

# **COMPETITION FOR SEABED RESOURCES IN THE INDIAN OCEAN**

**G.S. Roonwal**

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# *Preface*

Seabed mineral resources need to be used for the benefits of mankind. They need also to be used in responsible and sustainable way so that future generations do not pay for misuse. Suitable technology development and equipment for specific task are now available but await the right economic climate. Legal aspect need to be clarified through UNCLOS and ISA. The present state of uncertainty in profit sharing inhibits investment in ocean mineral mining, and mining of seafloor sulphide in particular. Fresh consideration need to be given to using the ocean through properly engineered waste disposal and storage with safeguards against irresponsible environmental degradation. UN through ISA/ UNCLOS could achieve income from licensing and fee for marine mineral mining in the international waters.

Like other oceans, the Indian Ocean has several mineral resources varying from coast to deep water. They include beach placers, phosphate nodules, cobalt rich crusts, manganese nodules, seafloor massive sulphide and above all sea water. In the continental shelf area, due to sediment pile possibility of hydrocarbon accumulation exists.

This review presents the marine minerals in the Indian Ocean, and how future may shape due to increasing interest to get potential area for seafloor sulphide in particular, and mining of manganese nodules. This marine mining desire shall certainly lead to competition, sign of which are visible. It is my hope that present synthesis would benefits those interested in the Indian Ocean. We look forward to Indian Ocean remaining a zone of peace.

G.S. Roonwal

New Delhi  
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## Chapter I

# *The Importance of Mineral Resources*

In his *Arthshastra* Kautilya observed: 'the wealth of the state has its source in the mining and (metallurgical) industry; the power of the state comes out of these resources'. Minerals constitute a fundamental component of a nation's material and economic base. Mineral products are so commonly used that they affect every facet of our lives; in fact, it is impossible to conceive and maintain today's industrial edifice and standard of living without mineral resources. The shelters we live in are made of brick, stone, cement, glass, iron, copper, aluminium, etc. Transportation - the backbone of modern civilization - would come to a grinding halt if materials such as fuel, steel, aluminium, copper and a host of other mineral products were not produced, and used. Almost all the things that make life smooth and comfortable are to a large extent mineral derived.

The importance of minerals and metals in the evolution of the human civilization as well as industrialisation can be judged from the fact that the different stages of civilization have been marked by man's progress in his use of minerals and metals. Thus, we have the Stone Age, the Iron Age, the Bronze Age, and the present Industrial Age. The earliest human led a life as a seed and fruit-gatherer, hunter and meat-eater. From this beginning, he gradually advanced into inventing tools and weapons. It at this point in history that minerals began to make a major impact on his life and, being inventive, he continued to refine their use. Civilizations have been simply named after these refinements.

Man used rock and earth to build his shelter, stone to make his weapons, and gradually understood that flint was hard and sharp, that was pliable and cohesive, and that bright stones were attractive. He searched for and utilized these materials for his own benefit within his own, small domain. Many centuries and millennia passed before he started looking for minerals beneath the ground. As time passed, man learnt the use of metals like copper, tin, lead, gold, silver and iron. He found copper, gold and silver in native form in the earth's crust, and meteoric iron in some locations. It is probable that the ores of tin and lead were accidentally smelted in camp fires that later led to the discovery and use of these metals. Although iron ore was much more difficult to reduce to metal, iron ore occurrences were discovered to be extremely widespread, and the making of sponge iron by accidental camp fire reduction is not inconceivable. Thus, from humble beginnings, minerals and metals have left their profound impact on the evolution of civilizations.

The mineral industry is not only directly essential for all elements of civilization, but also critically important to the conservation of other resources of mother earth. In developed economies, the mining industry has, by judicious planning, indirectly increased the size of the green cover, of recreational and ground water resources, and improved crop yields. To illustrate, one can see that the concept of intensive farming is based not only on good soil but also on the availability of fertilizers, pesticides, agricultural machinery, and fuels to propel them. All these elements are mineral based. As more and more food is produced from less and less land, the less efficient farmlands revert to being forests. The use of mineral fuels in place of wood has also contributed to the maintenance and preservation of large forest areas. Thus, as the mineral industry has used mined out land for plantation and recreating recreational centres. However, in developing countries, forest lands are steadily decreasing as there is heavy demand for land for agriculture, and wood for cooking and heating purposes. In India

and other developing countries, the pressure of population and lack of adequate employment opportunities take their toll not only on forests but has also led to illegal mining.

The analysis in this monograph looks at the currently on-going projects in Areas Beyond National Jurisdiction (ABNJ). These are waters under the supervision of the International Seabed Authority which also oversees exploration activities that are currently taking place in the Exclusive Economic Zone (EEZ) of individual states. Projects are defined as licenced exploration and exploitation activities aimed at deep-sea minerals. UNCLOS was accepted in November 2004 and India ratified it in June 2005.

So far, only exploration licences have been issued by the International Seabed Authority (ISA), a wing of the UN. Until May 2014, 19 applications have been approved.

- 13 concern the exploration of polymetallic nodules, four for polymetallic sulphides, and two the exploration of cobalt-rich polymetallic crusts;
- 12 of the exploration projects are located in the CCZ. This area is located in the international waters of the Pacific Ocean. The remaining projects are located in the Indian Ocean (3), the Atlantic Ocean (2) and the north-western Pacific Ocean (2);
- These 19 approved projects cover an area of 1 million km<sup>2</sup>. Six of these licenses will expire in 2016.

In 2013, seven additional applications, covering an area of around 234,000 km<sup>2</sup>, were made to the ISA for exploration projects. These were discussed at the ISA's 20th annual session in July 2014, and were approved, but still need to be contracted out. This means that, by the end of 2014/beginning of 2015, there will be 26 approved projects by the ISA, with a total covered area of around 1.2 million km<sup>2</sup>. This is an area nearly as big as Tamil Nadu, Kerala and Karnataka.

## Chapter II

# *Metallogeny in the Indian Ocean*

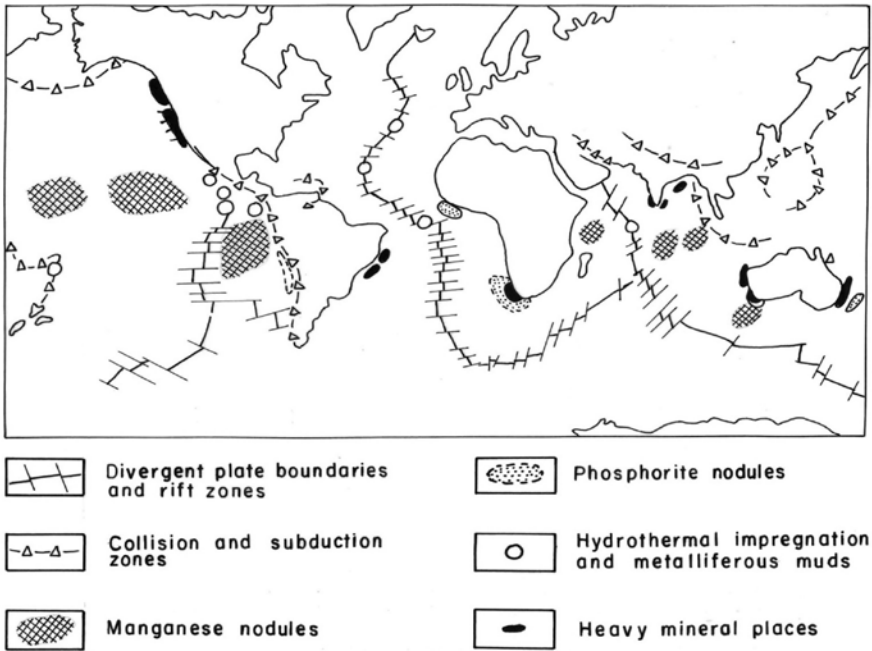
Seafloor minerals have become future resources for industry. As more and more reconnaissance and detailed surveys locate major tectonic, volcanic, and sedimentary features on the seafloor, a wide variety of mineral deposits with both scientific and economic interests have been identified. Moreover, our concepts of the origin of mineral deposits on land can be further refined by understanding the present processes and activity on the seafloor. So far direct observations seem to confirm theoretical models.

Our understanding and information of the distribution of seafloor minerals resources in the Indian Ocean has increased substantially over the past few decades. But considering the vast area of the ocean, there is scope for the systematic survey of mineral such as seafloor sulphides and the cobalt-rich crusts in the Indian Ocean. There is also a considerable need for the systematic surveys of both the Exclusive Economic Zone (EEZ) as well as the deeper parts of the ocean to make a realistic assessment of its mineral potential as well about the related technology needed for its eventual recovery.

### **Types of Deposits**

Two types of seafloor metalliferous deposits are known, and have attracted the attention of geologists and mineralogists in the past three to four decades. These two types of deposits have been formed under different processes. The manganese nodules and crusts widely

distributed on the floor of the major ocean basins are formed through sedimentary concretionary and biogenic processes. The metals they contain may be from hydrothermal or sedimentary sources, or be concentrated by the geochemical reaction of seawater and sediments. In the Indian Ocean, a few areas have been demarcated where nodules occur in abundance (Fig.1). One may refer to several publications on this theme, but a good synthesis is available in Roonwal (1986) and Mukhopadhyay et al. (2002).



**Figure 1:** *Map of World Oceans showing major tectonic zones and mineral occurrences.*

The other major metallogenic type is even more exciting because we can see its creation. Along fracture zones, faults, and the spreading ridges of the sea-floor, hydrothermal springs discharge solution containing iron, manganese, copper, zinc, lead, cobalt, silver, gold, platinum, and other metals. On a global map, these spreading centres

and mid-oceanic ridges are more than 60,000 km long, and are generally indicated by earthquakes, and sometimes by volcanoes. They make the so called divergent and converging boundaries of the rigid plates, some 100 km thick, and consist of earth crust and upper part of the mantle. Some of the metals mentioned above may be precipitated as carbonate, oxide, sulphide, sulphate or silicate minerals in crust, chimneys, or stacks around the hydrothermal vents. Some are disseminated in the sediments and siliceous zones or muds on the seafloor, forming metalliferous sediments such as in the Red Sea; and some are deposited in sub-surface fractures in the bedrock, forming stock-work below the vent and effusive outlets.

## **Manganese Nodules**

Manganese nodules as it was then thought would probably provide a commercial source of metals in the coming decades because they contain metal of vital interest to modern industry. The richest and most valuable nodule field located so far in the Indian Ocean lies in the Central Indian Ocean Basin (CIOB). It is for here that India has put its claim for mining of nodules to the International Seabed Authority (ISA), a wing of the UN. Other areas may still be found, as it is evident from the interest being shown by scientists in the nodules in West Australian Basin. Indeed, vast areas known to contain manganese nodules have not been closely explored yet.

Nodules were first discovered in the Pacific Ocean by the *HMS Challenger* expedition in 1872–1876. Since then, the nodules have been found widely distributed on the deeper part of the sea floor throughout the world where the rate of sediment accumulation is very low, and the biological productivity high. The best grade nodules are especially common in the seabed on both sides of the Equator, and away from the continents (Fig.1). These nodule are shaped like spheres, eggs, or bunches or grapes, and have concentric layers of different

mineral composition. They range in size from a few millimetres to tens of centimetres in diameter, but are commonly 0.5 to 20 cm in their greatest dimension. They are principally manganese and iron oxides, ranging from 15 per cent to 35 per cent, and 5 per cent to 20 per cent of these elements respectively. They also contain an average of 1 per cent nickel, and 0.77 per cent copper in larger areas south of the Equator in the Central Indian Ocean Basin (CIOB). The cobalt percentage ranges from 1 per cent and more, or to about as little as 0.01 per cent on continental margins.

The distribution, abundance, and composition of manganese nodules are indeed irregular, and we still do not clearly understand the fundamental aspects of their origin and growth. Areas with concentration of manganese nodules are shown in Fig.1, with parts of these areas where the nodules have a higher content of nickel, copper and cobalt being also indicated.

In some places, the dense concentration of manganese nodules seems to give way to patches of thin beds of manganese and iron crusts. These may be related to hydrothermal activity than are the nodules. Manganese rich crusts have been found in the deep seafloor and seamounts near ancient volcanoes, and even within associated hydrothermal vent system which are of hydrothermal origin. Some of the manganese rich crusts such as those reported near the Hawaiian Islands in the Pacific Ocean contain more than 1 per cent cobalt. They are being seriously considered as a source of cobalt and manganese. In the Indian Ocean, such deposits are likely to be found in areas of ancient seamount, where upwelling may take place (Roonwal, 1988).

### **Hydrothermal Deposits-Volcanogenic Massive Sulphides (VMS) or Seafloor Massive Sulphides (SMS)**

Hydrothermal systems producing metalliferous sediments, crusts, and chimneys on the seafloor are located in three tectonic settings.

- (a) On the spreading ridges which encircle the globe.
- (b) Along volcanic areas and fracture systems and the subduction zones related to them.
- (c) On seamounts of volcanic centres isolated from major fracture systems.

Active hydrothermal systems that are discharging metal bearing solutions have been investigated, in the past in the Red Sea; along segments of the East Pacific Rise; other parts of the Pacific; at present in the mid-Atlantic Ridge; as well as in the Indian Ocean. Their occurrence in the Indian Ocean can be seen in Figure 1 above. In 1993, a German Oceanographic expedition on board RV *Sonne* discovered a hydrothermal field north of the Triple Junction on the Mid-Indian Ocean Ridge (Halbach et al. 1994). All these deposits are obviously bound to the recent tectonic faulting. In each of these cases, sulphides were the original phase precipitated, although they may have suffered later partial oxidation. All these deposits are found together with warm water, which means they are hydrothermal in origin in the true sense.

Such hydrothermal systems producing metalliferous sediments and crusts associated with an active spreading centre may be divided into three types :

1. Sulphides deposits with silicates and oxides, as in the Red Sea.
2. Sharply fractioned silicate and oxide deposits in a very localized size, as seen on some mid-oceanic ridges in the open seas.
3. Widely dispersed predominantly oxide deposits of iron and manganese, which comprise the bulk of metalliferous sediments on mid-oceanic ridges.

These different deposits could all have been formed as a result of the fractional precipitation of metals from a hydrothermal solution

derived from sea water leaching of hot newly formed oceanic crust. Sulphide deposits represent the early formed precipitations followed by silicates and oxide. Widely dispersed predominantly oxide bearing metalliferous sediments deposits on mid oceanic ridges have been formed as a result of precipitation of iron and manganese bearing solutions. They represent residual liquid of sub-sea floor hydrothermal fractionation processes. Thus, their metal source is discharged from hydrothermal vents, together with some iron and manganese oxides. They become well mixed with bottom waters and precipitate their constituents relatively uniformly over a wide area.

In some places, a dense concentration of manganese seems to give way to patches or thin beds of manganese and iron crusts. Their formation is attributed to hydrothermal activity, and some of them contain more percentage of cobalt. Such crusts are known from submarine ridges such as the Carlsberg Ridge and other seamount regions (Roonwal and Mitra 1988, Roonwal 1993, and Roonwal 2013).

Hydrothermal mineralization on slow spreading oceanic ridges, such as the Mid Indian Ocean Ridge, is considered a product of multi-stage, episodic, high and low temperature hydrothermal activity, controlled by an intrusive-extrusive volcanic cycle. Evidence of this can be found in the Carlsberg Ridge crust between latitude 5°21 S and 10°N in the northwest Indian Ocean (Fig.1), and in the Mid-Indian Ocean Ridge (Halbach 1994; Halbach et al. 1996, 1998).

On the floor of the Red Sea, metalliferous mud is being formed in a trough or graben which is about 2000m deep. Here, thermal springs, with temperatures about 65°C, discharge along the faults of the rift zone on the spreading ridge. This metalliferous mud consists of banded iron oxides and silicates, interlayered with siliceous mud or ooze bearing iron and manganese. It closely resembles some types of banded iron formations in terms of composition and general appearance. Prominent facies in these chemically precipitated sediments are oxides, sulphide,

sulphate, carbonate and silicates, along with fine clastic muds, and siliceous oozes. Blanketing the metalliferous muds are hot dense layers of brine, derived from evaporated beds in the bed rocks of the graben structure. The Atlantic II graben basin (or deep) is one of several in the Red Sea. These comprise metalliferous muds, estimated to contain 1.7 million tons (mt) of zinc, 0.4 mt of copper, and 5000 tons of silver. The Atlantic II mud may be mined in the future. When dried, they would probably average about 3 to 6 per cent zinc, 1 per cent copper, and 50 grams per ton of silver. (The details for this may be obtained from Degens and Ross, 1969)

### **Mechanism of Formation**

Cold sea water seeps through the ocean floor as much as 5 km deep to local hot spots. It heats, expands, and rises, leaching metals from the lavas and sediments comprising the ocean floor (Figure 2a above). The mixture, now more than 350°C, bursts out of vents into the cold ocean water of about 2°C. In the turbulent mixing, the metals become heavy, dark, sulphide minerals. They build chimneys up to 30 meters in height, ejecting plumes known as 'black smokers' or 'white smokers', depending on the contents of the hot metal-laden water. Blankets of bacteria and exotic animals, including giant clams and blood-red tube worms, thrive around the vents (Figure 2b below). This process explains the mysteries about the composition of seawater. It was once thought that its minerals came from river runoff. The elements in the ocean water were out of balance with not enough magnesium and too much manganese. However, the direct sampling of seawater gushing out of the vents shows that during circulation deep in the oceanic crust, it drops off magnesium and picks up manganese.

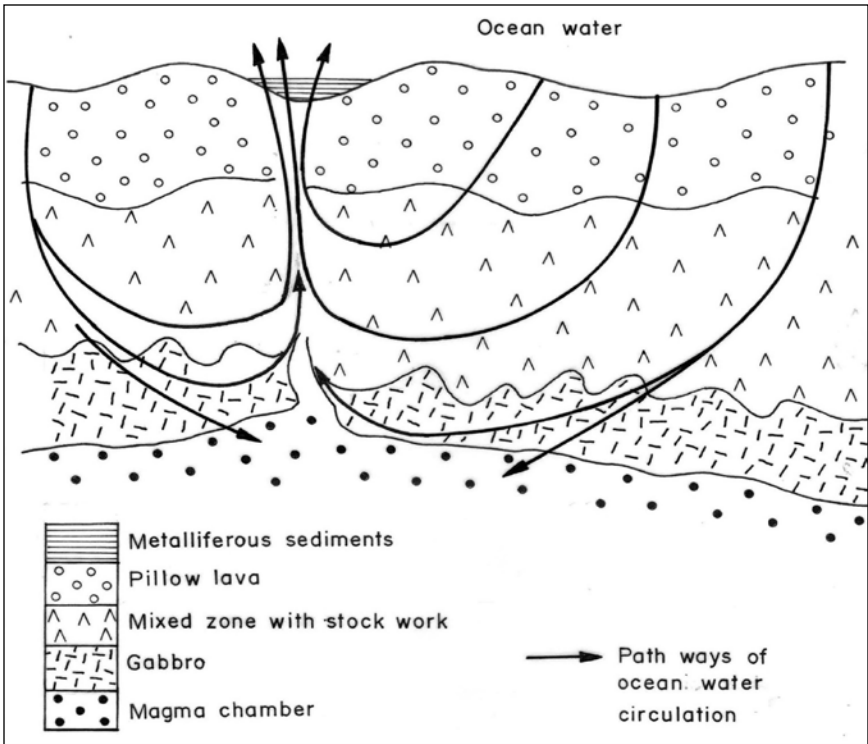


Figure 2a: Initiation of Hydrothermal System on the Mid-Ocean Ridges

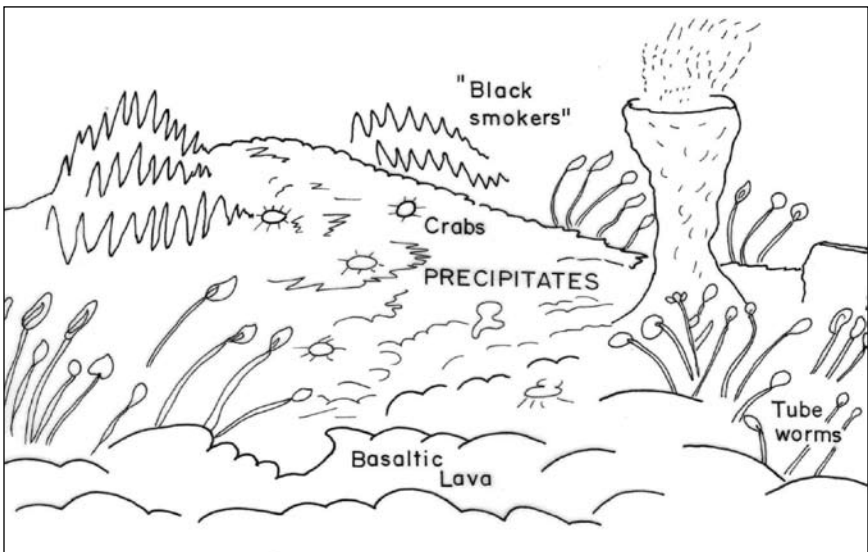


Figure 2b: Formation of Hydrothermal Chimneys and Precipitation of VMS

## Chapter III

# The Importance of Seabed Minerals for India

Seabed minerals are of great importance for India, and this is an opportune time to make a close analysis of seabed mineral resources as well as the state of the deep sea mining technology and its wider applicability and usefulness. The UN Convention on the Law of the Sea (or UNCLOS) came into force on 16 November 1994. This Convention provides a regime for deep-seabed mining, and includes numerous provisions about technology and technology transfers. Question as to who would give technology to CHM (Common Heritage of Mankind) and the ISA. More important is the profit sharing and different aspect of technology transfer and conditions. This is an important aspect of ISA if it is to be a self-sustaining wing of the UN.

In this context, we have to bear in mind the importance of technology in contemporary economic life. At least 80–85 per cent of economic growth today is based on innovations, research and development in technology and not on new inputs or materials, or even finance. The research and development dimension has grown beyond what would have been imaginable 3–4 decades ago. Moreover, technology is fundamentally important to making our economic development economically and socially sustainable. Thus, energy efficient technology which reduces the emission of green-house gases is a good example.

Seabed mining technology has to be developed so as to minimize its negative impact on the marine environment. Thus, the very nature of

contemporary high technology is qualitatively different from traditional technology. As compared to traditional technology which is based on hardware and is capital intensive, the newer technology is software oriented, and people oriented; it is information based, knowledge based, and one cannot buy it; one has to learn it. This, 'transfer' can be effected only through the establishment of the on-going contracts and joint relationships involving training, service, maintenance, repair, as well as updation and upgradation to the next generation of the technology in question. Thus, in many ways, it would emerge as a joint venture which would require the development of human resources.

An examination of the seabed non-living resource in terms of the Law of the Sea Convention (UNCLOS) and the 'New international technological order' that it might generate, we find it states that the International Seabed Authority (ISA) shall take measures to acquire technology and scientific knowledge relating to seabed mining in the international areas, and that it will promote and encourage the transfer this knowledge to developing states so that all parties benefit. These statements are amongst the most controversial of the UNCLOS and one of the reasons why industrialized states have been reluctant to ratify the UNCLOS, though the situation is changing. The set of seabed mining technologies that India and China are looking for may not be forthcoming so easily. In other words, the UNCLOS was conceived under the assumption that seabed mining would be a growing commercial concern by the time it came into force. However, this did not happen.

This monograph examines the various parameters from the perspective of India. It will take into account (a) land based resources, and (b) seabed minerals and incorporating both the minerals within the EEZ and the International area of the sea. It also identifies some emerging resource areas which could also demand national a security perspective in the marine sector. The Indian Navy and Coast Guards

have to formulate its future policies taking into consideration these critical issues of national importance. One big responsibility would be to guard offshore oil and gas installations as well as on coast located plants and refineries.

