

MINERAL RESOURCES OF THE INDIAN OCEAN AND RELATED SCIENTIFIC RESEARCH

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ABSTRACT

The sea floor of the Indian Ocean and the continental margins bordering the ocean are covered by a wide variety of terrigenous, biogenous and chemogenous mineral deposits.

The humid tropical climate of some of the land areas bordering the Indian Ocean accelerates weathering of the source rocks. This, coupled with the large river runoff and wave and current conditions, favours the formation of a variety of terrigenous heavy mineral placer deposits. As such, the beach and offshore placer deposits of the Indian Ocean are particularly abundant. Heavy mineral placers are known from the beaches of South Africa, Mozambique, Tanzania, Kenya, western India, Sri Lanka, Burma, Malaysia, Indonesia and Western Australia. The exploration of these deposits in offshore areas has been particularly encouraging off Mozambique, western India, Sri Lanka, Malaysia and Western Australia.

Biogenous deposits in the Indian Ocean include shallow-water and shelf bank sediments and carbonate and siliceous oozes in the deep sea. Biogenous deposits are a low-priced commodity and are likely to be exploited only locally for construction, cement and chemicals where onshore limestone deposits are not available. Shells and corals have local values for semi-precious and ornamental purposes. Calcareous sands, shells and corals are being exploited on a large scale in India for the manufacture of cement, and exploration in some of the areas has indicated reserves of over a thousand million tonnes. In many countries, especially islands whose economy is largely dependent on tourism, restraint should be exercised on the exploitation of these deposits. A study of these deposits undoubtedly would lead to a better understanding of their formation, production and sustainable yields and, in turn, to better management.

(Phosphorite deposits in the Indian Ocean are reported from continental margins (South Africa and western India) and seamounts (eastern and western Indian Ocean). Onshore deposits, however, are sufficient to meet requirements for the near future. Exploitation of the marine deposits would be feasible in those coastal areas where the cost of imported fertilisers is higher than the cost of marine mining. Future exploitation of phosphorites may provide a significant stimulus to the dominantly agricultural economies of many Indian Ocean countries.

The polymetallic nodules in the Indian Ocean cover an area of 10-15 million km², and the resources are estimated to be about 0.17 trillion tonnes. A study of over 900 chemical analyses from 350 stations shows that the deposits in most basins are submarginal. Deposits in the central Indian Ocean may be paramarginal (Ni + Cu + Co over 2.47 percent and abundance more than 5 kg/m²).

Exploration of the mineral resources of the Indian Ocean not only would add to an inventory of the resources in the world oceans but also would lead to a greater understanding of the formation of marine mineral resources.)

Present capabilities (trained manpower, equipment and vessels) for exploration for marine non-living resources in the region are confined to only a few countries. In this context, the programmes for exploration of non-living resources will require (i) compilation of the basic data for planning (ii) exploration of the inner shelf, (iii) exploration of the outer shelf, and (iv) exploration of the deep sea. In countries with limited manpower in marine geosciences, a beginning could be made by interactions between physical, chemical and biological oceanographers. This would be useful to identify the areas for the exploration for terrigenous deposits (heavy minerals placers), biogenous deposits (shells and corals) and chemogenous deposits. After initial planning, further work could be initiated on smaller vessels (even fishing trawlers) in the nearshore areas and later, with the acquisition

of equipment and larger vessels, on the continental shelf and in the deep sea. Indian scientists have developed collaboration programmes with Sri Lanka and Seychelles, and programmes are now being drawn up for collaboration with Mauritius.

INTRODUCTION

The Indian Ocean (Area: $74.917 \times 10^6 \text{ km}^2$, Water Volume: $291.945 \times 10^6 \text{ km}^3$, Average Depth: 3897 m) is the third largest of the world oceans. The lands bordering the ocean contain almost 40 percent of the world's population and contribute substantially to some of the essential mineral raw materials for the world economy; i.e., oil, tin, iron and manganese ores, mica and chromite.

The present paper reviews the surficial mineral resources of the Indian Ocean, excluding those in bedrock (oil, gas and sulphur etc.) and the metalliferous brine deposits of the Red Sea.

The minerals for the review have been grouped as (i) Terrigenous (ii) Biogenous and (iii) Chemogenous. The present review covers the Indian Ocean as defined by FAIRBRIDGE (1966), extending from the east of the African continent to the west of the Australian continent and from the Indian sub-continent to Antarctica.

SEDIMENT TYPES

TERRIGENOUS SEDIMENTS

Heavy mineral placers are known from the beaches of many countries bordering the Indian Ocean (Fig. 1). The placers contain ilmenite, rutile, zircon, magnetite, monazite, garnet, kyanite and tin in significant proportions. Many of these placers are economically exploited and contribute significantly to the world production (Table 1). The offshore extension of some of these placers has also been explored, but at present only offshore tin placers are being exploited.

The present onshore deposits of heavy mineral placers can provide a clue about the nature and distribution of offshore deposits in submerged valleys and beaches on the continental shelf. Though a large number of placers are known to occur on the beaches of the Indian Ocean, offshore extensions of only a few have been explored. These are reviewed below:

Mozambique: Known onshore placer deposits at Pebana, Vila Luiza and Micaune contain ilmenite, zircon, rutile and minor amounts of monazite. The R.V. VALDIVIA in 1971 and 1973 carried out detailed geological and geophysical surveys on the shelf off northern Mozambique (BEIERSDORF et al., 1980) to locate marine placer deposits. The heavy minerals included ilmenite (TiO_2 49.5; FeO 33.1 and Cr_2O_3 0.18 %), zircon (ZrO_2 63.05, TiO_2 0.71 %), rutile (TiO_2 87.7 %) magnetite, garnet, etc. Sediments on the Zambesi delta between water depth of 30 to 60 m are estimated to contain 50 million tons of ilmenite, 0.9 million tons of rutile and 4 million tons of zircon.

Tanzania: Placers containing garnet (4.3 million tonnes), ilmenite (3.6 million tonnes), rutile (0.4 million tonnes), kyanite, zircon, magnetite and monazite were reported (DUYVERMAN, 1981) along the coast of Tanzania. Heavy mineral concentrations, ranging up to 23 percent, decrease northwards except at Ndega beach. The data on either the size of resources or their offshore extension are not available.

India: Placers are known from a number of localities along the Indian coast (Fig. 2), of which the beach and dune placers along Kerala coast are best known. These deposits are reported to contain 17 million tonnes of ilmenite, 1 million tonnes of rutile, 1.2 million tonnes of zircon and 0.2 million

tonnes of monazite. Similar deposits with varying proportions of ilmenite, zircon, magnetite, and garnet have been described from Maharashtra, Tamil Nadu, Andhra Pradesh and Orissa (SIDDIQUIE et al., 1984 and references therein). The total reserves of ilmenite are estimated to be 163 million tonnes, and production in 1981 was 0.189 million tonnes (INDIAN BUREAU OF MINES, 1981).

The extension of the heavy mineral placers from the beach to the offshore areas was a subject of speculation until recently. Some of the richest deposits in India occur along the 25 km-long stretch of the coast from Neendakara to Kavankulam in Kerala. PRABHAKARA RAO (1968) explored the shallow offshore areas of this stretch to a depth of about 10 to 12 m and suggested that these sediments have been derived from the area immediately to the east. The heavy minerals (4 to 56 percent) in these sediments consist of kyanite, sillimanite, zircon, garnet, ilmenite, leucoxene and rutile.

Ilmenite placers along the Konkan coast contain 17 to 74 percent ilmenite, and reserves have been estimated at about 4 million tonnes (MANE and GAWADE, 1974). The National Institute of Oceanography initiated the offshore surveys of Konkan in 1975 to (i) delineate the offshore extension of the promising onshore placers, (ii) understand the geology, structure, recent sedimentation and tectonic history of the area, (iii) define the environment of deposition of heavy minerals and formation of placers, (iv) evaluate the techniques for the exploration of the deposits, and (v) examine the feasibility of their economic exploitation. A detailed survey of the 130 km long strip along the Konkan coast (Fig. 3) was carried out during 1975-80. Heavy mineral concentrations range up to 90 percent (Fig. 4), and the assemblage is dominated by ilmenite (Fig. 5) and magnetite (Table 2) with minor quantities of augite, epidote, zoisite, apatite, tourmaline, topaz, hornblende, rutile, zircon, limonite and kyanite. The magnetites in the sands are titanomagnetite or finely intergrown with ilmenite. SIDDIQUIE et al. (1979) reported 42 to 57 percent TiO_2 in the ilmenite, and trace element analyses of these heavy mineral concentrates indicate appreciable concentrations of vanadium (up to 0.5 percent) and chromium (SAHOO, 1980).

A representative seismic profile off the Konkan coast (Fig. 6) shows four to five major reflectors consisting of sand, clay, sand with pebbles, weathered trap and trap. The thickness of heavy mineral-bearing sands varies from 2 to 10 m (Fig. 6), and thicker sands (more than 10 m) are associated with river mouths and buried ancient river channels and local sand lenses. This is also confirmed from shallow cores and boreholes drilled in Mirya Bay; the sands are underlain by weathered basalt and in turn Deccan basalts (Late Mesozoic to Early Tertiary). Magnetic surveys were carried out to correlate the magnetic anomalies with heavy mineral concentrations, basement configuration and structural trends.

The surveys carried out so far indicate that the ilmenite-bearing sands cover over 96 km² of the seabed. Assuming an average ilmenite concentration of 10 percent and a minimum thickness of 1 m for ilmenite-bearing sands, the reserves are inferred to be about 12.5 million tonnes. Seismic profiles indicate that the thickness of ilmenite-bearing sands ranges from 2 - 10 m and these extend to water depths of about 20 m over an area of 436 km². Thus the probable reserves in the area are many times more than the onshore reserves of 4 million tonnes. A comparison shows a higher concentration of ilmenite in the offshore than in the onshore sands. The extensive onshore and offshore deposits offer possibilities for an integrated development. Further exploration of offshore placers will be guided by the proximity to onshore placers and upon examination of the relict sands on the middle and outer shelves (Fig. 7).

Sri Lanka: The Sri Lanka beaches have been fairly well studied, and placers of ilmenite, rutile, monazite, zircon and garnet (KRISHNAN, 1968; HEARTH, 1983) are reported from many localities. However, little exploration for offshore heavy mineral placers has been carried out. Some of the localities are:

- i) Beruwela in Induruwa (west coast) - extensive deposits of monazite with zircon and garnet.
- ii) Beaches near Kokkilai lagoon (east coast) - 75% ilmenite forming an estimated reserve at about 4 million tonnes.
- iii) Pulamodai and Triukkovil beaches - 25% zircon.

