First nodule to first mine-site: development of deep-sea mineral resources from the Indian Ocean

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Polymetallic nodules found on the deep seafloor (>4000 m water depth) have been recognized as an alternative source for certain metals, when land deposits get exhausted. Spread over millions of square kilometres on the seafloor of all the oceans, these deposits contain as much as 40% of combined metals (Mn + Fe + Cu + Ni + Co) and are generally found in the international waters (beyond the exclusive economic zone of any country). India is one of the eight 'Pioneer Investors' in the world with exclusive rights over an area of 75,000 sq. km in the Central Indian Ocean for the exploration and future exploitation of these mineral deposits; the others being France, Russia, Japan, Korea, China, Interoceanmetal, Poland and Germany in the Pacific Ocean. Ever since the recovery of nodules in 1981 in the equatorial Indian Ocean, India has conducted extensive exploration resulting in the identification of first-generation mine-site; assessment of potential environmental impact, creation of data for mining; as well as development of technologies for metallurgical processing and mining of the deep-sea minerals. Some of the key factors responsible for the success of the programme have been multi-agency networking, mixing experience with youth and emphasis on high-quality research. The programme has contributed in terms of science and policy, publications and patents, capacity building and diversification into exploration of other marine minerals. This article traces the development in the capabilities of deep-sea mineral exploration and exploitation in the Indian Ocean.

Keywords: Deep sea, exploration, mine-site, polymetallic nodules, seabed minerals.

Development of seabed mineral resources

SEABED minerals are being looked upon as the alternative source for metals in the future, especially in view of the depleting land resources and increasing industrial demands[1]. These minerals are associated with different topographic features (Figure 1), ranging from the placer minerals along the coasts, phosphorites on the shelf, cobalt crusts on the seamounts, sulphides on the mid-oceanic ridges and polymetallic nodules on the deep abyssal seafloor. Among these, the minerals for which economic assessment has been carried out are the coastal placer minerals that lie within the exclusive economic zone (EEZ) of different countries, and the polymetallic nodules that generally occur in the 'area' outside EEZ of any country and are regulated by the International Seabed Authority (ISA) established under the UN Law of the Sea. According to the stipulations laid down by ISA,

eight 'Pioneer Investors' have been given exclusive rights for exploration. Among these, seven have rights in the Pacific Ocean (France, Russia, Japan, China, Interoceanmetal, Poland, Korea and Germany) and one in the Indian Ocean (India)[2] (Figure 2).

The criteria for nodule mining, as laid down by the United Nations Ocean Economics and Technology Branch (UNOET)[3], are as follows:

- Cut-off grade : 1.8% Ni + Cu
- Cut-off abundance : 5 kg/m^2
- Topography : Acceptable (considered as <3° slope)
- Life of a mine site : 20 years
- Annual recovery rate : 3 million t/yr.

The factors in favour of mining of polymetallic nodules are: (i) they occur in millions of tonnes in all the oceans of the world; (ii) they are sources of several metals (Mn, Fe, Ni, Cu, Co, Pb, Zn, etc. aggregating up to 40%); (iii) they are loosely strewn on the seafloor and so are easy to mine, and (iv) they lie in the international waters and do

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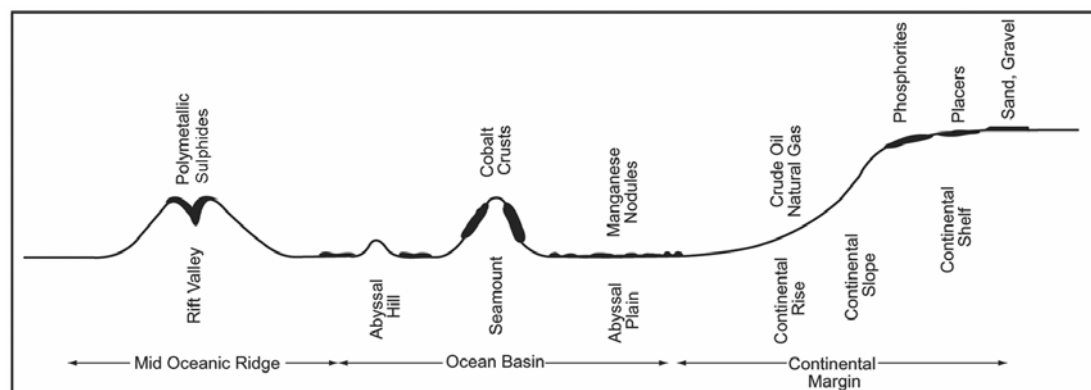e-mail: rsharma@nio.org

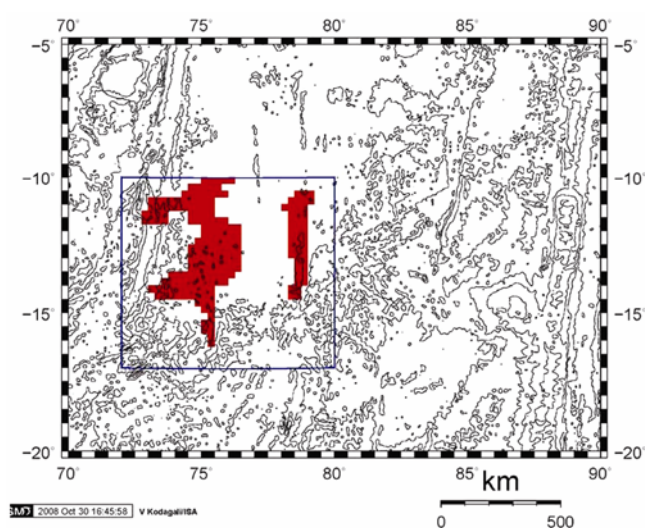**Figure 1.** Distribution of marine minerals on different seafloor topographic features[46].

