

## SUPERFICIAL MINERAL RESOURCES OF THE INDIAN OCEAN

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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 anthigenic 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 favour the formation of a variety of placer deposits. The beach and offshore placer deposits of the Indian Ocean may be some of the largest in the world.

The biogenous deposits in the Indian Ocean comprise the corals on shallow banks and on the continental shelves and the oozes in the deep sea. A study of these deposits is needed to acquire a better understanding of their formation, turnover, regeneration rates and sustainable yields.

The anthigenic deposits in the Indian Ocean comprise the phosphorites and the polymetallic nodules. Occurrences of phosphorite deposits have been found both 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.

The polymetallic nodules in the Indian Ocean cover an area of 10-15  $\cdot 10^6$  km<sup>2</sup> and the resources are estimated to be about 1.5  $\cdot 10^{11}$  tonnes. A study of over 900 chemical analyses from 350 stations shows that the deposits in most of the basins are submarginal; in the Central Indian Ocean they are paramarginal (Ni + Cu + Co >2.47% and concentrations >5kg.m<sup>-2</sup>).

Most of the exploration for minerals even on the continental margins of the Indian Ocean has been carried out by the developed countries from outside the region and little work has been carried out by the countries bordering the Indian Ocean. The development of capabilities within the region for exploration of the mineral resources should receive a high priority. The exploration of the mineral resources of the Indian Ocean would not only add to an inventory of the resources in the world oceans but also lead to a greater understanding of the formation of marine mineral deposits.

## INTRODUCTION

The Indian Ocean (area: 74.917 x 10<sup>6</sup> km<sup>2</sup>, volume: 291.945 x 10<sup>6</sup> km<sup>3</sup>, average depth: 3897m) is the third largest of the world oceans. The land areas bordering the ocean are inhabited by almost 40% of the world's population and contain substantial reserves of important minerals (e.g. oil, tin, iron and manganese ores, mica and chromite).

Until the 1960s, the Indian Ocean was the least studied of the world oceans but the International Indian Ocean Expedition considerably enhanced our knowledge of the ocean, and its mineral resources. The expedition provided an impetus to the development of oceanographic studies in the Indian Ocean coastal states and led to the creation of research institutions

and a cadre of trained scientists. Even so, the work on marine geosciences and marine mineral resources has been largely carried out by developed countries from outside the region.

The present paper reviews the superficial terrigenous, biogenous and authigenic mineral resources of the Indian Ocean, but excludes those in bed rock (oil, gas and sulphur etc.) and the metalliferous brine deposits in the Red Sea. It covers the Indian Ocean area as defined by Fairbridge (1966), which extends from the east of the African continent to the west of the Australian continent and is bounded to the north by the Indian Sub-Continent and Arabian peninsula and to the south by Antarctica.

#### TERRIGENOUS MINERALS

Heavy mineral placers are known from the beaches of many countries bordering the Indian Ocean (Fig.1), which contain ilmenite, rutile, zircon, magnetite, monazite, garnet, kyanite and tin in significant proportions. Many of these placers are already exploited and contribute

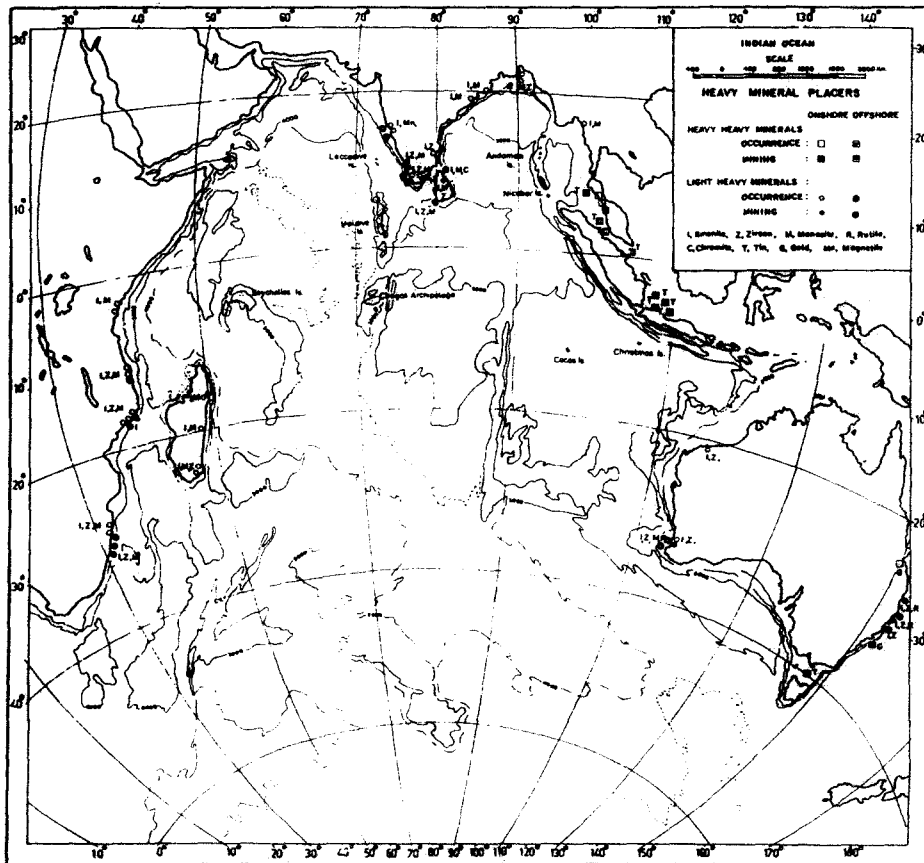


Fig.1. Map showing the heavy mineral placers in the Indian Ocean.

significantly to the world production (Table 1). The offshore extensions of some of these placer deposits have been explored, but only offshore tin placers are being exploited. The beaches of the Indian Ocean contain more numerous and more varied deposits of heavy mineral placers than other oceans. Their formation is related to the source rocks, weathering, transport and concentration. The high rainfall and humid climate in many of the countries bordering the Indian Ocean is conducive to the weathering of rocks, and the transportation of the minerals released from the rocks within the large volumes of sediment carried down to the sea by the rivers (Fig.2). The heavy minerals are further concentrated by wave action on the beaches (Fig.3).

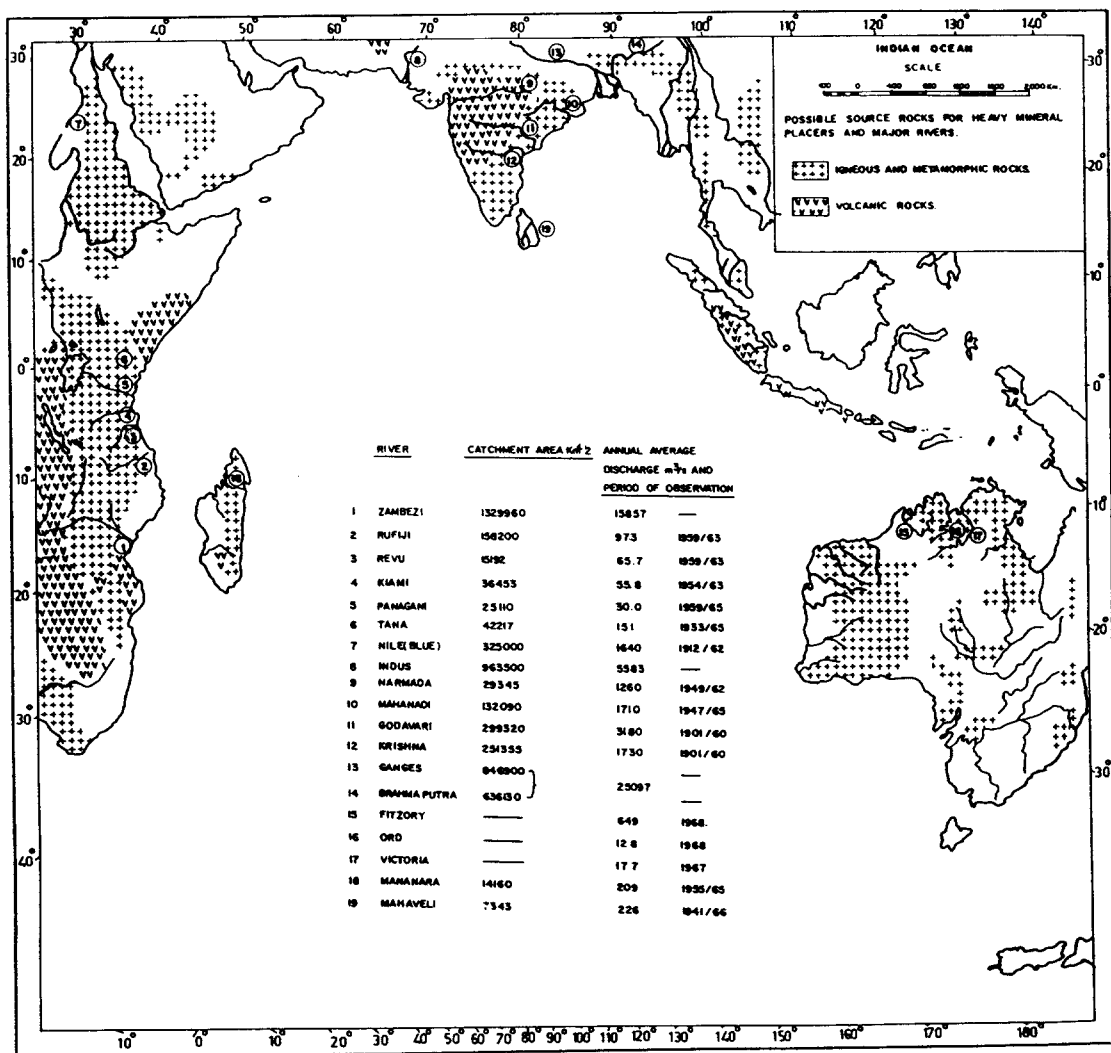


Fig.2. Map showing the possible source rocks for heavy mineral placers and major rivers.