Southeast Asia: Southeast Asia is the world's major producer of tin (WERNER, 1983); about 92 percent of the world's estimated resources are in this region. The tin province stretches for over 3600 km, from north Burma through peninsular Thailand and west Malaysia to the Tin Islands (Singkep, Bangka and Billiton) of Indonesia.

Offshore tin placers have been formed from the weathering and erosion of onshore deposits. These formations have been influenced by the interaction of the terrestrial and marine environments.

Although most of the production of cassiterite in southeast Asia has been from deposits on land, during the past ten years a considerable tonnage also has been obtained from submarine placers off the Indonesian Tin Islands and to the east of the Thai island of Phuket. A comparatively unimportant part of the belt is located in Laos, southeast Thailand and Anambas and Natuna Islands. Titaniferous magnetite is recovered from some of the beaches of Indonesia. Deposits of ilmenite, titaniferous magnetite, monazite and zircon also are reported in the offshore areas of western Indonesia.

The production of tin has declined since 1982 mainly because of depleted reserves, weak metal prices and cutbacks on exports.

Australia: The Australian beaches are well known for their heavy mineral placers. The total reserves proven and estimated for the east coast beaches of Queensland and New South Wales are 20 million tonnes and those of the west coast are 68 million tonnes. Between them these beaches produce over 90 percent of the world's rutile, 80 percent of zircon, 70 percent of monazite, >25 percent of ilmenite (CHARLIE, 1981).

BROWN (1971) reported encouraging results from offshore and estimated that a grade of 0.2 to 0.22 percent rutile and zircon could be mined. Reserves of over 375 million tonnes have been mapped, and indications are that another 500 million tonnes are present.

BIOGENOUS SEDIMENTS

Biogenous sediments cover large areas of the seabed (Fig. 1). They include pelagic oozes in the deep sea and coral and shell deposits in shallow areas.

Deep Sea

Deep-sea biogenic oozes accumulate in areas of high productivity (20°N - 40°S) and (for carbonate oozes) at depths shallower than the carbonate compensation depth (CCD). The approximate area covered by oozes in the Indian Ocean (FAIRBRIDGE, 1966) is given below:

Ooze	Area 10 ⁶ km ²	Latitude
Globigerina	40.45	Between 20°N and 40°S
Pteropod	00.74	Small patches NW of Australia
Diatomaceous	14.98	South of 50°S
Radiolarian (with red clays)	18.72	Between 10°N and 40°S

The deposits match in physical properties and chemical composition a wide variety of rocks/materials used on land, but they occur at too great depth and distance from land to be of any immediate economic interest.

Shallow Areas

Calcareous deposits dominate many shallow areas of the continental shelf, atolls and banks. Various maps by WELLS (1954) and ROSEN (1971) indicate that the highest generic diversity of reef corals occurs in a belt extending from 20°N to 20°S from Sumatra to Laccadives-Maldives, northern

Madagascar and the Red Sea. Within this area lie a number of atolls, coral reefs, submerged reefs and banks. Some of the banks are very large (i.e., Seychelles Bank covers 43,000 km², Saya de Malha, 40,000 km², Nazareth Bank 20,000 km² and the banks of the Chagos Archipelago 13,500 km²). The banks have general maximum depths of 33-90 m and most have a shallow rim (reef) at 8-10 m depth around at least part of their periphery.

Deposits of calcareous shells also occur in the shallow areas of the continental shelf. The deposits usually occur in areas of high benthic productivity and where influx of terrigenous sediment is low (MILLIMAN, 1974). The deposits in some of the areas comprise sub-recent fossil shells which have been or are being concentrated by recent or sub-recent marine processes.

The best known deposits off India are in the Jamnagar (Gulf of Kutch) district of Gujarat, North Kanara district of Karnataka, Alleppey and Kottayam (backwaters of Vembanad Lake), Kozhikode, Mallapuram and Cannanore districts of Kerala, Chinglepet district of Tamil Nadu and Nellore district (backwaters of Pulicat Lake) of Andhra Pradesh. The present production from these deposits is over 130,000 tonnes (Fig. 8).

The other, though minor, use of corals and shells from shallow waters is as ornamental and semi-precious stones. Among the Indian Ocean countries, substantial amounts of unworked shell have been exported by Indonesia (2,395 tonnes - 1978), India (151 tonnes - 1978) and Maldives (5 tonnes - 1977). India is becoming increasingly important as a supplier of ornamental shells, and exports have risen from 20 tonnes in 1969 to 466 tonnes in 1979. Exports of shells from Kenya reached a peak of 107 tonnes in 1978. Ornamental corals are also exported by Indonesia (5 tonnes - 1976), Maldives (0.038 tonnes - 1977) and India (0.016 tonnes - 1978).

For many types of shells and corals a concern rightly has been expressed regarding the depletion of their stocks, and the need for conservation has been emphasized. Because of this concern some countries have imposed a ban on exports and others are regulating the exploitation on a sustainable yield basis.

CHEMOGENOUS SEDIMENTS

Phosphorite

Phosphorite deposits have been found along continental margins (South Africa and western India) and around seamounts (eastern and western Indian Ocean). The continental margins of South Africa, East Africa, southern Arabia, western India and the Andamans are marked by strong upwelling and provide non-depositional environments which are conducive to the formation of phosphorite (Fig. 9, Table 3).

Agulhas Bank: The Agulhas Bank phosphorites are the largest known seabed deposits (BATURIN, 1982, and references therein), occupying a belt about 600 km long and 100 km wide at depths of 100 to 500 m. They consist of phosphoritic nodules and phosphatized limestones. The total reserves of phosphorite and phosphatized rocks are estimated to be 140 million tonnes of P₂O₅, assuming a mean deposit thickness of 1 m.

Andaman: TIPPER (1911) reported phosphorite nodules off the northern Andaman Islands. In the late 1960's extensive sampling for phosphorite was carried out in the same vicinity, but the results were not encouraging.

Western Continental Margin of India: The detailed surveys of the shelf between Goa and Bombay have identified a series of well defined (25 m height and 150 km length) NNW-SSE trending ridges. These ridges are composed of algal, coral and shelly limestones. Analyses of rock samples from these ridges show a wide range of P₂O₅ concentrations, between 0.8 and 11 percent (NAIR, 1985).

Seamounts: BEZRUKOV (1973) noted the occurrence of phosphorite on Christmas Island. Subsequently phosphorite also was dredged from a seamount, 13°45'S and 99°56'E, depth 3689 m, during R.V. VITYAZ's 54th cruise on the Cocos Ridge. These rocks consisted of phosphorite (22.7

to 32.5 percent of P_2O_5) and limestone blocks with lenticular intercalations of dense white and unconsolidated brownish phosphorite (BEZRUKOV et al., 1979).

Recently ORV SAGAR KANYA dredged samples of phosphorites from the Error Seamount in the northwestern Indian Ocean (ANON, 1983), at a depth of 400-460 m. The haul contained corals, rocks and limestones with fragments of brownish to yellowish phosphorites.

Polymetallic Nodules

The first polymetallic nodules from the Indian Ocean was collected by HMS CHALLENGER (1872-1876). Subsequently, WISEMAN (1937), MERO (1965), CRONAN and TOOMS (1967, 1968, 1969), GLASBY (1970, 1972), CRONAN (1972, 1975a,b), BEZRUKOV and ANDRUSCHENKO (1974), SOREM and BANNING (1976), CRONAN and MOORBY (1976, 1981), SIDDIQUIE et al. (1978), COOLEY et al. (1979), and FRAZER and FISK (1980, 1981) carried out mineralogical and geochemical studies on nodules, encrustations and sediments from various basins in the Indian Ocean (Fig. 9, Table 4).

Polymetallic nodules from 7000 locations on the ridges, seamounts and deeper basins of the Indian Ocean have been collected. Based on these data, the area covered by the nodules is estimated to be 10-15 million km^2 and the resources about 0.15 trillion tonnes.

BEZRUKOV and ANDRUSCHENKO (1974), CRONAN and MOORBY (1976) and SIDDIQUIE et al. (1978) noted the lack of extensive nodule deposits in the Arabian Sea and the Bay of Bengal due to high sedimentation. A nodule-rich belt similar to that in the eastern Pacific is located in the Central Indian Basin, which perhaps extends further east to the Wharton Basin. BEZRUKOV (1962) estimated from photos that the nodules cover up to 83.2 percent of the sea floor, with abundances up to 43 kg/m^2 . GLASBY (1973) estimated that the distribution of nodules ranges from 5 to 200 nodules/ m^2 in the Indian Ocean.

Central Indian Basin: (Figs. 10-16): The average depth is about 5120 m. CRONAN and MOORBY (1981) reported that the nodules associated with the siliceous sediments are enriched in Mn, Cu and Ni. The Cu/Ni ratio (>1.0) is similar to the high-grade nodules from southwest of Hawaii in the Pacific Ocean (FRAZER and WILSON, 1980). The nodules associated with pelagic clays, especially in the northern area, are depleted in Mn (15.4%), Cu (0.34%), Ni (0.6%) and Zn (0.07%), and enriched in Fe (12%), Co (0.17%) and Pb (0.1%) compared to average contents of siliceous oozes. Nodules associated with terrigenous sediments are lower in average Mn (14.2%), Cu (0.22%) and Ni (0.34%). The nodules contain mainly todorokite. Many workers (BEZRUKOV and ANDRUSCHENKO, 1974; SIDDIQUIE et al., 1978 and CRONAN and MOORBY, 1981) have pointed out that the nodules at many locations have a higher average Cu (0.74%), Ni (0.86%), Co (0.14%), Mn (20%) and Zn (0.1%) than the other basins in the Indian Ocean. FRAZER and WILSON (1980) indicated that para- and sub-marginal grades of nodules cover an area of 0.7×10^6 km^2 between 10° to 16° S in the Central Indian Basin. Based on the grade and abundance of nodules, FRAZER and WILSON (1980) and CRONAN and MOORBY (1981) concluded that only the nodules from the Central Indian Basin meet the criteria for first generation mining. However, available data on the grade and abundance are still inadequate, and detailed exploration is necessary for the identification of a prime area and estimation of resources.