Figure 2. Area allotted to India as a Pioneer Investor in the Indian Ocean (www.isa.org.jm).

not belong to anyone by right unless claimed through ISA. The limitations of mining these resources are: (i) they occur under extreme conditions, such as 500 bar pressure, 2°C temperature and no natural light; (ii) at large distances from the shore – thousands of kilometres, and (iii) at great working depths of > 4 km.

First century of nodule exploration

It was during an expedition of *H.M.S. Challenger* (21 December 1872–24 May 1876) that sailed from Portsmouth, England with a contingent of physicists, chemists, biologists and navigators, circumnavigated the globe and sounded the ocean bottom to a depth of 26,850 ft, that the first known samples of polymetallic nodules were collected with crude nets generally used for collection of biological samples from the seafloor. The expedition leader, C. W. Thomson, described the dredge haul of

7 March 1873 as 'peculiar black oval bodies about 1 inch long', whereas the chemist, J. Y. Buchanan revealed that they were 'almost pure manganese oxide' and 'Mn is of great commercial importance…' (www.wikipedia.org/wiki/HMSChallenger).

Later, the Albatross expedition (1899–1900) made extensive nodule collection in the Pacific (7–15°N) on the west coast of North America. However, it was Mero[4] who described the economic potential of manganese nodules, and predicted that mining would start in 20 years time. This caught the world's attention into developing polymetallic nodules as a resource for metals in the future. Subsequently, International Decade of Ocean Expedition sponsored the 'Fe–Mn deposits on ocean floor' conference at Lamont Doherty Geological Observatory (January 1972) to collate existing data on nodules. This was followed by studies that provided the basic data on geochemistry, mapping, environmental, legal and technical aspects (National Science Foundation, unpublished), data and methods[5], and factors which control the distribution of Fe–Mn nodules[6].

By this time, several consortia began putting together designs of nodule mining systems, such as the continuous line-bucket system (several buckets moving in a line), hydraulic lift system (airlift or pump lift by creating pressure difference) and modular mining system (several modules collecting nodules)[7]. By the late 70s, basic data were available on the genesis of manganese nodules[8] as well as the prime areas in different oceans[9] as follows:

- South Pacific : 1.0 million sq. km
- North Pacific : 4.2 million sq. km
- Indian Ocean : 0.5 million sq. km
- Atlantic Ocean and others : 0.85 million sq. km.

A fairly detailed description of the distribution of manganese nodules in world oceans was provided by Cronan[10], which was subsequently followed by a more comprehensive collection of information on nodules[11].

Exploration of Indian Ocean nodules

One of the early descriptions of nodules from the Indian Ocean was by Glasby[12] on geochemistry of manganese nodules from NW Indian Ocean, whereas more comprehensive data were published by Frazer et al.[13] in their report on availability of Cu, Ni and Mn from ocean Fe–Mn nodules based on data collected at Scripps Institution of Oceanography (SIO), USA. However, it was Frazer and Wilson[14], who provided a detailed description of manganese nodule resources in the Indian Ocean from five regions, based on 7000 samples and 700 analyses. Using the criteria of average 2.4% of Cu + Ni + Co, cut-off grade of 1.8% Cu + Ni + Co and cut-off abundance as 5 kg/m^2, they concluded that 'the Central Indian Ocean Basin offered potential sites for first-generation mine-site between 10°S and 16°S owing to low sedimentation rate (< 3 mm/1000 yrs)[15] and high Cu, equal or more than Ni'.

As the awareness about the potential of polymetallic nodules was growing in other parts of the world, the International Indian Ocean Expedition (IIOE) had already been launched. It was a cooperative multi-ship expedition (1960–65) in which 40 ships participated from 20 countries and collected physical, chemical and biological data from 270 expeditions[16]. This led to the formation of the National Institute of Oceanography (NIO), Goa (1966), with one of the objectives being 'to explore mineral resources of the seas around India'. Initially, the researchers at the Institute were involved with offshore surveys for oil and gas, and exploration of near-shore placer deposits[17].

By the end of 1980, with the inputs from SIO data and other sources, the first expedition for polymetallic nodules was launched on-board R. V. Gaveshani (1900 t), which was fitted with survey equipment such as satellite navigation, side-scan sonar, deep-sea echo-sounder, and sampling equipment such as deep-sea winches, grabs, freefall grabs, deep-sea pinger, dredges and gravity corer[18].

The first nodule samples were recovered on 26 January 1981 from the Equatorial Indian Ocean, which marked the beginning of the Indian polymetallic nodule programme. What had started as an exploratory expedition, soon developed into a national programme for extensive exploration and lead to the identification of the first-generation mine-site (FGM) as a result of 72 expeditions (aggregating to more than 7 years for exploration at sea) on-board specialized research vessels, chartered from several countries, fitted with state-of-the-art equipment available at that time. The schedule of activities from the collection of the first nodule to demarcation of FGM is given in Table 1.