TABLE 1: Heavy mineral placers, resources and production in the countries bordering the Indian Ocean  
(in thousand tons unless otherwise specified)

Country	Mineral	Resources		Production		Status of Offshore 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	3.03P(1982)	NA	
Tanzania	Garnet	NA	NA	30 kg (1979)	NA	Onshore placers reported
	Zircon	NA	NA	8 kg (1979)	NA	
Mozambique	Garnet	NA	NA	11.2 (1979)	NA	
	Ilmenite	NA	50,000 (1980)	NA	NA	
	Rutile	NA	900 (1980)	NA	NA	
	Zircon	NA	4,000 (1980)	NA	NA	
Kenya	Garnet	NA	NA	274kg (1979)	NA	
India	Ilmenite	138000(1977)	NA	165 (1979)	NA	Offshore exploration partly carried out on the western shelf and planned for other areas on the western and eastern shelf.
	Rutile	7000(1977)	NA	12 (1979)	NA	
	Zircon	2200(1979)	NA	10 (1979)	NA	
	Monazite	408(1975)	NA	2.8 (1979)	NA	
	Garnet	9(1979)	NA	6.0 (1979)	NA	
Sri Lanka	Ilmenite	4000(1982)	NA	13.0 (1982)	NA	Offshore exploration partly carried out on the eastern shelf, other areas need to be explored.
	Zircon	NA	NA	1.3 (1982)	NA	
	Rutile	NA	NA	12.0 (1979)	NA	
Bangladesh	-	-	-	-	-	Onshore placers of monazite and zircon are reported.
Burma	Tin	NA	NA	4.2 (1982)	NA	Offshore dredging is being carried out from 1982.
Thailand	Tin	NA	NA	26.1 (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	0.82 (1979)	NA	

TABLE 1: continued

1	2	3	4	5	6	7
Malaysia	Tin	NA	NA	52.3 (1982)	NA	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	187.0 (1979)	NA	
	Monazite	NA	NA	2.0 (1979)	NA	
	Zircon	NA	NA	0.9 (1979)	NA	
Indonesia	Tin	1614	(1977)	33.8 (1982)	12.7 (1979)	Offshore dredging is being carried out.
Australia	Tin	42800	NA	12.3	NA	Offshore exploration has been completed in some areas.
	Ilmenite	4000	NA	21.4 (1979)	NA	
	Rutile	13400	NA	218.0 (1982)	NA	
	Zircon	300	NA	443.0 (1982)	NA	
	Monazite	300	NA	NA	NA	
Madagascar	-	-	-	-	-	Onshore placers of ilmenite, monazite and zircon are reported.

P: Preliminary

NA: Not available

From: Indian Minerals Year Book (1977) and (1979)

US Bureau of Mines (1979)

Mining Journal, Annual Review (1982)

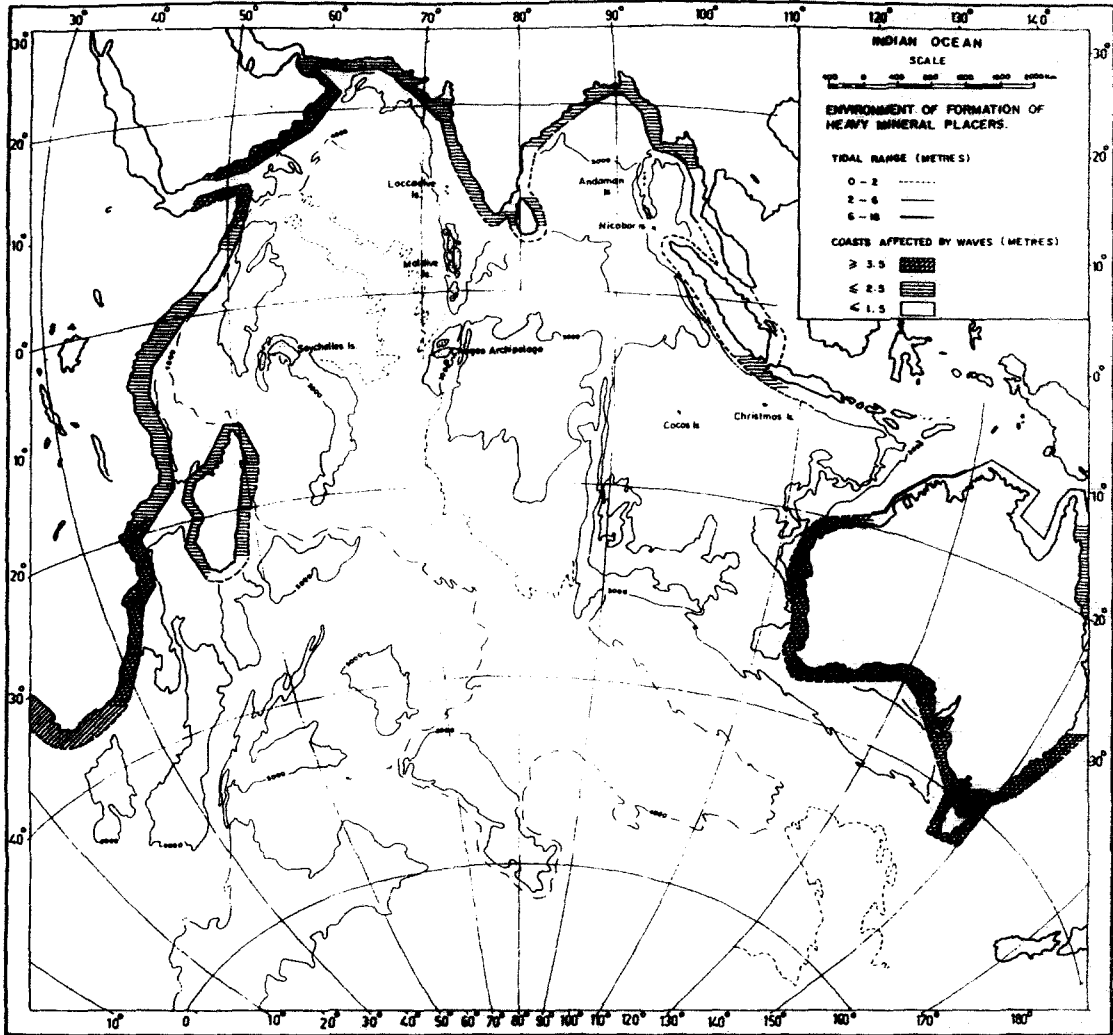


Fig.3. Map showing the environments of formation of heavy mineral placers.  
(From US Navy Marine Climatic Atlas of the World, 1973)

Known onshore deposits of placers provide clues as to where offshore deposits may be found in submerged valleys and beaches. Few of the potential offshore extensions of the numerous placer deposits known from the beaches of the Indian Ocean have been explored. The known deposits are reviewed below:

#### A. Mozambique

Onshore placer deposits occur at Pebane, Vila Luiza and Micaune which contain ilmenite with zircon and rutile and minor amounts of monazite. Detailed surveys on the shelf off northern Mozambique were undertaken in 1971 and 1973 from R.V. 'VALDIVIA' (Beiersdorf, Kudrass and Stackelberg 1980), to locate marine placer deposits and to study their formation (Fig.4). The surveys were carried out with satellite navigation, doppler sonar and radar and comprised dual frequency echosounding (12 and 110 kHz), side scan sonar, IBAK Underwater camera, seismics (5000cm<sup>3</sup> air gun), and magnetics and seabed sampling with grabs, spade and vibro-coreers. Over a thousand surface and core samples were analysed for their grain-size and composition which led to the evaluation of their economic potential and their depositional history.

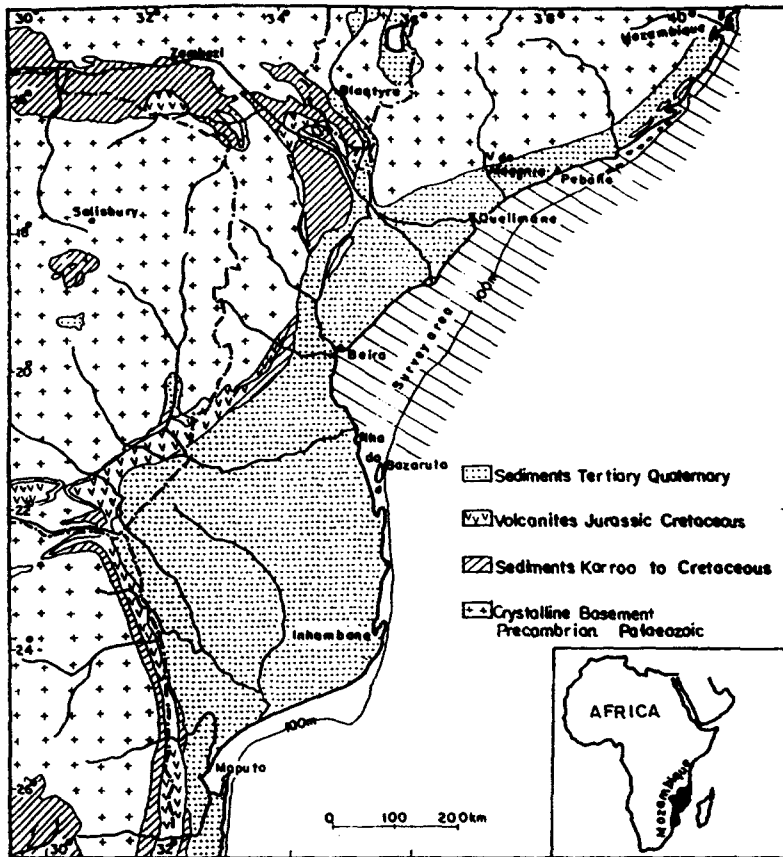


Fig. 4. Geological map of Mozambique and adjacent countries, location of survey area investigated by the German research vessel 'VALDIVIA' in 1971 and 1973. (From Beiersdorf *et al.* 1980).

Acoustically soft sediments were found nearshore and acoustically hard sediments on the central shelf, only the latter contained concentrations of heavy minerals. In the nearshore sediments, quartz and feldspar were the predominant terrigenous light minerals. In the surface sediments and cores (Fig.5), the heavy mineral content averaged 3.58%. The opaque heavy minerals were comprised of ilmenite, leucoxene, magnetite, titanomagnetite and spinel and the transparent heavy minerals of amphibole, pyroxene, epidote, garnet, zircon, tourmaline, titanite and rutile. The ilmenite contained 49.5%  $TiO_2$ , 33.1% FeO and 0.18%  $Cr_2O_3$ ; the zircon 63.05%  $ZrO_2$  and 0.71%  $TiO_2$ ; and the rutile contained 87.7%  $TiO_2$ .

