Cruise No.	No. of Days	No. of Stns.	Underway Data			No. of Boomerang Operations			Box/ Spade Core	Petter-son/ Vanveen Grab	Dredge oprms	Bulk Sample Collected From Dredge (in Kgs.)
				Bathy	Magnetics	Gravity	Total	BG	PBG				
				(in LKMS)									
1	GV- 86	19	34	5200	5200	---	24	14	10	--	12	--	---
2	GV- 87	20	12	5100	5000	---	13	11	02	--	17	03	50
3	GV-104	19	05	4211	4245	---	07	05	02	--	01	05	40
4	GV-105	19	12	3662	1800	---	--	--	--	--	12	--	---
5	GV-106	21	13	3860	3860	---	--	--	--	--	21	--	---
6	GV-111	20	19	5139	5139	---	60	60	--	--	03	--	---
7	GV-112	22	13	5670	5670	---	44	44	--	--	02	--	---
8	GV-113	24	18	7400	5364	---	11	11	--	--	18	--	---
9	FN- 1	48	62	11217	7292	---	341	330	11	--	08	03	10
10	FN- 2	45	34	16845	13140	---	231	194	37	03	01	10	150
11	FN- 3	45	61	8389	7637	---	259	259	--	--	33	--	---
12	FN- 4	45	42	9659	7607	---	181	131	50	01	01	29	350
13	FN- 5	45	49	12276	11541	---	288	224	64	--	04	02	200
14	FN- 6	45	63	13493	11413	---	126	63	63	--	--	--	---
15	FN- 7	45	66	11891	9602	---	420	333	87	--	--	04	15
16	FN- 8	45	21	17184	9884	---	85	63	22	--	01	44	4861
17	GR- 1	45	69	10400	7000	---	363	282	81	--	--	31	3790
18	GR- 2	45	09	14415	4975	---	44	35	09	--	--	--	---
19	GR- 3	45	73	7025	1541	---	323	240	83	03	--	31	1933
20	SS- 1	45	64	2100	10970	---	128	125	03	--	14	--	---
21	SS- 2	45	65	1000	12700	---	265	251	14	--	42	--	---
22	SS- 3	45	84	1890	6745	---	572	529	43	--	17	07	50
23	SS- 4	45	68	7623	7623	---	461	393	68	--	07	15	98
24	SS- 5	45	88	4440	5909	---	516	412	104	--	05	26	1524
25	SS- 6	45	56	10494	6136	---	335	245	90	--	--	47	914
26	SS- 7	45	65	11408	5711	---	336	313	23	--	--	24	557
27	SS- 8	45	58	11862	7656	---	368	292	76	--	01	13	1652
28	SS- 9	45	97	11081	7225	---	219	193	26	--	--	--	---
29	SS- 10	45	15	5960	---	---	14	10	04	02	03	107	12970
30	SS- 11	45	08	8132	---	---	--	--	--	02	01	79	9643
31	SS- 12	45	10	12038	---	---	04	02	02	--	02	38	8040
32	SS- 13	45	27	11615	8317	---	09	09	--	--	--	36	3548
33	SS- 14	35	27	10442	836	---	136	110	26	--	--	--	---
34	SS- 15	35	49	1500	---	---	298	226	72	--	--	--	---
35	SS- 16	35	58	2028	---	---	357	243	114	--	--	--	---
36	SS- 17	30	40	2946	---	---	100	89	11	11	11	7	25
37	SK- 6	27	17	7788	---	7178	119	85	34	--	--	--	---
38	SK- 7	45	29	13055	10690	10745	202	146	56	--	--	--	---
39	SK- 8	45	37	12768	5494	12049	207	158	49	--	--	21	731
40	SK- 11	45	72	12789	9528	7217	502	363	139	--	--	--	---
41	SK- 16	48	21	14014	10096	11261	42	31	12	06	--	08	30
42	SK- 20	45	64	13588	3822	---	303	267	36	08	03	03	---
43	SK- 23	45	79	13487	3884	8058	544	389	155	--	01	--	---
44	SK- 28	30	11	11600	7361	7670	44	32	12	--	01	--	---
TOTAL :		1712	1884	388704	258613	64178	8901	7212	1690	36	242	593	51181