The non-living resources which will be discussed are the following:

a) Within the EEZ:

- Sea Water
- Beach and offshore heavy mineral placers
- Volcanogenic massive sulphide (VMS) or Sea-floor massive sulphide (SMS)
- Hydrocarbon–Petroleum and Natural Gas
- Cobalt rich encrustations (Co-crusts)
- Gas hydrates
- Phosphorite
- Salt and chemicals

b) Open seas (International Waters)

- Deep-sea ferromanganese nodules
- Volcanogenic sulphides or SMS on mid oceanic ridges.

Examined below are the options and situations as they are likely to accrue in the year 2020 and 2030.

Let us briefly examine the meaning of the term mineral resources and when they are considered suitable for mining as commercial units. The new UN Framework classification on resources and reserves has

three axes: EFG, representing economic feasibility, and geology. While in the past also resources and reserves were considered with view to economic exploitation, now this has become more emphatic. This change is desirable because in the globalization of today, national borders will have to be crossed for trade and commerce, that is, the free supply and movement of goods for trade. No doubt this would also involve the strengthening of frontiers to maintain cultural, social, and ethnic styles and values.

Generally the term ‘mineral reserve’ implies that some type of physical measurements has been made of the grade and amount of mineral concentration *in-situ*, and that profitable extraction now, or in the near future, is technologically feasible. This is a very practical concept in mining, where reserves are usually classified according to the degree of certainty with which they are known. Thus, the mining industry has, traditionally, often used the qualifying terms ‘proved’, ‘probable’, and ‘possible’. For the broader purpose of regional and national resource appraisal, the qualifiers ‘measured’, ‘indicated’, and ‘inferred’ have been used, especially since World War II.

‘Resources’ is a wider term than ‘reserves’. Its focus includes ‘reserves’, but also goes far beyond. As a rule, it implies some degree of natural concentration, and includes both known and unknown stocks of minerals that may be or may not be of commercial value at present, but that seem likely to become so, under certain assumptions. Mineral resources may be defined according to appropriate sets of criteria that are either economic (such as cost per ton) or implicitly (such as all copper sulphides exceeding a particular minimum grade). Setting a maximum cost-per ton criterion, one might assume that certain extraction methods will become technologically feasible within the time frame considered. A relationship between reserve-resource terminology and the basic aspects of the natural stock can be seen in Table 1 below.

**Table 1: Reserve-Resource Relationship**

Term	Aspects		
	Occurrences	Economic	Technological
Reserves	Known	Present cost level	Economically feasible
Resources	Known + unknown	Any cost level specified	Currently feasible and feasibility indicated in future
Resource base	Known + unknown	Irrelevant	Feasible + infeasible

Today, the mineral industry in India is in a depressed state. The questions being asked in mineral commodity circles are as follows: How long will this slump period last? In what direction are the industries that produce and consume raw material heading? To attempt answers will involve looking first at past events. Resources in the earth are governed by the laws of nature, and no doubt geoscientists have done much to unravel and understand their formation.

In 1965, in his book *Mineral Resources of the Sea*, J. L. Mero suggested essentially limitless resources of more than 1 trillion metric tons of manganese nodules on the Pacific sea floor, implying that the supply of such metals as manganese, cobalt, nickel and copper was inexhaustible. This led to the launching of more than a hundred cruises of vigorous attempts at seabed exploration and mining over two decades. However, these ultimately resulted in very little return on investment. This initial phase of exploring the possibilities of seabed mining lasted from 1972–1982, shortly after the widespread abundance of metal nodules in the ocean was recognized. In India, the year 1981 marks the creation of a Department of Ocean Development (renamed as the Ministry of Earth Sciences in 2006) which supports India's long term interests in nodule mining.

The 1965 figure of 1 trillion metric tones of nodules in the Pacific Nodules Belt was revised by Mero in 1977 to become high grade nodules of about 11 billion metric tons of Mn, 115 million tons of

Co, 650 million tons of Ni, and 520 million tons of copper. The most recent resource estimates indicate that this area is not quite as rich, but still contains about 7.5 billion metric ton of Mn, 70 million tons of cobalt, 340 million tons of nickel, and 265 million tons of copper (Morgan 2000).

Many consortia were set up in the USA, Germany, the UK, France and Japan to investigate the possible commercial exploitation of nodules. This work culminated in the successful testing of a system to mine seabed nodules at the pilot plant stage in 1978. The entire mining system was lost over the stern of the ship after about 800 metric tons of nodule had been recovered from the seafloor. The Lockheed/OMCO consortia's claim of developing a mining system using the *Glomer Explorer* (the deep sea drillship platform built at a cost of US\$ 500 million to recover a sunken Soviet nuclear submarine) during 1976–78 raised false hopes. Eventually, a more realistic assessment of deep-sea resources now prevails. In case of nodules, the criteria for economic deposits of a combined nickel, copper and cobalt content is more than 2.5 per cent, and an abundance on the deep sea floor of more than 10 kg m<sup>2</sup> means that only a small percentage (less than 5 per cent) of nodule can be considered having the potential of economic use. These are mainly in the Pacific Nodule Belt and the Central Indian Ocean Basin.

The effects of depressed world metal prices in the last two decades are so great that land based mines are working at less than full capacity. High quality sources of metals on land have proved abundant enough to meet projected demands for nickel, copper and cobalt, for at least the next few decades. Thus, to go in for marine nodule mining would need a large subsidy. Economic grade nodules are found generally in the middle of the ocean, in water depths exceeding 4500 m. Lifting nodules from this depth is a formidable proposition. Although technically feasible, it remains a matter of discussion if this can be

done at a cost lower than that of mining land based ore deposit in the coming decades.

Because of the presumed possibility of huge revenues from the seabed mining, the group of 77 countries in the UN wanted to ensure that they were not denied their share of the wealth. On the basis of these expectations, a number of clauses were incorporated which made the perspective nodule mining consortia think afresh. These provisions included a parallel system of seabed mining in which a mining company would be required to explore two mine sites of, as far as possible, equal value, and relinquish one to the ISA. It further made it obligatory for the mining company to transfer technology to the 'Enterprise' a unit of the ISA for looking at the commercial aspect of seabed mining wing of the ISA on 'fair and reasonable terms and conditions' over a period of 10 to 20 years. The assumption was that the nodule mining consortia (industrialized countries) would be able to make substantial transfers to support nodule mining by the 'Enterprise'. The controversy surrounding these requirements eventually led to the refusal of several industrialized countries with an interest in nodule mining to sign the initial UNCLOS treaty in 1982.

There is no doubt that the potential of resources like cobalt-rich manganese crusts, the submarine volcanogenic massive sulphides is great. This discovery was clear even at the time of UNCLOS in 1994. Moreover, some of these deposits lie within the EEZ's of individual countries. However, while mining these one has to be cautious because of the potential of damaging the marine environment. This is especially so not so much in the territorial waters or the EEZs of individual countries, but in their contiguous oceans. The oceans are an open system. The use and misuse of the seas will affect the mankind. All stakeholders have to understand and work together in full understanding and faith, if we have to treat the resources of the seas as the 'Common Heritage of the Mankind' (CHM).

## Chapter IV

### *The Indian Ocean Scenario*

In the case of the Indian Ocean rim, it is clear that the world would find it difficult without South African minerals such as manganese, chromium, or vanadium as also Australian coal and iron ores. Differential distribution militates against self-sufficiency in minerals for all countries in a way that differential distribution of technologies and other factors does not militate against agriculture, self-sufficiency for most of them. Seed knowhow, fertilizers, manpower and, to an extent, even water is all transferable. Thus, in a physical if not economic sense, an agriculture growth policy is one that all but the very ill situated can contemplate. However, the same cannot be said for minerals: even if one takes into account the wonder working properties of modern technology, no country has a sufficiently ample resources base to allow it to produce the minerals it needs. Each state lacks some important minerals needed by its industries, and many others lack and would continue to lack a wide range of such industrial inputs. Without adequate sources of needed minerals, states have sought and will continue to seek foreign supplies. Such long term dependency on foreign supplies can be called 'cooperation' or 'resource diplomacy'. However, no country has shown interest in seabed mining not even Australia. However, Beach Placer mining is attracting attention because of REEs in them.

India occupies a land area of 3.288 million km.<sup>2</sup> Underneath approximately 25 per cent of this area lie hard and crystalline rocks, and is the most prospective region for non-fuel mineral resources. Trends in mineral discovery have been somewhat episodic. The discovery of

the Rampura-Agucha Zn/Pb deposit in Rajasthan, and lateritic bauxite overlying crystalline khondolites (garnet-sillimanite schist) on the east coast of Orissa are recent major finds.

**Table 2: India's Share in World Mineral Production and the Reserves of Selected Minerals**

	Per cent of world production (2012)	Per cent of world ore reserves
Iron ore	7	5
Chromium	7	4
Manganese	6	2
Bauxite	5	4
Copper	Negative	Negative
Zinc	2	Negative
Nickel	nil	Negative
Lead	Negative	Negative
Molybdenum	Negative	5
Vanadium	Negative	Negative
Tungsten	Negative	Negative
Rock Phosphate	Negative	Negative
Rare earths	5	1
Rutile	1	5
Zirconium	3	4

*Source:* Data from the U.S. Bureau of Mines (2012)

Table 2 above shows the share of India in world mineral production. No doubt emphasis will increase on the exploration of the land areas; but increase in demand will require new sources such as marine sources, because of increasing pressure on land for settlement and industry. Also, in India, agricultural land is gradually being replaced by industrial land. National reserves are deficient in various non-metallic minerals as well (See Table 3 in Chapter V).

## Chapter V

# *The Seabed Minerals of the Exclusive Economic Zone (EEZ)*

Data from the seas around India was collected during the International Indian Ocean Expedition (IIOE), and the key objectives for a survey of the EEZ were later identified. The addition of about 2 million km<sup>2</sup> of sea area in the EEZ confers an added responsibility on the country (Figure 3). As the Law of the Sea comes into effect, India must assess the long and short-term environmental effects of resource exploitation. Oceanographic and environment parameters were formulated in a workshop in Kochi (Cochin), and a number of articles have described the distribution and potential of economic minerals within the Indian EEZ (Roonwal 1986, Roonwal and Glasby 1996; Gujar et al. 1988; Cronan 1992).

India's 200 mile long EEZ extends over most of the submerged or uplifted subcontinent, as well as significant areas of the surrounding deeper ocean basins. As a result of the existence of the Andaman-Nicobar group of islands in the Bay of Bengal and the Lakshadweep group in the Arabian Sea, the Indian EEZ covers a considerable area (see Figure 3). A unique feature of the Indian Ocean environment is the monsoon. In the Arabian Sea, the southwest monsoon results in intense upwelling along the west coast of India. Although these account for a high biological productivity and fishery potential, both the Arabian Sea and the Bay of Bengal are subjected to large semi-diurnal tides, with amplitudes of 1–8 m; they are also influenced by the bi-annual reversal

**Table 3: Mineral Resources of India: Reserves and Production**

Mineral	Recoverable reserves 1990 (in million tones)	Operating mines 2010	Production 2013 (in thousand tones)
Apatite and phosphate	128	13	532
Barite	70	32	420
Bauxite	2,525	183	4,954
Chromite	88	22	1,088
Copper ore	325	14	5,153
Diamond	1,196,000 carats	2	17,649 carats
Dolomite	4,967	123	2,927
Gold-primary	20	8	1.89 kg
Gold-placer	24	-	-
Gypsum	239	43	1,224
Iron ore	12,745	239	54,637
Kyanite	3	9	10
Lead-zinc ore	167	7	2,719
Limestone	76,446	617	75,278
Magnesite	233	19	595
Manganese	176	180	1,858
Mica (crude)	-	123	2,564 (tones)
Sillimanite	50	6	19

*Source: Based on Indian Bureau of Mines (2013).*

of the monsoon winds. These factors result in the accumulation of heavy mineral sands along the coast, as well as phosphate precipitation in the immediate shallow water. Winds and tides also flush the coastal areas, and help disperse pollutants (Glasby & Roonwal 1995).

Although hydrocarbons are considered as separate from marine minerals, a passing reference is appropriate. The Persian Gulf is a classic example of a near-shore petroleum field in which organic-rich sediments have been deposited since Jurassic times. The majority of the Indian Ocean, however, has a thin sediment cover in the range

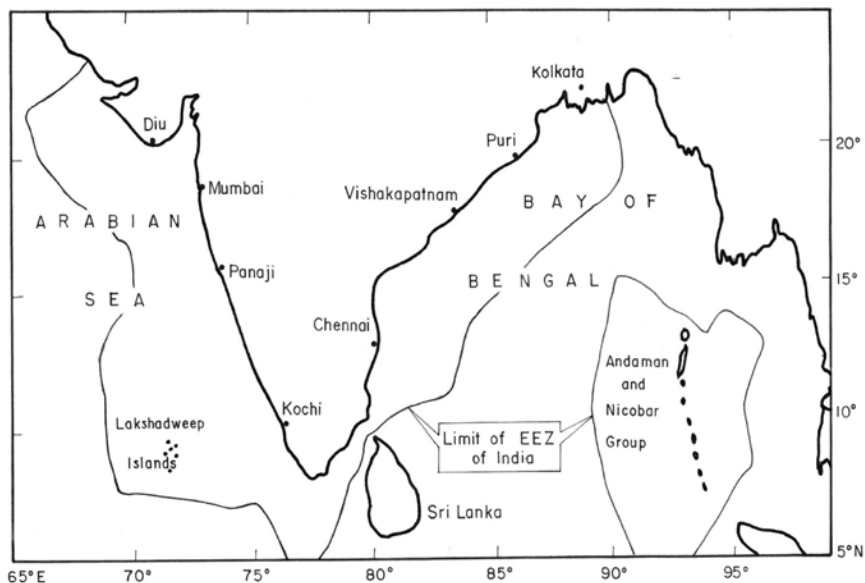


Figure 3: India's EEZ

of 100–500 m, and is generally not older than Eocene times, thus reducing the hope of a major part of the ocean being a possible reservoir for hydrocarbon deposits. Nevertheless, some coastal areas with great sedimentary thickness can be considered prospective for methane deposits. The most important areas are in the northern part of the Arabian Sea and the Bay of Bengal, that is, well within India's EEZ. As the greatest proportion of likely prospects lie in less than 200 m of water, current oil exploration is focused within the shallow areas. Most active current exploitation for oil and gas deposits is limited to fields surrounding the Bombay High, the Cambay Basin on the west coast, and the Godavari Basin and Tamil Nadu coastal belt on the east coast. The Andaman Sea environment suggests that there are possible hydrocarbon deposits there also.

## Seawater

The commercial use of seawater in the Indian Ocean is still very under developed. The first attempt in recent times has been the ring of 'sweet

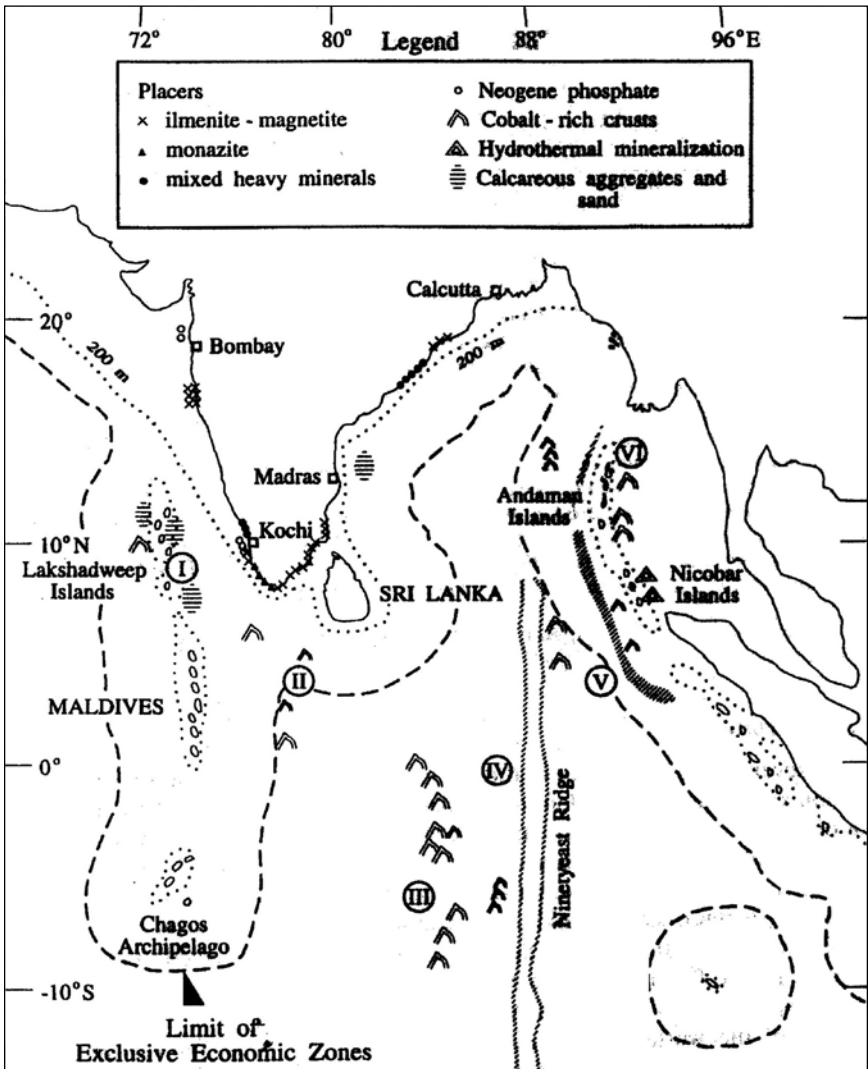


Figure 4: Major mineral occurrences and approximate EEZ limit in the northern Indian Ocean  
 Source: Roonwal 1997

water' conversion plants in the coastal areas of the Persian Gulf and the Arabian Peninsula. Seawater is a huge resource of salt, magnesium and its compounds, bromine, and other elements. Although no

desalinization plants are operative in the Indian EEZ, experiments in this direction have been conducted by the Central Salt and Marine Chemicals Research Laboratory at Bhavanagar in Gujarat, which has produced a special membrane for the purpose. Today Government of India provides desalinated drinking water to the people of Karaveti Island.

### **Beach and Offshore Heavy Mineral Placers and Rare Earths from Heavy Mineral Sands**

Placer deposits in the Indian Ocean have been worked since ancient times at locations such as Richards Bay in South Africa and Kerala (the Malabar Coast) in south India. More recently, ilmenite placers have been located in Ratnagiri in Maharashtra (Siddiquie et al. 1979, 1982; Siddiquie and Rajamanickam 1979), and south of Bombay on the west coast, (overview in Rajamanikam 2000; Roonwal 2005).

The occurrence of coastal and immediate offshore placer deposits in the Indian EEZ reflects the nature and association of the country rocks in the hinterland. The placer deposits along the coasts of India were mapped originally by the Geological Survey of India, which continues this activity. With the creation of the National Institute of Oceanography, a survey for placer deposits was conducted by NIO /GSI around Ratnagiri. This resulted in a full assessment of the magnetite-ilmenite placers there (Siddiquie et al. 1979, 1982). Along the east coast, placer investigations have located economic-grade deposits on the Narayanpur-Chatrapur-Gopalpur coast and Malud-Puri coast, as well as off the Chilka Lake in Orissa. These are primarily mixed heavy mineral assemblages comprising magnetite, ilmenite, garnet, sillimanite, rutile, zircon, and monazite association. This belt extends farther south in Andhra Pradesh. In Tamil Nadu, beach deposits are an association of mixed minerals of the type seen on the Kerala coast. In the coastal area from Kalingapatnam to Baruva, an association of

ilmenite-silimanite-garnet placers has been located, and assessments made by vibro coring (Geological Survey of India, 1992).

No known gold placers occur within the Indian EEZ. However, gold has been obtained by panning in the sands of the Subarnarekha River in its Bengal delta in West Bengal. Heavy minerals may be concentrated in the paleo-channels of buried rivers and reworked Pleistocene gravel on the continental shelf, particularly along the Orissa and Andhra Pradesh coasts. Recently, buried and submerged terraces have been reported off the west coast of India at 40, 60, 100, and 200 m water depth, with a possibility of offshore placer deposits (Rajamanickm 2000), as well as in the immediate shallow-water zone off the Kerala and Tamil Nadu coasts (Figure 5).

Known reserves of placer deposits on the Kerala coast which include the well-known deposits of Chavara, Varkala, and Muttam are ilmenite, 1.40 Mt (million tons), rutile, 0.14 Mt, zircon, 0.13 Mt, and sillimanite, 0.53 Mt, for a total of 2.20 Mt (Ravindran, 1994). These deposits are worked on the basis of blocks of 5-10 km<sup>2</sup>. Dredging is planned for the offshore areas adjacent to them, where high-grade occurrences have been confirmed. On the Ratnagiri coast of Maharashtra, the heavy mineral percentage varies between 54 per cent and 70 per cent in bulk samples consisting mainly of 14-39 per cent magnetite and 16-30 per cent ilmenite (Geological Survey of India, 1992; see also Figure 6 below). The commercial wings of mining of heavy mineral sands is the Indian Rare Earths Ltd. (IREL).

Asia has one of the largest reserves of Rare Earth ores. It is also a large producer of mined rare earths and rare earth intermediate, and is in the world's major market for rare earths. In 1997, Japan and South East Asia accounted for an estimated 24,500 t (37 per cent) of the 66,000 t of contained rare earth oxides (REO) consumed worldwide, with China consuming a further 12,000 t (18 per cent). A decline of these markets could have a serious effect on the supply and demand

balance. China supplied more than 60 per cent of the world’s rare earth production in 1997. Japan, the largest single consumer of rare earth, is forced to rely heavily on China for its rare earth raw material. Japanese imports of rare earth products from China were valued at a record US\$ 14.4 billion in 1997.

Some rare earth producers in China were slow to respond to demand, which meant disruption in supply and demand in 1998–99. Here lies an opportunity for India to get more into the world market. But this is possible only when we make efforts towards increasing production. At the same time, smaller producers have sometimes expanded too rapidly and often without evaluating the market’s future requirement accurately. As a result, an oversupply has developed for one or more rare earth products. This occurred with yttrium and other ‘heavy’ rare earth in the late 1980s; and with cerium and lanthanum oxide in 1996–97.

**Table 4: Rare Earth Minerals: Recent Production Figures**

	1996	1997
Monazite		
Brazil	200	400
India	2700	2700
Sri Lanka	120	120
<b>Total</b>	<b>3020</b>	<b>3220</b>
Bustnaesite		
China <sup>1</sup>	5,5000	5,0000
USA	2,0400	2,0000
<b>Total</b>	<b>7,5400</b>	<b>7,0000</b>
Xenotime		
Malaysia	340	300
Loparite		
CIS	6000	6000
<b>Final Total</b>	<b>8,4800</b>	<b>7,9500</b>

<sup>1</sup>Chinese bastanaesite figures include production of xenotime, monazite.

Source: Based on USGS and Mining; J. London, 1998, August.

By 2000, the demand for rare earth is expected to reach 70,000 t/y REO, and is valued at US\$ 660 million. In 1997, South East Asia and Japan provided the strongest and most rapidly growing market for key-applications, such as auto-catalysts permanent magnet, rechargeable batteries, and phosphorus aid advanced ceramic.

Rare earth prices were relatively static between early 1997 and early 1998 possibly reflecting the stabilizing effects of increased demand for 'mischmetal' (alloys or mixed metals) for batteries. Mischmetal prices experienced a small increase in their average market price range (from US\$ 6.80 (0.5 -10. 5/kg) to US\$ 6.80 -12kg) over the same period.