The shelf break in the area occurs at depths of 50-120m. Three prominent reflectors A, B and C occurred throughout the shelf (Fig.6); A at 10-30m, B at 20-65m and C at 100-200m below the bottom, because sea level often coincides with multiples and they were not traceable over long distances.

Off the Zambesi delta, the deposits lying at depths of 30-60m were estimated to contain  $50.10^6$  tonnes of ilmenite,  $0.9.10^6$  tonnes of rutile and  $4.10^6$  tonnes of zircon. During the Pleistocene much of the present shelf was dry and numerous beach placers were formed in the proto-Zambesi delta. However, during the early Holocene transgression which occurred between 10,000 and 7,500 B.P., these placers were intensively reworked resulting in homogenisation of light and heavy minerals and the present disseminated character of the placer deposits.

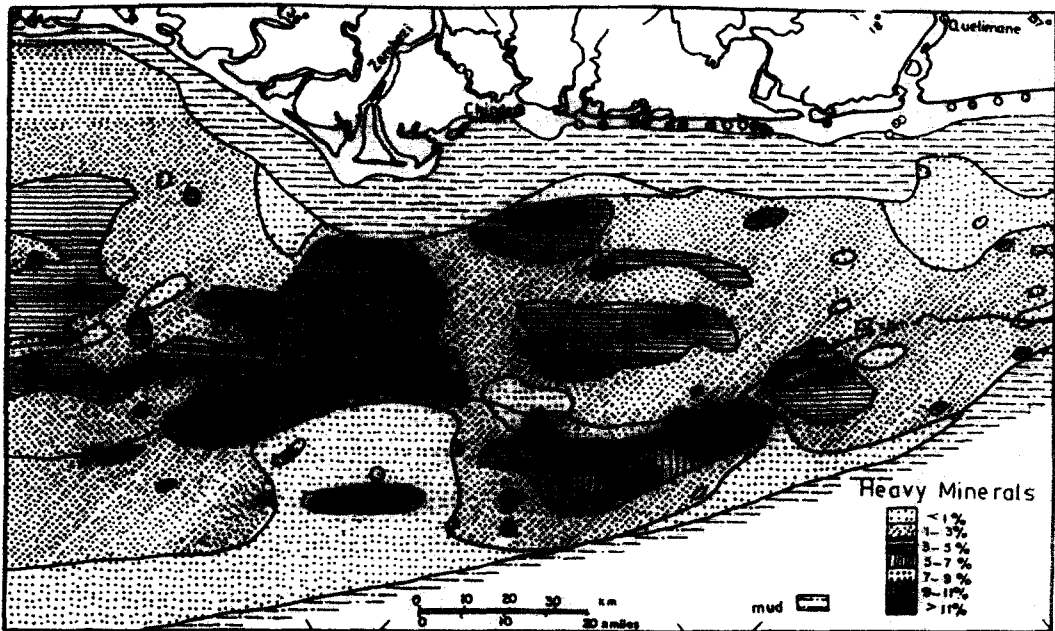


Fig.5. Distribution of the heavy minerals in the fraction 63-315 micron of the sandy surface sediments of the main survey area (from Beiersdorf et al, 1980).

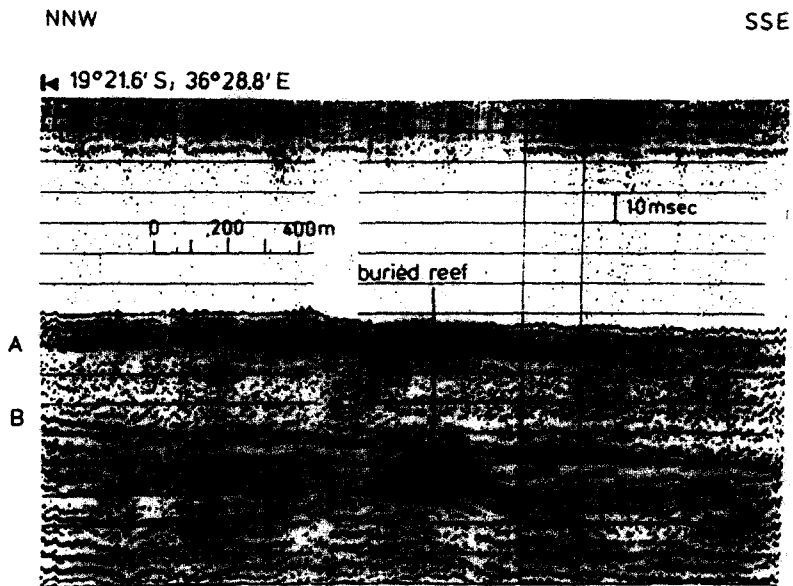


Fig.6

Fig.6. Reflection seismic profile from the shelf ca. 70km south of the Zambezi Delta showing position of seismic reflectors A and B. Below reflector B a structure can be seen which is interpreted as a buried reef. (From Beiersdorf et al, 1980).



B. Tanzania

Placers containing garnet, ilmenite, kyanite, zircon, magnetite and monazite were reported by Duyverman (1981) from the coast of Tanzania. The heavy minerals concentrations ranged up to 23%, but decreased northwards except at Ndega Beach which lies in a protected bay. The mineral content is fairly constant; 33.8% ilmenite, 39.2% garnet, 27% kyanite and zircon, and 3.8% rutile. The heavy minerals are restricted to the Mtoni Terrace which consists of lagoons, swamps, raised coral reefs, and beach ridges of Pleistocene to Recent origin. There are no data on either the size of the reserves or their offshore extension.

C. India

Placers are known from a number of localities along the Indian Coast, but are best known along the Kerala coast (Tipper, 1914; Brown and Dey 1955). Onshore they consist of high grade beach and low grade dune sands (Fig.7). Heavy mineral sands occur in an area extending

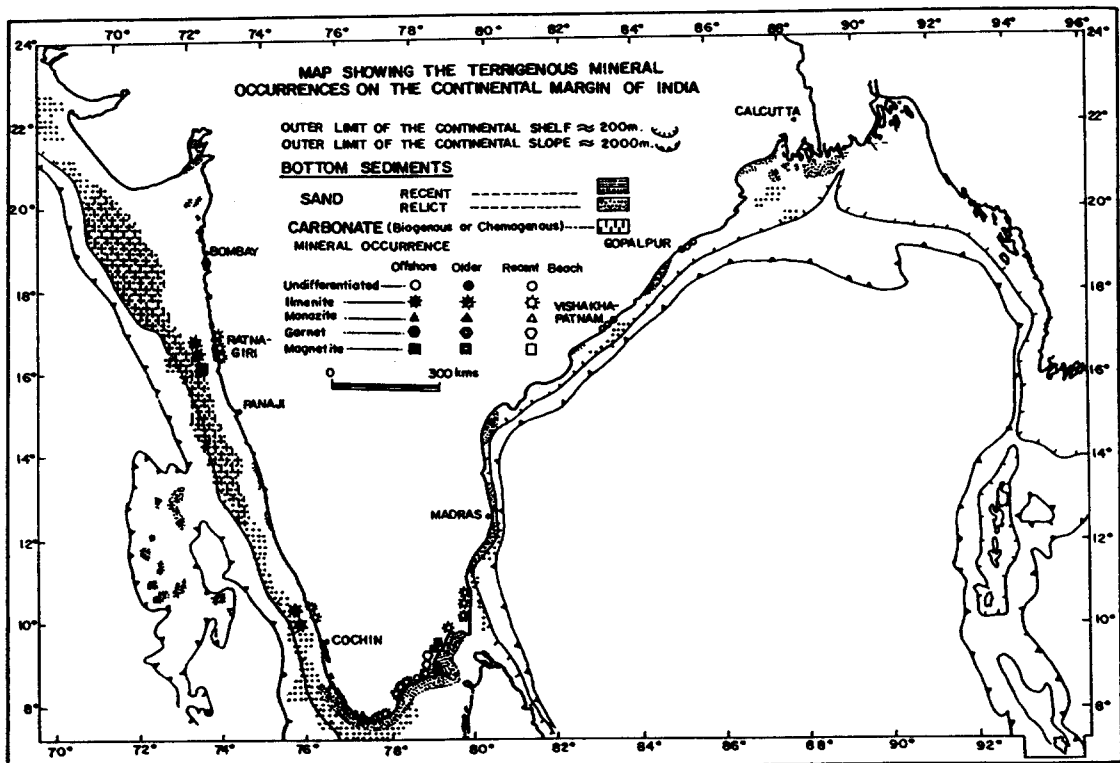


Fig.7. Map showing the terrigenous mineral occurrences on the continental margins of India. (Modified from Siddiquie et al, 1979).

from Quilon to Cape Comorin, and is estimated to contain  $17.10^6$  tonnes of ilmenite,  $1.10^6$  tonnes of rutile,  $1.2.10^6$  tonnes of zircon and  $0.2.10^6$  tonnes of monazite. Similar beach deposits with varying proportions of ilmenite, zircon, magnetite, and garnet have been described from Ratanagiri, Maharashtra (Krishnan and Roy 1945; Roy, 1958); Tinnavelli, Ramand and Tanjore, Tamil Nadu (Jacob 1956); Visakhapatnam, Yada, Waltair and Bhimunipatnam, Andhra (Mahadevan and Rao, 1958) and the coastal areas of Orissa (Officers of the GSI, 1949). The total reserves of ilmenite are estimated to be  $138.10^6$  tonnes; in 1979 the production was  $1.65.10^5$  tonnes (Anon, 1979).