- ABBREVIATIONS :
- 1) BG = BOOMERANG GRAB
 - 2) PBG = PHOTO BOOMERANG GRAB
 - 3) OPRNS = OPERATIONS
 - 4) GV = R.V. GAVESHANI, FN=M.V. FARNELLA, GR=G.A. REAY
SS = M.V. SKANDI SURVEYOR, SK=O.R.V. SAGAR KANYA
 - 5) LKMS = LINE KILOMETERS

SURVEYS FOR POLYMETALLIC NODULES
DATA PROCESSING

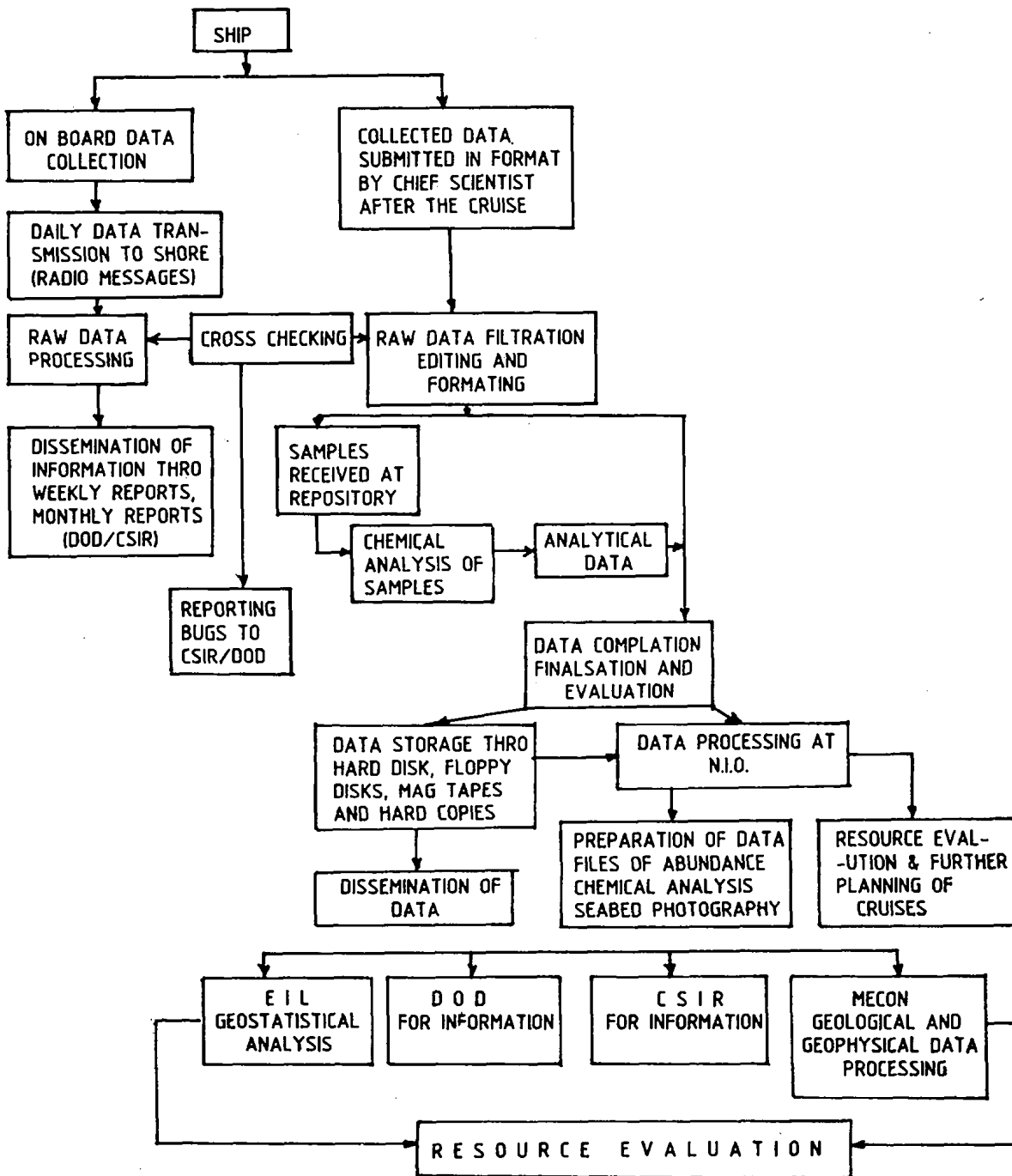


Fig. 41 Flow Chart of Data Processing.