Factors contributing to the success of the programme

Multi-agency networking

Involvement of several research and development organizations for different components of the programme, depending on their expertise (Table 2), was one of the key factors that contributed towards the success of the programme.

Mixing experience with youth

The experience of the available manpower at the time of initiation of the project (1981–82) was combined with the recruitment of a substantial number of younger professionals in different fields, with an emphasis on exploration and mapping of the resource (Table 3). Back-up by the technical manpower (mechanical, electronics and survey) provided the right impetus for the success of the exploration activity. Within a few years, the experienced manpower with either short-term or partial involvement in the project (owing to earlier commitments and interests in other fields) was replaced by the younger scientists with full-time involvement in the project.

Creating required infrastructure of equipment

Utilization of specialized research vessels equipped for working in high seas for long durations, acquisition of the

Table 1. Schedule of major activities in the Indian nodule exploration and environmental programmes

Schedule	Activity
1981	First nodule picked from the Equatorial Indian Ocean
1982	India recognized as a Pioneer Investor under UNLOS
1987	Area allocated to India (150,000 sq. km) in the Central Indian Ocean
1994	20% area relinquished (as per ISA requirement)
1996	10% area relinquished (as per ISA requirement)
1997	Indian deep-sea environment experiment
2001–2005	Monitoring the restoration of environment
2002	20% area relinquished (as per ISA requirement)
2003–2007	Environmental variability study for nodule mining
2007	First-generation mine-site (FGM) identified
2007–2012	Exploration and environmental data collection in FGM

Table 2. Involvement of R&D organizations for different components of the programme

Component	Organization
Exploration and resource evaluation	National Institute of Oceanography (NIO), Goa
Environmental data collection	NIO, Goa
Chemical and mineralogical analysis	Geological Survey of India, Kolkata; Indian Bureau of Mines, Nagpur; Hindustan Zinc Ltd, Udaipur
Metallurgical process development	Regional Research Laboratory, Bhubaneshwar; National Metallurgical Laboratory, Jamshedpur; BARC, Mumbai
Mining technology development	Central Mechanical Engineering Research Institute, Durgapur; Central Mining Research Institute, Dhanbad; National Institute of Ocean Technology, Chennai
Data archival and mine-site identification	Engineers India Ltd, Delhi

Table 3. Discipline-wise break-up of experienced and young members of the programme[18]

Discipline	Experienced personnel	Young recruits	Total
Geology/geophysics	15	23	38
Mechanical/Electrical Engineering Instrumentation	7	11	18
Marine survey	3	7	10
Physics	0	6	6
Biology	2	2	4
Chemistry	0	2	2
Ocean engineering	0	2	2
Total	27	53	80
Average age (yrs)	35 (approx)	25 (approx)	–
Extent of involvement	Short-term/partial	Long-term/complete	–

state-of-the-art equipment and training of manpower in these resulted in the confidence in data that were generated, as they were acceptable by any international standards owing to the techniques used. These included equipment that were tethered, freefall, deep-towed, remotely operated and moored on the seafloor. Integrating satellite navigation and position fixing with multibeam bathymetry survey system, as well as sampling equipment such as freefall grabs, box corers and dredges yielded the quality and quantity of data required for resource evaluation and mine-site identification (Table 4). In addition to sample collection and detailed bathymetry surveys, the distribution characteristics of nodules and their associated features on the seafloor (Figure 3) were analysed with underwater photographs to provide visual (ground truth) data. These data would also be used as inputs in the design and operation of nodule collection device of the deep-sea mining system, as well as in planning of nodule mining operations.

Emphasis on high-quality research

In addition to the identification of mine-site in the Central Indian Ocean Basin (CIOB), the scientists were encouraged to specialize in different aspects of marine research and publish in international scientific journals, which not only gave a global recognition to the individual scientists, but also to the Institute and the country for contributing towards the understanding of the deep-sea processes. The allied research conducted in addition to

exploration activities, resulted in over 250 publications in *SCI* journals and several international patents in fields as diverse as nodule and sediment geochemistry, micropalaeontology and palaeo-oceanography, volcanology, geophysics and plate tectonics and planetary geology[19–25].

Development of data for nodule mining

The critical parameters for nodule mining are:

- Abundance (quantity/unit area)
- Grade (metal value)
- Bathymetry (seafloor topography)
- Distribution characteristics
- Environmental setting.

Mining impact estimates show that for mining, 3 mt/yr with an average abundance of 5 kg/m^2, the total area disturbed would be 600 sq. km/yr. If the lifetime of a mine-site is 20 years, it would be $600 \times 20 = 12,000$ sq. km $= \sim 120 \times 100$ km $= 1.08° \times 0.9°$.

