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

Rahul Sharma

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. 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/m²
- 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...
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. Buchan 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 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, and factors which control the distribution of Fe–Mn nodules.

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). By the late 70s, basic data were available on the genesis of manganese nodules as well as the prime areas in different oceans 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, which was subsequently followed by a more comprehensive collection of information on nodules.
Exploration of Indian Ocean nodules

One of the early descriptions of nodules from the Indian Ocean was by Glasby on geochemistry of manganese nodules from NW Indian Ocean, whereas more comprehensive data were published by Frazer et al. 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, 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/m², 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) 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. 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.

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 cores.

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

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/m², 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 = $120 \times 100$ km = $1.08 \times 10^6$ m².

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

$$\text{Area} \times \text{depth} \times \text{coverage} = 540 \times 10^3 \text{ m}^3/\text{yr or}$$

$$108 \times 10^3 \text{ m}^3.$$
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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Quantities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area surveyed</td>
<td>&gt; 3 million sq. km</td>
</tr>
<tr>
<td>Sampling</td>
<td>&gt; 2500 locations</td>
</tr>
<tr>
<td>No. of sampling operations</td>
<td>~11,000</td>
</tr>
<tr>
<td>Sampling grid</td>
<td>6.25–111 km</td>
</tr>
<tr>
<td>Bulk nodule collection</td>
<td>200 t</td>
</tr>
<tr>
<td>Echosounding</td>
<td>500,000 km</td>
</tr>
<tr>
<td>Multibeam bathymetry</td>
<td>&gt;300,000 sq. km</td>
</tr>
<tr>
<td>Seabed photography</td>
<td>&gt;50,000 photos</td>
</tr>
<tr>
<td>Ships used</td>
<td>8 (Indian and foreign)</td>
</tr>
</tbody>
</table>

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 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 × 5 areas = 1500 km
- Sediment + nodule samples: 13 locations × 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.

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 monitor-
ing 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)

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 time27. Similarly,
long-term observations were also made in the entire nod-
ule 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 dis-
solution 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, Udaipur30. Also, a crawler being designed as a proto-
type for nodule mining has been tested offshore at 400 m
water depth and the system is being upgraded for higher
depths31. 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 pro-
gramme in the Indian Ocean.

Table 5. Data compiled for selection of test and reference areas27

<table>
<thead>
<tr>
<th>Area</th>
<th>Average abundance (kg/m²)</th>
<th>Average depth (m)</th>
<th>Average slope (degree)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>1.94</td>
<td>5217</td>
<td>1.1</td>
</tr>
<tr>
<td>R1</td>
<td>1.14</td>
<td>5330</td>
<td>1.4</td>
</tr>
<tr>
<td>T2</td>
<td>2.10</td>
<td>5327</td>
<td>1.1</td>
</tr>
<tr>
<td>T2</td>
<td>3.41</td>
<td>5217</td>
<td>1.7</td>
</tr>
<tr>
<td>R2</td>
<td>5.05</td>
<td>5297</td>
<td>1.7</td>
</tr>
</tbody>
</table>

Science and policy

- Evaluating geological history32, seafloor characteris-
tics33 and sediment properties34
- Mapping the diversity of benthic organisms35
- Identifying new species of fungi and bacteria36,37
- Providing advisories to ISA38,39
Table 6. Development of mining and processing technologies for polymetallic nodules in India vis-à-vis other Pioneer Investors

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

Publications and patents

- 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 Ph.D 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 phosphorites90. 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 programme91.

Exploration for Co crusts

Surveys for cobalt-rich ferromanganese crusts around seamounts such as the Afanasy Nikitin seamount in the Indian Ocean is one of the major programmes92.

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 basins93.

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/m²) rich in Fe and Co⁴⁴.

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.in), 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 government 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 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.

3. UNOET, Delineation of Mine Sites and Potential in Different Sea Areas, Graham and Trotman, 1987, p. 79.


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