FROM THE FIRST NODULE TO THE FIRST MINE SITE

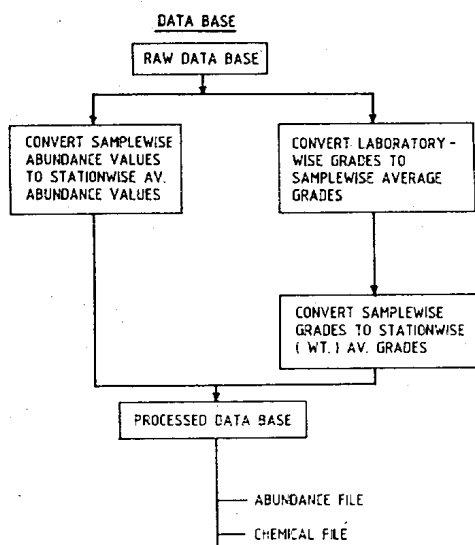


Fig. 42 Data Base Generation and Management Scheme.

(India) (MECON). In addition to these two agencies, NGRI and the Operational Research Unit (CSIR) were associated till the time the revised application was filed with the Preparatory Commission.

The main data base was generated following the different formats for the storage of data. A system of co-ordination was arrived at for the data transfer to the participating organisations for further processing and resource evaluation. Underway data processing was carried out at MECON whereas the geostatistical resource evaluation was done by EIL. EIL is associated with DOD/NIO in preparing Indian Application for submission to the Preparatory Commission for allocation of a mine site in the Central Indian Ocean. It evaluated R & D efforts in process development for metal extraction from nodules made by national research organisations like NML, RRL (Bhubaneshwar), HZL and HCL and shortlisted the potential processes for further work.

Based on the data available till November, 1983, two application areas of 150,000 sq. km each were demarcated in accordance with the Resolution II of United Nations Conference on the Law of the Sea. The two areas having equal abundance, grade, topography and resources were identified. The first application was filed with the Preparatory Commission on 12th January, 1984 for its decision to allocate to India one of the two application areas for Pioneer activities.

The processed data base containing station wise mean abundance and grades were used for the following statistical analysis by EIL.

- 1) Stationwise frequency distributions were computed for six variables - abundance, Mn, Co, Ni, Cu and grade.
- 2) Correlation studies using stationwise values were carried out for all the seven variables - abundance, Mn, Fe, Co, Ni, Cu and grade.
- 3) Variographic studies and Krigging : For grades, secondary variables known as grade accumulation were defined and the variographic computations were made in all the directions. These, in turn, were approximated by mathematical models.
- 4) Block estimations : The whole area under investigation was divided into blocks of 0.5° size. Using the variogram model parameters, each block of 0.5° was given an estimated value for abundance and grade of nodules by an optimal estimator technique 'krigging' which is an unbiased and minimum error estimator.
- 5) Impact of cut-off values : Using the block wise estimates, the impact of various cut-off values in respect of abundance and grades were also evaluated.

Further, the accuracies of estimates in relation to sample spacing were drawn and the potential areas were demarcated for close grid sampling.

The data base generated till 1986 was used for geostatistical processing and the selection of blocks for the Application Areas. Two areas, each of 150,000 sq. km were demarcated for equal commercial values (Fig. 43). A revised application was filed with the Preparatory Commission on July 20, 1987.

To determine the grade, the total percentage of Ni+Cu+Co provides the index. The average percentage of nodules in the Pioneer Area was found to be 2.31% (Ni+Cu+Co). Of these, percentage of nickel was 1.12, Copper 1.05, Cobalt 0.14. The average percentage of manganese was 24.

ABUNDANCE, GRADE AND RESOURCES IN PIONEER AREA OF THE CENTRAL INDIAN OCEAN BASIN.