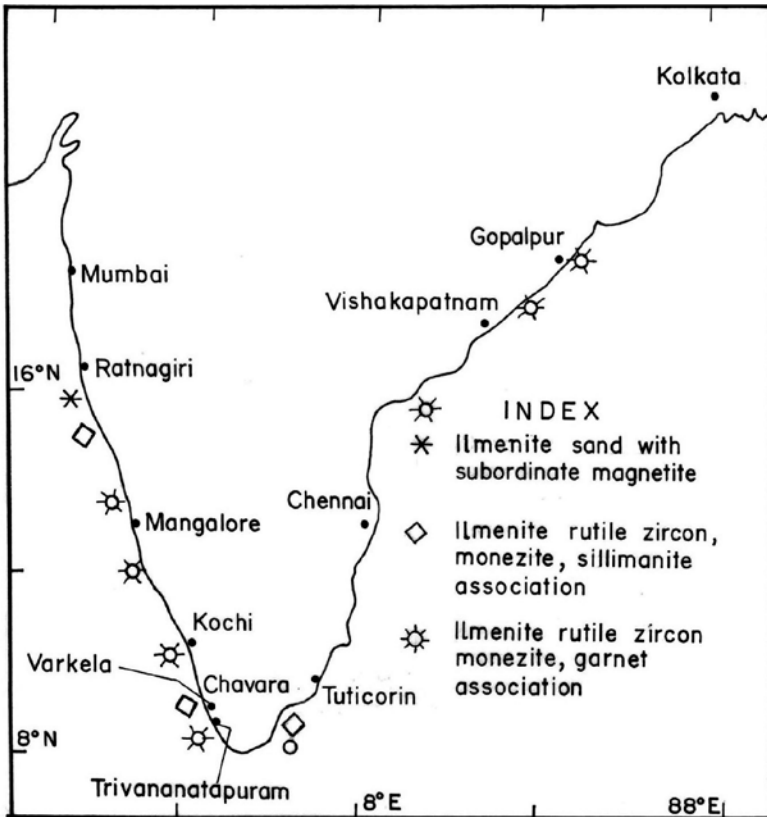


Figure 5: Beach Heavy Mineral Sand Deposits in India

Source: Roonwal, 1999

The average price has ranged from neodymium oxide 96 per cent to 99.99 (US\$ 140 - 160 kg) between the first quarter of 1997 and the first quarter of 1998; this has been due to the increasing demand for high purity neodymium oxide for neodymium non-boron magnet manufacturers (see Table 4).

## **Phosphorite**

The Indian EEZ does not seem to possess major phosphate occurrences; however, some phosphate has been reported off the Malabar Coast in phosphatic mud-banks, where 1–5 per cent  $P_2O_5$  content was measured in dry samples. The phosphate content is high in the dry season, with some samples assaying up to 18 per cent  $P_2O_5$ . However, because of the upwelling and turbulence associated with the monsoon, the phosphate content in the sediments is diluted seasonally. Phosphatic sediments have been located on the Bombay-Saurashtra coast. Phosphate accumulation is taking place on the seafloor in the form of nodules and grains at several sites between 30 and 400 m water depth, where upwelling high nutrient flux and biological activity coincide.

In the Bay of Bengal, phosphate nodules have been described in sediment samples collected north of the Andaman Islands, in which about 10 per cent  $P_2O_5$  content was reported by Russian oceanographers during the International Indian Ocean Expedition. The Geological Survey of India has begun a search for phosphate-rich sediments in the Arabian Sea, with an initial survey off the coast of Gujarat (Geological Survey of India, 1992).

## **Cobalt and Platinum-rich Ferro-Manganese Crusts on Sea Mounts**

Since India has no known resources of cobalt, the discovery of appreciable deposits of this metal in the Indian EEZ would be significant. Preliminary discussion of possible sites of occurrence of

cobalt-rich crusts within the Indian EEZ is available (Roonwal 2013; Roonwal and Glasby 1996). Although Co-rich crusts in the Pacific Ocean are well known, such crusts have not yet been recovered from the Indian Ocean. Ferromanganese crusts are also known to occur in the deeper areas (> 3,000 m) on the flank of the Carlsberg Ridge. The Geological Survey of Indian (GSI, 1992) has reported the recovery of manganese crusts off Tillanchard in the Andaman Sea, and from the slopes of Chetam Island in the Lakshadweep group (P.R, Chandra 1992). The composition of two grab samples is typical of crusts of hydrogenous origin; however, the cobalt contents were too low (0.08 per cent and 0.25 per cent, respectively) to be of economic interest. Based on previously stated criteria for the formation of Co-rich crusts, a number of locations where these crusts may occur in the Indian EEZ were selected by this writer (Roonwal 1988, 1990, 2013). These include the areas around the Lakshadweep Islands, on both sides of the Ninety-east Ridge and the northern Andaman Sea (see Fig. 6 below).

## **The Future**

At present, India is at an early stage in utilizing many aspects of ocean science and technology. However, in the near future, several factors are likely to quicken the pace of development in this field. India has a strong desire to explore hydrocarbon resources in offshore areas, and there is already large-scale activity being undertaken by the national Oil and Natural Gas Corporation as well as by Oil India Limited. In the field of the exploitation of non-living resources from the deep sea, India has invested in the Poly-metallic Nodules Project (Yates and Roonwal 1994a and b; DOD, 1992). India is currently more inclined to mine the offshore ilmenite-rutile-monazite placers along the coast of Kerala on the west coast, and the Gopalpur-Andhra coasts on the east.

In terms of terrestrial mineral resources, Indian domestic supplies of some metals are inadequate. Considering India's industrial and

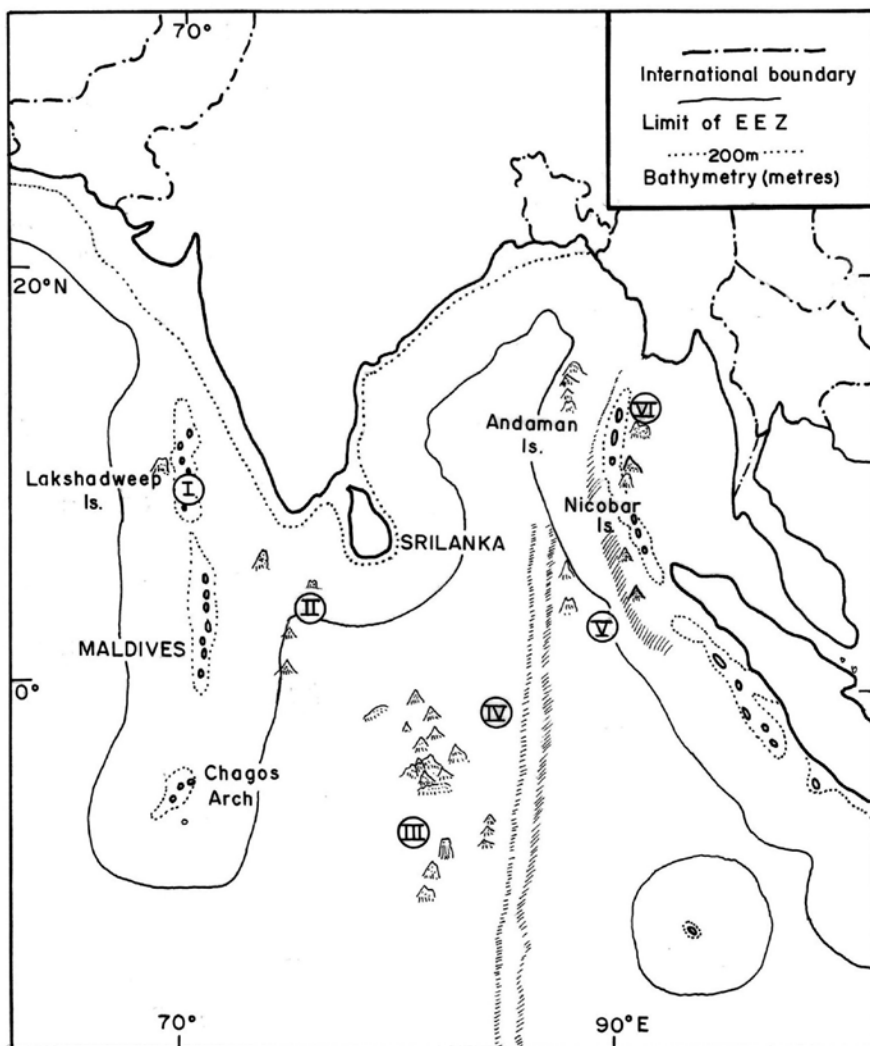


Figure 6: Possible Sites for Cobalt and Platinum Rich Crusts Within and Outside the EEZ, Northern Indian Ocean

Source: Roonwal 2013

economic development, there will be increasing demand for metals such as copper, nickel, cobalt, and silver, as well as gold and platinum-group metals. The level of development is such that, at present, there is a low level of consumption of metals compared to the industrialized

nations. This is bound to change substantially. For example, India's per-capita consumption of copper is 0.11 kg, compared to 7.7 kg for the industrialized nations, and 3.0 as a world average. This is true with respect to other nonferrous metals as well as for iron and steel.

The situation with regard to nickel and cobalt is even more depressing. India has no known deposits of cobalt, and the ore deposits of nickel are extremely low: 55 MT indicated and 82 MT inferred, totalling to 137 MT, with an average grade of 1.04 per cent Ni, compared to 8,600 MT (mean grade 3.3 per cent) in Canada. Table 3 shows the reserves and production of selected minerals. The situation with respect of manganese and rock phosphate is not very strong.

It seems certain that exploration activity both on land and sea will increase. In fact, joint ventures and foreign collaborations are becoming increasingly important. Since India proposes to be careful about environmental aspects, projects such as the one developed for the offshore mining of placer deposits on the Kerala coast have been designed with this in mind. With an industrial growth rate of 4.5–5 per cent and even up to 8 per cent in some sectors, India offers opportunities for resource exploitation, manufacturing, and marketing. The development of the EEZ is an integrated subject which requires the identification and analysis of the interests of the stakeholders in the utilization of known and inferred resources. In order to proceed in EEZ development, India will have to define priorities, and examine the environmental problems facing the EEZ, either now or during the exploitation activity. The Kochi (Cochin) workshop (Thiel et al. 1994) defined the first-order assessment of the likely future development in the utilization of the EEZ and related environmental impact. It is necessary to define the range and scale of these various aspects, and suggest research requirements to facilitate relevant future policies for the EEZ.

It is also necessary to develop a coherent management policy for the Indian EEZ which is based on sound environmental considerations.

Thus, a wide range of interests involving private and public sectors, and others concerned with effluent discharge, hydrocarbon and non-hydrocarbon mineral extraction in domestic shallow and deep waters, fisheries and mariculture, coastal farms, and tourism all will have to work together as recommended at the national seminar held in 1994 (Yates and Roonwal 1994b).

### **Calcareous Aggregates and Sands**

Calcareous and silica sands occur in the vicinity of the western and southernmost coasts of the Indian peninsula, where the biological productivity is high. Calcareous sands are particularly known in the Lakshadweep group of islands and reefs (Mallik 1983), where the carbonate content is as high as 50 wt per cent  $\text{CaCO}_3$  (Siddiquie and Rajamanickam 1979). Calcareous zones have been demarcated adjacent to the Lakshadweep Ridge, where  $\text{CaCO}_3$  content varies between 24 per cent and 90 per cent, averaging 51 per cent. Coral reefs occur along the coasts of Tamil Nadu and in the Andaman-Nicobar Islands. Submerged coral reefs have been inferred in the central-western continental shelf. The Geological Survey of India has undertaken surveys for calcareous aggregates and sands between Porbandar and Nevadra along the Gujarat coast (Geological Survey of India, 1992). On the east coast, a survey along Pentkola, near Kakinada in Andhra Pradesh, has located lime mud and calcareous oolite in the Chilka-Puri sector in Orissa (Geological Survey of India, 1992).

### **Economic Aspects of EEZ Resources**

Let us now consider Economic Aspects of EEZ resources. Since India has no known resources of cobalt, very poor resources of the platinum group of elements (PGE), as well as poor resources of copper and other base metals, it is but necessary to make an inventory and feasibility study of the available resources of these metals in the offshore area. It

is equally important to make a reassessment of the beach and offshore placer minerals which are a source of rare earth elements, with the special aim being to reduce the loss of resources at the mining sites and beneficiation. This will help in conserving the rich deposits of Kerala which should give a good yield for several years to come.

The mineral and hydrocarbon rich Andaman Sea is likely to attract attention in the strategic context. This area is away from the mainland, has limited development and human activity, and is a sort of taken for granted area. But it emerges that this could be the most difficult area for India, especially if Indonesia and Myanmar are encouraged to create direct trouble, with full but indirect backing of a powerful neighbour. Thus, the Andaman Sea and its island territories need special attention, and be seen from a long-term perspective in terms of national security aspects.

India would have to pay attention to seawater as a resource because of acute sweet water shortage in the coastal zone. This will have a two-fold impact: on the supply of sweet water, which would help reduce over exploitation of the groundwater resources in the coastal zones, as well as protect coastal zones from saline water infiltrate. Surveys for the exploitation of marine phosphorites, cobalt-rich ferromanganese encrustations and volcanogenic massive sulphide (VMS) are other minerals which require study and exploration. Near and within the EEZ, it is the Andaman Sea - where the geological setting is ideal - which could be a first grade target site for VMS and hydrocarbons (Roonwal 1998). India's immediate concern could be to upgrade the mining of heavy mineral sands and, hydrocarbon exploration. As hydrocarbons are a special theme, they are not discussed in this assessment.

## Chapter VI

# *Hydrothermal Mineralization in the Andaman Sea*

One area within the EEZ that is potentially prospective for hydrothermal mineralization is the Andaman Sea. The Sumatra earthquake and the resultant Tsunami havoc of 26 December 2004 have again focused attention to this region. Thus, it is important to review the mineral and hydrocarbon potentials of this region because, in the long term, it will be a site of large investments. The Oil and Natural Gas Corporation of India has committed of nearly US\$ 2 billion for the exploration of hydrocarbons in the Bay of Bengal. This is likely to increase in the coming years. References to the mineral resources of the Andaman Sea are available in Roonwal (1986, 1989, 1997, 1999, 2005, and 2009); Roonwal and Glasby 1996; and Anon 1991, 1992. References for petroleum resources are available with the Oil and Natural Gas Corporation (ONGC) of India (2004). See also, Roy 1983; Roy and Das Sharma 1991, 1993; Anon 1992; and in SPG 1998. The major interest lies in hydrocarbon deposits (cf. ONGC of India) and volcanogenic massive sulphides (VMS).

### **The Andaman Sea**

The Andaman Sea in the NE Indian Ocean, lies between 6°-14° N and 91°-94°E (Figures 7a and b, and 8), is heavily covered by sediment (up to 6000 m), and has an actively extending back-arc basin on the Indo-China continental margin. In this respect, the Andaman Sea is

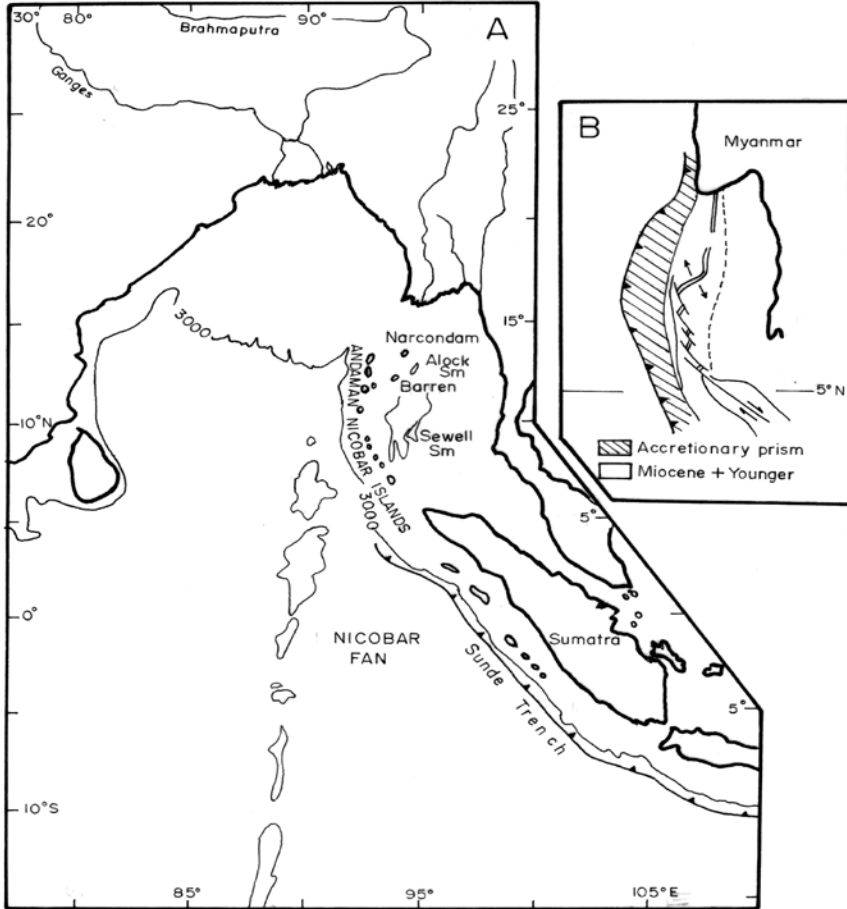


Figure 7: (A and B): Location of Andaman Sea in the NE Indian Ocean

an extensional basin, which began opening about 13 my ago (Middle Miocene), with a rate of about 37 mm/yr (Curry et al. 1982). The total opening of the basin has been about 460 km and it now occupies about 800,000 km<sup>2</sup> (Rodolfo, 1969) (See Figs. 8 A and B). Already, anomalous concentrations of Cu (up to 500 ppm), Zn (up to 500 ppm), and Pb (up to 900 ppm) have been reported in the coarse fraction (> 800 mesh) of clay sediments taken at about 1,500 m along the toe of a submarine valley, 12 km west of Narcondam Island (Banerjee et al. 1992).

The structure, tectonics, and geological history of the Andaman Sea are becoming better known (Rodolfo 1969; Curray et al. 1982; Mukhopadhyay 1988; Kumar 1990; Biswas et al. 1992). Magnetic anomaly data suggest that the Andaman Sea began to open about 13 Ma, with a spreading rate of about 37 mm/yr (Curray et al. 1982). Two islands (Barren and Narcondam) are volcanically active (Dutta 1991; Halder et al. 1992). The Andaman-Nicobar area can be considered a combination of a fan valley and an active spreading rift which shows striking similarity to the Gulf of California (Curray et al. 1979), where sediment-hosted hydrothermal mineralization is well documented in the Guaymas Basin. By analogy, therefore, the Andaman Sea may be considered highly prospective for submarine hydrothermal minerals (Roonwal 2009).

The bathymetry of the basin is complex. To the west lies the Andaman-Nicobar Ridge which marks the boundary between the Indian and Eurasian-China plates, and to the east the Malay continental margin. The main topographic features of the basin are (a) the Central Andaman Rift; (b) the Central Andaman Trough; (c) the Deep Through, and (d) the Barren Seamount Complex; the Alcock Seamount; and the Sewell Seamount (Rodolfo, 1969). The deepest part of the basin is the central axial rift trending NE-SW and centred at 10.5°N: 94.5°E, with a depth of 4000 m (Curray et al. 1982). The rift valley can be traced to the south but is offset by NNW-SSE faults at places (Anon 1981) (cf. Curray et al. 1982, Verma 1991) (Figs. 9, 10 and 11 below). The main sources of sediment to the basin are the Irrawaddy, Sittoung, and Salween rivers in Myanmar. The Irrawaddy presently discharges about  $265 \times 10^6$  tones of silty clay per year, 90 per cent of which is deposited in the continental shelf (Rodolfo 1969). During periods of high level, the bulk of the sediment is trapped in the delta area or on the continental shelf. However, during low sea-level stands, they are introduced directly into the basin (Curray et al. 1982).

The matrix data show that there is no direct input of sediment from the Bengal Fan into the Andaman Sea (Curry 1991). Sediment in the Central Andaman Trough is principally turbidity flows (silty clays), with an overall sedimentation rate of about 150 mm/1000 years (Rodolfo 1969). The Central Andaman Rift is both an active spreading centre and a fan valley analogous to that in the prospective for hydrothermal minerals (Professors P. Halbach (Berlin) and S.D. Scott (Toronto) - Personal discussions, Roonwal and Glasby, 1996). The distal fan deposits have buried the rift valley in the north but have not penetrated to the southern part of the rift (Curry et al. 1991, 1982; Anon 1981). The nature of neo-volcanism in the spreading zone is unknown. Magnetic stripping in the southern portion indicates that salt is likely to pre-dominate. However, the closest proximity of the spreading axis to the submarine active arc and the continental margin to the rest raises the possibilities that Felsic Volcanic maybe present.

## **The Geology and Tectonics of the Andaman Sea**

The geology and tectonics of the Andaman region are reasonably well known through the work of Peter et al. (1966); Weeks et al. (1967); Rodolfo (1969); Eguchi et al. (1979); Curry et al. (1979, 1982); Mukhopadhyay (1984); Maung (1987); Mukhopadhyay (1988); Kumar, (1990); and Biswas et al. (1992). Tectonic features of the Andaman Sea region are shown in Figs. 8, 9 and 10 above. The Indian Plate is under-thrusting the long and narrow Burma plate (part of Eurasian China plate), along the Sunda Trench. The northern portion of the Sunda Trench is completely filled with clastic sediments of material from the Himalayan, and Tibetan Plateaus being brought through the north Indian river system. The Burma Plate carries the active volcanic western Sunda Arc. The site of the 26th December 2004 earthquake whose epicentre was located at 3.3°N and 96.1°E - and sea bed to the west of it, is an accretionary prism that has been scrapped off the subducting plate, and is exposed, together with Cretaceous ophiolites

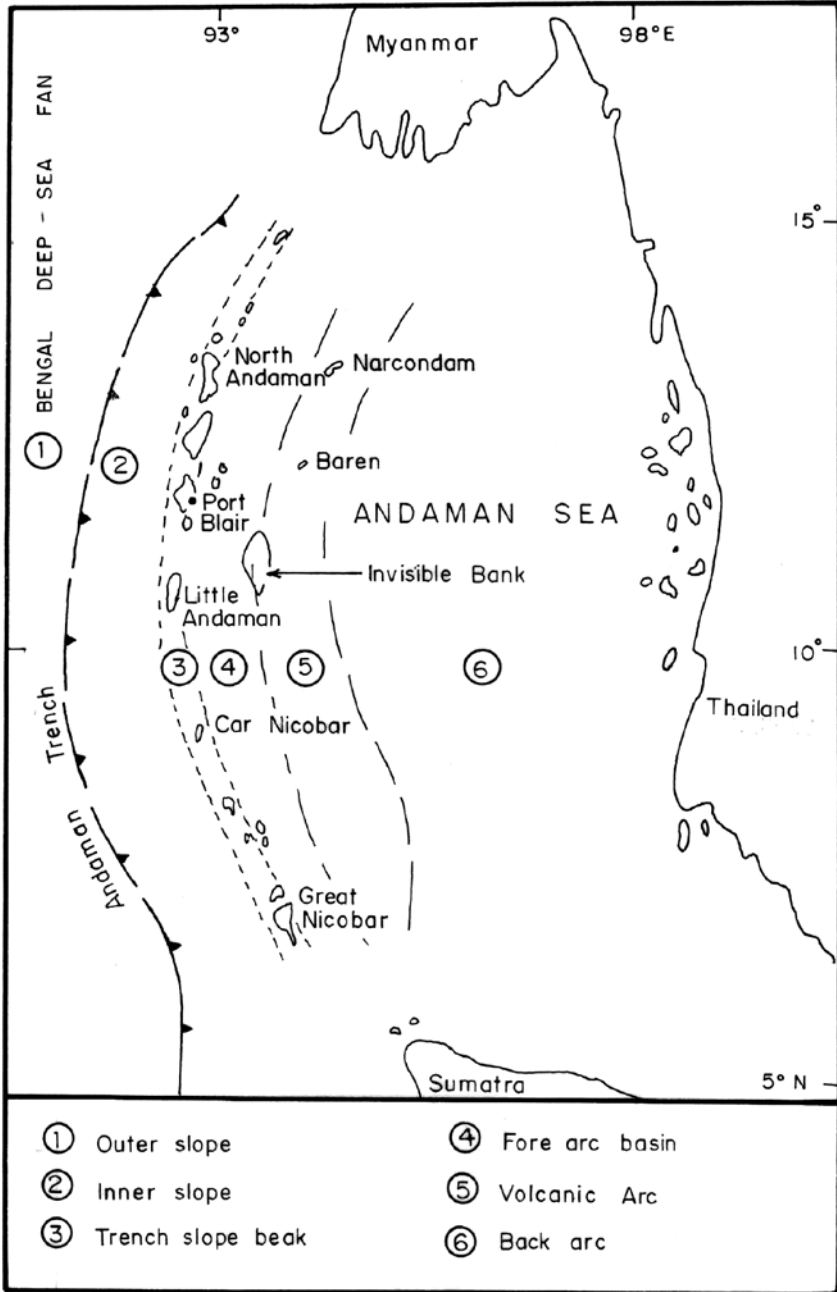
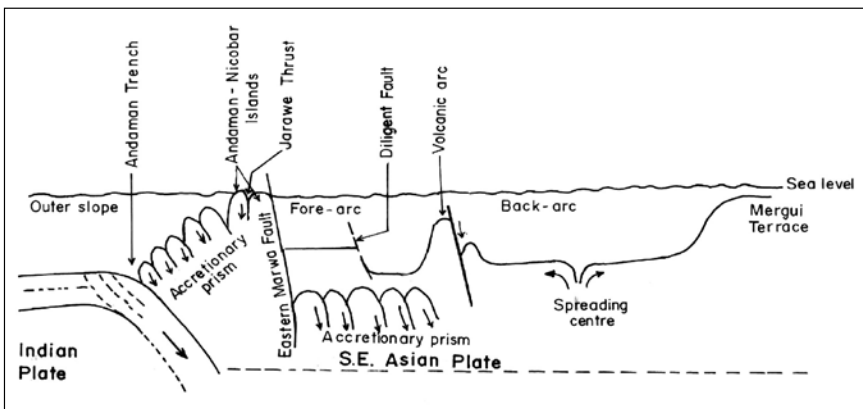


Figure 8: The Tectonics of the Andaman Sea  
 Source: Curray et al. 1982

and various younger sedimentary units, on the uplifted islands of the Andaman-Nicobar Ridge. Major transform faults along the backbone of Sumatra (Sumatran Fault System) to the South, and cutting off the Eastern Highlands of Burma (Saging Fault) to the north, are linked by short segments of back-arc spreading in the Andaman Sea. They constitute the boundary crust of the Andaman Sea, with the flanking volcanic arc and accretionary prism to the west and continental crust to the east being exposed on land in the Central Valley of Myanmar (Burma). This extensional zone was created by the north-westwards rifting of the continental region represented by the eastern Burma highlands and the Malay Peninsula. A review of the land geology of the Andaman is given by Pandey et al. (1992).