This area is not significant as it is just a small fraction of the total area covered by any ocean. However, the ratio of coverage of sediment to nodule on the seafloor is known to be 90 : 10, and considering a minimum penetration of the nodule collector into the sediment as 10 cm, the total volume of sediment disturbed in 20 years will be

Area $\times$ depth $\times$ coverage $= 540 \times 10^5$ m^3/yr or

108×10^7 m^3.
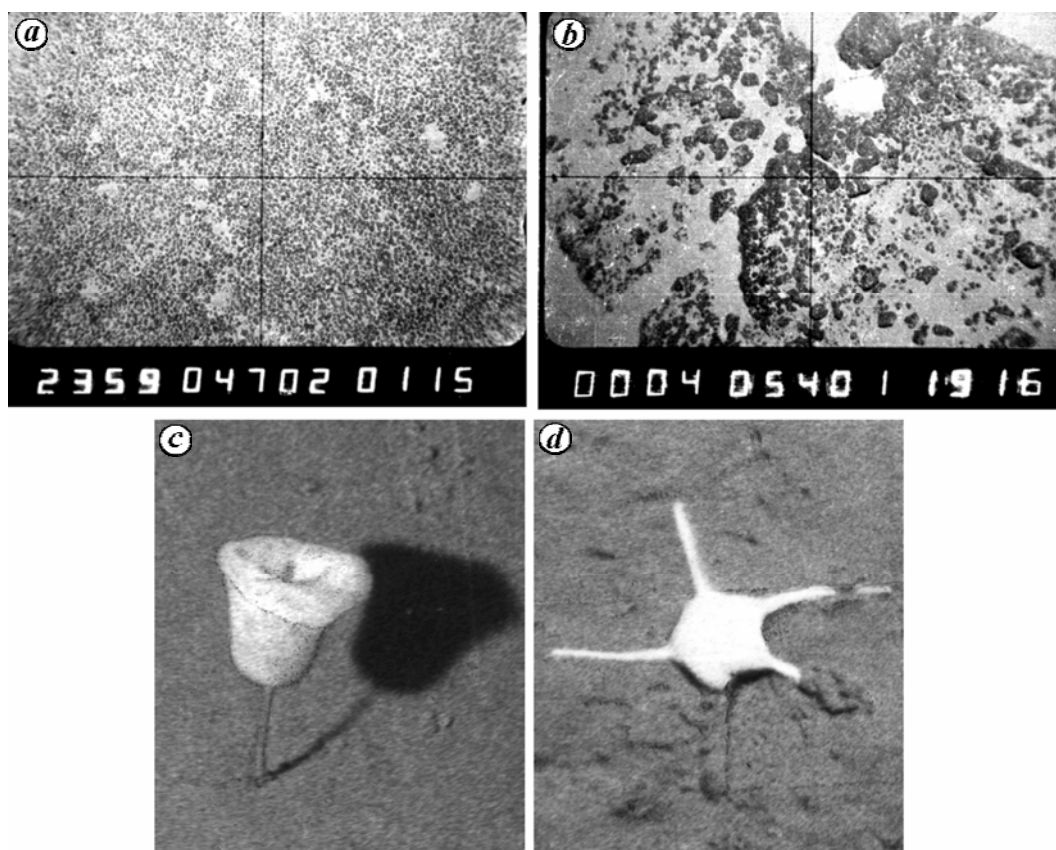
Figure 3. Seafloor photographs with dense polymetallic nodules (*a*), rock outcrops/ferromanganese crusts (*b*), a sponge (*c*) and a star fish (*d*) in the Central Indian Ocean Basin.

Table 4. Quantum of data collected for resource evaluation and mine-site identification

Area surveyed	> 3 million sq. km
Sampling	> 2500 locations
No. of sampling operations	~ 11,000
Sampling grid	6.25–111 km
Bulk nodule collection	200 t
Echosounding	500,000 lkm
Multibeam bathymetry	> 300,000 sq. km
Seabed photography	> 50,000 photos
Ships used	8 (Indian and foreign)

Source: NIO/PMN databank.

It is this volume of sediment which is expected to be responsible for a large-scale impact on the benthic environment. Hence, ISA has laid down certain requirements as a part of the statement of environmental impact assessment from the potential contractor, which include the following data/information:

- Baseline data in the proposed mining area
- Test and reference sites for environmental monitoring
- Results of simulated impact experiment
- Expected environmental impact due to mining
- Critical parameters for monitoring impacts
- Proposed measures to minimize the effects.

For this purpose, data on baseline water column characteristics were collected over the entire CIOB[26] as follows:

- Meteorology : 600×900 km
- Temperature, salinity : 600×900 km
- Currents (three levels/locations) : ~200 days
- Bottom currents in test area : ~ 200 days
- Productivity and chlorophyll : 600×900 km
- Chemical characteristics : 600×900 km.

Similarly, the following data were collected of the seafloor characteristics in five selected areas (of 10×10 nautical miles) in CIOB:

- Echosounding : 300 km $\times$ 5 areas = 1500 km
- Sediment + nodule samples : 13 locations $\times$ 5 areas = 65 stations

Based on these data, the seafloor environmental conditions were evaluated (Table 5) and two areas were designated as test (A1) and reference (T1) areas[27].

In order to simulate conditions similar to mining, a benthic impact experiment was conducted in a strip of 200×3000 m at 5400 m depth in the test area using a

hydraulic device. In all, 26 tows were conducted in 9 days for a total of 42 h along 88 km distance during which 3555 t (wet) or 580 t (dry) sediment was re-suspended. The results showed that suspended matter increased during the experiment and migrated laterally into the adjacent areas, as observed from the sediment trap data collected at different locations around the experimental strip[28].

This was followed by a systematic long-term monitoring programme to evaluate the restoration of seafloor environmental conditions after the mining experiment, as follows:

- Baseline (1996)
- Pre-mining (1997)
- Post-mining (1997)
- Monitoring-1 (2001)
- Monitoring-2 (2002)
- Monitoring-3 (2003)
- Monitoring-4 (2005).