Offshore some of the richest deposits reported so far in India occur along the 25km stretch of the coast from Neendakara to Kayankulam in Kerala. Prabhakar Rao (1968), explored the shallow offshore areas of this stretch to a depth of 10-12m. About 48 holes were drilled by a water jet from 1-6m into the seabed, and showed sand occurred in the southern part, silty sand in the central part, and a mixture of sand, silt and clay in the north. The heavy minerals (4-56%) consisted of kyanite, sillimanite, zircon, garnet, ilmenite, leucosene and rutile (Fig.8a). The highest concentrations of minerals were associated with the medium sand which occurred along the shore and in the southern part. The concentration of ilmenite ranged from 0.8-20% (Fig.8b). During the wet season period, the rivers discharge vast volumes of sediments derived from inland rocks into the sea which are then transported by long-shore currents. The sorting action of currents and waves concentrate the minerals.

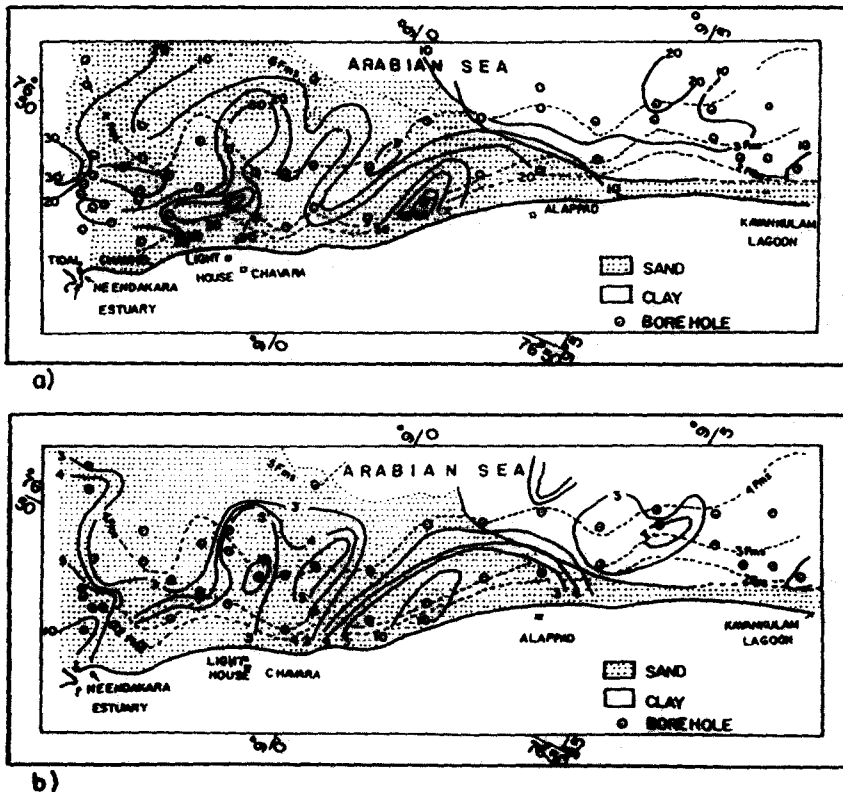


Fig. 8a Map showing the percentage distribution of heavy minerals in the sediments of Neendakara-Kayankulam region, India (Data reported from Prabhakar Rao, 1968).

8b Map showing the percentage distribution of ilmenite in the sediments of Neendakara-Kayankulam region, India (Data reported from Prabhakar Rao, 1968).

Along the Konkan Coast the placers containing 17-74% ilmenite form an estimated reserve of  $4.10^6$  tonnes (Mane and Gawade, 1954). The numerous small rivers discharging along this coast drain the plateau and hills covered by the Deccan Traps in the east. The tidal range is about 1-2m, and the annual rainfall is 2500-3000mm. The period of maximum precipitation and sediment discharge coincides with maximum turbulence and wave activity in the sea. Off the Konkan coast, the wave period is usually 5-14 seconds and the predominant wave directions are SW, WSW, W, and WNW (Reddy, 1976), yet the sediment movement is northwards. The wave refraction patterns result in the convergence and divergence of littoral currents in several bays and it is into these that the sediment transport is usually directed. In 1975 the National Institute of Oceanography began to survey the region in order to (i) delineate the offshore extension of the onshore placers, (ii) understand the geology, structure, recent sedimentation and tectonic history of the area, (iii) understand 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 130km stretch along the Konkan Coast (Fig.9) was surveyed in detail during the years 1975-1980, by echosounding (1889km), shallow seismic profiling (895km), magnetic survey (1228km), and seabed sampling (1320 grabs, 66 cores and 41 bulk samples).

The seabed was largely covered by silty sand, sandy silt and clay; sand covered the seabed in the bays to a water depth of 9-12m. The cores (maximum penetration 1.9m) showed that a reddish brown clay overlay olive grey clay which in turn overlay heavy mineral rich sands. Size analyses of sediments indicated a mixed depositional environment, i.e. dune/beach/river to barrier/lagoon and palimpsest type. The heavy mineral concentration ranged up to 90% (Fig.10) and included ilmenite and magnetite (Table 2) with minor quantities of augite, epidote, zoisite, apatite, tourmaline, topaz, hornblende, rutile, zircon, limonite and kyanite (Fig.11). The magnetites in the sands are titanomagnetite or finely intergrown with ilmenite. Some magnetite had been altered by weathering and oxidation to hematite, and minor quantities of anatase and leucoxene occurred. The relatively coarser size fractions (80-200  $\mu\text{m}$ ) were dominated by shell fragments, quartz and feldspar, whereas magnetite and ilmenite dominated the  $>100 \mu\text{m}$  fraction, but mostly 40-80  $\mu\text{m}$ . Siddiquie, Rajamanickam and Almeida (1979) reported 42-57%  $\text{TiO}_2$  in the ilmenite, and appreciable concentration of vanadium (up to 0.5%) and chromium have been found (Sahoo, 1980).

TABLE 2: The range (in %) of sand, silt, heavy minerals, magnetic and non-magnetic fractions and ilmenite in the offshore placers of Konkan Coast, Maharashtra, India. (Siddiquie, Rajamanickam, Gujar and Ramana, 1982).

Bay	Sand	Silt	Heavy Minerals	Magnetite	Non-Magnetic	Ilmenite
Jaigad	20-98	1-24	20-70	10-40	1-10	1-30
Ambwah	20-98	1-20	5-40	1-71	3-15	3-30
Varvade	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	1-95	1-15	1-40	1-07	1-9	1-21

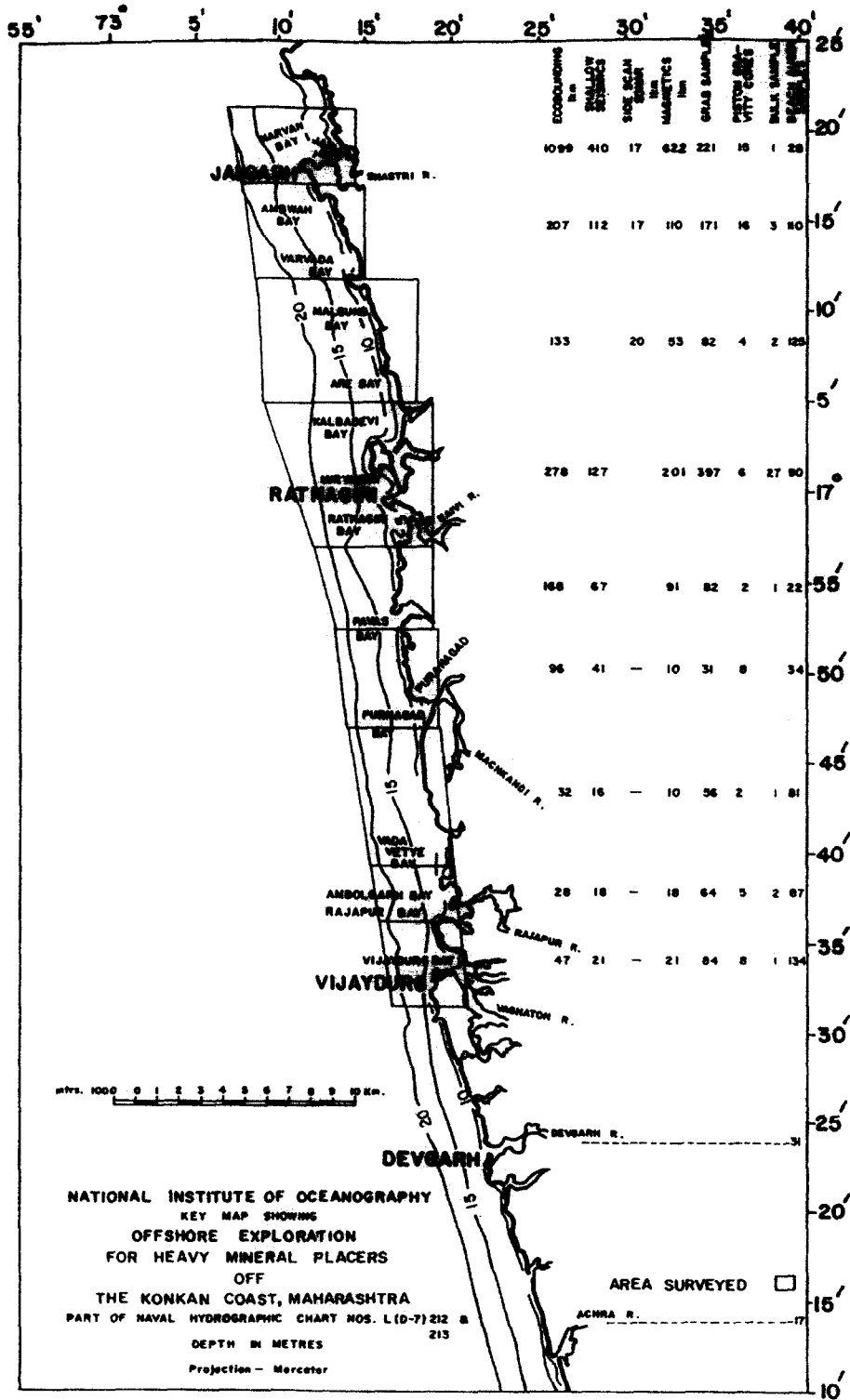


Fig.9. Map showing status of exploration for heavy mineral placers off the Konkan Coast, Maharashtra, India (Prom Siddiquie et al, 1982).