### The Nature of the Sediments

Data (Roonwal et al. 1997, a and b) show that the sediment from the Andaman Sea consists mainly of quartz, chlorite, illite, smectite, kaolinite and feldspar, with traces of calcite. These minerals occur in varying proportions. Sediments from the Central Andaman Trough contain higher amounts of illite than those from the flanks of the basin which contain higher amounts of smectite.



*Figure 9: Geological Zones of the Andaman Sea*

The mineralogy of sediments from the eastern flanks of the Upper Nicobar Fan is more variable. Samples from a depth greater than about 2500 m consist mainly of quartz, illite, chlorite, smectite, and traces of feldspar, whereas those from shallower depths consist mainly of calcite, with corresponding lower amounts of accessory minerals. Calculations of relative clay mineral abundances show that the Upper Nicobar Fan sediments contain about 30 per cent smectite, 46 per cent illite, and 25 per cent kaolinite on average, whereas those from the Andaman Sea contain about 35 per cent smectite, 39 per cent illite, and 26 per cent kaolinite, on average.

Data of the element concentration for the sediments from the Andaman Sea show them to be relatively uniform in composition, whereas sediment from the eastern flank of the Upper Nicobar Fan are much more variable in composition on account of the greater variability in the  $\text{CaCO}_3$  content (3.87 per cent).

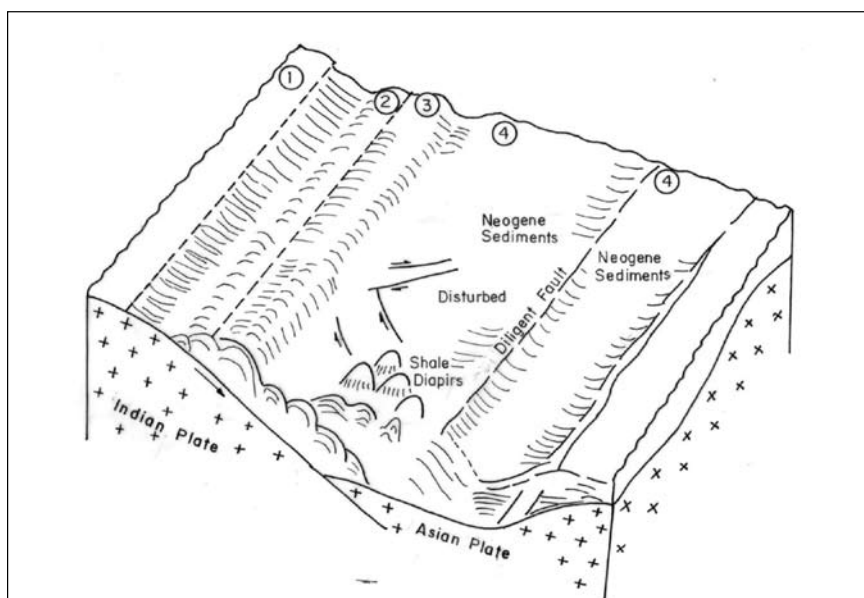


Figure 10: A Geological-Tectonic Model for East West 11°N in the Andaman Sea.

Note: Numbers are similar to as shown in Figure 4.

## **Seafloor Spreading and Implication for Volcanogenic Massive Sulphides (VMS)**

The discovery of 'black smokers' since 1979 on mid-oceanic spreading ridges (Rona 1988) has initiated a major breakthrough in understanding how ancient massive base metal sulphides ore bodies were formed. However, neither the tectonic setting nor the basaltic nature of volcanism at mid-oceanic ridges are clearly relevant to the majority of the ancient massive sulphide ores, which tend to be associated with felsic volcanic rocks, apparently formed in the continental margin environments. At least 3 occurrences have been discovered on the modern sea floor, which are clearly analogous to the land deposit mentioned above. These are: Jade deposits in the Okinawa Trough (Halbach et al. 1989); the Valu-Fa deposit in southern Lau Basin in the Back Arc Basin, (Fouquet et al. 1991); and the PACHMANUS deposit in the Manus Basin in the Back Arc Basin near Papua-New Guinea. The Andaman Sea is a substrate for back arc extension, and is a continental rather than an island arc crust.

The main spreading axis of the Andaman Sea centres at 10.5° N and 94.5° E. This is a very well defined linear, NE-SW trending, physiographic feature (Figs. 8 and 9 above) at about 10.5°N. To the south, very short spreading and transform segments alternate; but on comparing magnetic lineation with present day seismicity and topography, (Curry et al. 1982) it was concluded that the multiplicity of spreading axes is becoming simplified into long continuous segments. To the north of the main spreading axis, the spreading zone becomes curved, and the spreading axis is oblique to the trend of the axis. Alcock Seamount which forms the west margin of the axis here is an uplifted block of young oceanic crust consisting of augite basalts (Rodolfo 1969). Eguchi et al. (1979) concluded from teleseismicity and gravity data that another spreading segment may exist centred at 14°N and 96°E (See Figure 11 above 1 and 2 below); but is buried under a thick accumulation of clastic sediments.

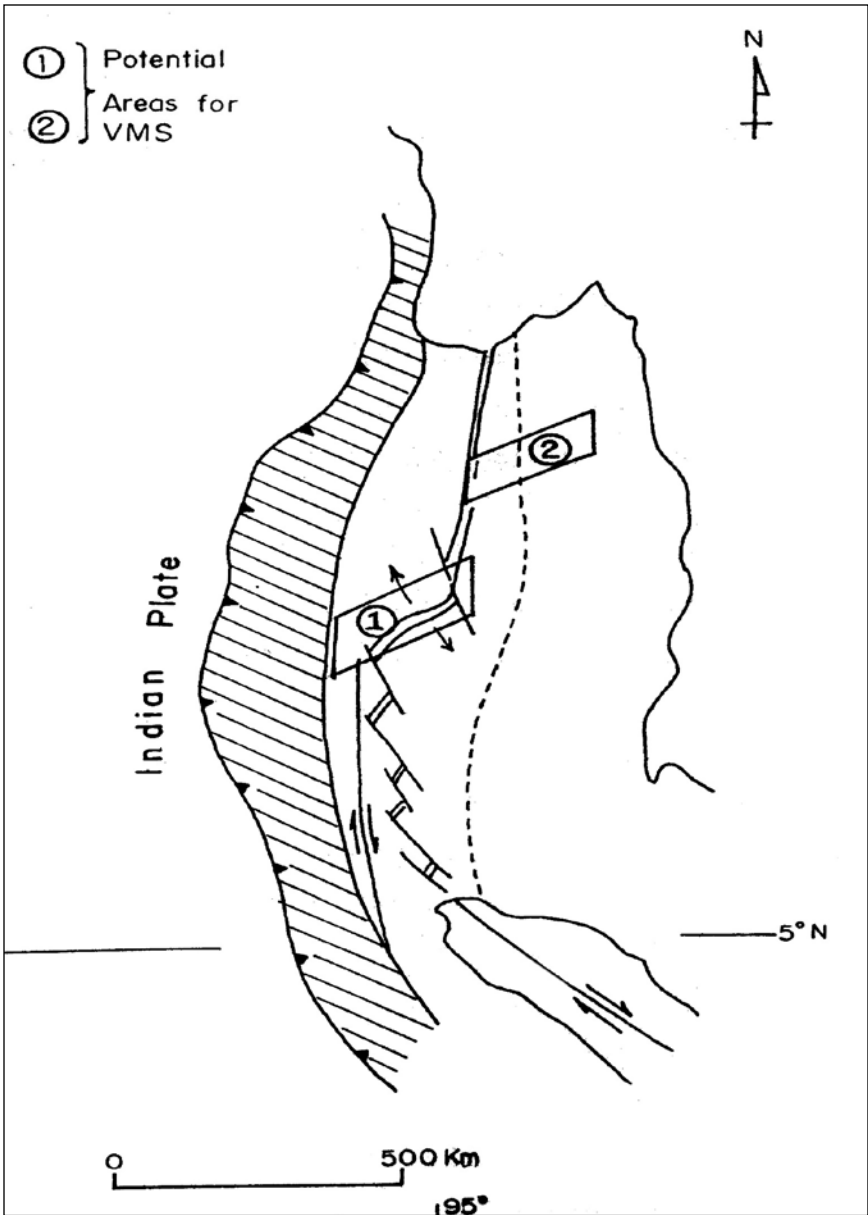


Figure 11: The Potential Areas for Volcanogenic Massive Sulphide: (1) Unsedimented spreading axis, (2) Sedimented spreading axis

The most prospective area for VMS is the main spreading axis, which is 5 to 8 km wide, and on the order of 500 m deeper than surrounding seafloor. At its NE end, it is developed within very thick sediments (about 2300 m; Curray et al. 1979). Bathymetry (Figure 11 above) shows that the flat sediment surface at 3000 m water depth is transected by the rift valley. Upturned edges of sediments in seismic profiles such as Fig. 7 A and B suggested to Curray et al. (1979, 1982) that the spreading has been continuous, with episodic deposition of sediments coinciding with periods of Quaternary low stands of sea level. As a consequence, the NE part of the main spreading axis at about 94°2'E is heavily sedimented, whereas the remainder and the short spreading segments to the south are relatively sediment free.

Thus, in the Andaman Sea, there are possibilities of encountering hydrothermal venting in both a heavily sediment piled and a relatively sediment-free setting within the same spreading system. It may be noted here that the largest known seafloor deposits are in sedimented spreading centres. Why this is so, is not known; but it could be that the sediments act as a thermal insulation barrier to fluid flow which results in a more focused discharge of hydrothermal fluid to the seafloor. The Andaman setting may provide answers to this question (Figure 11 above).

## **Hydrocarbon Resources**

India's energy sources are very limited, or are untapped. The energy produced is also not gainfully used because of loss in transmission and other political factors such as permitted theft of electricity. The hydrocarbon potential is known to be also limited, unless of course efforts underway with modern technology yield promising results. Nearly 75 per cent of the required hydrocarbon demand is met through imports which means that a major share of export earnings go towards paying for the hydrocarbons. Added efforts are needed to locate hydrocarbon deposits to meet the increasing need of hydrocarbon. The

major offshore discovery in the Bombay High region is already now 'old'. Exploration efforts in the immediate offshore basins on the west (Cambay, Lakshadweep) as well as others on the east coast have given potential results.

Lying between oil-bearing Indonesian basin to the south and Burma basins to the north, the Andaman Basin has been explored by many wells, resulting in the discovery of the accumulation of non-commercial gas. The Paleogene sequence has generally remain unexplored. Hydrocarbon potential in the Andaman Sea appears to be confined to the fore-arc basin (Figures 9 and 10). The basin has a 4000–6000 m thick succession of Cretaceous to Quaternary marine sediments, overlying the Cretaceous ophiolites basement. Extrapolation of surface geological mapping on the Andaman group of islands, as well as the data from drilled wells in this fore-arc offshore give a variation in the stratigraphy and lithologs between the two areas. Within the fore-arc, rapid change in the stratigraphy in short distances are found, and has suggested a presence of major Neogene-pre-Neogene unconformity as well as a general paucity of reservoirs in Neogene succession. Major information on stratigraphy has been obtained through multi-channel COP data. This has shown that the Paleogene and older sections are highly distributed, with poor, chaotic, nature and isolated broken reflections, which are in sharp contrast to the fair reflection obtained in relatively less distributed Neogene sediments. Exploratory wells drilled by the ONGC of India in the fore-arc have shown gas in Middle Miocene limestone which is type III Kerogene and support hydrocarbon generation in the basin. Further attempts are needed for the Paleogene and other sedimentary sections where the presence of good reservoirs and mature organic matters are established.

The exploration for hydrocarbon deposits in the Andaman Sea began in 1959, and has been confined to fore-arc basin. According to the ONGC of India, one well drilled through the Middle Miocene Limestone has yielded gas. Otherwise, the drilling results have been

negative. This need not be seen as disappointing because the fore-arc regions are known potential areas for hydrocarbon accumulation. The Andaman Sea fore-arc basin shows both a genetic and morphological similarity to other areas. In the Andaman Sea fore-arc basin prospective areas would be structural traps, uplifted portions, Neogene carbonate sediments, turbidite, reefs, and shoreline deltas. The hydrocarbon potential in the fore-arc basin is enhanced by tectonic re-structuring in the development of traps of en-echelon folds, fault block, thrust faulted folds, and stratigraphic traps adjacent to volcanic upheavals. The limiting factors are the youthfulness of the basins, low geothermal gradient, and shale diapirism.

The major hydrocarbon plays that could be identified are the pre-Neogene unconformity; all seismic data below it is poor, making prospect assessment in the palaeogene and older section difficult, though some strong reflections spread over a small area have identified a few locations (ONGC, 1993). The oldest possible play identified includes structural traps and reverse faults associated traps of the Palaeocene-Cretaceous age around the Middle Andaman region. Some structural closures of similar ages have been recorded in the southern zone of the Andaman-Nicobar Archipelago. Structure closures, together with the combination traps in the east of the Middle Andaman, which wedge out and pinches at the Invisible Bank, presents possible Oligocene plays. Further, the angular unconformity traps against the pre-Neogene unconformity points towards more hydrocarbon plays in the southern Andaman and the Invisible Bank. Due to faulting in the east of the Dilignet Fault (Figures 9 and 10 above) in the southern Andaman Sea, several intra-graben type reversals are observed in deep waters, which could hold prospective exploration targets. Further areas would include the Wedgeouts, pinchouts, and carbonates build ups on the western flanks of the Invisible Bank where a Middle Miocene carbonate sequence is present.

All data such as heat flows, geochemical sampling, and analyses are inadequate at present to fully estimate the potential of source rock as well as the maturation characteristics of the sediments. Also, we lack facies analysis of the sequences; so also is the palaeontologic control. Therefore, a proper assessment of the Andaman Sea hydrocarbon potential is only possible with more information. The ONGC of India may like to plan joint ventures or award contracts for areas for the purpose.

### **Gas Hydrates Resources**

Today, gas hydrates could be named as an attractive, non-conventional source of the gaseous hydrocarbons identified. Such hydrates may occur in deep oceanic sediments in tropic regions in disseminated, dispersed, nodular layered or massive forms. The occurrence is controlled by conditions of temperature, pressure, and the composition of the available gases (Figures 10 and 11 above). Information suggests that, in the Andaman Sea, a complex series of Neogene fold packages the progressively under-thrusting from east to west in a N-S trend. It appears that the area around South Andaman in the fore-arc region (Figure 9 above) was subjected to maximum subsidence in the Neogene period. These Neogene sediments contain good organic matter but are immature, suggesting biogenic gas prospects within the younger rock (Roy and Sharma 1991, Chandra et al. 1998).

India's ONGC will be conducting deep-water resource mapping exercises. The Indian Oil Ministry shall coordinate the gas-hydrate resource mapping exercise by drilling for cores at locations in the deep-water of the Andaman Islands, as also in Goa and Andhra Pradesh. The Directorate General of Hydrocarbons is expected to solicit an expansion of interest for the deep-water drill ship that can drill in the depth of 1000 to 2000 meter. Pre-drill studies such as shallow, high resolution seismic surveys, as well as current and wind surveys will proceed core

drilling. It is important to note that almost US\$ 20 million has been set aside for the survey, while US\$ 12 million is expected to be the hire charges for the drill ship ([http:// peroleum.nic.in](http://peroleum.nic.in)).

### **The Andaman Sea and its Significance to India**

The Andaman Sea in the NE Indian Ocean, lies between 6°-14°N and 91°-94°E (Fig. 8) is heavily sediment piled (upto 6000 m), actively extending back-arc basin on the Indo-China continental margin. In this respect, the Andaman Sea is an extensional basin, which began opening about 13 my ago (Middle Miocene) with a rate of about 37 mm/yr (Curry et al., 1982). Total opening of the basin has been about 460 km and it now occupies about 800,000 Km<sup>2</sup> (Rodolfo, 1969). The bathymetry of the basin is complex. To the west lies the Andaman-Nicobar Ridge which marks the boundary between the Indian and Eurasian-China plates, and to the east the Malay continental margin. The main topographic features of the basin are (a) the Central Andaman Rift, (b) the Central Andaman Trough, (c) the Deep Trough, and (d) Barren Seamount Complex, Alcock Seamount and Sewell Seamount (Rodolfo, 1969). The deepest part of the basin is the central axial rift trending NE-SW and centred at 10.5°N: 94.5°E, with a depth of 4000 m (Curry et al., 1982). The rift valley can be traced to the south but is offset by NNW-SSE faults at places (Anon, 1981) (cf. Curry et al., 1982). The main sources of sediment to the basin are the Irrawaddy, Sittang and Salween rivers in Myanmar. The Irrawaddy presently discharges about 265 x 10<sup>6</sup> tonnes of silty clay per year, 90 per cent of which is deposited in the continental shelf (Rodolfo, 1969). During periods of high level, the bulk of the sediment is trapped in the delta area or on the continental shelf. However, during low sea-level stands, they are introduced directly into the basin (Curry et al., 1982). The matrix data show that there is no direct input of sediment from the Bengal Fan into the Andaman Sea (Curry 1991, Roonwal et.al. 1997 a and b). Sediment in the Central Andaman Trough are principally

turbidity flows (silty clays) with an overall sedimentation rate of about 150 mm/1000 years (Rodolfo, 1969). The Central Andaman Rift is both an active spreading centre and a fan valley analogous to that in the prospective for hydrothermal minerals. The distal fan deposits have buried the rift valley in the north but have not penetrated to the southern part of the rift (Curry et al., 1991; 1982; Anon, 1981).

From commercial / resource view of Andaman Sea is important for its likely hydrocarbon potential, but more important for seafloor volcanogenic sulphides. Therefore when these are located in the Andaman Sea, it would need efforts to make it an entry point for seabed mining. This area also has scientific interest. The SMS in the southern side (area 1 – please see Figure 11) is non-sediment covered whereas area 2 in the northern side is covered by sediments of Irraveddy river. So it should help understand the process of ore formation and exploration by understanding this model.

## Chapter VII

# Seabed Minerals outside the EEZ (International Area of the Ocean)

It is also apparent that information regarding the distribution of marine minerals in the Indian Ocean has increased during the last two decades. This has been so largely due to the efforts of GSI, NIO, and ONGC, other oil corporations, as well as several expeditions by overseas groups undertaken by the British, French, US, German, Japanese, Pakistani, Chinese and the South Koreans. Actual production is restricted to heavy mineral sands for Rare Earths minerals, ilmenite, and garnet. Special discussion on the Rare Earth assessment in relation to world market was discussed earlier. The projected development in seabed mineral mining viz. manganese nodules has not taken place, and is unlikely to be mined in the immediate future.

No doubt, there is a considerable scope for the systematic survey for minerals and the hydrocarbon potential of both the EEZ as well as the deeper part of the ocean to make a realistic assessment of the mineral resources. The survey and assessment of manganese nodule resources in the Central Indian Basin by India has been more or less complete, so that the International Seabed Authority has granted it Pioneer Status (see DOD Report 1987-88). The DOD has defined the work in terms of the different stages of exploration and prospecting: the development of mining technology; the development of beneficiation and metallurgy technology; and the environmental aspects of mining.

Several publications are available regarding the presence of manganese nodules in the Indian Ocean, the important being Mero (1965), Cronan (1980), Frazer and Wilson (1980) Roonwal (1986). As India has claimed an area for the future mining in the Central Indian Basin, the International Seabed Authority (ISA) has also granted India Pioneer Investor status. India has since conducted more detailed study of the claims area to define and reduce it to half as per the requirement of the ISA, and this release will go to the 'Enterprise' as the site area to be exploited by the ISA. Details of this claimed area and the nodule resources therein are now available. It must be mentioned here that though broadly comparable to the nodules in the Central Pacific Ocean nodule belt' (Cu + Ni = 1.026 weight per cent), the resources described in the Central India Basin do not show as high a level of copper and nickel concentration (Co + Ni = 0.758 weight per cent).

The Department of Ocean Development (DOD Report 1987, 88) which coordinated this study authorised the National Institute of Oceanography (NIO) in Goa to act as its agent. The DOD budget shows that, of the total allocation, 35 per cent was spent on Antarctic research and 25 per cent on nodule prospecting. As many as 35 scientist staff members of the NIO have been regularly involved in nodule work since 1981. Thus, over 30 years, the exploration and prospecting work has been conducted on a priority basis.

### **Cobalt and Platinum-rich Ferromanganese Crusts on Sea Mounts**

Although ferromanganese crusts were obtained first during the famous *HMS Challenger* Expedition (1872–1886), a cruise dedicated to their study was not forthcoming until 1981. Scientist on board Germany's RV *Sonne* studied the ferromanganese encrustation from the Mid-Pacific Mountain (MPM) and Line Islands in 1981, 1983, 1984 (Halbach et al. 1982; Halbach et al. 1983, Halbach and Manhein 1984, Halbach et al. 1984, and Puteanus 1984).

In 1983 and 1984, scientists on board USGS's RV *S.P. Lee* studied crusts from the Nector Ridge (near the Hawaii Islands) (Hein et. al. 1985, 1986, 1987, 1988). About this time, the University of Hawaii conducted several cruises around the Hawaiian Islands (within EEZ limits).

Ferromanganese crusts collected prior to these specific cruises were incidental to the other studies. However, several publications have been devoted to the analysis and interpretation of data pertaining to crusts collected prior to 1981 (see Glasby 1977; Cronan 1980; Roonwal et al. 1986; and Bischoff et al. 1984).