The major environmental parameters analysed during the monitoring phase were:

- Sediment thickness and nodule distribution
- Sediment size and mineralogy
- Shear strength and water content
- Sediment geochemistry
- Pore-water geochemistry
- Sediment biochemistry
- Bacterial diversity and abundance
- Fungal diversity and abundance
- Meiofauna diversity and abundance
- Macrofauna diversity and abundance.

The salient findings after 7 years of monitoring were that whereas the benthic conditions were being restored gradually, the degree of restoration was different for each parameter and that the natural variability had masked the artificial disturbance over a period of time[29]. Similarly, long-term observations were also made in the entire nodule area of CIOB, on an inter-annual basis, to evaluate the environmental variability of all the parameters.

The results show that although there will be an initial impact on the seafloor environment due to mining of

nodules, over a long term, the natural variability would restore the environmental conditions. Moreover, the area of mining would be so limited that it would be a small fraction of the total area covered by the ocean, and so the impact is not expected to affect large areas of the marine environment, especially if certain measures can be taken in designing and operating the mining system, as follows:

- Minimize sediment penetration
- Restrict sediment dispersal to seafloor
- Induce high rate of sedimentation
- Minimize nodule–sediment transport to surface
- Discharge tailings below oxygen minimum zone
- Treat tailings before discharging.

The other critical environmental inputs being evaluated for design and operation of the mining system are as follows:

- Atmospheric – wind, rainfall, cyclone
- Surface – waves, temperature, currents
- Water column – currents, temperature, pressure
- Seafloor – topography, micro-topography, slopes
- Sub-seafloor – sediment thickness, shear strength
- Mineral characteristics – abundance, grade, size
- Associated substrates – sediments, rocks, crusts.

Development of technologies for metallurgical extraction and mining

A process based on pyro-metallurgical leaching has been developed, in which the first stage (leach-I) leads to dissolution of cobalt and the second stage (leach-II) is used to dissolve mainly copper and nickel. A pilot plant with a capacity 500 kg/day has been set up at Hindustan Zinc Ltd, Udaipur[30]. Also, a crawler being designed as a prototype for nodule mining has been tested offshore at 400 m water depth and the system is being upgraded for higher depths[31]. These developments have put India ahead or at par vis-à-vis the other Pioneer Investors (Table 6).

Major outputs of the programme

In addition to identification of mine-site and creation of an environmental database for mining, there have been several other outputs of the polymetallic nodules programme in the Indian Ocean.

Science and policy

- Evaluating geological history[32], seafloor characteristics[33] and sediment properties[34].
- Mapping the diversity of benthic organisms[35].
- Identifying new species of fungi and bacteria[36,37].
- Providing advisories to ISA[38,39].

Table 5. Data compiled for selection of test and reference areas[27]

Area	Average abundance (kg/m^2)	Average depth (m)	Average slope (degree)
T1	1.94	5217	1.1
R1	1.14	5330	1.4
T1	2.10	5327	1.1
T2	3.41	5217	1.7
R2	5.05	5297	1.7

Table 6. Development of mining and processing technologies for polymetallic nodules in India vis-à-vis other Pioneer Investors

Pioneer Investor	Mining technology	Processing technology
France[47]	Model studies on self-propelled miner with hydraulic recovery system	Tested pyro and hydro-metallurgical processes for Ni, Cu, Co
Japan[48]	Passive nodule collector tested at ~ 2200 m depth	Developed a process to recover Cu, Ni, Co
India[49]	Design includes flexible riser and multiple crawlers, Crawler tested at ~ 410 m depth	Tested 3 possible routes, Pilot plant set up for 500 kg/day for Cu, Ni, Co
China[49]	Includes rigid riser with self-propelled miner	Developed a process to recover Mn, Ni, Cu, Co, Mo
Korea[49]	Design includes flexible riser system with self propelled miner developed 1/20 scale test miner	(Not known)
Russia[49]	Collector and mining subsystems in conceptual stage	Recovered Mn, Ni, Cu, Co from nodules
IOM[49]	Conceptual design includes nodule collector, buffer, vertical lift system	Economic assessment of different schemes
Germany[49]	Considering innovative concepts for mining	Considering different options for processing

Publications and patents

- Special issues of international journals dedicated to the results of the programme (*Marine Georesources and Geotechnology*, 2000 and 2005; *Deep-Sea Research-II*, 2001).
- Publications in international technical journals.
- Articles in books written by experts.
- Presentations at national and international symposia and conferences.
- Patents of new products and processes developed under the programme.

Capacity building

- Training of fresh graduates and postgraduates in analytical techniques.
- Internship of foreign students with hands-on experience in marine research.
- Guiding of PhD students with research problems related to polymetallic nodules and mining.
- Dissertations conducted by college and university students on live projects.

Diversification into exploration for other marine minerals

EEZ mapping and phosphorites

An area of 2.2 million sq. km is being surveyed around the coastline of India for mapping and locating the occurrence and extent of mineral deposits such as phosphorites[40]. The programme aims at creating contours and 3D models, seafloor characterization and evaluation of sediment properties.

Studies on hydrothermal sulphides

The areas of study include Carlsberg Ridge, Central Indian Ridge and Andaman Backarc Spreading Centre. Geological, geophysical and biological research form the main components of the programme[41].