Wharton Basin: (Figs. 10-16): The average depth is 5260 m. CRONAN and MOORBY (1981) reported higher Mn, Cu and Ni and lower Fe, Co and Pb compared to the Indian Ocean average. Todorokite is common in the nodules. Nodules associated with siliceous oozes have significantly higher values of Mn (20.3%), Cu (0.56%), Ni (0.7%) and Zn (0.1%) and a higher average Mn/Fe ratio (1.78), and those associated with pelagic clays have lower Mn (16.1%), Cu (0.26%), Ni (0.48%), Pb (0.07%), Zn (0.06%) and Mn/Fe ratio (1.4). The Mn/Fe ratio (1.4) for the nodules with pelagic clays is higher than for similar nodules in the other basins in the Indian Ocean. The limited data on the abundance and grade (3 stations with a range of <5 to 15 kg/m^2) suggest that ore grade nodules in the Wharton Basin do not cover a large area.

South Australian Basin: (Figs. 10-16): Average depth is 4710 m; sediments in the basin range from pelagic clays to carbonate oozes. The nodules are marked by comparatively high averages of Mn (19%), Ni (0.68%), Cu (0.34%), and Zn (0.08%) and lower Co (0.17%) and Pb (0.08%). Nodules from the carbonate ooze region are higher in average Mn (19.7%), Cu (0.34%), Ni (0.71%) and Zn (0.84%) but lower in Fe (13.0%), Co (0.17%) and Pb (0.08%) than those from pelagic clays. The economic potential of possible resources in the basin is judged to be sub-marginal (FRAZER and WILSON, 1980).

Crozet Basin: (Figs. 10-16): The average depth is 4570 m, and the sediments include siliceous oozes, pelagic clays and carbonates. Nodules associated with each sediment type show marked differences in composition and mineralogy (LECLAIRE and PERSEIL, 1979). Average Fe, Cu, Pb and Zn contents are comparable to the Indian Ocean average, but the Mn/Fe ratio (0.79) is lower. Average values are near to those of the first two basins, whereas Mn (12.2%), and Cu (0.18%) are lower. Nodule concentrations vary from >5-10 kg/m².

Madagascar Basin: (Figs. 10-16): The average depth is 4620 m. The nodules in the basin are characterized by low average contents of Mn (12.5%), Ni (0.21%), Cu (0.12%) and Zn (0.05%) and high contents of Fe (16.4%) and Co (0.27%); the Mn/Fe ratio (0.75) is intermediate between the nodules on mid-ocean ridges and seamounts and aseismic ridges. The nodules associated with carbonate oozes and pelagic clays do not show significant compositional variations except for Co (0.31%) and Pb (0.12%). KOBLENTZ- MISHKE et al. (1970) reported high biological activity, which is perhaps reflected in the higher Mn/Fe ratio. Delta-MnO₂ is common in the nodules from seamounts in the basin.

Mozambique Basin: (Figs. 10-16): The average depth is 4880 m. The nodules, which are not widespread (VINCENT, 1972), are characterized by large variations in Mn and Fe and the Mn/Fe ratio (1.0 to 1.21). The average values for Cu (0.17%), Ni (0.27%), Co (0.12%) and Zn (0.05%) are much lower than the other basins in the Indian Ocean except perhaps the Madagascar Basin. Nodules associated with terrigenous sediment are higher in average Mn (11.9%), Fe (14.4%), Cu (0.10%), Ni (0.3%), Co (0.13%), Pb (0.12%) and Zn (0.06%) compared to the nodules from carbonate oozes.

Seychelles-Somali Basins: (Figs. 10-16): The average depth is 4500 m. The nodules average values for Mn (16%), Cu (0.22%) and Ni (0.41%) and Mn/Fe ratio (1.17) are higher than those reported for the Crozet, Madagascar and Mozambique Basins. Copper is higher (0.28%) in the nodules compared to the pelagic clays, whereas other elements are enriched in the nodules relative to the carbonate ooze.

PROSPECTS

TERRIGENOUS

The heavy mineral placers on the beaches and offshore areas of the Indian Ocean are perhaps more widespread and richer than those in other oceans. This is perhaps related to the source areas/rocks and favourable humid tropical climate in some of the land areas bordering the ocean which accelerates weathering of the rocks, erosion and transport of large volumes of sediments by large rivers. The heavy minerals are initially deposited as the rivers enter the sea and on the beaches where they are further sorted and concentrated by currents and waves.

The onshore placers provide the best clue for the exploration of the offshore deposits. While the offshore deposits in the vicinity of some onshore placers have been explored, most offshore areas still remain to be explored, a necessary step to assess the potential of these offshore deposits. A study of the Quaternary history of the continental shelves, the rise of the sea level, and the distribution of sediments (especially relict sediments) is also necessary in the areas where the placers occur. Such

studies would not only provide data on the mineral potential of the shelf, but would also provide a conceptual framework for the exploration for offshore placers.

BIOGENOUS

Large areas of the deep and shallow Indian Ocean are covered by biogenous sediments. Calcareous and siliceous sediments, however, are low-priced commodities, and it is doubtful whether any deep-sea deposits could be of economic interest in the near future. The increase in demand for construction material, however, might lead to the exploitation on a comparatively large scale of calcareous deposits (i.e., corals and shells) from shallow areas.

CHEMOGENOUS

Systematic exploration of phosphorites has been carried out only on the continental margins of South Africa and India. The upwelling and non-depositional environments, particularly off the Somali and the Arabian coasts, need to be explored, as well as those areas where phosphorites already are indicated (the western shelf of India and the Andaman islands). Moreover, the Indian Ocean has a number of seamounts, and only a few (eastern Indian Ocean and Error Seamounts) have been explored. New data will add to an inventory of the resources and, under favourable situations, the deposits may even be exploited in the near future.

In terms of area covered and estimated resources, the polymetallic nodules in the Indian Ocean are second only to the Pacific Ocean. Available data show, however, that most Indian Ocean nodules do not meet the requirement of a first generation mine site, except perhaps those in the Central Indian Ocean. The exploration and exploitation of mineral deposits in the Indian Ocean (Fig. 17) will lead to a greater understanding of the formation and development of marine sediment deposits.

PLANNING

MARINE MINERAL EXPLORATION

In view of the limited expertise, equipment and research vessels, the exploration for marine mineral resources in the Indian Ocean region may have to take place in discrete and sequential phases: compilation of basic data for planning, exploration of the inner shelf, exploration of the outer shelf and the slope, and lastly the deep sea. In countries with limited expertise in marine geosciences, a limited beginning could be made by association of scientists from other disciplines (i.e., physical, chemical and biological oceanography) in the compilation of the basic data to identify target areas for exploration.

The planning for marine mineral exploration would require compilation of the available data from the literature (published and unpublished) and maps. A beginning could be made with the preparation of maps from notations on navigational charts (in addition to the seabed information or samples collected from research vessels) to prepare sediment distribution on the continental margins. These would provide some basic information on the distribution of sediments, shells, corals and rocks, and would lead to identification of the environments of sedimentation and the types of mineral deposits. It must be emphasized, however, that besides marine mineral exploration, it is necessary that basic research in marine geosciences also be encouraged, for the basis for further marine mineral exploration.

Sediment distribution maps combined with a study of the geology of the drainage basins would be useful for identifying potential placer areas and the expected minerals in these placers.

Offshore placers are likely to occur in areas covered by terrigenous sediments and near known onshore placers. Physical oceanographic studies also would be useful to indicate and to identify areas in which the energy regime is sufficient for such deposits to be formed. Collected data could be used for postulating models which would aid in the development of exploration strategies and techniques.

Biogenous deposits (i.e., corals and shells) are typical of tropical waters, and it would be appropriate if scientific studies result not only in economic potential and utilization, but also in achieving a basic understanding of the environmental parameters necessary for formation of these deposits. The basic studies on calcareous deposits also could provide insights into the formation of reservoir rocks for petroleum.

The countries in the Indian Ocean region with limited resources perhaps initially could study chemogenous deposits in shallower areas of the continental margins, likely areas for the formation of phosphatic deposits (i.e., upwelling and non-depositional environment), as these would provide valuable clues in understanding both recent and ancient deposits. This could be followed later by the exploration of the deep-sea deposits, i.e. polymetallic nodules.

PRESENT INDIAN COLLABORATION PROGRAMMES

Indian scientific institutions already have collaborative programmes with Sri Lanka and Seychelles, and a programme is being discussed with Mauritius. As a part of the programme with Sri Lanka, NIO has organized a cruise in Sri Lankan waters, and some Sri Lankan scientists have been trained in marine techniques at Goa. At the request of the Government of Seychelles, the R/V GAVESHANI surveyed the Exclusive Economic zone (EEZ) of Seychelles and collected interesting information on the topography, sediments and the distribution of polymetallic nodules of this island state. As a part of this programme, parallel work was carried out in the nearshore areas; the resources of seaweeds were assessed, and the morphology of the coast and rate of siltation in the harbour were studied.

At the request of Government of Mauritius, NIO is designing a programme to survey the EEZ of Mauritius. This survey will be begun after approval by the two Governments.

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Table 1. Heavy mineral placers, resources and production in the countries bordering the Indian Ocean (in thousand tonnes unless otherwise specified).

Country Offshore	Mineral	Resources		Production		Status of Exploration
		Onshore	Offshore	Onshore	Offshore	
1	2	3	4	5	6	7
South Africa	Titanium sand	NA	NA	41.74 (1979)	NA	Offshore occurrences reported
	Tin	NA	NA	2.7 (1983)	NA	
	Ilmenite	+99770 (1981)	NA	46.26 (1978)	NA	
	Rutile	+ 5442 (1981)	NA	45.25 (1981)	NA	
	Zircon	10884 (1981)	NA	P63.49 (1985)	NA	
	Monazite	+ 10.88 (1980)	NA	NA	NA	
	Garnet	4988 (1980)	NA	P11.79 (1985)	NA	
Mozambique	Garnet	NA	NA	11.2 (1979)	NA	
	Ilmenite	11791 (1980)	50,000 (1980)	NA	NA	
	Rutile	1088 (1980)	900 (1980)	NA	NA	
	Zircon	NA	4,000 (1980)	NA	NA	
Tanzania	Garnet	4280 (1980)	NA	30 kg (1979)	NA	Onshore placers reported
	Zircon & Kyanite	2329 (1980)	NA	8 kg (1979)	NA	
	Ilmenite	3628 (1980)	NA	NA	NA	
	Rutile	408 (1980)	NA	NA	NA	
Kenya	Garnet	NA	NA	274 kg (1979)	NA	
Egypt	Ilmenite	9070 (1980)	NA	NA	NA	
India	Ilmenite	163620 (1981)*	12500 (1982)	189 (1981)	NA	Offshore exploration partly carried out to the western shelf and planned for other areas on the western and eastern shelf. The offshore reserves are likely to be many times more than presently estimated.
	Rutile	8170 (1981)	NA	87 (1981)	NA	
	Zircon	20640 (1982)	NA	12 (1981)	NA	
	Monazite	1075 (1981)	NA	4.2 (1983)	NA	
	Garnet	52940 (1981)	NA	5.4 (1982)	NA	
	Kyanite	172200 (1981)	NA	34 (1982)	NA	
	Sillimanite	11990 (1981)	NA	12 (1982)	NA	
Sri Lanka	Ilmenite	4000 (1982)	NA	45.0 (1983)	NA	
	Zircon	1361 (1980)	NA	6.0 (1983)	NA	
	Rutile	272 (1980)	NA	13.0 (1983)	NA	
	Garnet	NA	NA	P90.7 (1985)	NA	
Bangladesh	--	--	--	--	--	Onshore placers of monazite and zircon are reported