Ferromanganese crusts or encrustations contain three strategic and economically important metals in abundance: Mn, Co, and Pt. In addition, Ni, Pb, Ti and Ce are significantly enriched in crusts. Ocean-floor ferromanganese nodules are rich in Cu, Ni, and Co in that order. However, in ferromanganese crusts, cobalt is 3 to 6 times more abundant than in the nodules or even in ores mined on land (Foose 1984).

However, in several papers published prior to 1981 data concerning the ferromanganese encrustation, analysis, and their interpretation have been incorporated (Craig, Andrews and Meylan 1982; Aplin and Cronan 1985). This contrasts with the extensive literature dealing with ocean floor ferromanganese nodule literatures which have been reviewed several times (Glasby 1977, which also includes a Bibliography on Nodules).

## **Mineralogy of the Crusts**

The dominant minerals in the vast majority of crust is  $\text{MnO}_2$  (Vernadite), with only to X-ray reflections at  $24^\circ$  and  $1.42 \text{ \AA}$ . Todorokite has been found on an average in one sample per seamount studied. Carbonate fluorapatite has been found to be abundant in the inner part of several

crusts. X-ray amorphous FeO-OH. X H<sub>2</sub>O is the other dominant phase present, along with delta-MnO<sub>2</sub> in all crusts. Delta-MnO<sub>2</sub> forms epitaxial intergrowth with FeO-OH.xH<sub>2</sub>O (Burns 1976). Other common minerals include plagioclase, quartz, and goethite; and the minor minerals include barite, potash feldspars, calcite, manjiroite (= Na analog of cryptomelane with the formula [Na, K] 1-2 Mn<sub>8</sub>O<sub>16</sub> x H<sub>2</sub>O, zeolites, and clay minerals (see Table 4).

The quartz, and some of the plagioclases, are aeolian in origin and reflect the position of crust coated seamount relative to atmospheric wind belts (Hein et. al. 1985 a). The rest of the plagioclase as well as pyroxene, potash feldspar, zeolites, and others are derived from the substrate—probably by the re-suspension of the weathered material. Calcite and phosphorite are derived relatively from biological activity in the surface water. The amount of phosphate present could reflect the intensity of upwelling around the seamount (Hein et. al. 1985 a).

**Table 4: Average Chemical Composition of Various Elements in Ferromanganese Crusts in Pacific Areas.**

Areas	Mn	Fe	Co	Ni	Cu	Pb	Ti	Fe/ Mn
Hawaii and Midway (Axis)	24	16	0.91	0.45	0.05	---	1.1	0.73
Johnston Islands	22	17	0.70	0.43	0.11	0.17	1.3	0.81
Marshall Island	21	13	0.74	0.45	0.08	0.14	0.9	0.61
French	23	12	1.2	0.60	0.11	0.26	1.0	0.56
Tonga Ridge	16	20	0.33	0.22	0.05	0.16	1.0	1.26
Average Pacific	22	15	0.63	0.44	0.08	0.16	0.98	0.81

*Source: Adapted from Hein et al. 1987*

The examination of the crusts has shown that Co is commonly enriched in the outer layers of crusts, whereas Pt is enriched in the inner layers. Co, Pt, Ni, Ce, As, Mo, Cd, and Zn concentrations are possibly

correlated with Mn-contents, and Cu, Ce are possibly correlated with Fe (Glasby 1997; Halbach et al. 1982, 1984; Aplain 1984; Aplin and Cronan 1985; and Hein et al. 1985, 1988). Al, Si, Ti and K compose the aluminosilicate fraction, with part of the Ti as well as V, Sr, and Pb partitioned between the iron and manganese oxide phases.

According to different studies, the crust chemistry changes regularly with latitude and longitude. It is suggested that Mn, Ni, Cu and Co increases and Fe decreases to NW (along the Hawaiian Islands) viz. with increasing age of the substrate. A similar trend was reported by Craig et al., (1982). Co and Ni are enriched in crusts of the Line Islands relative to the more northerly MPM (Halbach et al. 1982; Halbach and Puteanus 1984).

A strong negative latitudinal correlation exist for Mn, Co, Mo, Ni and Cd in the outer layers (younger generation) of crusts. It appears that the processes likely to control such regional trends include deep and intermediate depth current systems, biological productivity, differences in the position of the carbonate compensation depth (CCD), and the degree of depletion of oxygen in the oxygen minimum zone as well as the vertical extent of the zone.

### **Processes of Formation**

Cobalt rich ferromanganese crusts are hydrogenetic and, all the metals (except minor contributions from detrital phases) are derived from sea water. Substrates could be ruled out as contributors to crust chemistry due to the lack of correspondence between substrate type and the crust composition. Also, hydrothermal contribution could be ruled out since, of the abundant minor metals (Co, Ni etc.) present, there is a lack of hydrothermal manganese phases such as todorokite and birnesteite as also of more complete fraction between iron and manganese that is characteristic of hydrothermal deposits. According to Koski et al. (1985), the crust found in island arcs with low to moderate cobalt content may have some hydrothermal component

However, what initiates the precipitation of the first molecular layer from sea water on to volcanic or other substrate is unclear. Once the process of precipitation begins, however, it becomes perhaps autocatalytic. Although suggestions have been made that iron was deposited first either on organisms and encrusting substrates, or by some other mechanism, the iron in turn catalyzed the deposition of Mn (Burns and Burns 1977). This process of early formed iron oxide, however, has not been observed in crust deposits. Hein (1985–87) stressed the possibility of  $Mn^{+3}$  oxides may form first at the crust surface, and then followed by conversion to  $MnO_2$  through disproportionate.

However, the relative amount of the oxide phases in crust is determined by their ratio in the collided flocs suspended in the surrounding sea water. The major element crust chemistry reflects both the particulate and dissolved sea water chemistry. In the water column, manganese and iron oxides probably occur together in the colloidal flocs. Within the oxygen-minimum zone which ranges from 200 to 2000 m in depth the manganese is highly soluble and, therefore, also occurs in the dissolved form. The Fe/Mn ratio is smaller in the oxygen-minimum zone that is below that zone. Thus, the manganophile elements Co, Ni, Pb, etc. would be more concentrated within crusts and flocs from the oxygen-minimum zone.

The higher cobalt contents in the outer part of the crusts imply the more recent growth rates were slower than the earlier growth rates. The decrease in cobalt with the depth of water can also be explained by faster rates of growth due to additional amounts of iron incorporated into the crust. The increased supply of iron has been related to the dissolution of iron bearing biogenic calcite below the calcite compensation depth (Halbach and Puteanus 1984) though Cronan (1984) rejected the idea that calcite dissolution was the source of iron below 2000 m depth in water. Whatever be the source of additional iron in the deeper water crusts, it does act as a dilatant to the minor metals.

## Indian Ocean Occurrences

Several areas, as in the Indian Ocean, have geological environment where exploration strategy could be employed. These are (see Fig.12): (a) old sea mounts (more than 20 m of age); (b) well developed oxygen minimum zones; (c) areas of strong currents; (d) ideally between 500 to 1500 m water depth; and (e) in equatorial zones ( $15^{\circ}$ - $20^{\circ}$ ) latitude each side of the equator (Roonwal 1984, 1986, 1989, 2009, 2013).

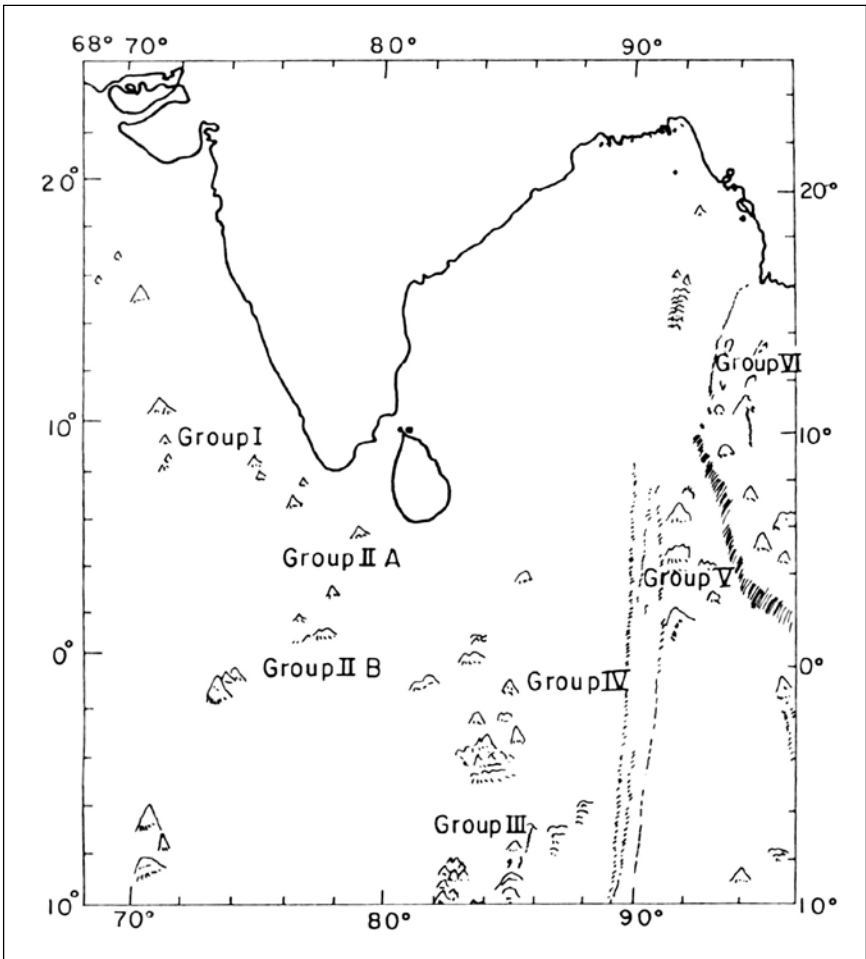


Figure 12: Suggested Sites for Cobalt Rich Crusts in the Indian Ocean  
Source: Roonwal 1988

The Afanasy-Nikitia seamount near 85° East Ridge is also attracting attention.

In such an exploration campaign, one has to be careful of the following: (a) avoid areas with atolls and coral reefs; (b) avoid areas near the continent; and (c) select areas with flat top of the sea mounts for better picking/sampling leading to, perhaps, eventual detailed exploration to mining prospects; (d) the average crust thickness of more than 4 cm, cobalt

Grade of more than 0.8 per cent, and sub-divided microphotography areas with extensive development of crust; and (e) seismic (air gun) survey to apply criteria to eliminate areas of slump, talus deposits and sediment cover.

Thus, in the Indian Ocean, the areas immediate to India worth consideration are: (1) Laccadive Islands (only seamounts without reefs); (2) the southern tip of Kerala; (3) the seamount between 84°–88° E at 10° S; (4) the seamount at 86° E 14°S; (5) the SE Andaman around 91° E, 7° N, and 93°–96° E, and 10°–13° N. The areas can be extended to the south of Ninety East Ridge, plus several other covers which may be within the EEZ of India.

The study of cobalt rich ferromanganese crusts on seamounts and ridges has just begun. Early studies did answer some broad questions; however, since then many more specific questions have arisen. The kinds of information needed to make professional choices regarding potential mine sites, and the exploitation of deposits is still far from being in hand although the USA has come up with several exploration, beneficiation and metallurgical schemes, which leave no reason for delays in mining, if the political decision is taken.

### **Manganese Nodule Mining Feasibility**

The new phase of commercial interest in deep sea nodules has involved Japan, China, Korea and India. The main factor driving this development

is the perceived shortage of resources in India. The eventual ratification of UNCLOS in 1994 led to the setting up of the International Seabed Authority (ISA) in Jamaica to supervise deep sea mining (Das 2001). Those countries and organizations that have accepted pioneer investor status (India, Korea) are obliged to fulfil a work programme within their registered mine site areas. However, as discussed elsewhere in this document, the world metal prices have remained depressed, so that there can be no hope of deep-sea mining being profitable. The commercial viability of nodule mining is, therefore, by no means assured. Moreover, the discovery of the Voisey's Bay Ni-Co-Co deposit in Newfoundland (Canada) in 1994 has re-informed this assessment. This deposit is considered to be largest mineral discovery in Canada in the last 30 years, and one of the great nickel finds of the 20th century. The future of deep-sea mining, therefore, lies elsewhere in VMS and Co-crusts.

In addition to the NIO, several other public sector organizations such as the Engineers India Ltd. (EIL) and Hindustan Zinc Ltd. (HZL), as also several research laboratories were involved in joint studies. The latter include the Institute of Minerals and Materials (earlier called Regional Research Laboratory), Bhubaneswar; the Central Mechanical Engineering Research Institute (CMERI) in Durgapur; and the National Metallurgical Laboratory (NML) in Jamshedpur. The Responsibility was divided between them, with the CMERI responsible for developing mining technology, and the EIL for beneficiation and metallurgy. The idea was to test more than one system. During these years, the CMERI in Durgapur developed a Deep-sea Mining Module using a mining caterpillar device. They also developed a small robotic for this purpose. This was developed in a water tank the size of a swimming pool especially made for this purpose. Further technology advancements are required the present achievements are only the beginning.

During 1994, the Department of Ocean Development (DOD) created a new institution called the National Institute of Ocean

Technology (NIOT). The objectives of the NIOT are to develop technologies and engineering units for off-shore mining both shallow (coastal) as well as deep sea. It is learnt that the NIOT is currently working on a module for experiments in seabed nodule mining. They are also involved with the Indian Rare Earth Ltd. (IREL) for the development of dredges, and other mechanisms for the mining of beach/placer deposits on the Kerala coast.

The environment will play an important role in any future mining activity both on land and offshore. Realizing the awareness of the local population, and their dependence on fisheries in the coastal zone, a pilot study has been initiated to realize the environmental parameters of any mining activity on the immediate coastal regions of Kerala (Thiel 1994). Today, the DOD alone has spent a several million rupees (64 INR = 1 US\$) on the study of nodules and the development of mining technology options. It is not clear whether mining will take place in the near future. This is not so much because of the unavailability of clean technology overseas but because of the black of information on environmental aspects. The DOMES (Deep Ocean Mining Environmental Study) of the 1980s has been followed in part by Germany in the Peru Basin and Japan, and by others in the Central Pacific Ocean.

However, economic considerations also are likely to weigh heavily on the decision to go ahead with further mining activities. It will all depend on whether any such effort is worth a return reward. It is possible that India may commence in a real terms to develop technology for offshore coastal mining of beach placers. Perfecting and testing the technology in shallow water will give the necessary experience as well as the expertise to venture in the deep water. UNCLOS, the world economic situation, and especially falling metal prices are not likely to attract large consortia to risk the investment of high sums. Therefore, the option before India is to redefine priorities in marine research and

technology, reduce the priority for nodules, but give high priority to SMS and other non-living seabed mineral resources such as cobalt-rich crusts and phosphorite within and outside EEZ and undertake the reassessment of placer deposits more earnestly. The low grade, large deposits of heavy mineral sands along eastern coast in Orissa, Andhra Pradesh and Tamil Nadu may receive attention if they are made available to joint ventures for the purposes of exploitation.

Concurrently with the commercial investigation of the deep-sea floor, the UNCLOS was being debated as the largest ever forum for international diplomacy. The ISA was set up to regulate deep-sea mining outside 200 nautical miles EEZ of individual nations. Because of the presumed possibility of the large revenues from deep-sea mining, the group of 77 wanted to ensure that they were not denied the share of the wealth. Therefore clauses such as parallel mining system of seabed mining in which a mining company would be required to explore two mine site of approximately equal value, and relinquish one to the ISA. Transfer of technology to the ISA (Enterprise) etc. led to the refusal of several industrialized countries with no interest in nodule mining to sign the UNCLOS.

### **Volcanogenic Massive Sulphides (VMS)/SMS deposits on the Mid-Indian Ocean Ridge**

The Indian Ocean ridges have been considered relatively less favourable targets for the exploration of hydrothermal mineralization because of their low to medium spreading rates. This view changed with the discovery of massive sulphides and vent biota in the TAG area of the Mid-Atlantic Ridge in 1985. During the GEMINO cruises by R.V *Sonne*, a hydrothermal field was discovered on the Central Indian Ridge, about 200 km NW of the Rodriguez Triple Junction (Herzig and Pluger 1988; Pluger et al. 1990). In the 1994 cruise in this area, massive sulphides were recovered (Halbach et al. 1994). Other

indications of submarine hydrothermal activity in the Indian Ocean have been summarized by Roonwal (1986); Herzig and Pluger (1988); Roonwal and Mitra (1988); and Halbach and Munch (2000).

Oceanographic research during this century has revealed an increasing number of marine mineral deposits. One of the most recent of these discoveries are marine polymetallic sulphide deposits. These deposits are high-grade, localized, and form in areas of active undersea volcanism, normally at a depth of 2000–3500 m. Their discovery in the late 1970's has been heralded as one of the most important scientific findings in marine science in this century. The regions which host such sulphide deposits have provided geologists with the first opportunity to study primary ore-forming hydrothermal systems in real time. In addition, these systems support a unique and varied fauna, which depend upon this volcanic activity for their existence. Finally, the quantity of minerals added to seawater by this volcanism has radically altered current theory on the factors which contribute to the chemical composition of the oceans.

Poly-metallic sulphides are so called because of the wide range of minerals they contain (up to 20). Many samples recovered so far have average grades which on land would make them an extremely valuable resource. This has fuelled speculation that one day VMS may provide an alternative source of metals to traditional land-based supplies. However, at present, not enough is known of the true abundance of the deposits, nor what represents an 'average' deposit. Nevertheless results to date have been encouraging and, as more high-grade deposits are discovered, commercial interest in VMS is likely to grow. It is, therefore, necessary to examine what technological alternatives exist or are likely to be developed which will enable commercial extraction to take place. Seabed mining is no longer confined to the drawing board. Several sophisticated systems have been developed with a view to extracting manganese nodules at depths of 4–6,000 m. Moreover, a project in the

Red Sea has proved the viability of pumping metalliferous muds from over 2,000 m depth.

Many elements of the systems mentioned above may well be applicable to VMS extraction. However, one major problem remains to be overcome. Unlike the Red Sea muds and manganese nodules, VMS are hard consolidated deposits, similar in form to land based sulphide ore bodies. This means that any system for mining them will have to include a mechanism for disaggregating the deposit *prior* to transport to the surface. At present, the technology for achieving this in the deep ocean does not exist. Alternatives have been suggested such as solution mining or vent capping. However, this report will show that the physical crushing of the ore is still viewed as the most likely solution by engineers who have addressed themselves to the problem. It is no doubt likely that these ideas will be substantially refined as the knowledge base on MPS continues to grow.

Technological requirements are not the only criteria which will dictate whether or not MPS ever become a viable economic resource. Consideration must also be given to non-technological factors; world demand for the contained metals, the status of deep sea deposits in international law, and environmental considerations.

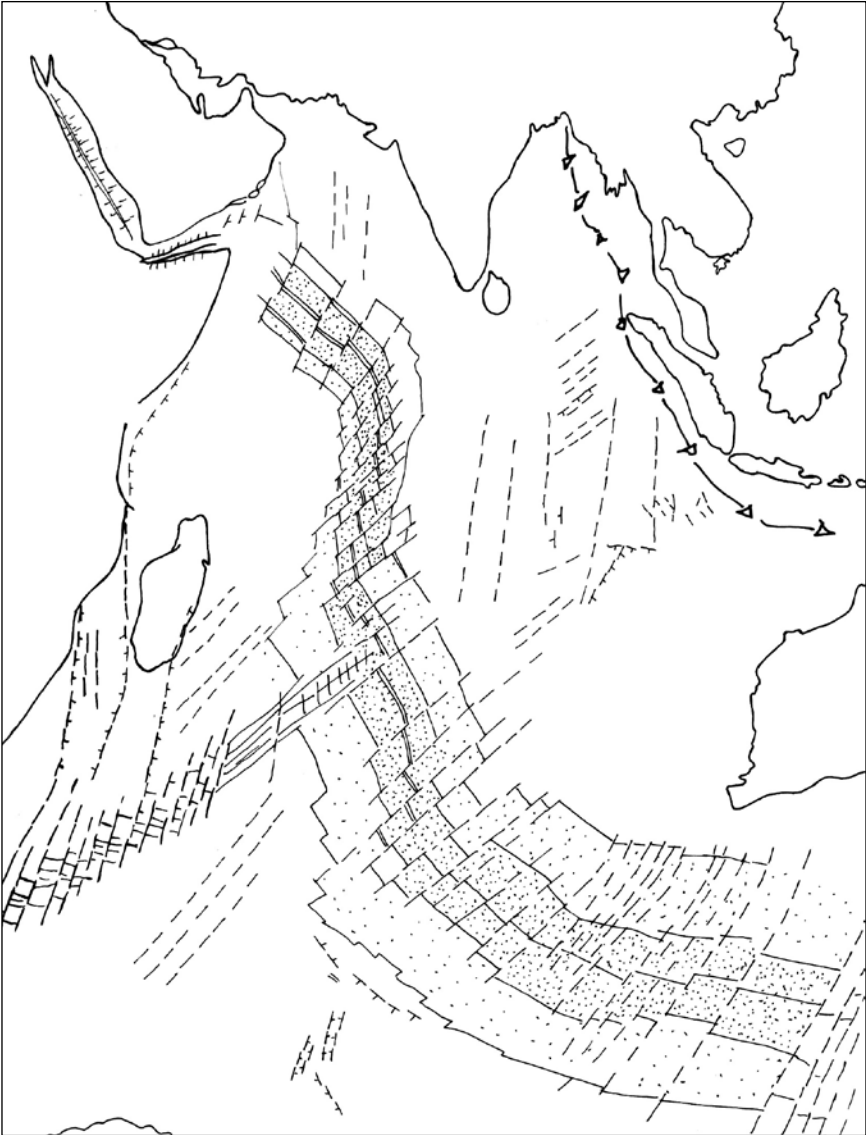
### **The Nature and distribution of VMS/SMS Deposits on the Mid-Indian Ocean Ridge**

For the purposes of this report, VMS deposits are defined as 'massive' marine poly-metallic sulphides meaning deposits which comprise more than 60 per cent sulphide material. This section examines current theories of their mode of formation, a brief review of the distribution of the largest known deposits, and finally, the details of the grades and likely global extent of the deposits. It is important to stress that the current data base on VMS is no longer small. The vast majority to date have been located on active spreading centres, which extend for some

50,000 km across the floor of the world's oceans. However, around 1150 km of these systems have yet to be investigated in sufficient detail to reveal any VMS deposits which exist there. In addition, recent evidence suggests that back-arc basins, and associated geological regimes may also host sulphide deposits. If this is so, it would greatly increase the global potential for VMS formation. In the India Ocean, India's Andaman Sea is seen as having this geological setting.

Plate tectonic theory postulates that the outer surface of the earth is divided into around ten 'plates', irregular shaped sections of crust that run thousands of kilometers across. The crust itself may be oceanic or continental in composition. Oceanic crust is predominantly basaltic, dense and relatively thin (10–12 km), and forms a continuous skin around the earth. This oceanic layer in places is overlain by a less dense granitic layer, the combined thickness forming continental crust (23–35 km). Each plate may be composed of oceanic or continental crust, and is normally a combination of the two. The plates are rigid masses of solid rock, but 'float' on the relatively mobile mantle beneath which is partially molten. They are subjected to various lateral movements thought to be the result of convection within the mantle. The boundaries between the plates are divided into three basic categories, schematic cross sections of which are given in figure 13.

Transform or converging boundaries are where one plate merely slips past another one, and crustal material is neither created nor destroyed; convergent or destructive boundaries (subduction zones) as in the Andaman Sea area, are formed by oceanic crust being pushed into the continental crust, resulting in the denser oceanic material being thrust into the mantle, and destroyed. Divergent or constructive boundaries are regions where new basaltic oceanic crust is created. Two oceanic plates move apart, and basaltic magma (molten rock) wells up into the gap creating a new seafloor. These 'spreading ridges' cover vast areas of the ocean floor, and are characterized by extremely high geothermal gradients (the rate at which the temperature of the rock increases with



*Figure 13: Ridge Systems in the Indian Ocean*

depth). It is these huge sutures in the earth's crust which determine the configuration of today's oceans, as the large areas of dense basaltic crust create topographic lows with respect to the less dense continental masses.