	Total Application Area	Area A	Area B
Area (sq.km)	300,000	150,000	150,000
Average abundance (kg/m ²)	4.51	4.39	4.45
Total nodules in (million tonnes)	1335.0	676.5	658.5
Combined metal Values of Ni+Cu+Co (million tonnes)	21.84	10.88	10.96

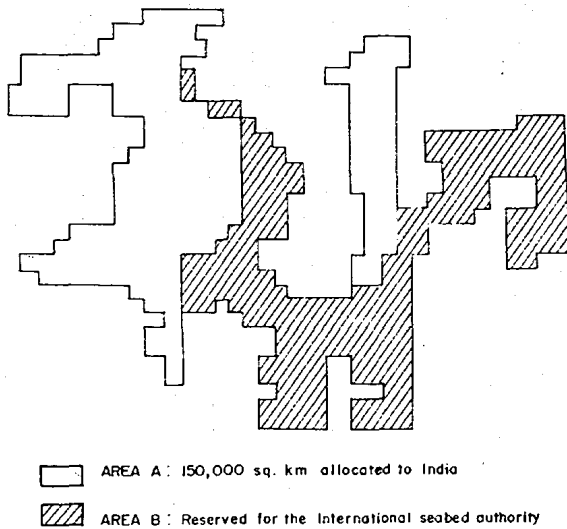


Fig. 43 Illustrative Chart Showing The Mine Site allocated to India in The Central Indian Ocean.

BATHMETRY

Bathymetry is an important factor governing the distribution of polymetallic nodules. Bathymetry of the Indian Ocean was carried out by 3.5 and 12 KHz echosounders. A total of 388,00 line km of bathymetry has been carried out so far. With the help of these bathymetric records 100 m bathymetric contour interval maps were prepared at MECON, Ranchi.

MAGNETICS

Magnetic measurements were carried out by a proton precision magnetometer and 250,000 1km of magnetic data from Central Indian Ocean have been collected. Magnetic anomaly maps were prepared at MECON (Ranchi), by the NIO scientists and the data were utilised for crustal structure interpretation.

DREDGING

Extensive dredging has been carried out by different types of indigenous dredges and a total of 51 tonnes bulk samples were collected during different cruises. These bulk samples were sent to the different metallurgical laboratories for developing metal extraction processes. About 2.5 tonnes of nodules were sieved on board to find out their size distribution. Nearly 75 - 80% of the nodules are in the range of 2-6 cm and confining the use of nodules of these sizes for metallurgical purposes is expected to give higher metal yield.

SAMPLING

Sampling was carried out by using Preussag freefall grabs. Initially sampling was carried out at 100 km interval. Later this interval was reduced to 50 km, and 12.5 km. Alongwith the boomerang grabs, photoboomerang grabs were also used for underwater photographs to know the distribution of nodules (Fig. 30). A Benthos underwater towed camera was also used for continuous photography. From the underwater photographs, nodule coverage, size and other associated biological features on the sea floor were studied. To date 7,000 boomerang and photoboomerang operations were carried out. Besides, a number of Pettersson grab, Vanveen grab, gravity cores and spade cores were used for the sediment sampling.

CHEMICAL ANALYSIS

Since the number of nodule samples was very large, it was felt that the results of the chemical analysis would be more rapidly available if they were distributed to various laboratories and in order to ensure reliability of the results an intercalibration exercise was undertaken in advance by distributing a standard Indian Ocean sample to the participating laboratories. These laboratories were Hindustan Copper Ltd (HCL), Hindustan Zinc Ltd (HZL), National Metallurgical Laboratory (NML) and Regional Research Laboratory, Bhubaneshwar (RRLB). With this approach, it was possible to analyse some 4700 samples for Mn, Fe, Co, Ni and Cu at a reasonably rapid pace.

R & D EFFORTS IN EXTRACTION METALLURGY OF POLYMETALLIC NODULES

BACKGROUND :

R & D efforts for extraction of metals from the nodules was started by leading research centres in the country as early as 1983-84. Regional Research Laboratory (Bhubaneshwar), National Metallurgical Laboratory (Jamshedpur), Hindustan Zinc Ltd. (Udaipur), Hindustan Copper Ltd. (Khetri) took the lead in initiating such efforts. A wide variety of processes were studied by these centres which may broadly be classified as :

- Acidic sulphate medium based processes (H_2SO_4 leach, SO_2 roast leach etc.)
- Ammoniacal medium based processes (roast reduction leach $FeSO_4/SO_2$ reduction leach etc.)
- Nodule smelting processes.