Table 1. (continued)

Country Offshore	Mineral	Resources		Production		Status of Exploration
		Onshore	Offshore	Onshore	Offshore	
1	2	3	4	5	6	7
Burma	Tin	907 (1980)	NA	4.2 (1982)	NA	Offshore dredging is being carried out from 1982.
Thailand	Tin (concentrated)	5560 (1980)	NA	4.2 (1982)	9.08(1982)	Offshore dredging for tin is being carried out but production has now fallen due to the depletion of the reserves in the easily exploited shallow areas.
	Ilmenite	NA	NA	0.78 (1979)	NA	
	Monazite	NA	NA	0.72 (1979)	NA	
	Zircon	NA	NA	2.0 (1983)	NA	
Malaysia	Tin (concentrated)	4700 (1980)	NA	41.3 (1983)	NA	Production of tin has declined compared to 1982 mainly because of the combined effects of ing reserves weak metal prices and reserves cut back on export. as world's largest alluvial tin deposit in any one location, the Kuala Langate tin field will be jointly dredged by the Selonger State Government and Malaysia Corp. If this project is successful it would help the country to maintain position as a leading producer even with depleting reserves.
	Ilmenite	7814 (1981)	NA	145.0 (1981)	NA	
	Monazite	NA	NA	2.0 (1979)	NA	
deplet- Described	Zircon	181 (1980)	NA	2.0 (1979)	NA	
Mining its						
Indonesia	Tin	2630 (1980)	NA	26.5 (1983)	12.7 (1979)	Offshore dredging is being carried out.
	Ilmenite	907 (1980)	NA	NA	NA	

Table 1. (continued)

Country Offshore	Mineral	Resources		Production		Status of Exploration
		Onshore	Offshore	Onshore	Offshore	
1	2	3	4	5	6	7
Australia	Tin	913 (1982-83)	NA	9.5 (1983)	NA	Offshore exploration has been completed in some areas.
	Ilmenite	42800 (1982)	NA	888 (1983)	NA	
	Rutile	9000 (1982)	NA	200 (1983)	NA	
	Zircon	13400 (1982)	NA	3832 (1983)	NA	
	Monazite	300 (1982)	NA	NA	NA	
	Garnet	5896 (1980)	NA	P18 (1985)	NA	
Madagascar	--	--	--	--	--	Onshore placers of ilmenite, monazite and zircon are reported.

P: Projected +: Reserve *: Inferred of Konkan, Maharashtra (SIDDIQUIE et al., 1982)

NA: Not available

From, INDIAN MINERALS YEAR BOOK (1977), (1979) and (1981)
U.S. BUREAU OF MINES (1979)

MINING JOURNAL, ANNUAL REVIEW (1982), (1983) and (1984)

MINERAL FACTS AND PROBLEMS, BUREAU OF MINES BULLETIN 671,
US DEPARTMENT OF INTERIOR, 1980.

Table 2. The range (in percent) of sand, silt, heavy minerals, magnetic and non-magnetic fractions and ilmenite in the offshore placers of Konkan Coast, Maharashtra, India.

Bay	Sand	Silt	Heavy Minerals	Magnetite	Non-Magnetic	Ilmenite
Jaigad	20-98	1-24	20-70	10-40	1-10	1.30
Ambwaha	20-98	1-20	5-40	1-71	3-15	3-30
Varvada	33-99	1-27	15-82	1.10	1-8	10-64
Kalbadevi	48-99	1-42	7-91	1-38	5-60	3-52
Mirya	12-99	1-37	5-72	3-48	1-51	1-35
Ratnagiri	8-99	2-69	1-78	1-59	1-50	1-22
Pawas	3-73	1-27	1-25	1-03	7-80	1-20
Purnagad	1-90	1-20	1-91	1-23	1-10	1-58
Vijaydurg	1-85	1-15	1-40	1-07	1-9	1-21

From SIDDIQUE et al. (1982)

Table 3. Phosphate, resources and production (in million tonnes) in the countries bordering the Indian Ocean.

Country	Resources	Production
South Africa	1000 (1982)	2.742 (1983)
Tanzania	NA	0.01 (1982)
Kenya (Guano)	NA	0.019 (1978)
Egypt	NA	0.65 (1982)
Iraq	NA	1.2 (1982)
Pakistan	NA	0.00065 per day plant capacity
India	Phosphorite 129.8 (1981)	0.38 (1982)
	Apatite 8.8 (1981)	0.016 (1981)
	Guano 0.12 (1981)	NA
	Phosphatic nodules 4.4 (1981)	NA
Sri Lanka	* 40 (1984)	NA
Thailand	NA	0.0045 (1979)
Indonesia	NA	0.001 (1979)
Australia	2000 (1980)	0.285 (1978)
Seychelles (Guano)	NA	0.005 (1979)
Christmas Islands	NA	1.095 (1983)

NA: Not available * Inferred
 From: U.S. BUREAU OF MINES (1980)
 MINING JOURNAL, ANNUAL REVIEW (1983), (1984)
 INDIAN MINERAL YEAR BOOK (1981)

Table 4. Chemical composition of polymetallic nodules from the Indian Ocean

Basin/Ridge	No. of locations	No. of analyses	Mn	Fe	Ni	Maximum		Ni+Cu+Co
						Cu	Co	
Central Indian Ocean	48	84	19.33	12.75	0.71	0.55	0.12	1.26
Wharton Basin	81	105	17.99	11.73	0.49	0.33	0.20	1.03
South Australian Basin	13	25	19.00	13.40	0.68	0.34	0.17	1.19
Crozet Basin	31	68	13.49	15.93	0.33	0.15	0.20	0.68
Madagascar Basin	28	64	14.55	19.60	0.28	0.14	0.34	0.68
Mozambique Basin	46	101	11.82	16.05	0.41	0.12	0.21	0.73
Seychelles/Somali Basin	37	323	18.12	16.61	0.36	0.12	0.40	0.85
Carlsberg Ridge	28	73	12.67	17.50	0.25	0.11	0.20	0.58
Average Indian Ocean	299	818	15.42	15.75	0.40	0.16	0.30	0.88

Basin/Ridge	No. of locations	No. of analyses	Mn	Fe	Ni	Minimum		Ni+Cu+Co
						Cu	Co	
Central Indian Ocean	48	84	1.80	4.50	0.50	0.06	0.04	0.15
Wharton Basin	81	105	3.47	3.80	0.06	0.04	0.03	0.13
South Australian Basin	13	25	2.43	5.35	0.03	0.01	0.03	0.07
Crozet Basin	31	68	5.00	8.00	0.10	0.09	0.08	0.18
Madagascar Basin	28	64	8.50	9.70	0.06	0.06	0.08	0.20
Mozambique Basin	46	101	0.79	4.25	0.01	0.05	0.01	0.70
Seychelles/Somali Basin	37	323	3.72	1.33	0.09	0.02	0.03	0.14
Carlsberg Ridge	28	73	1.50	9.60	0.02	0.02	0.03	0.07
Average Indian Ocean	299	818	0.79	1.33	0.01	0.01	0.01	0.07

From: UNOET/SIO Data Bank

Table 4. Chemical composition of polymetallic nodules from the Indian Ocean (continued)

Basin/Ridge	No. of locations	No. of analyses	Mn	Fe	Ni	Average		Ni+Cu+Co
						Cu	Co	
Central Indian Ocean	48	84	32.25	24.90	1.57	1.64	0.39	3.60
Wharton Basin	81	105	26.26	18.76	1.10	1.01	0.68	2.79
South Australian Basin	13	25	27.60	19.20	0.95	0.63	0.31	1.89
Crozet Basin	31	68	18.60	23.30	0.74	0.31	0.45	1.50
Madagascar Basin	28	64	19.50	26.45	0.75	0.29	0.69	1.63
Mozambique Basin	46	101	23.80	42.50	1.20	0.32	0.61	2.13
Seychelles/Somali Basin	37	323	32.30	24.13	0.79	0.48	1.04	2.31
Carlsberg Ridge	28	73	24.30	22.70	0.81	0.30	0.41	1.52
Average Indian Ocean	299	818	32.30	42.50	1.57	1.64	1.04	3.60