Consequently, all active spreading ridges are subaqueous; but the actual lines of the ridges are characterized by linear undersea mountain ranges caused by the upwelling magma, and these may occasionally reach the surface. Divergent plate boundaries appear to form an evolutionary sequence. Original rifting may occur within a continental land mass the East African Rift Valley is believed to represent such a phase. Eventually, the continental masses separate and seawater fills the rift, as in the case of the Red Sea today. The two land masses continue to move away from each other as a new seafloor is created. This process may continue for hundreds of millions of years. Finally the spreading rate (rate of separation of the two masses) will slow, and may stop altogether. This mature stage is apparent on the present Mid-Atlantic Ridge. Spreading rates vary depending on the geological setting—from 2 cm/year to 20 cm/year. However, generally, separation occurs at around a few mm per year at same rate that human nails grow. It is at these spreading ridges that the vast majority of VMS deposits known today have formed.

VMS deposits are believed to be the product of hydrothermal systems. Figure 2 (a and b) shows two schematic diagrams of such systems at oceanic ridges. Seawater enters the deep fissures present at ridges due to the flexing of the crust caused by vertical and lateral movements, and rapidly becomes heated by the high geothermal gradient. Seawater may descend to depths of up to 5 km, and be heated to 300–600°C. (1) As it percolates through the hot rocks, it leaches out certain components: transition metals, silicon, calcium, potassium, hydrogen and sulphur. The super-heated metal-laden brines are much less dense than the surrounding material, and will shoot back to the surface wherever possible. On reaching the seafloor, still at temperatures of up to 350°C, they emerge into near freezing abyssal water (average temperature 2°C). This rapid cooling produces a drastic reduction in solubility, and sulphide and oxide minerals precipitate out as a cloud of particles, producing an effect known as ‘smoking’. These vent emissions tend to be darker in colour as the temperature rises, leading

to a subdivision between 'white smokers' (relatively low temperature), and 'black smokers' (high temperature).

It now appears likely that some level of mineralization is present at all locations which have at some time hosted undersea volcanic activity. Rona lists over 60 sites where sulphides have been located on the seabed. However, the vast majority of these findings are merely small, low-grade samples of no economic significance. Below are brief reviews of each area found to date which has revealed mineralization which may possess some economic potential. However, with the exception of the Red Sea deposit, none have yet been investigated in sufficient detail to produce a viable estimate of the size of the resource.

It is apparent from the preceding sections above that a reliable estimate of the global resource potential of VMS deposits is fraught with difficulty. Apart from the obvious paucity of useful data on the size and distribution of the deposits, there are technological difficulties which militate against the collection of the necessary information. Before discussing the possible size of such a resource, it is important to define what is meant by a VMS prospect. If, as seems likely, sulphide formation at spreading centres is routine, then it follows that all of the ocean floor will be peppered with deposits, or their remnants. These will have been covered by subsequent lava flows and sediments. Are these to be considered a possible resource also? Cann estimates that one of these deposits can be expected once in every  $2 \times 10^7$  m<sup>2</sup>, and that the probability of drilling one at random would be around 0.005 (Cann 1980).

At present there is no geophysical method which could easily pinpoint such sub-surface deposits, though it is conceivable that a suitable system could be developed. Even so, given the technical problems involved in merely dredging the seafloor in the seabed, it is most unlikely that these relict VMS will be considered an economic resource in the foreseeable future. Thus, only deposits on or near the seabed can be described with any accuracy (see below). In other words,

only those VMS which are mid-oceanic ridge/subduction zones require attention as immediate mining sites.

It is important that deposits which manifest themselves at the surface should be considered in three dimensions. It has been shown (see Chapter 2) that systems have already been conceived which, in theory at least, could mine deposit down to its full vertical extent. This brings us to the crucial point of the probable extent of VMS deposits in the third dimension. Unfortunately, spreading ridges present special technical problems which, until very recently, have prevented conventional drilling. Sedimentary cover is necessary to 'key in' a traditional drill bit, and this does not normally exist on the new basalt found at spreading centres. Consequently knowledge of the vertical extent of the deposits is almost exclusively inferred.

Embryonic systems do exist which will be able to gauge the thickness of the deposits using geophysical and electrical methods. Thus, the Ocean Drilling Project has attempted to drill into a ridge crust this year, using a special yoke to guide the drill bit. While these techniques are discussed in detail (see below), the point remains that, at the moment, virtually nothing is known about the depth to which mineralization is likely to extend below the seafloor. Work on land based deposits thought to represent ancient VMS analogues uplifted onto the continents (ophiolites) suggests that some form of stock work mineralization may extend for 100 m or more below the surface in favourable geological conditions. However, it would be premature to assume that the same applied to modern day deposits until tangible evidence is obtained through drilling and coring or by other geophysical methods.

The central Indian Ridge is the boundary between the African and Indian plates, and forms a SSE trending, mid-oceanic accretionary system in the equatorial Indian Ocean (see Figs. 1 and 13). To the north is the Carlsberg Ridge spreading centre. The CIR terminates at

**Table 5: Typical Contents wt per cent of Selected Metals from the Seabed: sulphide samples and related ancient massive sulphide ores**

Location	Modern						Ancient	
	21°N Active Vents	Cyamex Area	Juan de Fuca Ridge			Mid-Indian Ocean Ridge Cp Spl	Cyprus	Canadian Precambrian
			Northern	Southern	Axial Seamount			
Zinc	32.3	40.8	6.3	54.0	19.2	0.14 31.10	0.2 – 0.5	5.0
Copper	0.8	0.6	0.5	0.2	0.13	31.6 0.71	2.5 – 4.0	2.0
Lead	0.3	0.05	0.1	0.3	0.4	-		0.0
Silver ppm	156	380	30	260	288	44 8	39	50
Gold ppm	0.17	-	0.08	0.13	-	890 260	0.3	181.76

*cp* = Copper ore (*Chalcopyrite*); *sp* = Zinc ore (*Sphalerite*)

Source: adopted from different sources.

the Rodrigues Triple Junction (25°30'S, 70°06'E) by intersection with the southwest Indian Ridge (SWIR) and the southeast Indian Ridge (SEIR). Crustal divergence of the CIR proceeds at slow to intermediate rates, with a progressive increase in the rate of accretion towards the south. The present half-spreading rate and ridge trend change from 1.8 cm/y and 142° at the equator to 2.7 cm/y and 152° immediately north of the triple junction (Munschy and Schlich 1989). The topography of the central-rift zone is rather smooth compared to slow spreading analogues such as the SWIR or MAR; but it is slightly more rugged than the SEIR (Mitchell 1991). The rift valley is 500–800 m deep, 10–15 km wide and generally well defined. The inner floor is often relatively flat along the axis, more variable in the cross section, and lies at 2700–3200 m water depth. Off-set fracture zones trend generally 60° in the southern parts of the CIR, and laterally displace median valleys by as much as 8 km. The length of individual spreading segments varies between a few meters or kilometres (Munschy and Schlich 1989).

Study of massive sulphide samples from the Indian Ocean (Halbach et al. 1998) shows that multiple hydrothermal events over a period of several ten thousands of years formed mineral occurrences which are, more or less, N-S arranged in the MESO mineral zone of the central Indian Ridge. The site of this deposit is located in the central

part of the fourth segment (about 270 km N of the RTJ) on a neo-volcanic intra-rift ridge. The particular stage of chemical and physical disintegration of the extinct sulphide deposit has been going on for at least 11000 y: The chimney structures have been, therefore, more or less destroyed by weathering processes. Nevertheless, three types of sulphide mineralization formed by hydrothermal venting processes were sampled and distinguished: (1) Cu-rich massive sulphides (chalcopyrite-bornite-digenite-pyrite assemblage); (2) pyrite-marcasite massive sulphides; (3) sphalerite-bearing jasper breccia; the main gangue phases are barite and amorphous silica (see Table 6 below).

On-land, massive sulphide deposits of the Cyprus type (fossil mid-ocean ridge massive sulphides) only rarely show a preservation of complete chimney structures; occasionally there is evidence of layered chimney fragments. Our results show that hydrothermal chimneys are short-lived features which disintegrate after waning of hydrothermal activity. This is consistent with the observation that complete chimney structures are often lacking in the fossil environment of former mid-ocean ridge hydrothermal sites. Assuming normal deep-sea conditions, chimney dissolution and disintegration will take place within several thousand to several ten thousand years, due to the disequilibrium (retrograde solubility) of anhydrite and sulphide minerals with ambient oxidizing seawater. Only underlying massive and stock-work mineralizations may be preserved in the geological record.

**Table 6: Chemical analyses of selected *Sonne* Sulphide Field massive sulphides from Central Indian Ocean Ridge**

		Chalcopyrite type				Sphalerite-jasper type		
		Method	18-34	18-25	18-67	18-107	18-82	18-109
Zn	Wt per cent	ICP	0.07	0.04	0.14	31.10	23.40	27.30
Cu	Wt per cent	ICP	31.60	7.39	9.85	0.43	0.42	0.71
Ag	ppm	INA	33.00	44.00	11.00	<5.00	<5.00	8.00
Au	ppb	INA	220.00	890.00	240.00	250.00	240.00	360.00

*Source: after Halbach et al. 1998*

## Chapter VIII

# *Technology Options for Seabed Mining*

Opportunities for discovery in ocean science abound; yet progress requires sustained investments in developing new technology. Based on the recommendation of researchers and engineers, the ocean science community has been particularly active during the past years, with many new ideas and concepts to improve and enhance access to the sea. These include accessing both the deep ocean and shallow seas with the pioneering efforts of human occupied submersibles (HOV) developed first in the USA more than three decades ago as well as the much improved remotely operated vehicles (ROVs). These have helped in being able to make precise research plans. Through its on-line observations, the Ocean Floor Observation Systems (OFOS) is of immense help in this activity. The future lies in the application of Autonomous Underwater Vehicles (AUVs).

Shallow seas, including surrounding atolls and islands, are significant for resources because they are extensions of the continental shelves which provide many of the non-living resources that are essential for modern civilization. They include much of the oil and gas, increasing proportions of building materials, and some detrital minerals all of which have been concentrated in the surface sediments by the erosion associated with wave activity and migrating sea levels. Shallow seas also contain a rich and varied biota fed by nutrients from the land and upwelling from oceans. The water quality of the shallow seas is in part

a balance between the flushing side of ocean water and the input of materials, including nutrients and contaminants from the land.

The surveys (see Figure 14 below), assessment, and the investigation of the potential economically viable marine mineral resources made by India during the last two decades have been very significant. These have helped to make assessments of both deep seas and shallow seas. This achievement has been made possible by the liberal support of the Government of India. Several university teachers have also actively participated, and contributed to this activity. The University of Delhi has been particularly active in palaeo-oceanographic and geologic studies. Its past interest in deep sea manganese nodules has now been replaced by current interest in mid oceanic ridge regions and eustatic sea level changes. This research has been continuous at the Inter University Accelerator Centre, New Delhi.

India has surveyed areas for manganese nodule mining in the Central Indian Ocean Basin (CIOB) where specific areas have been demarcated and accepted by the International Seabed Authority (ISA). India's other priority is an assessment of marine mineral resources in

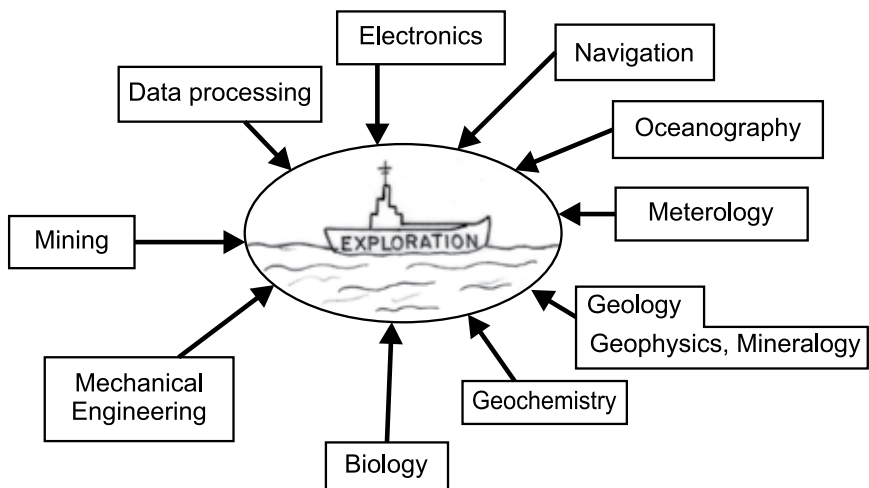


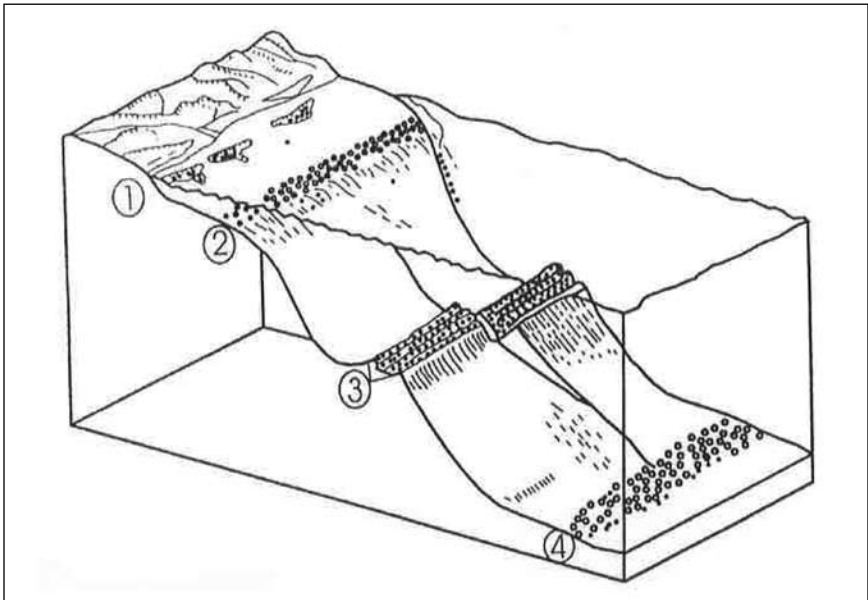
Figure 14: Different Parameters Associated with Exploration

the Exclusive Economic Zone (EEZ) as also in the deep sea with respect to the mid oceanic VMS / SMS of hydrothermal origin (see Figure 15 below).

India is also going to perform resource mapping exercises for gas hydrates by drilling for cores at locations in the deep waters off the coasts of Andhra Pradesh, Goa, and the Andaman Islands. India has an ongoing engineering experiment for the mining of seafloor manganese nodules which include the following:

- 1) Heavy mineral placers
- 2) Phosphorite
- 3) Hydrothermal metalliferous impregnation and deposits
- 4) Manganese nodules

Details of the tectonics and geology of the Andaman Nicobar group of Islands, and the Andaman Sea can be seen in several publications;

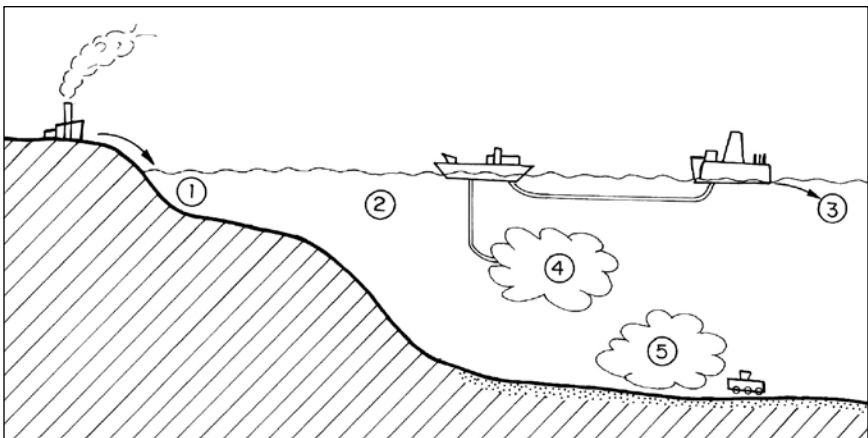


*Figure 15: Location of Marine Minerals According to Topography of the Sea Floor*

and a summary of mineral and petroleum resources can be found in Roonwal 1999, a and b.

It is now accepted that Indian scientists are making attempts to move from the status of being a developing country which it is at present to becoming a developed nation. This is reflected in the shift of our prime concerns away from the production of food only and move towards industrialization. Since many raw materials are non-renewable, the search for land deposits has to increase, especially with the help of new techniques and technology. Amongst the non- fuel minerals, we have achieved self-sufficiency and have adequate reserves in a variety of minerals, such as coking coal, iron, bauxite, as well as a range of low value raw materials, such as limestone. The situation regarding many other minerals is not so promising. We are not really so well endowed with mineral resources (Roonwal and Wilson 1998). It is quite obvious that greater attention will be diverted not only to hidden land resources but to the resources that lie in the oceanic environment.

The commercial exploitation of several minerals has taken place in the territorial waters of 27 nations. However, sea-floor minerals should not be seen as a vast cornucopia of riches, waiting to be readily



*Figure 16: The Concept of Nodule Mining*

exploited. The seafloor does not give up its mineral riches very easily. Successful exploitation of seafloor deposits requires a blend of good planning, high technology, adequate capital, a great deal of courage, and an element of luck (Roonwal 1986, 1999, 2000 and 2005).

In the future, oceanic mineral exploitation will probably be governed to a great extent by supply shortages as well as strategic considerations rather than by the possibility of finding cheap and abundant metals. As oceanic minerals are both widely scattered (such as manganese nodules) as well as localized (such as massive sulphides), ocean mining will not be a simple affair. While unconsolidated surface deposits such as sand aggregate, diamonds, nodules can be dredged, consolidated sub surface deposits such as coal, iron ore mined from land, hydrocarbon, and sulphur are reached by drilling. Exploration, exploitation, and mining activity will need good eco sounds, sonar and sea-beam systems, cameras, dredges and drills, as well as underwater TV for ocean floor observations and accurate sampling devices of the spotted deposits (Kunzendorf 1986, Roonwal 1986). However, above all, the environmental impact of their activity on the now quiet oceanic regime will be applicable.

Exploration activities are planned after a detailed discussion of plans accepted. This involves the consideration of several aspects which have been summarized in Figure 4 above. One has to depend on both indirect and direct methods to observe the geology and nature of the deposits, and here one may refer both to relevant books (Roonwal 1986; Kunzendorf 1986) as well as essays on recent advances available in issues of *Sea Technology*, *Marine Georesources* and *Geotechnology*.

Marine mineral exploration is an expensive job. A well-equipped research ship is a pre-requisite for every such job. Various techniques involving sampling devices have been developed to bring out the material from the ocean floor having a water depth which varies between a few meters to as much as 5000 meters. Conventional

dredges are sunk to the ocean bottom, and slowly dragged for 1–2 kms on the sea-floor. However, for a more accurate and quicker survey, a system of sampling called the ‘Free fall grab’ sampling device has been developed. This device is now used because of its easy handling and accurate sampling, especially for manganese nodule surveys. Of course, this sampling is carried out only after the details of sea floor topography of the area has been determined by eco-sounding or multi beam or even seismic systems. Figure 6 (above) shows an example of a model field investigation. An evaluation is subsequently carried out on the basis of average weighted grade of total Cu + Ni + Co sum as 2.27 per cent is considered economic. Since nickel is rarer and is 220 times more costly than copper, the economic consideration of manganese nodules are determined after being calculated on this basis. This could mean that (Cu + Ni) in nodules has been defined as  $(Cu + 2.2Ni) = 3.76$  per cent. Similarly,  $Cu + 2.2 - 2 Ni$  must total 3.0 per cent for a cutoff grade.

As already mentioned, hydrothermal VMS deposits are attracting scientific and economic interest because they are concentrated through the occurrence of clusters of ‘black smoker’ chimneys. The technology needed for mining them would be of different type than that needed for mining manganese nodules. Thus, large TV controlled pneumatic grabs could be the possible options for a detailed exploration, assessment and the estimation of reserves and even mining (see Figure 16 above). Such grabs are already available, and necessary modifications to enhance carrying capacity could be effected. The one used by us in exploration campaign was prepared in Germany, and carried up to 750 kgs material; it operated at compressed air pressure of 200 bars and 0.53, and could be used in water depths up to 4000 meters.

### **Industrial Interest in Nodule Mining**

The mining system of manganese nodules has been developed by a consortia of primarily US enterprises which first succeeded in a mining

experiment in 1975. Following this success, Japan, India, and other countries began to research and develop mining technology. In India, this work is pursued by the National Institute of Ocean Technology (NIOT).

The methods of mining are basically divided into three categories:

- A suction system using a transport pipe
- A line bucket system using many buckets on a rope
- A modular mining system by an unmanned submarine

Until now, the systems which have been successful in mining are the suction system and the line bucket system. There are two different types of suction system: a pump lift system using several large underwater pumps; and an airlift system using compressed air (see Figure 17 above).

Japan has been developing an in-suction system (Sakasegawa and Matsumoto 1997). In particular, the air lift system has several mechanical underwater pumps, which require electricity supply into the water. If any trouble is encountered within the system, it must be useful up on board for repairs. Conversely, if the air lift system has a compressor aboard to generate compressed air, its maintenance is much easier. The suction system consists of four main sub-systems.

The requirements are:

- A collection system for manganese nodules
- A lifting system to transport manganese nodules collected by the collector to a mining vessel
- A handling system to transport, connect, descend, and suspend underwater equipment such as a collector, underwater pumps, etc. suspended by lifting pipes.
- A measurement and control system to monitor the operating condition of each equipment to carry out a safe and effective operation.

## **Industrial Interest in VMS/SMS Mining**

Generally speaking, industries appear interested in the potential offered by VMS/SMS as they possess a major advantage over manganese nodules as a possible resource. The reasons for this are four-fold.

- a) Average grades are some thousand times more concentrated than those found in nodules
- b) VMS/SMS tends to occur at approximately half the depth of nodules (2500 m compared to 5000 m for nodules).
- c) Many VMS/SMS deposits are known to occur within the EEZ whereas major nodule deposits are found in the international waters, thus greatly simplifying rights of tenure for VMS in international law.
- d) Processing of VMS/SMS ore is likely to be less problematic than of nodules.

A very strong opinion emerged from the survey concerning factors necessary to stimulate industry to take more positive stance on VMS/SMS. Presently both companies Nautilus and Neptune are preparing to mine of VMS/SMS on the seabed. They have demonstrated technology option for seabed mining when environmental impact assessment (EIA) report is approved by the ISA mining in the south west pacific could begin in the time frame of the 5-10 years from now.

As regard the Indian Ocean, we need to do more research for a detail exploration of SMS in the Indian Ocean, This involves:

- a) More data needs to be available concerning the distribution, grades and general geology of the VMS
- b) The metal market must improve, making extraction a more attractive commercial proposition
- c) A predictable and stable legal regime needs to be formalized, relating specifically to the extraction of these deposits.

By and large, technology is available for the scooping-mining of VMS/SMS. Japan, Finland, Norway, Germany, France, USA, the UK and Canada are leading researchers in these studies. South Korea and China are also new players in the Indian Ocean, besides India. An overview of licenses given for the exploration of nodules and VMS/SMS in the India Ocean is summarized in Table 7 (below).