Exploration for Co crusts

Surveys for cobalt-rich ferromanganese crusts around seamounts such as the Afanasiy Nikitin seamount in the Indian Ocean is one of the major programmes[42].

Gas hydrates

Bathymetry, seabed temperature and geothermal gradient data yielded a Gas Hydrate Stability Zone thickness map as a precursor to predict the gas-hydrate zones. Drilling has confirmed the presence of gas-hydrate deposits in Krishna–Godavari, Mahanadi and Andaman basins[43].

International collaborations as offshoots of the programme

Exploration in EEZ of Seychelles (1984)

- 4000 km survey done around Seychelles islands.
- Geological, chemical, biological, physical data collected.
- Sediments, nodules and biological samples analysed.
- Report on data and samples given to Seychelles government.

Surveys for marine minerals off Mauritius (1987)

- Polymetallic nodules in Mascarene Basin (~11,900 sq. km area).
- Morphology, internal structures, composition, growth rates studied.
- Nodules (abundance = 1–10 kg/m^2) rich in Fe and Co[44].

Indo-Myanmar joint oceanographic studies (2002–)

- Training of scientists from Myanmar.
- Joint cruises for sample collection, data analysis, interpretation.
- Geological, geophysical, chemical, biological data analysed.
- Exchange visits and joint publications.

India–Iran cooperation (2006–)

- With Marine Geology Division, Geological Survey of Iran, Tehran.
- Iranian National Center for Oceanography, Tehran, Iran
- For training of scientists and joint cruises in the Gulf of Oman and Persian Gulf.

Training in analytical techniques

For students from several countries, including Vietnam, Sri Lanka, Saudi Arabia, Ghana, Egypt, France and Germany.

Technical Assistance Programme for Marine Research (TAP–MAR)

A programme under the aegis of Endowment Fund of the ISA (www.isa.org.jm), to provide technical assistance to professionals (scientists, engineers, policy makers, lawyers) from developing countries, with interactive sessions on:

- Marine surveys for inter-disciplinary research.
- Exploration of marine minerals and resource evaluation.
- Marine ecosystems and biodiversity.
- Environmental impact assessment of offshore projects.
- UN Law of the Sea.

Discussion

Recognition of deep-sea minerals as an alternative source of metals came about in the second half of the 20th century with the finding of polymetallic nodules, hydrothermal sulphides and ferro-manganese crusts in different topographic regions of the seafloor. The need for regulating the exploration and exploitation of seabed minerals in the deep-sea 'areas' (outside the national jurisdictions) led to the formation of ISA, under the UN Law of the Sea.

Among the eight registered 'Pioneer Investors', seven (France, Japan, Russia, China, Interoceanmetal, Poland, Korea and Germany) have claimed areas in international waters in the Pacific Ocean whereas India has claimed a large area in CIOB with exclusive rights for exploration of polymetallic nodules. Based on initial reports from SIO and the Russian Academy of Sciences, a small group of scientists and technicians from NIO, Goa struck first nodule samples from the Arabian Sea in 1981, and went on to claim an area of 150,000 sq. km in CIOB in 1987. This was made possible by deploying state-of-the-art exploration tools, adequate training for the personnel, and the strategic combination of a few experienced scientists with young, promising recruits, who were assigned specific areas of specialization for research and development.

Besides the much needed financial support from governmental agencies (erstwhile Department of Ocean Development and presently Ministry of Earth Sciences, Govt of India), it was a network of several scientific organizations in the countries in different fields such as exploration, sample analysis, metallurgical extraction, technology development and data-processing that gave the necessary confidence and impetus to the programme. Although initially inexperienced in marine research, scientists from these organizations geared up with the available data, and gaining experience through the years, have not only completed the resource evaluation of polymetallic nodules in CIOB, but have also identified FGM based on data collected and analysed from 72 cruises and 11,000 samples, as well as 300,000 sq. km of multi-beam sounding data.

In order to meet the requirement of ISA from a potential contractor, the Indian Deep-sea Environment Experiment successfully conducted a simulated mining experiment in the nodule area, evaluated the ensuing environmental impact, and monitored the restoration process of environmental conditions on the seafloor; thus creating a large database of environmental parameters ranging from physical (current, temperature and salinity), chemical (dissolved oxygen, chlorophyll and metals), biological (phytoplankton, zooplankton and benthos) and geological (mineralogy, sedimentology, geochemistry, petrology, stratigraphy, bathymetry and seafloor features) to provide inputs for devising methods for environmental conservation, as well as design and operation of the mining system.

Establishing a pilot plant for metallurgical processing (with 500 kg/day capacity) and development of mining

technology (to operate at > 5 km water depth) has brought this 'Pioneer Investor' at par with all others in the field of deep-sea mineral exploration and exploitation. On the one hand, this experience is being used for exploring other deep-sea minerals such as hydrothermal sulphides and ferromanganese crusts in the Indian Ocean, contributing to scientific research through publications in technical journals, memberships in international steering groups and providing advisories to ISA in formulating guidelines for deep-sea mining; on the other, it is also extending cooperation in the training of scientific manpower in marine sciences from other countries.