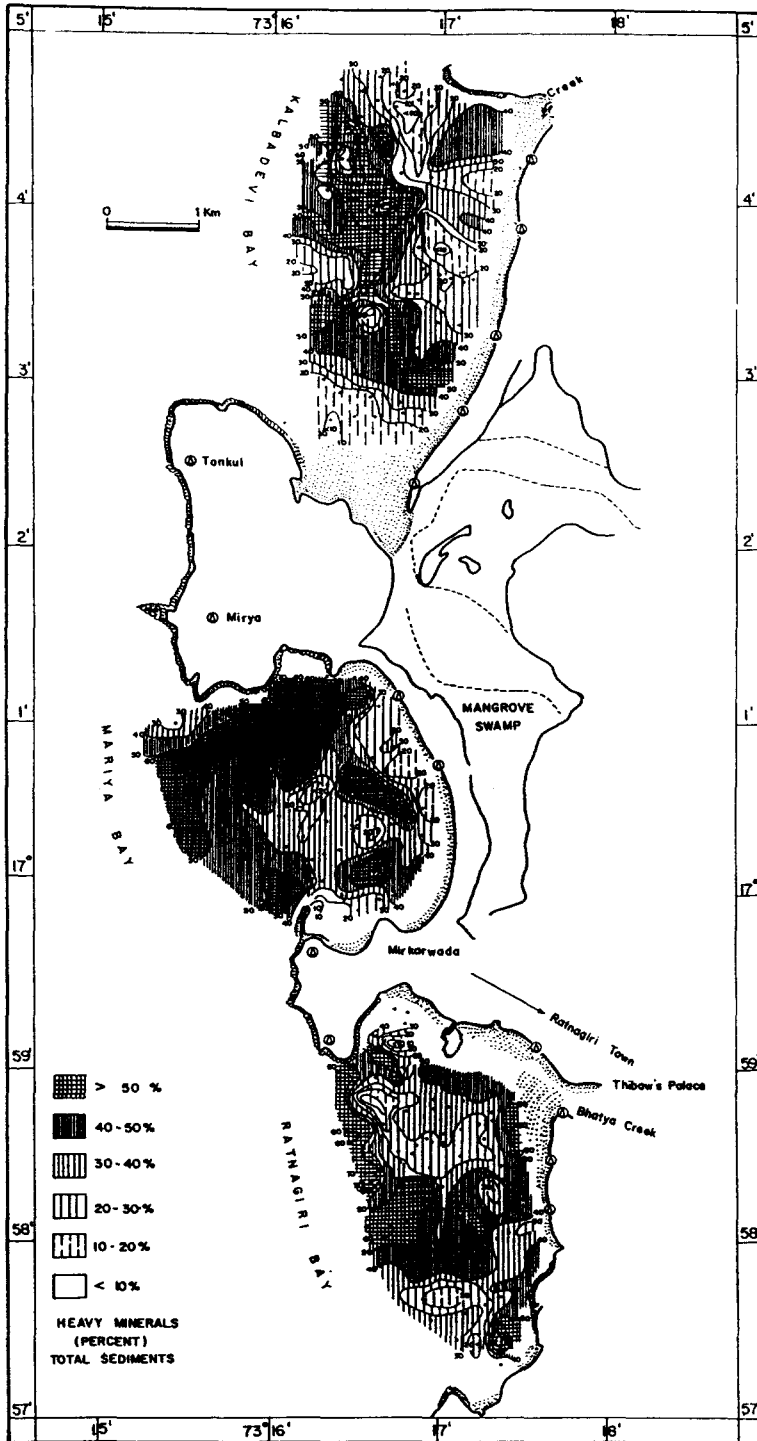


Fig.10. Map showing the distribution of heavy minerals in the sediments of Kalbadevi, Mirya and Ratnagiri Bays, Konkan coast, Maharashtra, India (From Siddiquie *et al.* 1979).

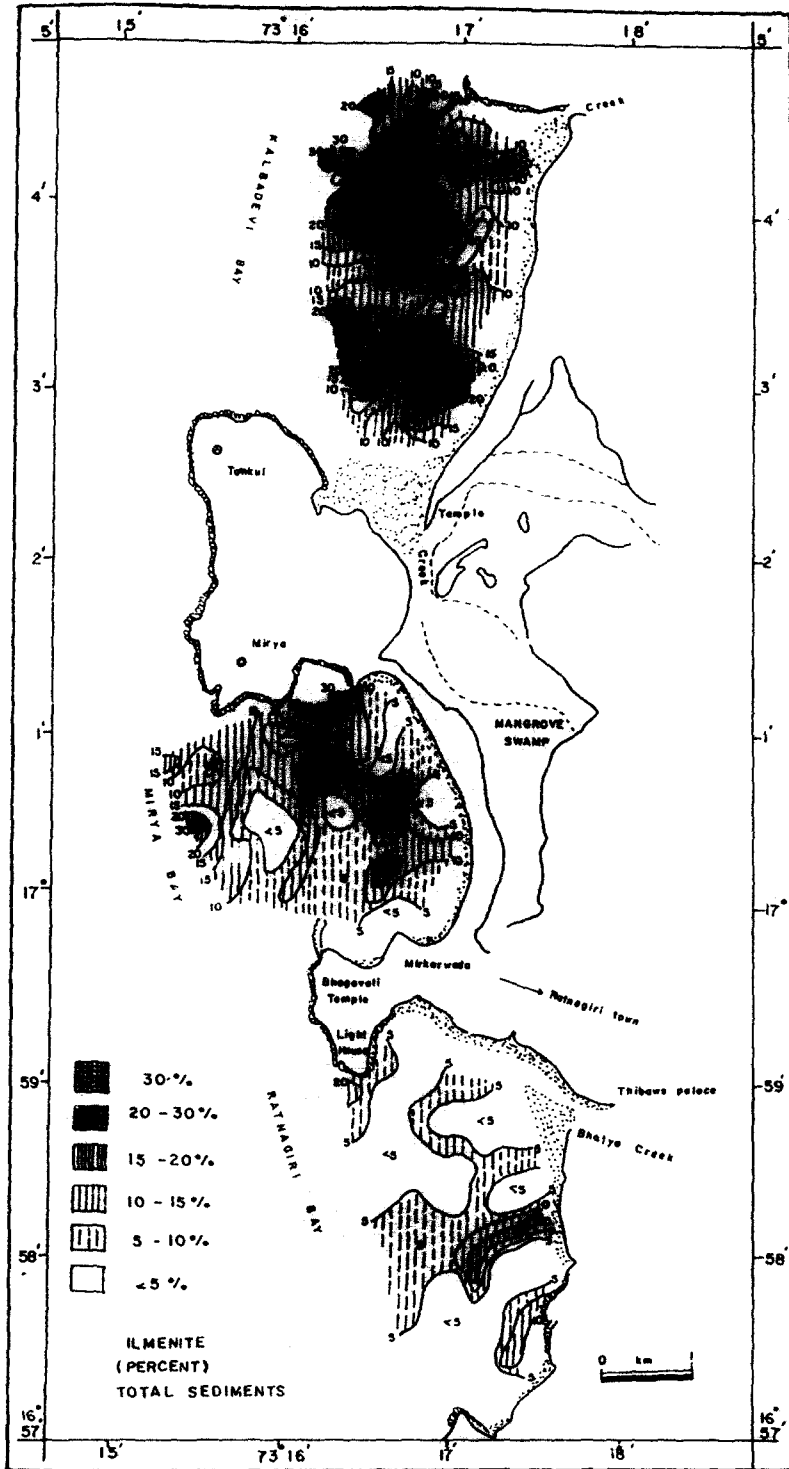


Fig.11. Map showing the distribution of ilmenite in sediments of Kalbadevi, Mirya and Ratnagiri Bays, Konkan coast, Maharashtra, India (From Siddiquie et al. 1979).

A representative seismic profile (Fig.12) shows the nearshore first reflector which is produced by heavy mineral sands. At water depths >10-15m these are overlain by clays and the seismic profiles indicate that the heavy mineral bearing sands extend below the clays to water depths down to 20m. The heavy mineral sands varied in thickness from 2-10m (Fig.13); even thicker layers of sand (>10m) were associated with river mouths, buried ancient river channels and local sand lenses (Fig.14). The sands are underlain by weathered basalt and in turn the Deccan basalts (Late Mesozoic to Early Tertiary).

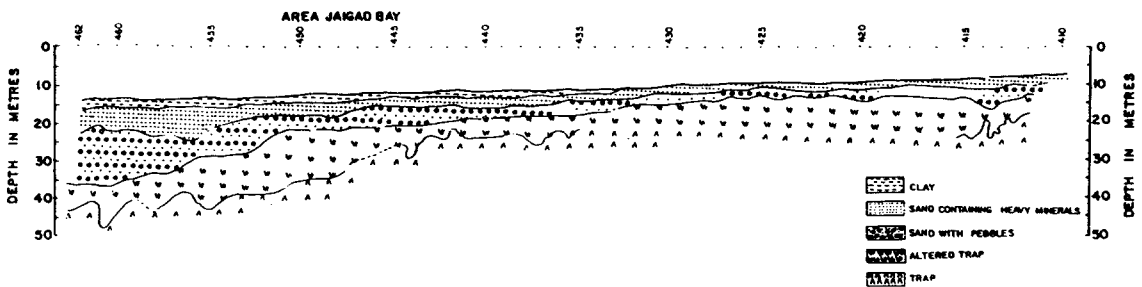


Fig.12 Interpreted seismic profile across the ilmenite placers off Jaigad, Konkan coast, Maharashtra, India. (From Siddiquie *et al.* 1982).