**Table 7: An Overview of Licenses for Seabed Mineral Exploration in the Indian Ocean**

Contractor	Draft entry into the contact	Expiry	Sponsoring state	General location of the exploration area under contract	Type	Depth	Area (km <sup>2</sup> )
Government of India	25 March 2002	24 March 2017	India	Indian Ocean (Central Indian Ocean Basin)	Nodules	5000-5700	75000
China Ocean Mineral Resources and Development Association (COMRA)	18 Nov. 2011	17 Nov. 2026	China	South West Indian Ridge	Sulphides	-	10000
Government of Republic of Korea	1 May 2014	30 April 2029	Korea	Central Indian Ocean Ridge	Sulphides	-	10000
Government of India	Approval to be agreed		India	Central Indian Ocean Ridge	Sulphides	3000	10000
Federal institute of Geosciences and Natural Resources of Germany	16 May 2015		Germany	Central Indian Ocean Ridge	Sulphides	2600-3300	10000

## Chapter IX

### *The Ocean Commission*

The year 1998 was declared the Year of the Ocean (YOTO) by the United Nations. In India, there were several activities. On 9–10 February 1998, the Society for Indian Ocean Studies in New Delhi organized an international seminar on the ‘Indian Ocean in the Twenty First Century: Linkages and Networking’ at Vigyan Bhawan. This was a grand beginning for a nation which has a large community of ocean scientists and technologists. The theme attracted almost 100 participants, representing, at least ten ministries/departments of the Government of India, 9 Indian universities; 5 NGO representatives from 6 diplomatic missions in India, and 5 commerce related organizations, such as the en. The overseas participants came from Bangladesh, Indonesia, Sri Lanka, Oman, Iran, Malta, the UK and Canada.

The seminar was thoughtfully planned around 4 themes: (1) Ocean Governance and the Present Global Scenario; (2) Resources Management and Social impact; (3) Frontiers in Ocean sciences; and (4) Regional Cooperation and linkages. All these are vital channels for any programme. India has several unique features regarding the growth of Marine Science and Technology (MST). India is, perhaps, the only country in the world which had a sub-ministry Department of Ocean Development (DOD) in the government. It was created by a Presidential Notification dated 21 July 1981. The DOD was placed directly under the Prime Minister, which shows the significance which the Indian government attaches to Marine Science and Technology

(MST) in the national perspective. Amongst the responsibilities defined for the DOD are: policy formulation, regulatory measures, and developments concerning the oceans. They also include Research and Development (R&D), technology development, survey for living and non-living resources, energy, as well as the development of the required manpower to meet country's needs. The Ocean policy was adopted by the Parliament in 1982. Such a step was taken thanks to the vision of Prime Minister Indira Gandhi. Progress in oceanography and science has taken place in leaps and bounds. However, what needs to be done in the future is also important.

India has a 7,500 kms coast line, a coastal zone, and several island territories. 25 per cent of country's population lives in coastal areas. Many major cities are located along the coasts, including Kolkata, Chennai (Madras), and Mumbai (Bombay). In all, there are 11 major, 16 intermediate, and 78 minor ports in India. We need to pay attention to the management of the thin yet thickly populated, highly active coastal zone. We have recreation centres along the coast. The tourist industry depends heavily on this resource. We have the famous mangroves, the coral reefs, the turtles, the fishes, the beach placers, and offshore minerals, salt and chemicals, sea weeds and medicinal plants, and the oceans as a source of energy.

In more than one way, India's ocean-land relationship is a gift of nature. The monsoon currents bring rain. Thus, a unique feature of the Indian Ocean is the monsoon gyre. In the Arabian Sea, the SW monsoon results in intense upwelling along the coast, and thus accounts for high productivity and the potential for fisheries. India has a vast Exclusive Economic Zone (EEZ). As a consequence of the coming into force of the United Nations Convention on the Law of Sea of 1982, India has gained an EEZ of more than 1.02 million kms<sup>2</sup> of sea along her eastern and western coasts, as well as around the Andaman-Nicobar Islands a gain of area which amounts to roughly 18.7 per cent of country's landmass.

A large part of the ocean is rich in living and non-living resources. It has a considerable impact not only on meeting the food, energy, minerals, waste disposal, and recreation demands of our already large and increasing population but also on world climate which includes monsoon currents and biological diversity across the country. In other words, India is considerably dependent on its surrounding oceans. This also includes trade and commerce, harbours, ports, and tanker routes through the Indian Ocean, among other aspects.

Each year, the Bay of Bengal and the Arabian Sea get several intense cyclones which result in huge losses of human life and property. Both the Arabian Sea and the Bay of Bengal are subject to large, semi-diurnal tides, with amplitude of 1–8 m which are also enforced by the biannual reversal of the monsoon winds. No doubt these two factors result in the flushing of Indian coastal areas which helps in the dispersal of pollutants. Nevertheless, coastal pollution is an even increasing problem in India, contributing factors being domestic sewage, industrial wastes, pesticides, and finally erode oil. To use the marine resources on a sustainable basis also means the protection of our entire environment: the mangroves, forests, estuaries zone, the endangered coral reefs, the exploitation of fish resources, the beach placers, and oceanic minerals.

After the UNCLOS, we understand that marine resources and their governance will be shared by many stakeholders. These subjects were discussed in a seminar in 1994, and useful recommendations were made (Qasim and Roonwal 1996). It is time to adopt these and take up issues for their development. Our future is linked to the Ocean. It is time to evolve an Ocean Commission to achieve the goals set for an Ocean Charter. An Ocean Commission could be one in which the government, relevant institutions/universities, and industries are represented. It should coordinate and monitor ocean management (see Figure 17 below). The Commission may be charged with the following: the responsibility of a creating network data base; making policies for a

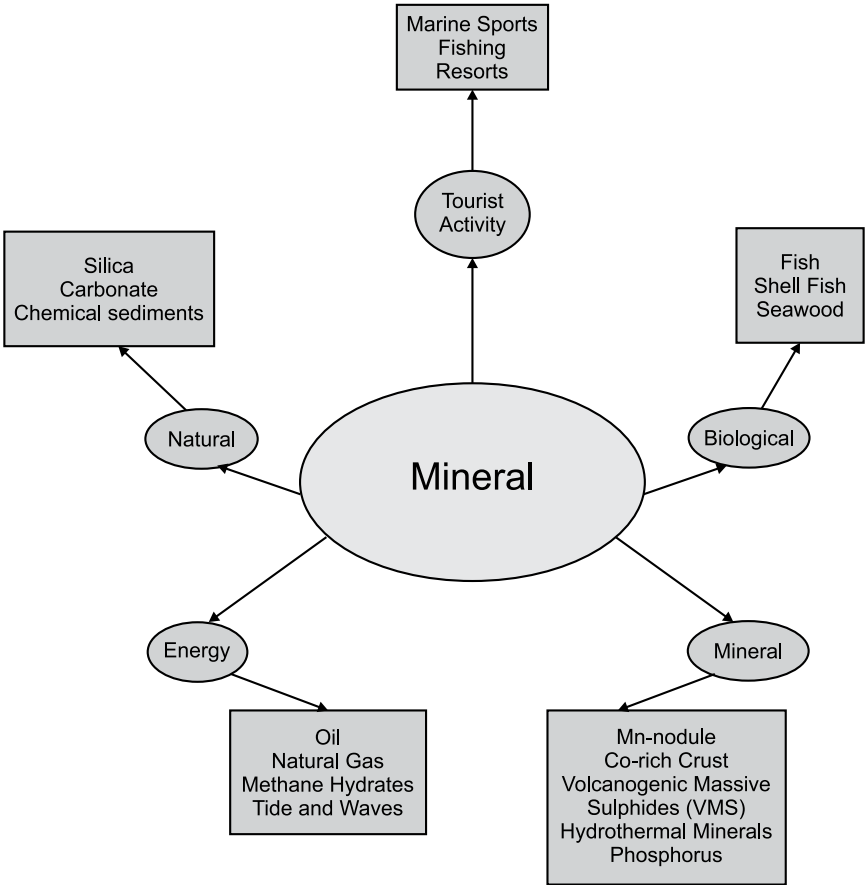


Figure 17: Seabed Resources

major assessment of research potential; planning its future development requirements; looking out for environmental problems; the utilization of resources; making policies of sustainable development; and the use of appropriate clean technology. All these will take care of a responsible utilization of the Indian EEZ and the Ocean (see Figure 18 below).

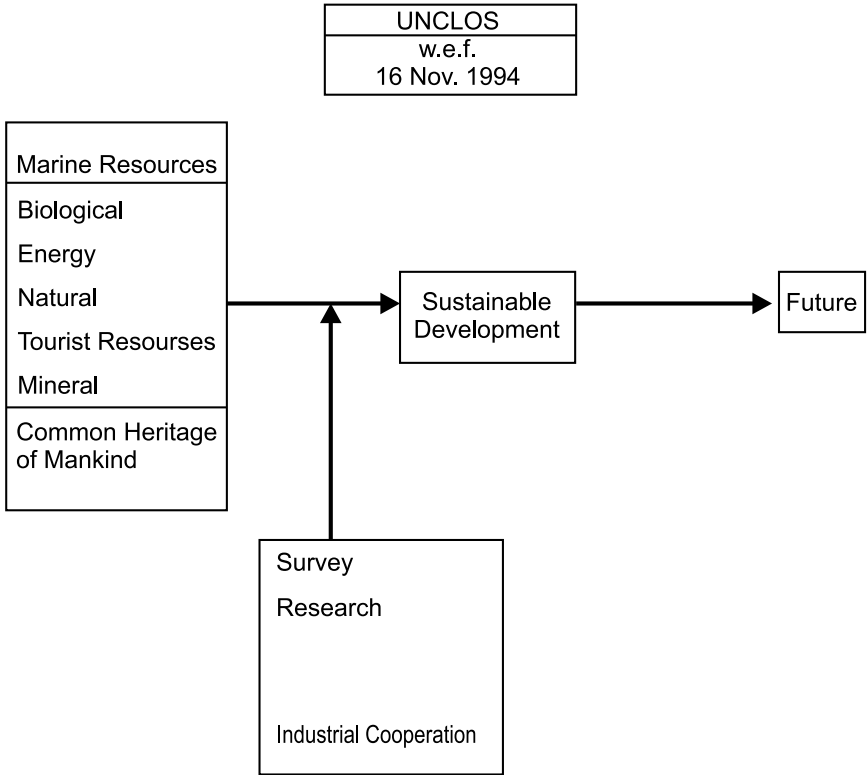


Figure 18: The Goals of the Ocean Commission

## Chapter X

### *Synthesis – Indian Interest*

Forecasting is a difficult and dangerous exercise. Many difficulties are faced by those who attempt to forecast the supply and demand for metal. Below are some key factors that are likely to come up in the long and short terms.

One example is the forecasts in respect of copper and zinc made by the US Bureau Mines in the late 1970s overestimated future demand growths for the two metals. In the case of copper, even if low, forecast attenuation was higher than actual demand in 2000. In fact, almost all the US forecasts for metal demand in the year 2002 were too high.

Why did this forecast go wrong? A part of the explanation is the slowdown in global economic growth that took place in the 1980s. A more important explanation is that most forecasts underestimated the extent of the mineral intensity the world economy would face. The result was a shift towards the service sector besides an increase in prices. The latter drove efforts towards finding greater fuel efficiency in transport. This was mainly achieved by the creation of lighter vehicles through the use of less, and different, materials.

Short term forecasts (that is, up to two to three years) differ from long term forecasts in several important aspects. Short term forecasts of metal and mineral production, business executives, and practical planners use consumption and prices, and people rely on them. The forecast are often wrong, particularly when it comes to prices. The forecasting situation at present is even more uncertain, given that

influencing events such as the War in Iraq and its aftermath have had important effects on the outlook.

Mineral resources are increasingly becoming difficult to mine on land. Because of high density of population limited land is available. Minerals are site specific when mineral occur in either intense agricultural areas, forest areas or even in the tribal areas, which is always a difficult decision to do mining by displacing people, cutting pristine forest or double crop agricultural areas.

Recent research in the deep sea has identified ore deposits that may be economically extractable through the development of a deep sea mining industry within the next decade (Fujita 2001). Deep sea mining exploration has already begun. Both manganese nodules and seafloor massive sulphides are attracting attention. Since the early 1960s, significant increases in the commercial use of copper, nickel and cobalt have driven metal prices upwards, focusing attention on the need to increase mining deep sea manganese nodules. As nodules are mostly found in international waters, four mining companies were started, and the governments of the Soviet Union, China and India sponsored deep sea mining groups (Yamazaki 2005a). At that time, the United Nations and UNCLOS began to consider who exactly owned the mineral deposits on the sea floor in international waters. This ultimately led to the establishment of the International Seabed Authority (ISA) to collect fees and royalties in the name of the 'heritage of mankind' for commercial groups interested in mining these deposits (Division of Ocean Affairs and the Law of the Sea, 2006 of the ISA). However, before deep sea mining become a viable business enterprise, major land deposits of nickel (in Canada) and copper were discovered in the 1970s, driving metal prices downwards. This led to mining manganese nodules commercially unviable (Ifemer 2005). Close to US\$ 0.5 billion went into developing the technology and processes necessary for the mining of manganese nodules.

As we enter the twenty first century, and assuming that mining companies are findings deposits of sufficient size and grade, there are three possible economic drivers needed for Deep-sea Mining (DSM) to become a viable industry: (a) deep sea mining may actually be cheaper than land mining, as has been suggested by the work of the Nautilus Mineral Company (Heydon 2005) which shows that DSM for copper could cost about half the price of developing land based mining; (b) though unproven, the concept of the 'surgical mining' of relatively small Seafloor Massive Sulphide (SMS) deposits may have less impact on the environment than the land based mining (Heydon 2005); and (c) India and China would both need large quantities of copper to a build power grid infrastructure. This encourages deep sea mining (Yamazaki 2005). This can be summarized in the following Figure 19 below.

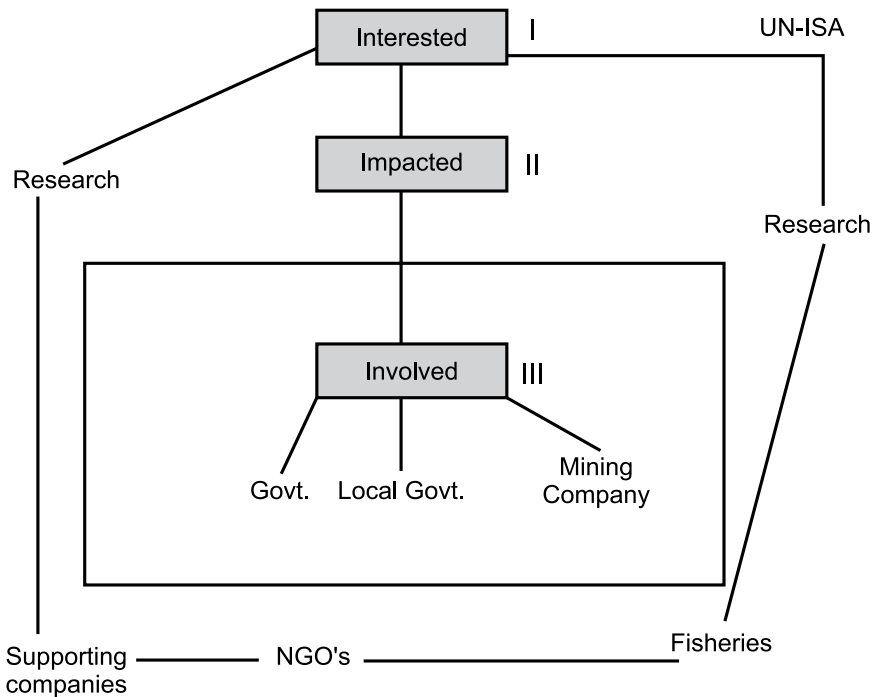


Figure 19: Showing 3 important aspects of the feasibility seabed mining

Since the discovery of seafloor massive sulphides (SMS) and the metal values in them, mining interest has shifted from manganese nodules to SMS. The implementation of commercial deep sea mining of SMS associated with hydrothermal vents is possible in the near future within a period of 5–10 years. The primary reasons for the mining industry's current interest in DSM are 3 fold: (a) SMS deposits are located at relatively shallow depths, and are accessible by current technology; (b) DSM may be cheaper than land based mining; and (c) the global demand for minerals is increasing, specially the emerging economies of India and China both may need large quantities of copper, thus making DSM even more economically viable (Yamazaki 2005a).

The purpose of this review and assessment study is to recognize and research the primary issues surrounding DSM, and to guide the industry in India before they invest in exploration either as joint ventures with the Govt. of India and or separately by industry. To achieve this objective, India needs to work out a programme which should requires an analysis of the following aspects:

- (a) An estimate of the SMS resources
- (b) An assessment regarding the extent of environmental impact of operations on the communities found in the locations of potential mining sites.
- (c) The choice of specific technology since the design and application of DSM technology will largely determine the impact on the environment.
- (d) Clear laws and policies addressing deep sea mining operations. These should cover how effective the management of marine minerals extraction will be, and how the ocean environment will be protected. DSM issues involve international legislation, national legislation, and environmental regulations.

Keeping the above as well as Indian interests in mind, some suggestions are listed below:

1. The Bay of Bengal could emerge as a difficult area because of seafloor Cu-Zn deposits; hydrocarbons in the Andaman Sea Gas hydrates in the Bay; as well as hydrocarbon and gas finds along the East coast and offshore.
2. In the international waters, international groups are looking at manganese nodules in the Central Indian Ocean basin and the VMS deposit in the Sonne Field around the Triple Junction in the mid-Indian Ocean Ridge systems. This is important and will have to be kept in mind.
3. As regards competition in the exploration of such deposits, at present only exploration and assessment has been carried out for nodules and SMS. We do not yet have mining technology, or full information regarding processing, or about Environmental Impact Assessment (EIA). Technology for this is available with industrialised nations such as the USA, Canada, the European Consortium (Germany, Poland and others), Japan, and South Korea.
4. The emergence of China as a major player in minerals and metals also deserves mention here. Since 1996, China has been the World's largest producer of Crude Steel; and in the year 2013, China was, for the first time, the world's largest iron ore importer. Changing Chinese demands determine the direction of metal market and prices. In aluminum, China's expansion is rapid, and important. China has also become a major factor in the supply of metals.
5. Rare earth elements in beach sands needs special attention for export on assured supply. Gold for India is important because our demand is 900 tons per year, out of which we produce

2 tons per year. We have to extract this metal from tailing through use of high technology.

6. Mining and metal costs will rise mainly because mining will become expensive due to the costs of environment rehabilitation. Oil prices are likely to go up from the present low, therefore the use of high technology for fuel saving metal extraction, substitution, and alloys is likely to be seen.
7. While China has claimed mining rights for VMS in the Mid-Indian Ocean Ridge, quite close to the Triple Junction, India has also taken up exploration in the adjoining area. In the meantime, Germany has also proclaimed its interest in mining VMS in the Sonne Field Area. This partly overshadows India's interest on the Mid-Indian Ocean Ridge.

## References

- Aplin, A.C., 1984, 'Rare Earth Element Geochemistry of Central Pacific Ferromanganese Encrustations', *Earth and Planetary Science Letters*, Vol. 71, pp. 13–22.
- Alpin, A.C. and Cronan, D.S., 1985, 'Ferromanganese Oxide Deposits from the Central Pacific Ocean, I. Encrustations from the Line Islands Archipelago', *Geochimica et Cosmochimica Acta*, Vol. 49, pp. 427–436.
- Alpin, A.C., 1984, 'Rare Earth Element geochemistry of Central Pacific Ferromanganese Encrustations', *Earth and Planetary Science Letters*, Vol. 71, p. 13–22.
- Anon, 1992, *Recent Geoscientific Studies in the Bay of Bengal and the Andaman Sea*, Geological Survey of India, Special Publication, No. 29, p. 278.
- Anon. 1981, Andaman Sea - Gulf of Thailand (Transect IT). *Studies in East Asian Tectonics and Resources* (SEATAR), CCOP, Bangkok: p. 37–51.
- Banerjee, P. K., B.K. Saha, S. Majumdar, S. Rakshit, D.K. Deb Roy, J.K. Sinha, and D. Bhattacharya, 1992, 'Nature and Origin of Anomalous Base Metal Enrichments in the Recent Sediments around the Narcondam Island in the Andaman Sea' in *Recent Geoscientific Studies in the Bay of Bengal and the Andaman Sea*, Geological Survey of India, Special Publication No. 29, pp. 111–116.
- Barns, R.E., 1964, 'Sea Bottom Heat Flow Measurement in the Andaman Sea', *Journal of Geophysical Research*, Vol. 69, pp. 4918–4919.
- Biswas, S., Majumdar, R.K., and Das Gupta A., 1992, 'Distribution of Stress Axes Orientation in the Andaman-Nicobar Islands Region; a Possible Stress Model and its Significance for Extensional Tectonics of the Andaman Sea', *Physical Earth Planet Interiors*, Vol. 70, pp. 57–63.
- Burns R.G., and Burns V.M., 1977, 'Minerology', in G.P. Glassby's *Marine Manganese Deposits*, Elsevier, pp. 185–208.

- Cann, J.R., 1980, 'Availability of Sulphide Ores in the Ocean Crust', in *Journal of the Geological Society*, London: Vol. 137, pp. 381–384.
- Chandra, K., Singh, R.P., and Julka, A.C. 1998, 'Gas Hydrate Potential of Indian Offshore Area', pp. 359–368, in Proc. 2nd Conf. & Exposition Petroleum Geophys. Soc. Petrol. Geophys. Dehradun, 560.
- Chandra, K., Singh, R.P., and Julka, A.C., 1998, 'Gas Hydrate Potential of Indian Offshore Area', pp. 359–368, in Proc. 2nd Conf. & Exposition Petroleum Geophys. Soc. Petrol. Geophys. DehraDun, 560.
- Chandra, P.R., 1992, Records, Geological Survey of India, p. 125.
- Chung, J.S., 2005, 'Deepsea Mining Technology: Development II', ISOPE Ocean Mining Symposium.
- Craig, J.D., Andrews, J.E., and Meylan, M.A., 1982, 'Ferromanganese Deposits in the Hawaiian Archipelago', *Marine Geology*, Vol. 45, pp. 12–157.
- Cronan, D. S. 1992, *Marine Minerals in the Exclusive Economic Zones*, London: Chapman & Hall.
- Cronan, D.S. 1980, *Underwater Minerals*, London: Academic Press.
- Cronan, D.S., 1984, 'Criteria for the Recognition of Areas of Potentially Economic Manganese Nodules and Encrustations in the CCOP/SOPAC Region of the Central and South-western Tropical Pacific', *South Pacific Geological Notes*, Vol. 3, pp. 1, 17.
- Curry, J.R., 1991, 'Possible Green Schist Metamorphism at the Base of 22 km Sedimentary Section, Bay of Bengal', *Geology*, South Pacific Geological Notes, Vol. 19, pp. 1097–1100.
- Curry, J. R., D.G. Moore, L.A. Lawver, F.J. Emmel, R.W. Raitt, M. Henry, and R. Kieckhefer, 1979, 'Tectonics of the Andaman Sea and Burma', *American Association of Petroleum Geologists: Memoirs*, Vol. 29, pp. 189–198.
- Curry, J.R., D.G. Moore, L.A. Lawver, F.J. Emmel, R.W. Raitt, M. Henry, and R. Kieckhefer, 1982, 'Structure, Tectonics and Geological History of the North-eastern Indian Ocean', in A.E.M. Nairn and F.G. Stehli (eds.) *The Ocean Basin and Margins: The Indian Ocean*, Vol. 6, pp. 399–450, New York: Plenum Press.