From: UNOET/SIO Data Bank

FIGURE - 1

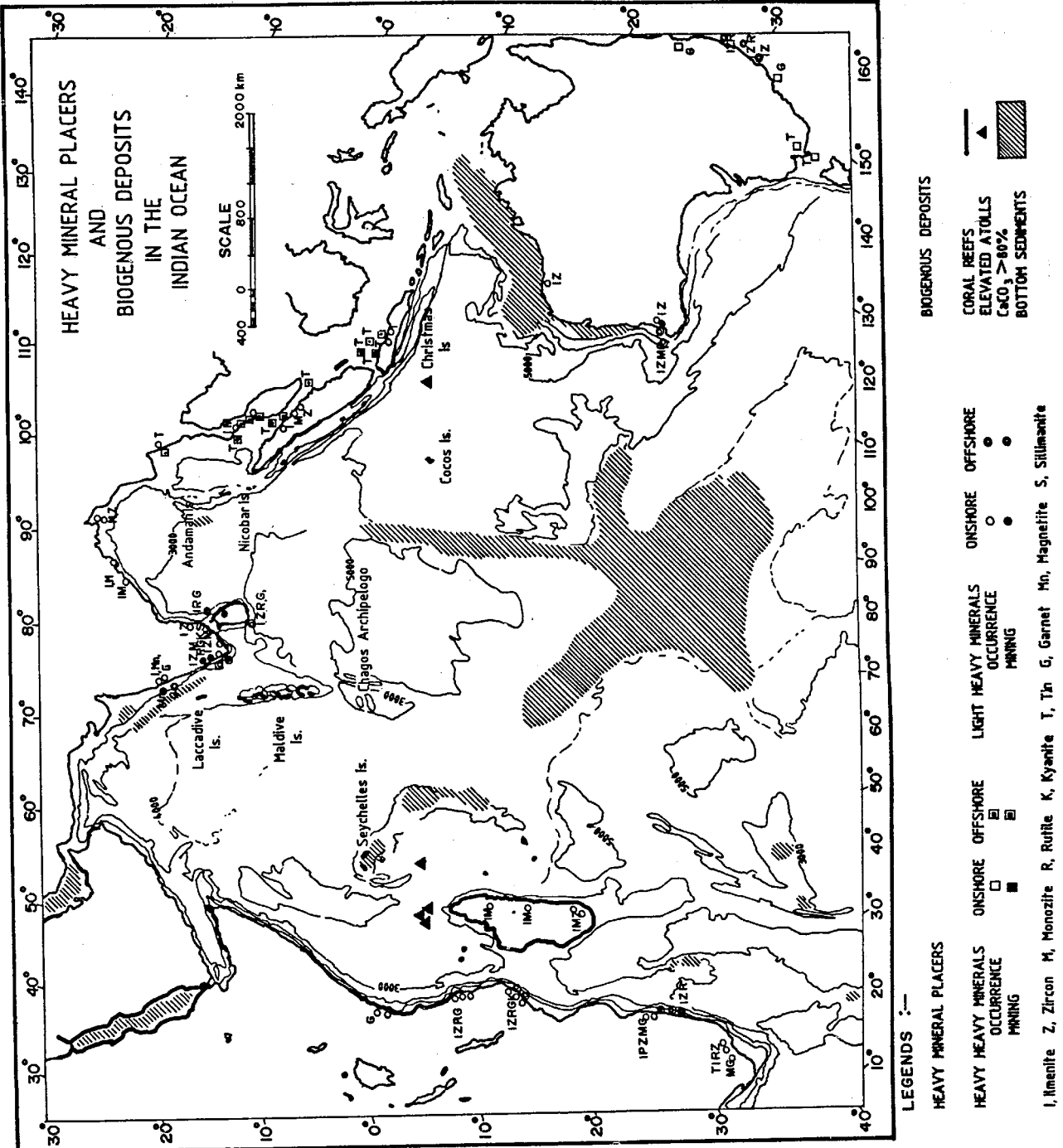


Figure 1. Heavy mineral placers and biogenous deposits in the Indian Ocean.

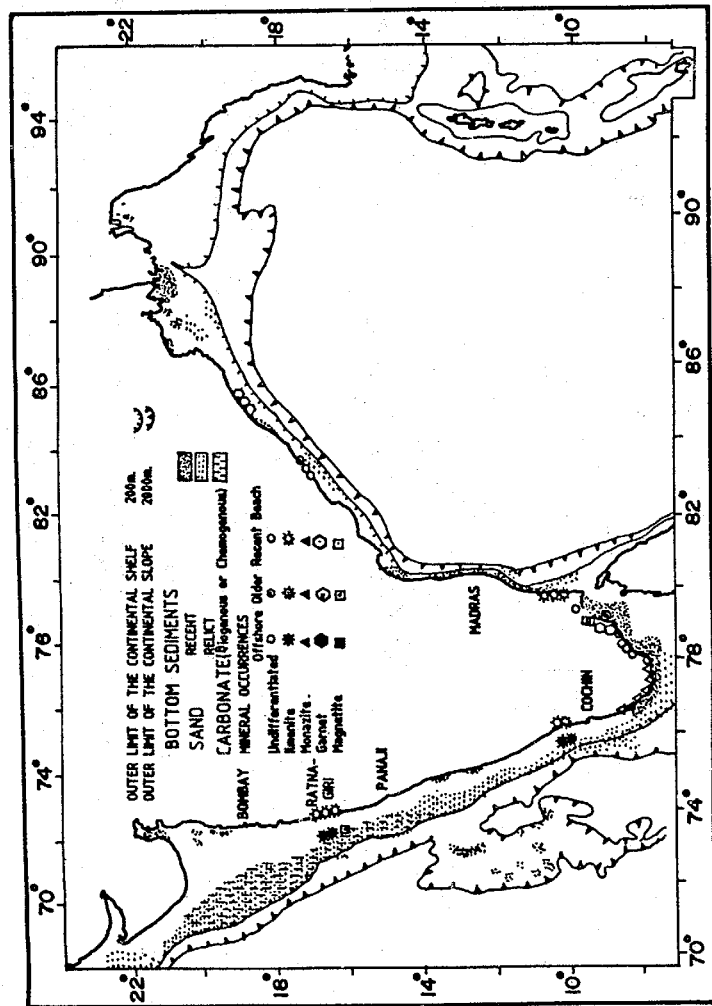


Figure 2. Map showing the terrigenous mineral occurrences on the continental margins of India.

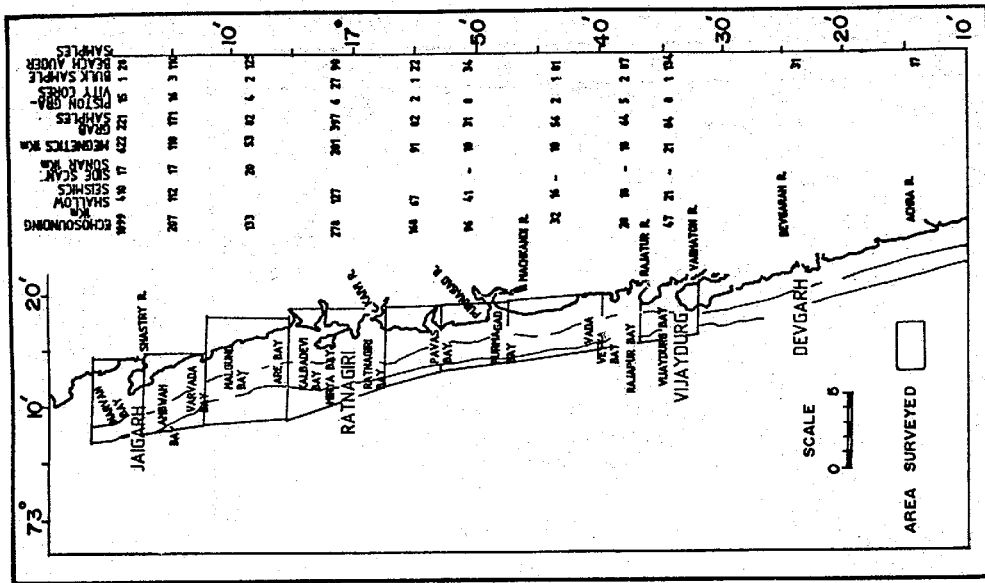


Figure 3. Map showing status of exploration for heavy mineral placers off the Konkan coast, Maharashtra, India (from Siddiquie et al., 1982).

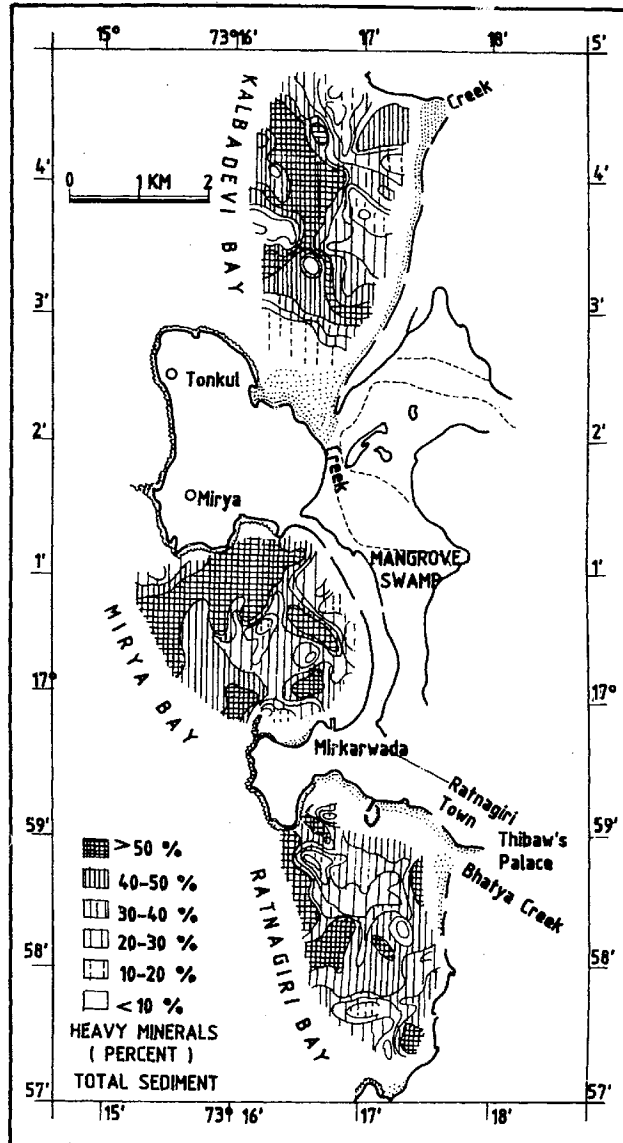


Figure 4. Map showing the distribution of heavy minerals in sediments of Kalbadevi, Mirya and Ratnagiri bays, Konkan coast, Maharashtra, India (from Siddiquie *et al.*, 1979).

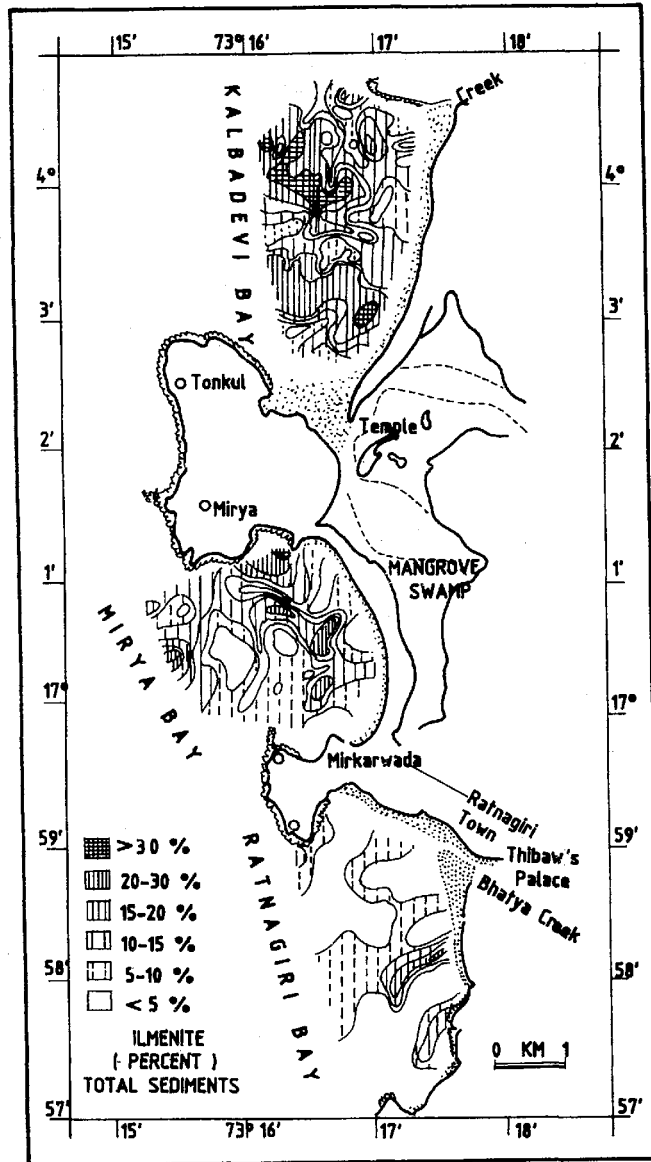


Figure 5. Map showing the distribution of ilmenite in sediments of Kalbadevi, Mirya and Ratnagiri bays, Konkan coast, Maharashtra, India (from Siddiquie *et al.*, 1979).