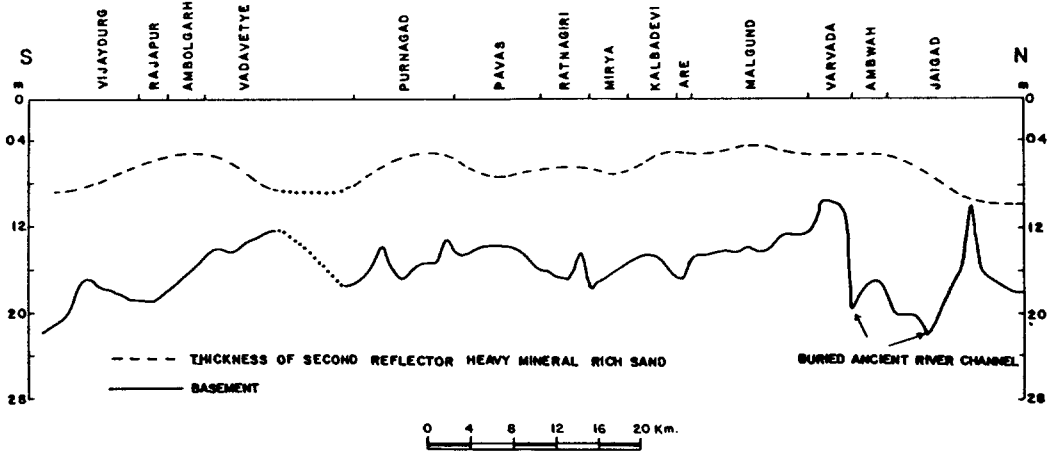


Fig.13 Schematic diagram showing the variations in the depth of basement and second reflector (sand containing heavy minerals) along the Konkan coast, Maharashtra, India (From Siddiquie *et al.* 1982).

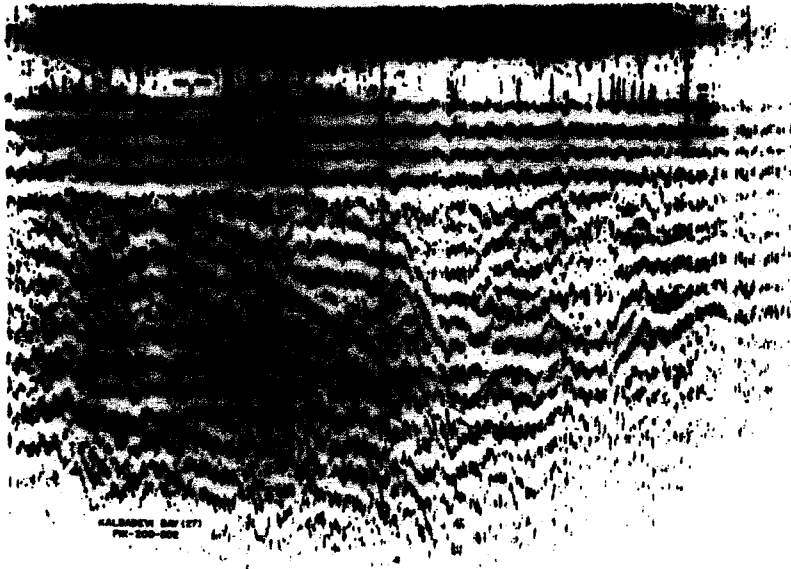


Fig.14

Fig.14. Seismic record showing the sand lens.

Magnetic surveys were carried out to correlate the magnetic anomalies with heavy mineral concentrations, basement configuration and the structural trends (Fig.15). Two types of magnetic anomalies were seen (a) N-S trending high amplitude and long wave length anomalies (300-350nT, about 800m), and (b) low amplitude and short wavelength anomalies (100-150nT, about 100m). The low amplitude and short wave length anomalies (about 200nT, 200m) may represent magnetic response of heavy minerals. A number of medium to high amplitude short wavelength anomalies along the coast indicate the extension of the heavy mineral placers below the seabed.

The surveys so far carried out indicate that the ilmenite bearing sands cover over 96km<sup>2</sup> of the seabed. Assuming an average ilmenite concentration of 10% and a minimum thickness of 1m, the reserves are estimated to be 12.5.10<sup>6</sup> tonnes. The seismic profiles indicate that the thickness of ilmenite bearing sands ranges from 2-10m and extend to water depths of about 20m over an area of 436 km<sup>2</sup>. Thus the reserves in the area will greatly exceed the onshore reserves of 4.10<sup>6</sup> tonnes. Concentrations of ilmenite are higher in the offshore than in the onshore sands. Whereas the onshore deposits are restricted chiefly to a narrow coastal tract of beach sand, the offshore deposits are fairly widespread.

Further, exploration of offshore placers will be guided by the proximity to onshore placers and an examination of the relict sands on the middle and outer shelves. The present data indicate that along much of the western shelf, from the Gulf of Kutch to the vicinity of Mangalore (lat. 12°-13°N) the relict sands consist of oolites and biogenous material with an insignificant terrigenous component. The relict sands in this belt and also those west of Ratnagiri, are not promising as sources for heavy mineral placers. Further south off Kerala the relict sands are terrigenous, but these have not been explored in detail except in a small area, but the close proximity of known extensive and rich onshore placers including ilmenite, monazite and garnet make these sands promising for further exploration. The extensive zone of potentially interesting sands continues east to the Gulf of Mannar. The known reserves of heavy mineral placers are not as extensive on the east coast as on the west coast. South of Madras the sands on the middle and outer shelves are terrigenous and these may be relict and are promising for further exploration. Whereas off Visakhapatnam the sands consist largely of oolite, and the probability of finding placers is limited. However, the extensive terrigenous sands on the middle and inner eastern shelf need to be carefully examined before ruling out the possibility of finding heavy mineral placers there (Fig.16)



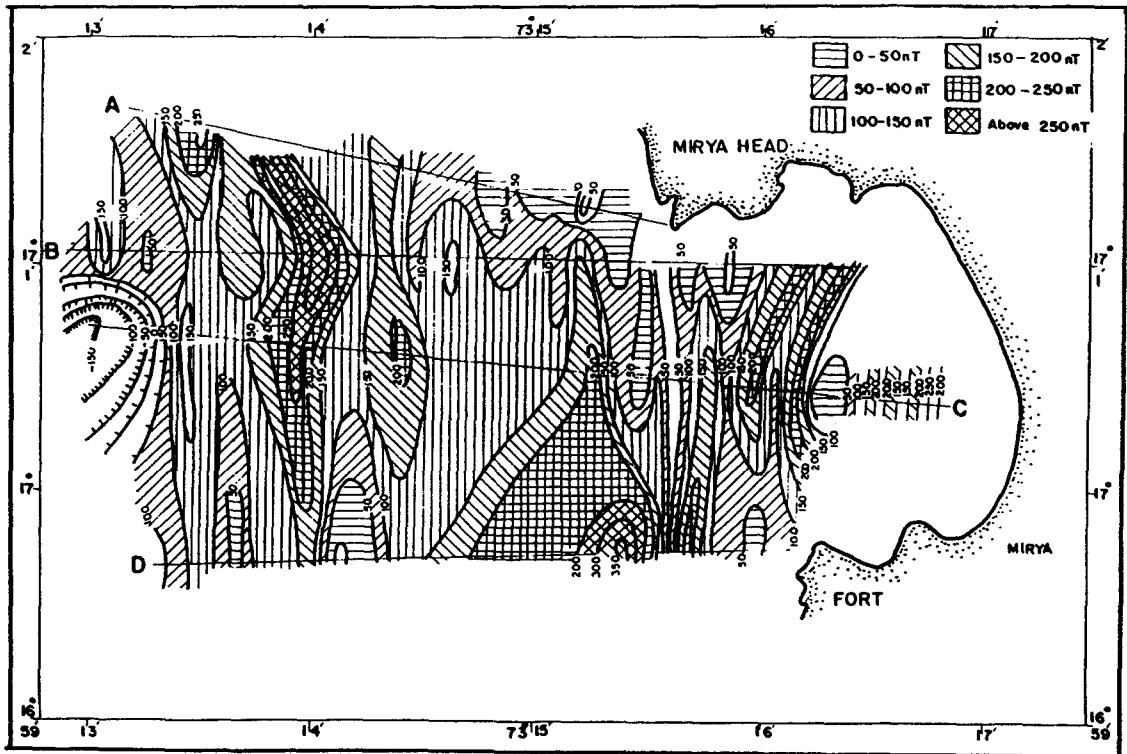


Fig.15. Residual magnetic anomaly map of Mirya bay, Konkan coast, Maharashtra, India (From Siddiquie *et al.* 1982).

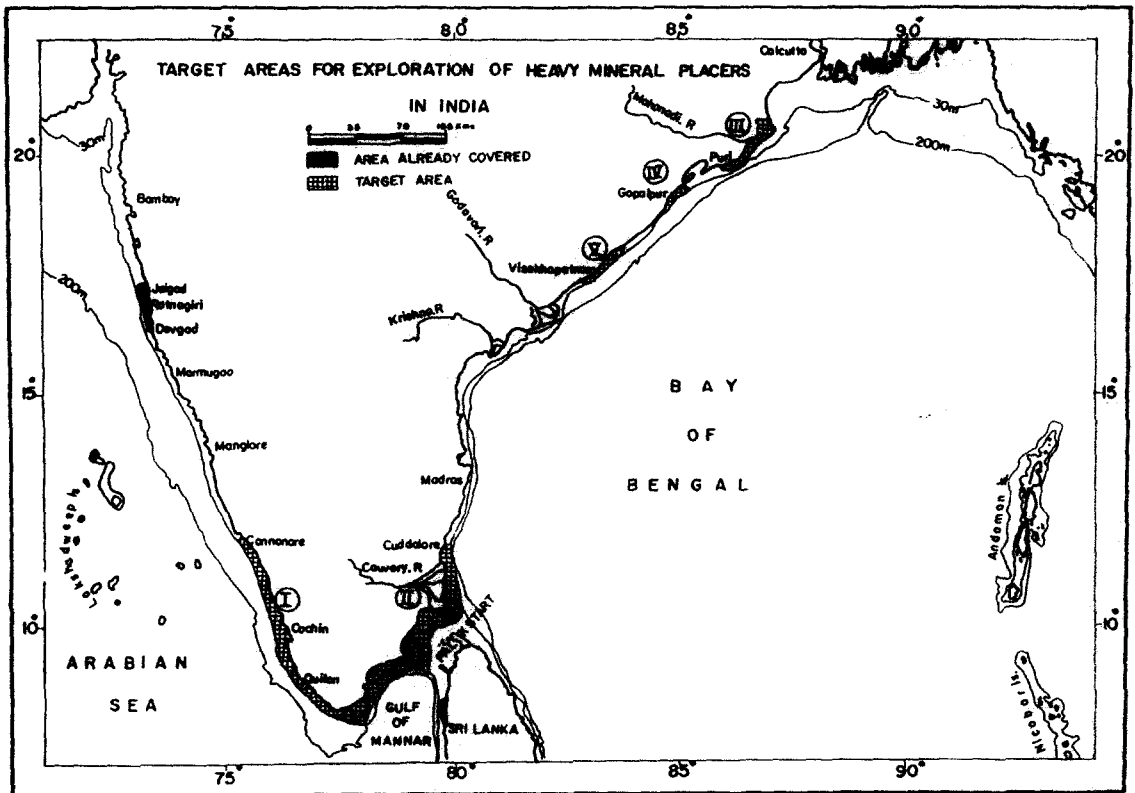


Fig.16. Target areas for exploration of heavy mineral placers - India.