- Curry, J.R., Emmel, F.J., Moore, D.G., and R.W. Raitt, 1982, 'Structure, Tectonics, and Geological History of the North-eastern Indian Ocean', in A.E.M. Naira and F.G. Stehli (eds.) *The Ocean Basins and Margins: The Indian Ocean*, Vol. 6, pp. 399-450, New York: Plenum Press.
- Das, S.K., 2001, 'Indian Polymetallic Module Programme', *Proceeds of the 4th Ocean Mining Symposium*, 2001, p. 14-19.
- Degens, E.T., and Ross, D.A., 1969, Itot Brives (eds.) Recent Heavy Metal Deposits in the Red Sea *Springer*, New York, 600 pp.
- Department of Ocean Development (DOD), 1992, New Delhi: *Annual Report 1991-92*, p. 130.
- Dutta, S., 1991, 'Barren Island Volcano Spits Fire', Geological Survey of India, *Marine Wing Newsletter* 7(2), pp. 3-5.
- Eguchi, T., Uyeda, S., and Maki, I., 1979, 'Seismotectonics and Tectonics History of the Andaman Sea', *Technophys*, Vol. 57, pp. 35-51.
- Fouquet, Y., Stackelberg, U. von, Charlou, J.L., Donwal, J.P., Foucher, J.P., Erzinger, J., Herzig, P., Muhe, R., Weidicke, M., Soakai, S., and Whitechurch, H., 1991, 'Hydrothermal Activity in the Lau Back-arc Basin: Sulphides and Water Chemistry', *Geology*, Vol. 19, pp. 303-306.
- Fujita R., 2001, 'Protecting Deep-sea Eco System from a New Era of Mining,' *Environ. Def.* p. 3.
- German, C.R., Baker, E.T., Mevel C., Tamake, K., and the Fuji Science Team, 1998. 'Hydrothermal Activity Along the Southeast Indian Ridge', *Nature*, 395, pp. 490-493.
- Glasby, G. P., and G. S. Roonwal, 1995, 'Marine Pollution in India: an Emerging Problem. *Current Science*, 68(5), pp. 495-497.
- Geological Survey of India (GSI), 1991, Annual Report Records, 124(2).
- Gujar, A.R., Nath, B.N., and Banerjee, R., 1988, 'Marine Minerals: the Indian Perspective', *Marine Mining*, Vol. 7, pp. 317-350.
- Halbach, P., and Manheim, F.T., 1984, 'Potential of Cobalt and Other Metals in Ferromanganese Crusts on Seamounts of the Central Pacific Basin', *Marine Mining*, Vol. 4, pp. 319-336.
- Halbach, P., and Munch, U., 2000, 'Mineral Deposits at 23°S Central Indian

- Ridge: Mineralogical Features, Chemical Composition and Isotopic Investigation', *Handbook of Marine Mineral Deposits* (ed.) D.S. Cronan, Boca Raton: CRC Press.
- Halbach, P., 1986, 'Cobalt-rich and Platinum-bearing Manganese Crusts: Nature, Occurrence, and Formation', in C.J. Johnson and A.L. Clark (eds.) *Pacific Mineral Resources: Physical, Economic, and Legal Issues*, Proceedings of the Pacific Marine Mineral Resources Training Course, East-West Centre, Honolulu, Hawaii: pp. 137–160.
- Halbach, P., and Puteanus, D., 1984, 'The Influence of the Carbonate Dissolution Rate on the Growth and Composition of Co-rich Ferromanganese Crusts from Central Pacific Seamount Areas', *Earth and Planetary Science Letters*, Vol. 68, pp. 73–87.
- Halbach, P., Puteanus, D., and Manheim, F.T., 1984, 'Platinum Concentrations in Ferromanganese Seamount Crusts from the Central Pacific', *Naturwissenschaften*, Vol. 71, pp. 577–579.
- Halbach, P., Segl, M., Puteanus D., and Mangini, A., 1983, 'Co-fluxes and Growth Rates in Ferromanganese Deposits from central Pacific Seamount Areas', *Nature*, Vol. 304, pp. 716–719.
- Halbach, P., Blum, N., and Plugger, W., 1994, 'The Sonne Field: The First Massive Sulphides from the Indian Ocean floor', Abstract, 25th Underwater Mining Institute Conference, Monterey Bay (California).
- Halbach, P., Nakamura, K., Wahsner, M., Lange, J., Sakai, H., Kaselitz, L., Hansen, R.D., Tamano, M., Post, J., Seifert, R., Michaelis, W., Teichmann, F., Kinoshita, M., Marten, A., Ishibashi, J., Czerwinski, S., and Blum, N., 1989, 'Probable modern Analogue of Kuroko-type Massive Sulphide Deposits in the Okinawa Trough Back-arc Basin', *Nature*, Vol. 338, pp. 496–499.
- Halbach P., Blum N., Munch U., Plugger W., Kunh T., 1996), 'The Sonne Sulphide Field is Not Alone in the Indian Ocean', *BRIDGE Newsletter*, Vol. 10, pp. 51–54.
- Halbach, P., Blum N., Munch, U., Plugger, W., Garbe-Schonberg, D., Zimmer, M., 1998, 'Formation and Decay of a Modern Sulphide Deposit in the

Indian Ocean', *Mineralium Deposite*, Vol. 33, pp. 302–309.

- Halder, D., Laskar, T., Bandopadhyay, P.C., Sarkar, N.K., and Biswas, J.K., 1992b, 'Volcanic Eruption of the Barren Island Volcano, Andaman Sea', *Journal of the Geological Society of India*, Vol. 30, pp. 411–419.
- Hein, J.R., Manheim, F.T., Schwab, W.C., and Clague, D.A., 1986, 'Cobalt-rich Ferromanganese Crusts from the Central Pacific', *Proceedings of the Offshore Technology Conference*, Richardson, TX: OTC 5234, pp. 119–126.
- Hein, J.R., Morgenson, L.A., Clague, D.A., and Koski, R.A., 1987a, 'Cobalt-rich Ferromanganese Crusts from the Exclusive Economic Zone of the United States and Nodules from the Oceanic Pacific', in D.W. Scholl, A. Grantz, and J.G. Vedder (eds.) *Geology and Resource Potential of the Continental Margin of Western North America and Adjacent Ocean Basins: Beaufort Sea to Baja California*, Circum-Pacific Council for Energy and Mineral Resources, Earth Science Series, Vol. 6, Houston, TX: Circum-Pacific Council for Energy and Mineral Resources, pp. 753–771.
- Hein, J.R., Schwab, W.C., and Davis, A.S., 1988a, 'Cobalt- and Platinum-rich Ferromanganese Crusts and Associated Substrate Rocks from the Marshall Islands', *Marine Geology*, Vol. 78, pp. 255–283.
- Hein, J.R., Manheim, F.T., Schwab, W.C., Davis, A.S., Daniel, C.L., Bouse, R.M., Morgenson, L.A., Sliney, R.E., Clague, D., Tate, G.B., and Cacchione, D.A. 1985a, 'Geological and Geochemical Data for Seamounts and Associated Ferromanganese Crusts in and near the Hawaiian, Johnston Island, and Palmyra Island Exclusive Economic Zones', *U.S. Geological Survey, Open File Report*, pp. 85–292, 129.
- Hein, J.R., Manheim, F.T., Schwab, W.C., and Davis, A.S., 1985b, 'Ferromanganese Crusts from Necker Ridge, Horizon Guyot and S.P. Lee Guyot: Geological Considerations', *Marine Geology*, Vol. 69, pp. 25–54.
- Hein, J.R., Schwab, W.C., Foot, D.G., Masuda, Y., Usui, A., Davis, A.S., Fleishman, C.L., Barna, D.L., Pickthorn L.B., Larson, D.A., Ruzzi, P., Benninger, L.M., and Gein, L.M., 1987c, 'Far-nella Cruise F7-86-HW: Cobalt-rich Ferromanganese Crust Data Report for Karin Ridge and

- Johnston Island, Central Pacific', *U.S. Geological Survey Open File Report*, pp. 87–663, 34.
- Herzig, P., and Pluger, W.L., 1988, 'Exploration for Hydrothermal Activity Near the Rodriguez Triple Junction, Indian Ocean', *Canadian Mineralogy*, Vol. 26, pp. 721–736.
- Heydon, D., 2004, Exploration of Pre-feasibility of Mining Poly-metallic Sulphides: A Commercial Case Study, ISA workshop.
- Ifremer, French Research Institute for Exploitation of the Ocean Resources.
- Minerals Year Book*, 2002/3, Indian Bureau of Mines, Nagpur: Government of India.
- International Sea-bed Authority websites: [www.isa.org.jn/en/default.htm](http://www.isa.org.jn/en/default.htm)
- Jamous D., Meremy L., Andrie C., 1993, 'The Distribution of Helium-3 in the Deep Southern and Western/Central Indian Ocean', *Journal of Geophysical Research*, Vol. 98, pp. 1123–1128.
- Jean-Baptiste P., Mantsi F., Pauwells H., 1992, Hydrothermal He and Manganese Plumes at 19°29 S on the Central Indian Ridge, *Geophysical Research Letters*, Vol. 19, pp. 1787–1790.
- Johnson, C.J., Clark, A.L., and Otto, J.M., 1985, 'Pacific Ocean Minerals: The Next Twenty Years', East-West Centre, Resource Systems Institute, Honolulu, Hawaii: (unpublished).
- Kang, J.K., 1987, 'Mineralogy and Internal Structures of a Ferromanganese Crust from a Seamount, Central Pacific', *Journal of the Oceanological Society of Korea*, Vol. 22, pp. 168–178.
- Kolla, V., and Kidd, R.B., 1982, 'Sedimentation and Sedimentary Processes in the Indian Ocean', in: A.E.M. Narin and F.G. Stehli (eds.) *The Ocean Basins and Margins: The Indian Ocean*, Vol. 6, pp. 1–50, Plenum, New York.
- Kumar, S., 1990, Gravity Anomalies, Seismicity, Subducting Slab Folding and Surface Deformations in the Orogenic Belts: an example from the Andaman-Nicobar Region', *Journal of Geodynamics*, Vol. 12, pp. 39–63.
- Kunzendorf, H., (ed.) 1986. *Marine Mineral Exploration*. Elsevier, Amsterdam, XN + 300.

- Mallik, T.K., 1983, 'Recent Sediments around the Indian Subcontinent with Emphasis on Mineral Distribution Pattern and Mineral Resources', *Revista de Ciencias del Mar Thalassas*, Vol. 1, pp. 23-39.
- Mangini, A., Halbach, P., Puteanus, D., and Segl, M., 1987, 'Chemistry and Growth History of Central Pacific Mn-crusts and their Economic Importance', in P.G. Teleki, M.R. Dobson, J.R. Moore, and U. von Stackelberg (eds.) *Marine Minerals: Advances in Research and Resource Assessment*, Dordrecht, Holland: D. Reidel, pp. 205-220.
- Manheim, F.T., 1986, 'Marine Cobalt Resources', *Science*, Vol. 232, pp. 600-608.
- Maung, H., 1917, 'Transcurrent Movements in the Burma-Andaman Sea Region', *Geology*, Vol. 15, pp. 911-912. Comments and Reply in *Geology*, Vol. 17, pp. 93-98.
- Medford, R.D., 1969, *Mining Magazine*, 121 (no.5), pp. 309; *Mining Magazine*, 121 (b), pp. 474.
- Mero, J.L., 1965, 'The Mineral Resources of the Sea', *Elsevier*, Amsterdam: pp. 312 .
- Mero, J.L., 1977, in *Marine Manganese Deposits*, (ed.) G.P. Glasby, *Elsevier*, Amsterdam: pp. 321-355.
- Meylan, M.L., Glasby, G.P., Knedker, K.E., and Johnston, J.K., 1981, 'Rotalliferous Deep: All Sediments', in *Handbook of Strataound and Stratiform Ore Deposits*, (ed.) Kottwold, *Elsevier*, pp. 77-178.
- Mitchell N.C., 1991, 'An Evolving Ridge System Around the Indian Ocean Triple Junction', *Marine Geophysical Research*, Vol. 13, pp. 173-201.
- Morgan, C.L., 2000, in *Hand Book of Marine Mineral Deposits*, (ed.) D.S. Cronan, Boca Raton: CRC Press, pp. 145-170.
- Mukhopadhyay, M., 1984, 'Seismotectonics of Subduction and Backarc Rifting under the Andaman Sea', *Tectonophysics*, Vol. 108, pp. 229-239.
- Mukhopadhyay, M., 1988, 'Gravity Anomalies and the Deep Structure of the Andaman Arc', *Marine Geophysical Research*, Vol. 9, pp. 197-210.
- Mukhopadhyay, R., Iyer S.D., and Ghosh A.K., 2002, 'The Indian Ocean Nodule Field: Petro-technonic Evolution, and Ferromanganese Deposits', *Earth Science Review*, Vol. 60, pp. 67-130.

- Munsch M., and Schlich R., 1989, 'The Rodrigues Triple Junction (Indian Ocean): Structure and Evolution for the Past One Million Years', *Marine Geophysical Research*, Vol. 11, pp. 1-14.
- Pandey, J., Agarwal, R.P., Dave, A., Maithani, A., Trivedi, K.B., Srivastava, A.K., and Sugh, D.N., 1992. *Geology of Andaman Bull*, O.N.G.C., Vol. 29, pp. 19-103.
- Peter, G., Weeks, L.A., and Barnes, R.E., 1966, 'A Reconnaissance Geophysical Survey in the Andaman-Nicobar Island Area', *Journal of Geophysical Research*, Vol. 71, pp. 495-509.
- Peter, J. M., and S. D. Scott, 1991, 'Hydrothermal Mineralization in the Guaymas Basin, Gulf of California', *American Association of Petrologists Geological Memoirs*, Vol. 47, pp. 721-741.
- Peter, J.M., and Shanks W.C., 1992, 'Sulfur, Carbon and Oxygen Isotope Variations in Submarine Hydrothermal Deposits of Guaymas Basin, Gulf of California', *Geochimica Cosmochimica Acta*, Vol. 56: pp. 2025-2040.
- Pluger, W.L., Herzig, P.M., Becker, K.P., Deismann, G., Schops, D., Langer, J., Jensich, A., Ladage, S., Richnow, H.H., Schulzee, T., Michaelis, W., 1990, 'Discovery of Hydrothermal Field at the Central Indian Ridge', *Marine Mining*, Vol. 9, pp. 73-86.
- Qasim S.Z., and Roonwal, G.S., (eds.) 1996, *India's Exclusive Economic Zone*, New Delhi: Omega Publishing House, p. 338.
- Rajamanikam, G.V., 2000, 'Light and Heavy Minerals on the Indian Continental Shelf: Including Beaches', in *Handbook of Marine Mineral Deposits* (ed.) D.S. Cronan, Boca, Raton: CRC Press, pp. 13-26.
- Ravindran, M., 1994, 'Indian Underwater Mining programme: its Long term and Short Term Objectives', Abstract, 25th Underwater Mining Institute Conference, Monterey Bay California.
- Rodolfo, K.S., 1969, 'Bathymetry and Marine Geology of the Andaman Basin: Tectonic Implications for Southeast Asia', *Geological Society of America Bulletin*, Vol. 80, pp. 1203-1230.
- Rona, P.A., 1988, 'Hydrothermal Mineralization at Oceanic Ridges', *Canadian Mineralogist*, Vol. 26, pp. 431-465.
- Rona, P.A., Bostron, K., Laubier, L., and Smith, K.L., (eds.) 1983, *Hydrothermal Processes at Sea Floor*, New York: Pleunum, p. 796
- Rona, P.A., 1985, 'Hydrothermal Mineralization at the Slow Spreading Centres: Red Sea, Atlantic Ocean and the Indian Ocean', *Marine Mining*, Vol. 5, pp. 117-146.

- Rona, P.A. 1984, 'Hydrothermal Mineralization at the Sea Floor Spreading Centers', *Earth Science Review*, Vol. 20, pp. 1-104.
- Roonwal, G. S., 1986, 'The Indian Ocean: Exploitable Mineral and Petroleum Resources', *Springer-Verlag*, Heidelberg: Vol. XVI, p. 198.
- Roonwal, G.S., 1988, 'Cobalt and Platinum-rich Ferromanganese Crusts in the Indian Ocean', *Journal of Geological Society*, Bangalore, India: Vol. 29, pp. 358-361.
- Roonwal, G.S., 1988, 'New Ore Finds in the Pacific: Fourth German Research Cruise in the Active Plate Margin on the East Pacific Rise', Results of the Cruise Geometep 4, *Journal of the Association of Exploration Geophysicists*, Hyderabad: Vol. 9, pp. 123-130.
- Roonwal, G.S., and Mitra A., 1988, 'Hydrothermal Sulphide Mineralization on the Sea Floor Spreading Centers: A review', *Indian Journal Marine Science*, Vol. 17, pp. 249-257.
- Roonwal, G.S., 1989, 'Marine Minerals in the Indian Ocean', *Journal of the Geological Society of India*, Vol. 34, pp. 182-191.
- Roonwal, G.S., 1991, *India and Marine Minerals in the Indian Ocean*, Scientific challenge and socio-economic necessity. IASSI. Quart. 9, 209-215.
- Roonwal, G.S., 1993, 'Oceanic Minerals', pp. 357, 352, in S.Z. Qasim (ed.) *Science and Quality of Life*. Offsetters, New Delhi: 620.
- Roonwal G.S., 1993, 'Oceanic Minerals', pp.357-372. in *Science and Quality of Life* (ed.) S.Z. Qasim, Off setters, New Delhi: 620.
- Roonwal, G.S., S.Z. Qasim (ed.) *Science and Quality of Life*, Offsetters S., 1994. 'New Ore Finds on the Sea-floor after the Law of the Sea Conference (UNCLOS): Implications for India', *Journal of Indian Ocean Studies*, New Delhi: 1(2), pp. 50-58.
- Roonwal G.S., and Glasby G.P., 1996, 'Co-rich Manganese Crusts and Hydrothermal Mineralization in the Indian Exclusive Economic Zone', in S.Z. Qasim and G.S. Roonwal (eds.), *India's Exclusive Economic Zone*, New Delhi: Omega Science Publishers, p. 238.
- Roonwal, G.S., 1997, 'Marine Mineral Potential in India's Exclusive Economic Zone: Some Issues before Exploitation', *Marine Georesources and Geotechnology*, Vol. 15, pp. 21-32.
- Roonwal, G.S., Glasby, G.P., and Roelandts, I., 1997a, 'Mineralogy and Geochemistry of Surface Sediments from the Andaman Sea and Upper

- Nicobar Fan, Northeast Indian Ocean', *Journal Indian Association of Sedimentologists* 16(1), pp. 89–101.
- Roonwal, G.S., Glasby, G.P, and Chugh, R., 1997 b, 'Mineralogy and Geochemistry of the Surface Sediments from the Bengal Fan, Indian Ocean', *Journal of Asian Earth Science*, Vol. 15, pp. 33-41.
- Roonwal, G.S., and Wilson, G.C., 1998, India's Mineral Potential: Present Status and Future Trend', *International Geology Review*, Vol. 40, pp. 865–895.
- Roonwal, G.S., 1999, 'Mineral and Petroleum Resource of the Andaman Sea', *EEZ Technology*, London: Vol. 4, pp. 29–33.
- Roonwal, G.S., 1999b, *Oceanic Minerals*, National Institute of Science Communication CSIR, New Delhi: pp. 89
- Roonwal, G.S., 2000, 'Indian Efforts on the Exploitation of Marine Minerals in the Indian Ocean', pp. 228–234, In: *Indian Ocean in the 21st Century*, (ed.) S.Z. Qasim Sai, Pub., New Delhi and SIOS New Delhi, 257.
- Roonwal, G.S., 2002, 'India's Heavy Mineral Sand Industry', in *Journal of Indian Ocean Studies*, 10(3), pp. 486–492.
- Roonwal, G.S., 2005, 'Compatibility of Indian Reserves and Resources Classification with the UN framework Classification', *The Mining, Geological & Metallurgical Institute of India* (MGMI), Trans. 101(1&2), pp. 99–109.
- Roonwal, G.S., 2005, 'Mineral Endowment of the Indian Ocean', in *Oceanology* (ed.) H.K. Gupta, pp. 75–91, University Press, 222.
- Roonwal, G.S., 2009, 'Sea bed Sulphides, Gas Hydrates, and Hydrocarbon Resources in the Andaman Sea: North East Indian Ocean', *Proceedings of the 8th ISOPE Ocean Mining Symposium*, pp. 96–101.
- Roonwal, G.S., 2013, 'Sea mounts and Cobalt-Platinum rich Fe-Mn Crust Resources in the Indian Ocean', *Proceedings of the 10th ISOPE, Ocean Mining and Gas Hydrate Symposium*, Szezecin, Poland: pp. 22–26.
- Roy, S.K., and Das Sharma, S., 1993, 'Evolution of the Andaman Fore-arc Basin and its Hydrocarbon Potential', Proc. Second Sem., *Petroliferous Basins of India*, Vol. 1, pp. 407–435.
- Roy, T.K., 1983, Geology and Hydrocarbon Prospects of the Andaman-Nicobar Basin', *Petro Asia Journal*, Vol. 6, pp. 37–50.

- Roy, T.K., Chopra, N.N., 1987, 'Wrench Faulting in the Andaman Fore-arc Basin, India', *Offshore Technology Conference*, USA, pp. 393-402.
- Sakasegawa, T., and Matsumoto, K., 1997, *Deep Sea Manganese Nodule Mining*, UNIDO, Vienna: Energy Tech SRL, pp. 1-18.
- Sames, C.W., 1986, *Anaconda-Bericht aus der Rohstoffwelt*. Munchan, Wirtschaftsverlag. Langer-Mulla, pp. 363.
- Siddiquie, H.N., and Rajamanickam, G.V., 1979, 'Surfacial Mineral Deposits of the Continental Shelf of India', *Offshore Mineral Resources Documents, BRGM*, Vol. 7, Orleans, France: pp. 233-258.
- Siddiquie, H. N., Rajamanickam, G.V.,. Gujar, A.R, and Ramana, M.V., 1982, 'Geological and Geophysical Exploration for Offshore Ilmenite Placer off the Konkan Coast, Maharashtra, India', *14th Offshore Technical Conference*, pp. 749-755.
- Siddiquie, H.N., Rajamanickam G.V., and Almeida F., 1979, 'Offshore Ilmenite Placers off Ratnagiri, Konkan Coast, Maharashtra, India', *Marine Mining* Vol. 2, pp. 91-118.
- Society of Petroleum Geophysicists, 1998, 'Proceedings of 2nd Conference & Exposition Petrol', *Geophysics*, 560.
- Stow, D.A.V., Cochran, J.R., and Leg O.D.P., 1989, 'The Bengal Fan: Some Preliminary Results from ODP Drilling', 116 Shipboard Scientific Party, *Geo -Mar. Lett.*, Vol. 9, pp. 1-10.
- Thiel, E., Prasad Rao, J.V.R., and Schrier G., 1994, 'Environmental Risk Studies in the Deep Sea: Need for International Cooperation', 25th Underwater Mining Institute, Monterey Bay (California): Abstracts.
- UNCLOS, 1982. United Nations, New York.
- UNFPA, 2002, *The State of World Population*, New York: United Nations.
- I.U.S. Bureau of Mines 2002, *Mineral Commodity Survey*, Washington, DC: U.S. Government Printing Office.
- United Nations, 1996, *United Nations International Framework Classification for Reserves/Resources*, UN Economic and Social Council, 174 pp.
- US Bureau of Mines, Various years. *Minerals Yearbook*. Washington, DC, Vol. 1.
- Verma, R.K., 1991, *Geodynamics of Indian Peninsula and the Indian Plate Margins*, A.A. Balkema, Rotterdam: p. 357.

- Weeks, L.A., Harbison, R.N., and Peter, G., 1967, 'Island Arc system in the Andaman Sea', *The American Association of Petroleum Geologists*, Vol. 51, pp. 1803, 1815.
- Woodruff L.G., Shanks W.C., (1988), 'Sulfur Isotope Study of Chimney Minerals and Vent Fluids from 21°N, East Pacific Rise: Hydrothermal Sulphur Sources and Disequilibrium Sulphate Reduction', *Journal of Geophysical Research* Vol. 93: pp. 4562–4572.
- Yates, J., and Roonwal G.S., 1994a, 'Marine Science and Technology in India: Current Status', *Marine Policy*, 18(1), pp. 59–68.
- Yates, J., and Roonwal G.S., 1994b, 'Conference Review: Environment Management of Indian E.E.Z', *Journal of the Geological Society of India*, Vol. 44, p. 694.
- Yawazaki, D.T., 2005a, 'The Coming Copper Crisis', in *Important Role of Deep Sea Mineral Resources in Fulfilling Japan's Demand*, 35th Underwater Mining Institute.





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