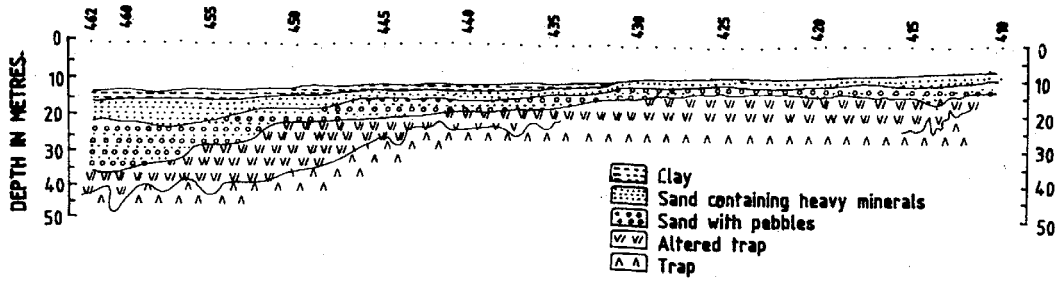


Figure 6. Interpreted seismic profile across the ilmenite placers off Jaigad, Konkan coast, Maharashtra, India.

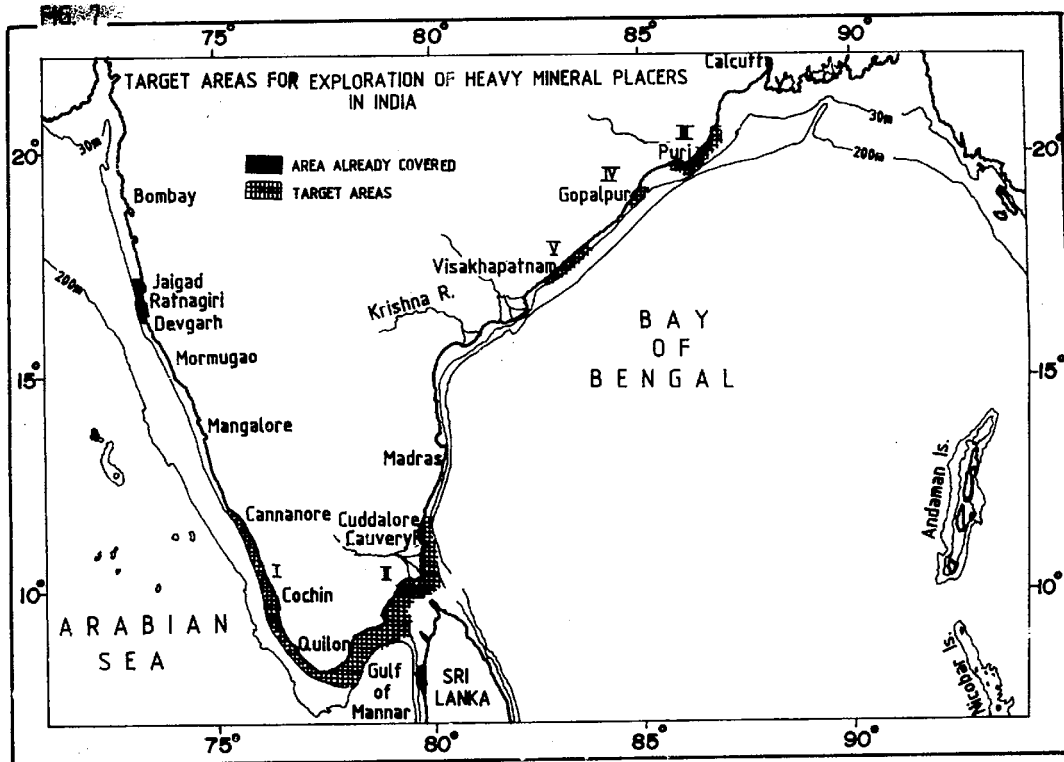


Figure 7. Target areas for exploration of heavy mineral placers in India.

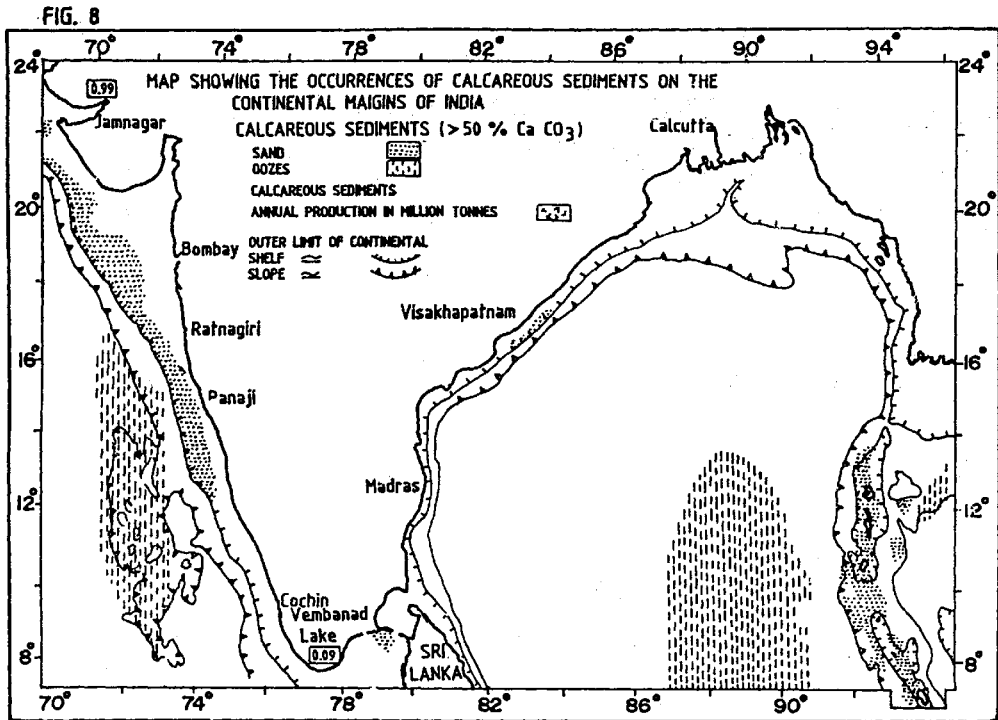


Figure 8. Map showing the occurrences of calcareous sediments on the continental margins of India.

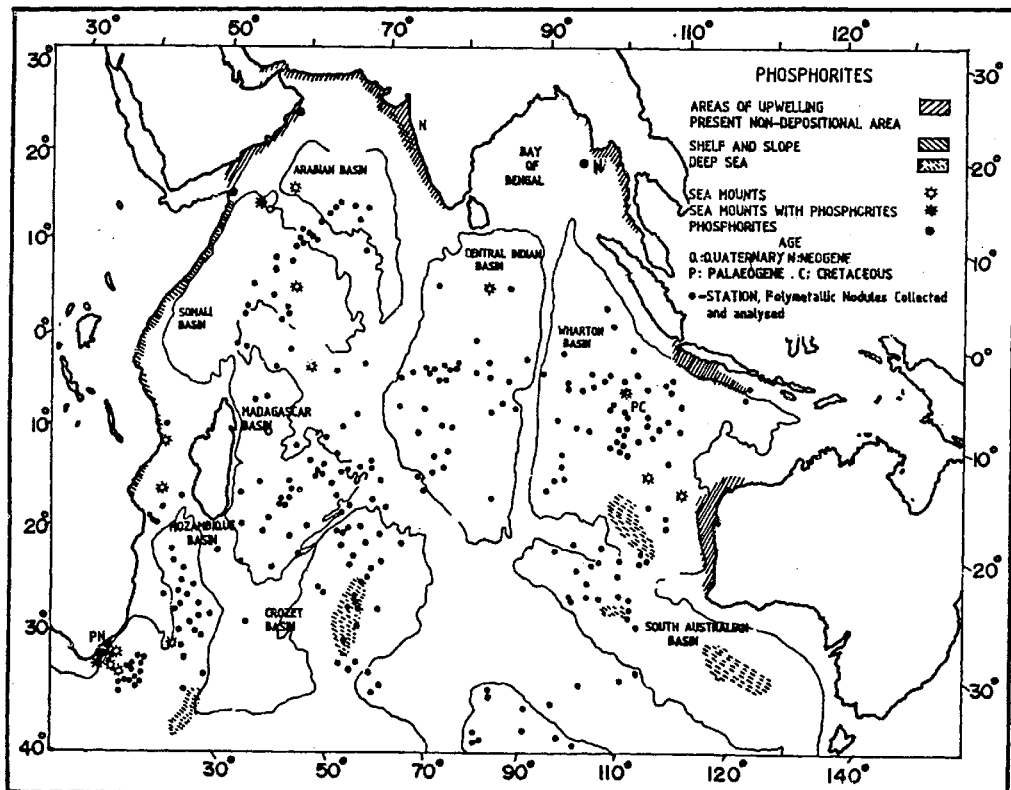


Figure 9. Map showing the phosphorites deposits and locations for polymetallic nodule samples in the Indian Ocean.