Conclusion

In view of the estimated metal resources (> 6 mt of Cu + Ni + Co) in the area retained by India (75,000 sq. km) in CIOB, with no proven land reserves of Co and Ni[45] to bank upon, the development of indigenous capability in exploring and exploiting the deep-sea mineral resources has put India in a significantly strong position among the developing countries as well as the world.

1. Kotliski, R., Mineral resources of the Worlds Ocean – their importance for global economy in the 21st century. In Proceedings of the 4th ISOPE Ocean Mining Symposium, Poland, 2001, pp. 1–7.
2. ISA, Plans of work of exploration of Govt of India, Inst. Francais de Researche pour L'exploration de la mer; Deep Ocean Resources Development Co, Japan; Yuzhmorgeologiya Russia; China Ocean Mineral Resources R&D Association; Interoceanmetal joint organization, and Govt of Republic of Korea. International Seabed Authority, Report of the Secretary General, ISBA/4/A/1/Rev.2, 1998, p. 47.
3. UNOET, Delineation of Mine Sites and Potential in Different Sea Areas, Graham and Trotman, 1987, p. 79.
4. Mero, J. L., The Mineral Resources of the Sea, Elsevier, 1965, p. 312.
5. Sorem, R. K. and Fewkes, R. H., Manganese Nodules: Research Data and Methods of Investigation, IFI/PLENUM, New York, 1973, p. 97.
6. Horn, D. R., Horn, B. M. and Delach, M. N., Factors which control the distribution of ferromanganese nodules, LDGO Report No. 8, National Science Foundation, Washington DC, 1973, p. 20.
7. Pearson, J. S., Ocean Floor Mining, Noyes Data Corporation, New Jersey, 1975, p. 201.
8. CNRS, La genese des nodules de manganese. In Proceedings of the International Seminar, Centre National de la Researche Scientifique, Gif Sur Yvette, 25–30 September 1978, 1979, p. 410.
9. UNOET, Manganese Nodules: Dimensions and Perspectives, D. Reidel, 1979, p. 194.
10. Cronan, D. S., Underwater Minerals, Academic Press, 1980, p. 362.
11. Cronan, D. S. (ed.), Marine Mineral Deposits Handbook, CRC Press, 2000, p. 406.
12. Glasby, G. P., The geochemistry of manganese nodules from the northwest Indian Ocean. In Ferromanganese Deposits on the Ocean Floor (ed. Horn, D. R.), National Science Foundation, Washington DC, 1972, pp. 93–104.
13. Frazer, J. Z., Fisk, M. B., Elliot, J., White, M. and Wilson, L., Availability of copper, nickel, cobalt and manganese from ocean ferromanganese nodules, Scripps Institution of Oceanography (SIO reference no. 78–25), National Technical Information Services, US Department of Commerce, 1978, p. 138.
14. Frazer, J. Z. and Wilson, L. L., Manganese nodule resources in the Indian Ocean. Mar. Min., 1980, 2, 257–291.
15. Udintsev, G. B., Geological–Geophysical Atlas of the Indian Ocean, Pergamon, 1975, p. 151.
16. IIOE, Oceanographic Atlas of International Indian Ocean Expedition, National Science Foundation, Washington DC, 1971, p. 531.
17. Siddiquie, H. N., Rajamanickam, G. V. and Almeida, F., Offshore ilmentite placers of Ratnagiri, Konkan Coast, Maharashtra, India. Mar. Min., 1979, 2, 91–119.
18. Qasim, S. Z. and Nair, R. R., From the first nodule to first mine-site: An account of the polymetallic nodules project, National Institute of Oceanography, Goa, 1988, p. 50.
19. Banerjee, R. and Mukhopadhyay, R., Nature and distribution of manganese nodules from three sediment domains of the Central Indian Basin, Indian Ocean. Geo-Mar. Lett., 1991, 11, 39–43.
20. Pattan, J. N. and Parthiban, G., Do manganese nodules grow or dissolve after burial? Results from Central Indian Ocean Basin. J. Asian Earth Sci., 2007, 30, 696–705.
21. Gupta, S. M., Orbital frequencies in radiolarian assemblages of the central Indian Ocean: implications on the Indian summer monsoon. Palaeogeogr., Palaeoclimatol., Palaeoecol., 2003, 197, 1–16.
22. Jauhari, P. and Iyer, S. D., A comprehensive view of manganese nodules and volcanics of the Central Indian Ocean Basin. Mar. Geores. Geotechnol., 2008, 26, 231–258.
23. Kodagali, V. N., Influence of regional and local topography on the distribution of polymetallic nodules in the Central Indian Basin. Geo-Mar. Lett., 1988, 8, 173–178.
24. Kamesh Raju, K. A., Magnetic lineations, fracture zones and seamounts in the Central Indian Basin. Mar. Geol., 1993, 109, 195–201.
25. Prasad, S., Gupta, S. M. and Kodagali, V. N., Two layers of Australasian impact ejecta in the Indian Ocean? Meteorit. Planet. Sci., 2003, 38, 1373–1381.
26. Sharma, R., Indian Deep Sea Environment Experiment (INDEX): Achievements and applications. In Proceedings of the Third Ocean Mining Symposium, NIO, Goa, November 1999, pp. 118–125.
27. Sharma, R. and Nath, B. N., Selection of test and reference areas for the Indian Deep-sea Environment Experiment (INDEX). Mar. Georesour. Geotech., 2000, 18, 177–187.
28. Sharma, R., Nath, B. N., Parthiban, G. and Sankar, S. J., Sediment redistribution during simulated benthic disturbance and its implications on deep seabed mining. Deep-Sea Res. II, 2001, 48, 3363–3380.
29. Sharma, R. et al., Do natural changes mask artificial impacts on benthic ecosystem over a period of time? Abstracts of 37th Underwater Mining Institute, Tokyo, Japan, October 2007.
30. Sen, P. K., Processing of sea nodules: status and commercial evaluation of India's programme. In Workshop on Polymetallic Nodule Mining Technology – Current Status and Challenges Ahead, ISA, National Institute Ocean Technology (NIOT), Chennai, 18–22 February 2008.
31. Atmanand, M. A., Status of India's mining program. In Workshop on Polymetallic Nodule Mining Technology – Current Status and Challenges Ahead, ISA, NIOT, Chennai, 18–22 February 2008.
32. Nath, B. N. et al., ^{210}Pb, ^{230}Th and ^{10}Be in Central Indian Basin seamount sediments: signatures of degassing and hydrothermal alteration of recent origin. Geophys. Res. Lett., 2008, 35, L09603.
33. Chakraborty, B. and Kodagali, V. N., Characterising Indian Ocean manganese nodule bearing seafloor using multi-beam angular backscatter. Geo-Mar. Lett., 2004, 24, 8–13.
34. Khadge, N. H. and Valsangkar, A. B., Geotechnical characteristics of siliceous sediments from the Central Indian Basin. Curr. Sci., 2008, 94, 1570–1573.