- Chloride medium based processes.
Evaluation of R & D work on these routes by EIL in early 1986 led to identification of following short listed processes considered to have potential for further development :
- Roast reduction ammoniacal leach (NML).
- SO₂ roast leach (RRL-B)
- Acid pressure leach without reductant (RRL-B).
- Ammonia SO₂ leach (RRL-B).
- Acid pretreatment leach - pressure leach (HZL).

The other routes studied were associated with various limitations e.g. high chemical consumption, insufficient process development.

PRESENT EFFORTS :

After initial evaluation and short listing of process routes, RRL-B, NML and HZL continued their efforts on the respective routes. HCL is also doing exploratory work to generate necessary data for a review. Considerable progress has now been made at these laboratories for conceptualisation of the flow schemes being followed at different laboratories. Efforts are now being made to optimise the process parameters. It is expected that during 1988, 2 to 3 process routes will be selected for piloting. The pilot plant will have the capacity of 250 kg/day.

RESEARCH AND DEVELOPMENT SPINOFFS

During the execution of the project, many developmental techniques and studies were carried out by the project personnel. These studies being directly related to the project are expected to yield results in improving exploration techniques and contribute to the understanding of the detailed scientific studies such as the distribution pattern, growth rate, mechanism of incorporation of elements into nodules and the genesis of nodules.

Dredge Development

For bulk sampling of the nodules in the early cruises, the standard bucket dredges were utilised. But they proved to be inefficient due to their incapability to retain the nodules during dredging and hauling up operations. To improve the efficiency of the dredge and in turn to obtain more nodules in a given dredge, designs were developed with the technical assistance of Central Water and Power Research Station, Pune. While improving the dredge design, their efficiency was directly checked in the field continuously.

Photo-Sledge Development

To supplement the data from the photoboomerang operations, a continuous photography system was developed. To mount the cameras, flash and other accessories a towing frame was devised and it was tested with the technical assistance of Ocean Engineering Centre of IIT, Madras. It was important that the towing body should be hydrodynamically stable to operate at 5000-6000 m depth with a 5-7 m clearance from the sea-bottom.

Geochronology Laboratory

This laboratory consists of sophisticated equipments like spectrometer, α , β and γ counting systems, and multichannel analysers.

The U-Th series isotope and disequilibrium studies were carried out on a few ferromanganese encrustations and nodules to understand their growth histories. The results indicate that it is simultaneous from both the sides (top and bottom) of nodules. However, the magnitude of the metal fluxes and the growth rate or the accumulation rate of oxides vary considerably on both sides. The Indian Ocean nodules fall in the category of slow growth where the maximum growth recorded is not more than 3 mm/million years in contrast to the Pacific nodules where growth rates upto 15 mm/million years are recorded. The ferromanganese encrustations studied showed a very slow growth rate of the order of 1-1.5 mm/million years and are of hydrogenetic in nature.

Pore Water

Pore water studies play an important role in understanding the diagenetic reactions taking place at sediment water interface and their role in the formation of manganese nodules. As a part of these studies, interstitial water squeezer was fabricated based on an existing design (Fig. 44). Interstitial waters from 3 cores were collected with this squeezer from the manganese nodule area in the Central Indian Basin and were analysed for nutrients. Nitrification with intermediate low nitrate and high organic carbon was found in the mottled zones of the pelagic cores. Gradual increase in the phosphate profiles is related to the mobilization of iron host oxyhydroxides.

While working with the above squeezer, some problems were encountered. To overcome these, a modified teflon lined squeezer was designed. The modified version facilitates the extraction of pore water sample for trace metal analysis without exposure to the atmosphere and oxidation effects.



Fig. 44 Modified squeezer for pore water extraction from sediments.

Phosphorites

During the third test cruise from Malta to India of the ORV Sagar Kanya phosphatised limestones were recovered by dredging from the flanks of the Error Seamount, Northern Arabian Sea. P_2O_5 content of these phosphorites ranged from 18 to 21%. Scanning electron microscope, equipped with X-ray analyses investigations indicated that the cyanobacteria and elemental sulfur are the important components in these phosphorites and that bacteria are responsible for phosphatisation.

Biostratigraphy :

Ichthyoliths, the phosphatic micro-remains of fishes in the nuclei and substrates of nodules and encrustation indicate Paleogene age. Though ichthyoliths of Paleocene, Eocene, Oligocene and lower Miocene are encountered in various samples, the majority of nuclei and substrates are of Eocene (> 35.0 million years) and lower Miocene (> 15 million years) age.