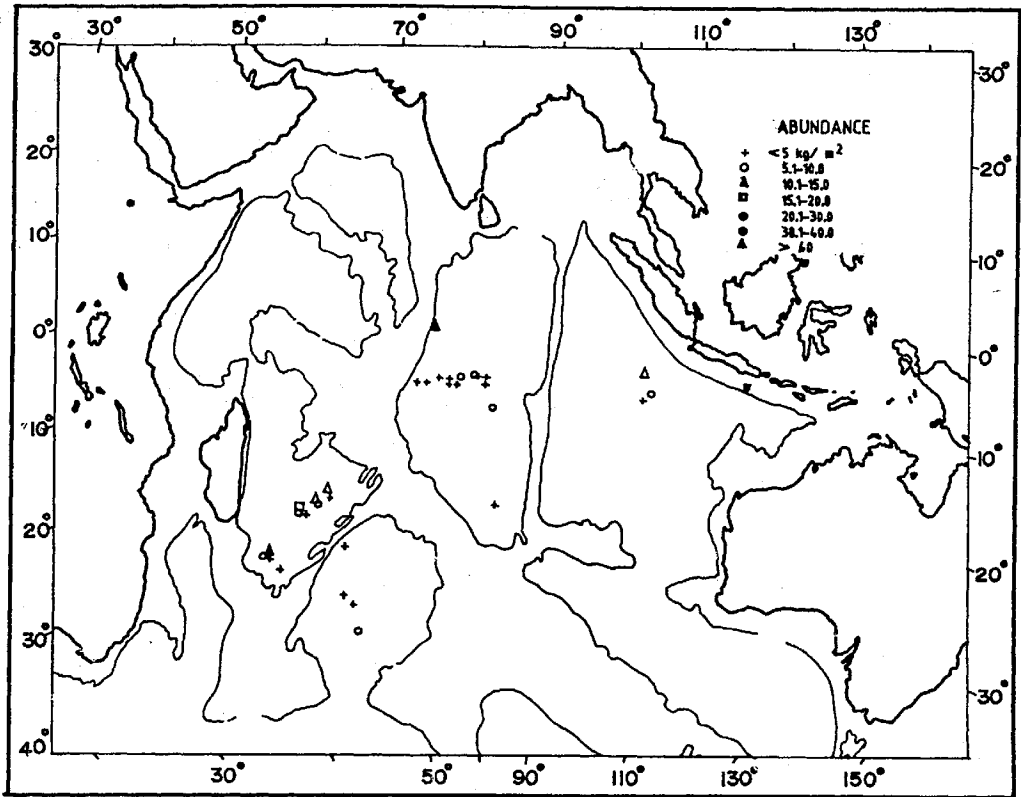
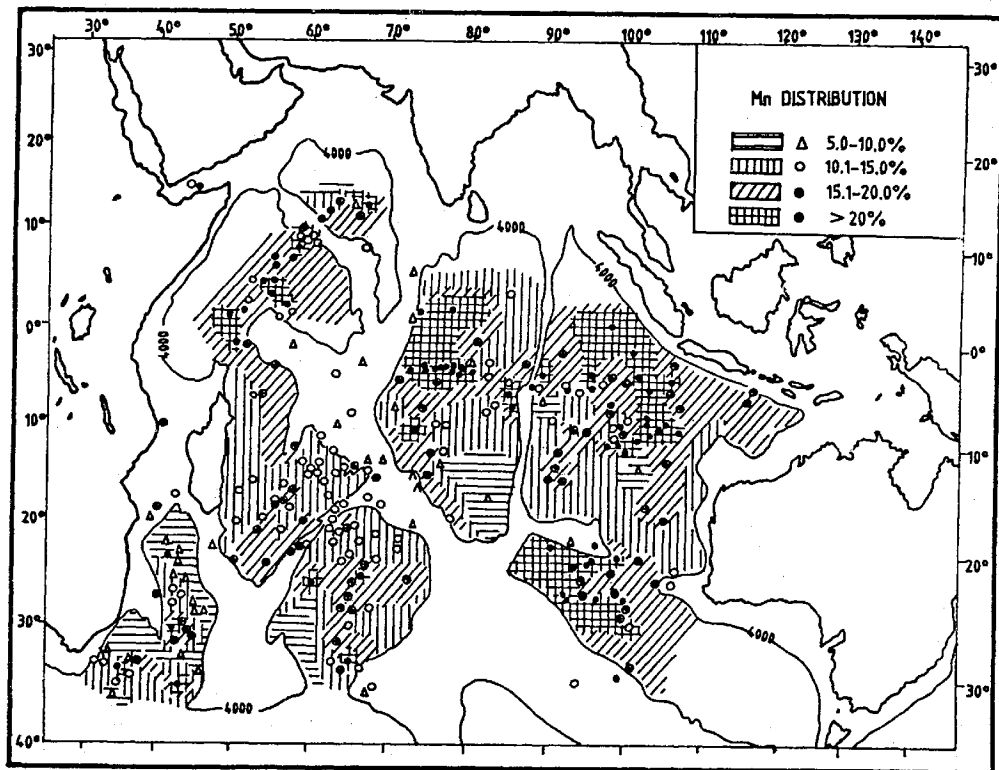


Figure 10. Map showing the abundance of polymetallic nodules.



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Figure 11. Map showing the distribution of Manganese.

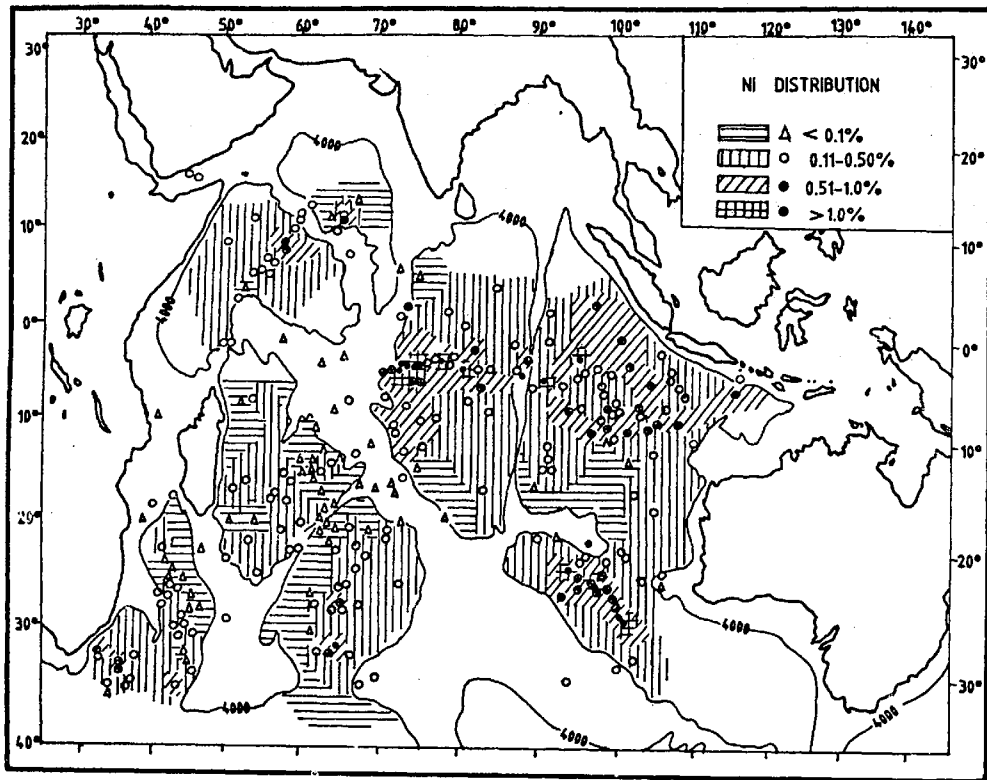


Figure 12. Map showing the distribution of nickel.