35. Ingole, B. S., Macrobenthic abundance in the viscinity of spreading ridge environment in Central Indian Ocean. *Curr. Sci.*, 2003, **85**, 328–333.

36. Loka Bharathi, P. A. and Nair, S., Rise of the dormant: simulated disturbance improves culturable abundance, diversity, and functions of deep-sea bacteria of Central Indian Ocean Basin. *Mar. Georesour. Geotechnol.*, 2005, **23**, 419–428.

37. Raghukumar, C., Raghukumar, S., Sheelu, G., Gupta, S. M., Nath, B. N. and Rao, B. R., Buried in time: culturable fungi in a deep-sea sediment core from the Chagos Trench, Indian Ocean. *Deep-Sea Res. I*, 2004, **51**, 1759–1768.

38. Sharma, R., Standardization strategies. In Proceedings of Workshop on 'Standardization of Environmental Data and Information: Development of Guidelines'. ISA, Jamaica, 25–29 June 2001, 2002, pp. 472–573.

39. Sharma, R., Proposed exploration and mining technologies for cobalt-rich ferromanganese crust deposits. In Proceedings of Workshop on 'Polymetallic Sulphides and Cobalt Rich Ferromanganese Crust Deposits: Establishment of Environmental Baselines and Associated Monitoring Programme during Exploration', ISA, Jamaica, 6–10 September 2007, pp. 87–107.

40. Rao, V. P., Hegner, E., Naqvi, S. W. A., Kessarkar, P. M., Ahmad, S. M. and Raju, D. S., Miocene phosphorites from the Murray Ridge, northwestern Arabian Sea. *Palaeogeogr., Palaeoclimatol., Palaeoecol.*, 2008, **260**, 347–358.

41. Kamesh Raju, K. A., Chaubey, A. K., Amarnath, D. and Mudholkar, A. V., Morphotectonics of the Carlsberg Ridge between 62 degrees 20 minutes and 66 degrees 20 minutes E, northwest Indian Ocean. *Marine Geol.*, 2008, **252**, 120–128.

42. Banakar, V. K., Hein, J. R., Rajani, R. P. and Chodankar, A. R., Platinum group elements and gold in ferromanganese crusts from Afanasiy–Nikitin seamount, equatorial Indian Ocean: sources and fractionation. *J. Earth Syst. Sci.*, 2007, **116**, 3–13.

43. Ramana, M. V. *et al.*, Multidisciplinary investigations exploring indicators of gas hydrate occurrence in the Krishna–Godavari Basin offshore, east coast of India. *Geo-Mar. Lett.*, 2009, **29**, 25–38.

44. Nath, B. N. and Prasad, S. M., Manganse nodules in the EEZ of Mauritius. *Mar. Min.*, 1991, **10**, 303–335.

45. Sudhakar, M. and Das, S. K., Future of deep seabed mining and demand-supply trends in Indian scenario. Proceedings of 8th ISOPE Ocean Mining Symposium, India, 2009, pp. 191–196.

46. NIO, Sagar – a pocketbook on ocean with special reference to waters around India. National Institute of Oceanography Publication, NIO/P&R, 2006, p. 32.

47. Herrouin, G., Lenoble, J-P., Charles, C., Mauviel, F., Bernard, J. and Taine, B., French study indicates profit potential for industrial manganese nodule venture. *Trans. Soc. Min., Metallur. Expl.*, 1991, **288**, 1893–1899.

48. Yamada, H. and Yamazaki, T., Japan' ocean test of the nodule mining system. Proceedings of Int. Offshore and Polar Engineering Conference (Montreal, Canada), 1998, pp. 13–19.

49. ISA, Executive summary of the International Seabed Authority's Workshop on Polymetallic Nodule Mining Technology: Current Status and Challenges Ahead, International Seabed Authority (Jamaica), Report, 2008, pp. 10–20.