Lithostratigraphy and biogenic structures of the substrates and nuclei of nodules and encrustations suggest that they are hardened pelagic clays (hard grounds) with scour marks, ripple marks and omission surfaces. The hard ground suggest scouring and exhumation of hardened sea floor by the abyssal current, probably during mid-Oligocene and mid-Miocene time in the Central Indian Ocean Basin.

Hydrothermal mineralisation :

The expertise developed during the progress of nodules project was utilised for searching other types of deep sea mineral deposits such as hydrothermal deposits along the Indian Ocean Ridge system. The project participants have organised and taken part in

four cruises, two in collaboration with FRG scientists on FS SONNE and two on ORV SAGAR KANYA on the Carlsberg Ridge and Mid Indian Ocean Ridges. The area explored lies between $6^\circ N$ to $22^\circ S$. Hydrothermal encrustation with todorokite as its principal mineral was recovered in two locations. Water column indicators like thermogenic methane and total dissolved manganese were high in one area ($22^\circ S$) which also had basalts depleted in potassium indicating possible hydrothermal source. The Ocean Floor Observation System (OFOS) revealed young tectonic fissures suggesting seafloor spreading activity in the area. Factor analyses of sediment elemental data also indicated the probable hydrothermal factor much similar to the East Pacific Rise sediments.

Cosmic spherules

The deep sea regions of the world oceans are the largest storehouses of extraterrestrial matter. Cosmic particles from deep seas although of small sizes, provide information on several aspects such as the role of comets in the $>10^4$ tons of dust accreted by the earth, and catastrophic events such as mass extinctions.

During the course of investigations for cosmic dust in the Central Indian Ocean Basin (Fig. 45) it is found that larger concentration of extraterrestrial matter accumulate in areas of lower sedimentation rates such as the siliceous oozes and pelagic clays. In one such location, a very large deposit of cosmic dust has been found. Preliminary observations reveal that the matter comprising this deposit has not been subjected to the heating process during entry into the earth's atmosphere, and therefore retains unmelted primordial matter.

Underwater array system for bathymetry :

The use of a transducer array system in the field of acoustic transmitting/receiving system, particularly



Fig. 45 Cosmic spherules extracted from CIOB sediments.



Fig. 46 (a) Deep - sea mooring being recovered on Sagar Kanya.



Fig. 46 (b) Sediment trap on deck of Sagar Kanya.

for seabed surveys has great importance. Though workers in this field developed an array system to get better directivity, the ideas in connection with the development of array system of higher band width did not materialise to full extent, especially in the field of linear acoustics.

Therefore a study was undertaken for a special geometrical array arrangement of circular disk radiators. The array is well known as "Coaxial circular array." It consists of three concentric circles of different radii. Highly directive beam patterns were obtained at different frequencies (3.5 KHz, 12 KH, 20 KHz, 30 KHz, and 60 KHz) with symmetrical beams. Mutual interaction between elements was studied at different elements to take different shading techniques and as well as uniform illumination shading method has also been developed in the form of 'Multiplative Array' for sidelobe suppression.

Sediment trap

The study of flux, size distribution, composition and mineralogy of particulate matter is of prime importance in many fields of oceanography. The downward flux of particulate matter is dominated by large particles or particle aggregates which are collected by sediment traps (Fig. 46 a & b). The study

of geochemistry of particulate matter in the sea will help us to understand the flux of metals of manganese nodules on the sea floor and also the origin of manganese nodules.

As the technology involved in fabricating and deploying sediment trap and moorings is very complicated, the work was planned in three stages 1) deployment in shallow waters (100 m) on the continental shelf to understand the terrigenous contribution of particles. 2) deployment in the Arabian sea to study the contribution of major rivers like the Indus river and 3) deployment in the Central Indian Ocean in the Manganese nodule area.

In the first stage, the sediment traps and moorings were fabricated indigenously and deployed throughout the monsoon of 1985.

The second stage is under progress and is being carried out with the help of experts from other disciplines in NIO and the Federal Republic of Germany. Data have been collected for more than one year and results are being interpreted. In the final stage, sediment traps will be deployed in the Central Indian Ocean Basin along with the other instruments like meteorological buoys and current meters in the proposed deep sea mooring programme for collection of base-line environmental data.