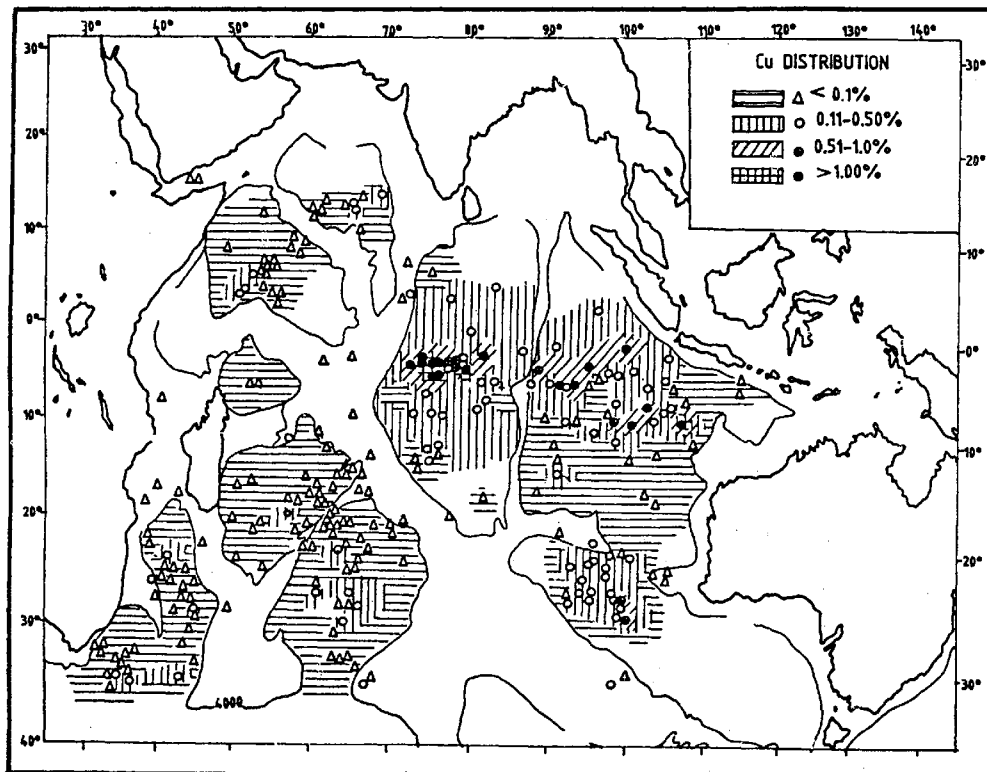


Figure 13. Map showing the distribution of copper. 148

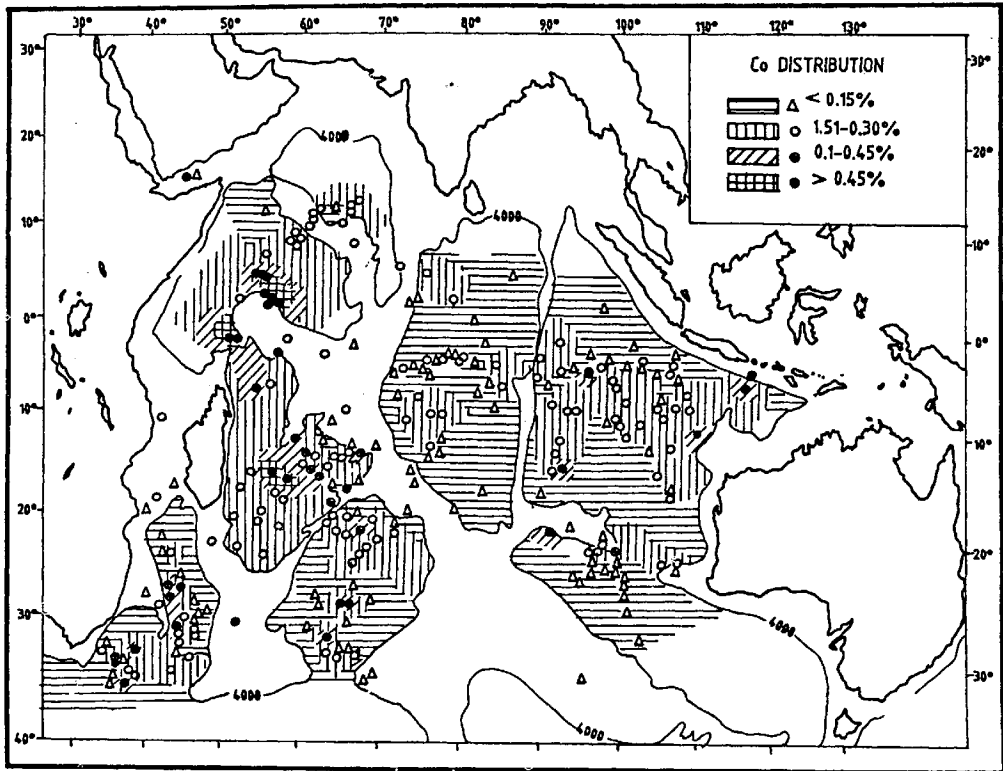


Figure 14. Map showing the distribution of cobalt.

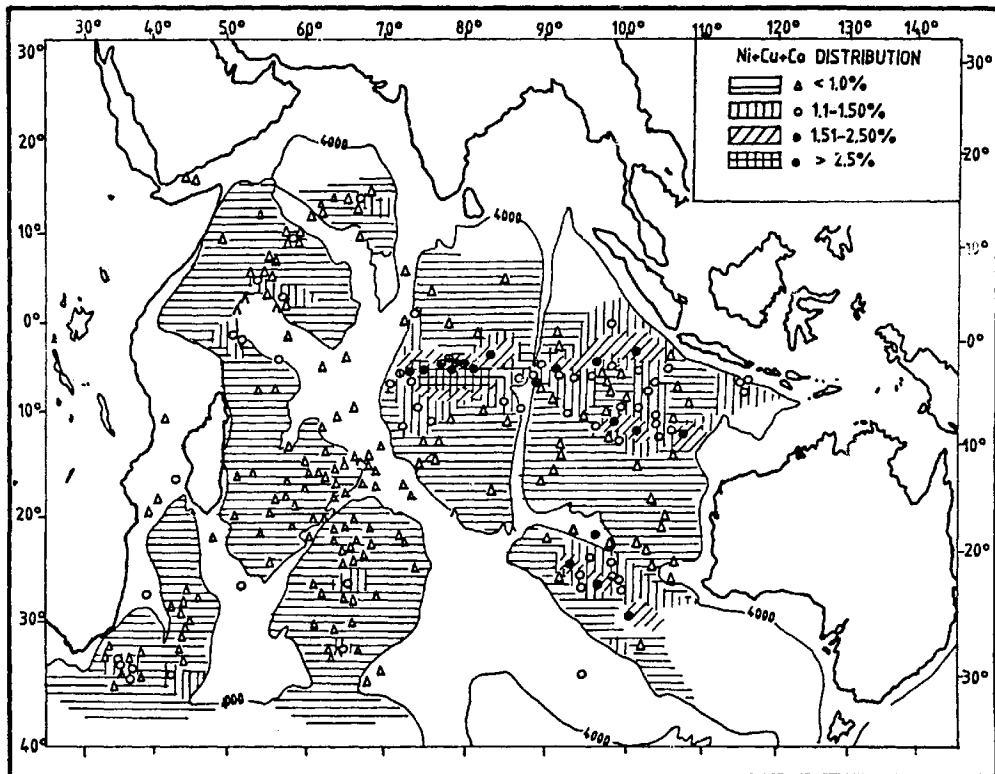


Figure 15. Map showing the distribution of nickel + copper + cobalt.

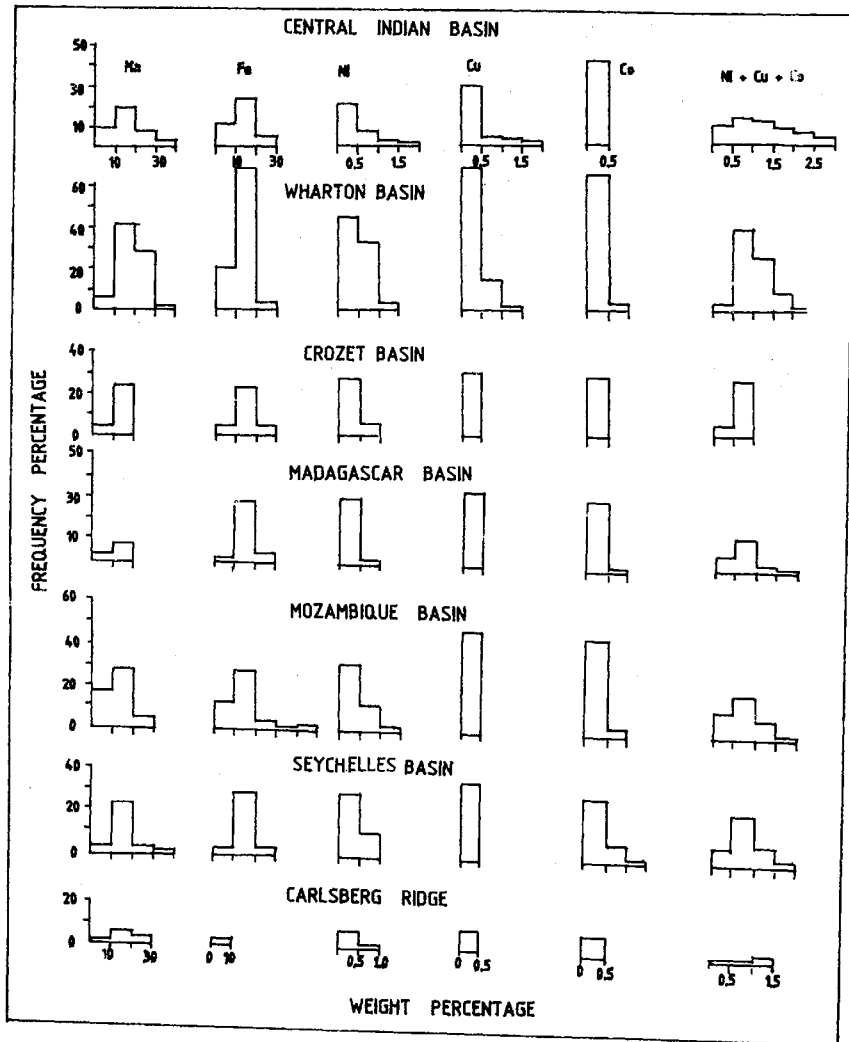


Figure 16. Frequency of manganese, nickel, copper, cobalt and grade (Ni+Cu+Co)

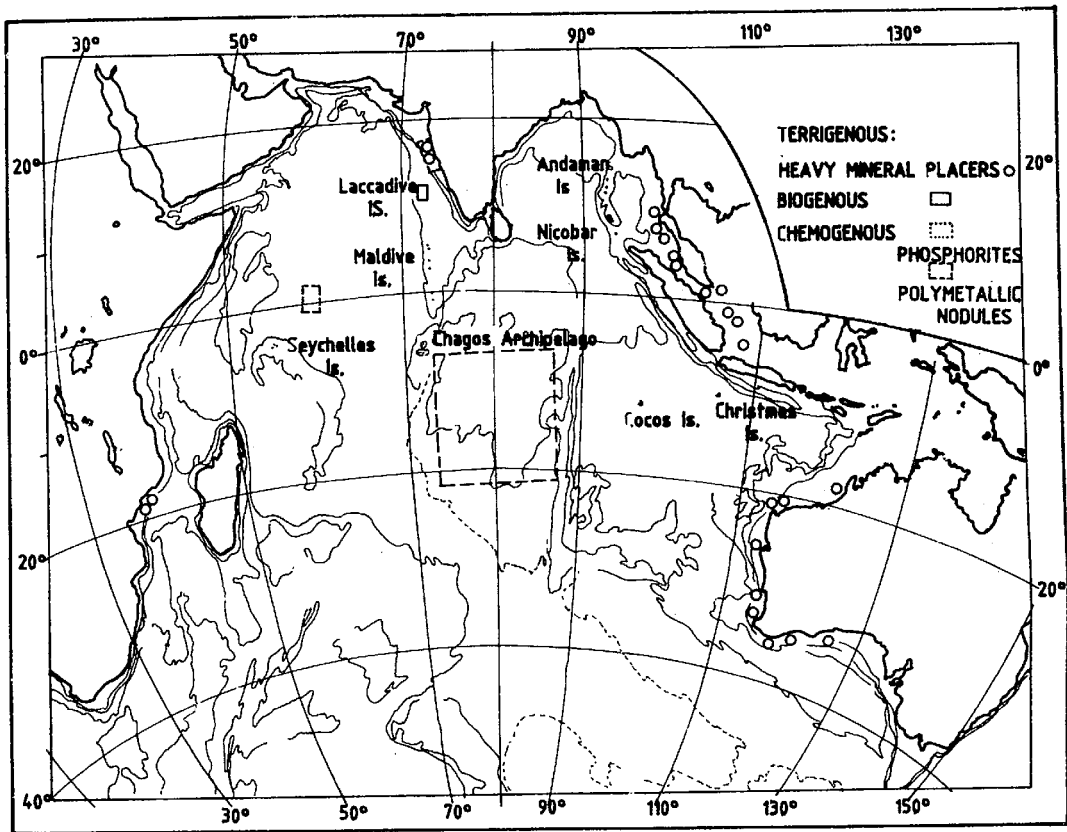


Figure 17. Marine mineral exploration/recent activities.