### C. Sri Lanka

The Sri Lankan beaches have been fairly well studied and placers of ilmenite, rutile, monazite, zircon and garnet have been reported from many localities (Krishnan, 1968; Hearth, 1983). However, little exploration for offshore heavy mineral placers has been carried out.

On the west coast the placers are largely high grade beach and low grade dune deposits. They include the extensive deposit of monazite with rutile, zircon and garnet found at Beruwela in Induruwa. On the east coast, the deposits are found at two places. An ilmenite beach placer extends for more than 6.5km near Kokkilai Lagoon about 56km north of Trincomalee. This deposit contains about 75% ilmenite forming an estimated reserve at about  $4.10^6$  tonnes. On the Pulamoddai and Triukkivil beaches the sands contain about 25% zircon. The concentrations of monazite vary but the best deposit reported is the ilmenite-monazite-zircon placer on the Induruwa beach (south of Colombo), where some patches yield as much as 40% monazite.

The Ceylon Mineral Sands Corporation has been exploiting the Pullomoddai beach deposit for several years and after offshore exploration (Fig.34) in 1980 high concentrations of ilmenite and rutile were reported.

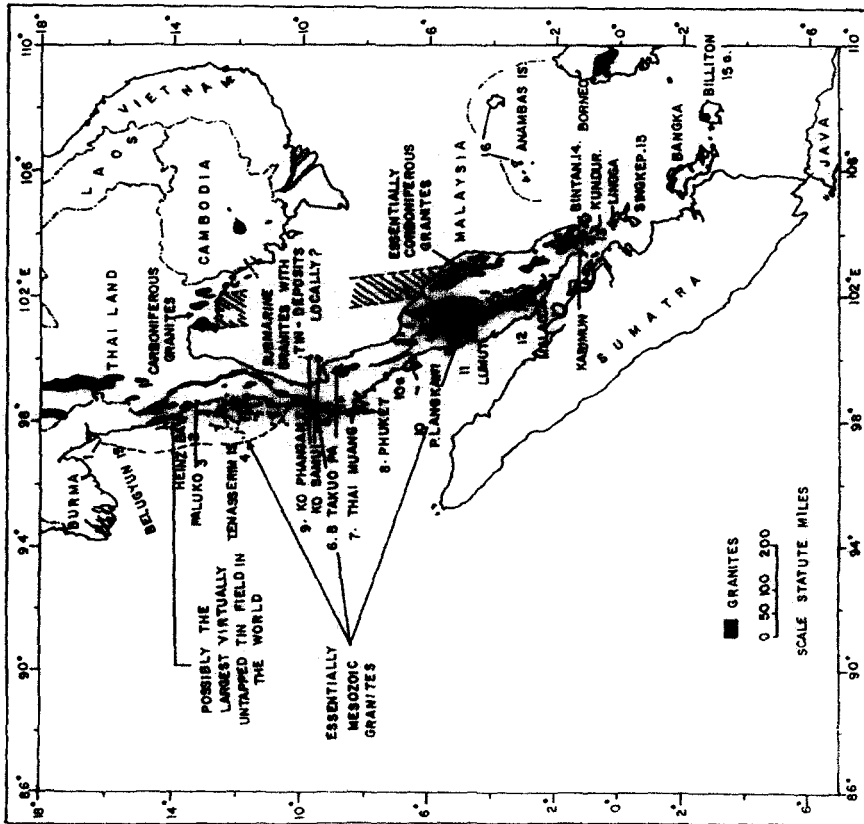
### D. SOUTH EAST ASIA

South East Asia is the world's major producer of tin (Werner Gocht, 1983) where 92% of the world's known reserves occur. The tin province stretches over 3600km from north Burma through peninsular Thailand and west Malaysia to the Tin Islands (Singkep, Bangka and Billiton) of Indonesia (Fig.17). The Indonesian tin belt, about 1000km long is its southernmost extension. The tin islands generally follow the strike of sedimentary rocks in these islands. Granitoid igneous rocks were intruded into the sedimentary rocks of these islands in late Triassic time ( $217 \pm 5.10^6$  B.P). The occurrence of tin is related to granite intrusions as the cassiterite mineralisation occurs in the contact zone or in the granite body adjacent to it.

The offshore tin placers have been formed from the weathering and erosion of onshore deposits, and influenced by the interactions of changes in the terrestrial and marine environments. Deposits occur in traps in quaternary valleys which have facilitated concentration of transported cassiterite, and in inshore and backshore terrace deposits in which sediments on banks and on the sea-bed have undergone elutriation and sedimentation during the Pleistocene and Holocene.

The vertical sequence of these deposits is young alluvial layers, young marine sedimentary layers, old alluvial layers, and finally old marine sedimentary layers. These layers are thinly covered by recent sandy mud mixed with coral fragments, which represents the recent sea floor. The maximum concentration of tin occurs along the axis of the current. All the major tin deposits of Thailand are located in the Southern Peninsular area and the deposits of economic importance are associated with Mesozoic granite. The area belongs to a metallogenic province in which tin-bearing acidic dykes and veins are confined to granite bodies (Isarangkoon, 1973).

In western Malaysia, tin deposits are associated with granites ranging from Carboniferous to early Tertiary (Hosking, 1971). Although most of the production of cassiterite in SE Asia has been from deposits on land; during the last decade exploitation of submarine placers off the Indonesian Tin Islands and to the east of Thai Island of Phuket has increased considerably. A comparatively unimportant part of the belt occurs in Laos, south-east Thailand and Anambas and Natuna Islands. In these areas the tin is derived mostly from cassiterite weathered from primary deposits during recent geological times, and concentrated as placers by river transport and by current and wave action in the sea.



Key to locations 1 to 16 shown on figure

1. BELUGYUN ISLAND : Stanniferous placers. From here to the Thai border at Ranong scores of good offshore targets exist.
2. HEINZE BASIN : Cassiterite dredged from tideways.
3. SPIDER ISLAND (AT MOUTH OF PALAUK RIVER) : Cassiterite (and wolframite) recovered from beach sands.
4. TENASSERIM DELTA AND LAMPA AND NEIGHBOURING ISLANDS : Cassiterite recovered from these localities.
5. RAMONG AND COAST TO SOUTH : Onshore placers locally extend to coast. Primary tungsten deposit at coast (at Kow Chai). A good target area.
6. TAKUOYA : Section dredge working offshore.
7. THAI MUANG : Cassiterite in beach sands. Offshore potential?
8. PHUKET : Dredges operating off east coast. Some bays on west coast to contain important concentrations of cassiterite. Recent illicit offshore mining off west coast. Dredges to operate off west coast soon.
9. KO PHANGSAN AND KO SAMUI : Poor tin mineralization on islands. Cassiterite occurs offshore but potential uncertain.
10. RAYONG : Cassiterite in beach sands and offshore.
10. LANGKAVI ISLANDS : 2% of Sn in andradites; Stannites (slight) locally present. "Trace" of cassiterite in beach sands; possibly an offshore potential exists between the islands and the mainland.
- 10a. KO RA WI AND KO LA DAM (NW of Langkav) : Cassiterite reported recently.
- 10b. ISLANDS WEST OF KEDAH PEAK : Cassiterite in beach sands.
11. LUMUT - DINDINGS : Cassiterite in beach sands and offshore at Tanjung Hantu and Pulau Ketak. Site of recent illicit offshore mining.
12. MALACCA : Cassiterite in mainland beach sands and offshore, from S. Linggi to S. Udang. also in beach sands of Pulau Besar (an island), with (II), the most promising Malaysian offshore area.
13. KARIMUN AND KUNDUR : Tin-bearing islands but mineralization not strong; possibly an offshore potential exists.
14. BINTAN : Small placers on island; possibly an offshore potential exists.
15. THE TIN ISLANDS : Substantial offshore mining and exploration activity.
- 15a. Submarine tin granites between Billiton and Borneo (where tin reported)?
16. ANAMBAS AND NATUNA ISLANDS : Cassiterite reported but outside tin belt proper. It is unlikely that an offshore potential exists.

Fig. 17. Map showing the offshore areas of Southeast Asia, and the general distribution of the granites and tin belts (from Hosking, 1971).

Locally in Malacca and Perak, cassiterite has been recovered from modern beach sands and other coastal deposits adjoining the western tin belt. Off the west coast of Thailand, cassiterite has been recovered east of Phuket Island, at Takuopa and substantial deposits are reported from Kamera Bay, Bang and Thao Bay. Production from these offshore placers has increased considerably and now in some cases exceeds the onshore production (Fig.34) (Table 3). In Western Malaysia exploration is concentrated in the western onshore/offshore area because the western tin belt is richer than the eastern belt.

TABLE 3: Production of tin concentrates (containing on an average 72% tin) from onshore and offshore areas of Thailand.

Year	Offshore tonnes	Onshore tonnes	Offshore : Onshore
1970	3,451.9	26,279.6	1 : 7.6
1971	3,498.9	26,110.4	1 : 7.5
1972	4,686.6	25,446.3	1 : 5.43
1973	5,216.3	23,345.1	1 : 4.48
1974	6,169.8	21,596.9	1 : 3.50
1975	4,161.0	18,253.8	1 : 4.39
1976	8,417.5	19,503.6	1 : 2.32
1977	13,045.5	19,998.8	1 : 1.53
1978	19,180.0	22,030.0	1 : 1.15
1979	23,496.0	22,868.0	1 : 0.87
1980	23,754.0	22,234.0	1 : 0.94
1981	13,296.0	9,367.0	1 : 0.70
1982 (Jan-May)	9,080.0	26,100.0*	

From Werner Gocht (1983) and \*Mining Journal (1983).

Titaniferous magnetite is being recovered from some of the beaches of Indonesia. Deposits of ilmenite, titaniferous magnetite, monazite and zircon have also been reported offshore of Western Indonesia.

#### E. AUSTRALIA

The Australian beaches are well known for their heavy mineral placers, the total reserves proven and estimated of the east coast beaches of both Queensland and New South Wales are  $20.10^6$  and of the west coast are  $68.10^6$  tonnes, already between them they produce over 90% of the world's rutile, ~80% of zircon, 70% of monazite and >25% of ilmenite (Charlie, 1981). Most of the production is from the west coast as ~40% of the east coast reserves of rutile and zircon are inaccessible for mining because of environmental conditions. Tin is produced from the beaches in Tasmania and gold from those of the south coast of New South Wales. The Australian heavy mineral placers contain 45% rutile and 20% ilmenite, together with zircon and monazite.

The ilmenite contains up to 54%  $TiO_2$ , 22% FeO, 20%  $Fe_2O_3$ , and 0.05%  $Cr_2O_3$ . The zircon contains up to 67%  $ZrO_2$ , 0.5%  $TiO_2$  and 0.004%  $Cr_2O_3$ . The Monazite contains up to 26.7%  $CeO_2$ , 16%  $La_2O_3$ , 6.8%  $ThO_2$ , 27%  $P_2O_5$ , and 11%  $Nd_2O_3$  (Macdonald, 1971).

The continental shelf of Australia covers an area of over 2.5 million  $km^2$  of which the eastern shelf is about 0.8 million  $km^2$ . Brown (1971) reported that the results of offshore exploration for rutile and zircon placers are encouraging. He estimated that if a grade of 0.2-0.22% rutile and zircon is mined, reserves of over  $375.10^6$  tonnes of the sands have

been mapped and the indications are that a further  $500.10^6$  tonnes are present.

Over most of the Australian continent the climate is arid or semi arid and the river runoff into the sea is generally very small. Furthermore, the topography is low and flat and so erosion is so slight that only trivial amounts of terrigenous sediment are being deposited at present on the continental shelf. Benthic sediment samples show that sedimentation is occurring in only small areas around the mouths of rivers. Away from river mouths, the sediments of the continental shelf are predominantly formed from coarse shells, gravels and sands which are quite different and possibly much older than the recent silty sediments. Thus Pleistocene heavy mineral placers are unlikely to have been covered because of the low rate of recent sedimentation.

#### BUILDING AGGREGATES

Sand and gravel from the continental shelves are increasingly being exploited for construction work. Sand and gravel is low cost material, so their offshore mining has to compete with exploitation of onshore deposits, for example in coastal areas where there are large urban centres and intense building activity.

#### BIOGENOUS

The biogenous deposits include the deep-sea pelagic oozes and the coral and shell deposits of shallow areas. The pelagic oozes can be composed of calcareous material (from foraminiferans, nannoplankton and pteropods) or siliceous (from radiolarians and diatoms). The coral and shell deposits are calcareous in the mineral forms of either aragonite or calcite.

#### Distribution

Biogenous sediments of different types cover large area of the seabed (Fig.18). Deep sea deposits include the oozes which accumulate in tropical and subtropical latitudes ( $20^{\circ}\text{N}$  -  $40^{\circ}\text{S}$ ) wherever the depth is shallower than the depths of dissolution for carbonate or silicate. The approximate areas covered by various oozes in the Indian Ocean are a) Globigerina ooze,  $40.45.10^6\text{km}^2$  between  $20^{\circ}\text{N}$  and  $40^{\circ}\text{S}$ ; (b) pteropod ooze,  $0.74.10^6\text{km}^2$  in small patches NW of Australia; (c) diatomaceous ooze,  $14.98.10^6\text{km}^2$  south of  $50^{\circ}\text{S}$ ; and (d) radiolarian ooze (with red clays),  $18.72.10^6\text{km}^2$  between  $10^{\circ}\text{N}$  and  $40^{\circ}\text{S}$ .

The deposits match the physical and chemical properties of a wide variety of rocks/materials used on land. However, they occur too deep to be of any immediate economic interest.

#### Shallow Areas

The calcareous deposits found in shallow areas of the continental shelf, and on atolls and banks are chiefly comprised of corals and shells. The ideal conditions for the growth and formation of corals occur in warm tropical waters where they are limited discharges of fresh water and sediment. The maps of generic diversity (Wells, 1954; Rosen, 1971) indicate that the highest generic diversity occurs in a belt extending from  $20^{\circ}\text{N}$  -  $20^{\circ}\text{S}$  from Sumatra to Laccadives-Maldives, Northern Madagascar and the Red Sea (Fig.19). Within this area lie a number of atolls, coral reefs, submerged reefs and banks, some of which are very large Seychelles Bank covers  $43,000\text{km}^2$ , Saya de Malha,  $40,000\text{km}^2$ , Nazareth Bank  $20,000\text{km}^2$  and the banks of the Chagos Archipelago  $13,500\text{km}^2$ . Over the banks maximum depths are 33-90m which shallow to a rim at 8-10m depth around at least part of the periphery.

Deposits of calcareous shells also occur in the shallow areas on the continental shelf, usually in areas of high benthic productivity where they are concentrated by hydrodynamic processes. In some areas the deposits are made up of subrecent fossil shells which have been or are being reworked and concentrated.

Deposits of shells, corals and calcareous sands in the coastal areas have been utilised on a small scale from the early historical times for construction and making lime. The large scale exploitation of these deposits for cement and chemical industries is comparatively

recent. In the Indian Ocean region offshore exploration for calcareous sediments is being actively carried out in India where the offshore deposits have begun to be exploited.

The best known deposits are in the Gulf of Kutch and in the Vembanad Lake (backwaters) of Kerala, from which the present annual production is over a million tonnes. The shell deposits in the backwaters of Kerala consist of *Crassostrea madrasensis*, *C. cucullata*, *Villorite cyprinoides*, *Modiolus* sp. and *Meritrix* sp.; the two oyster species are dominant constituents in the estuarine deposits and the last three are predominant in the Vembanad Lake. The estimated reserves are estimated at  $1.7-2.6 \cdot 10^6$  tonnes in the Vembanad Lake,  $4-5 \cdot 10^5$  tonnes in the Kadarundi and  $1 \cdot 10^6$  tonnes in the lower reaches of Pullet and Thathapalli rivers.

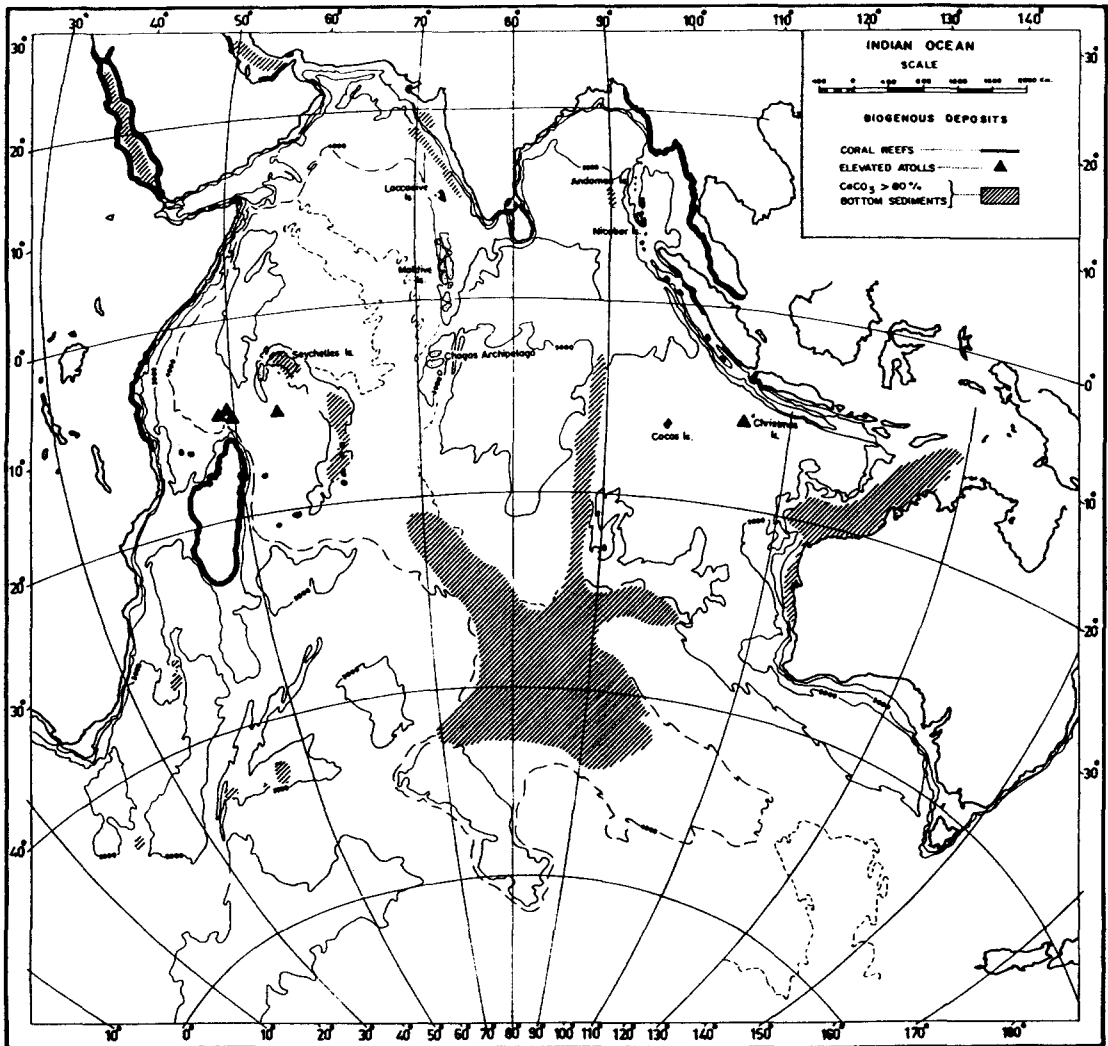
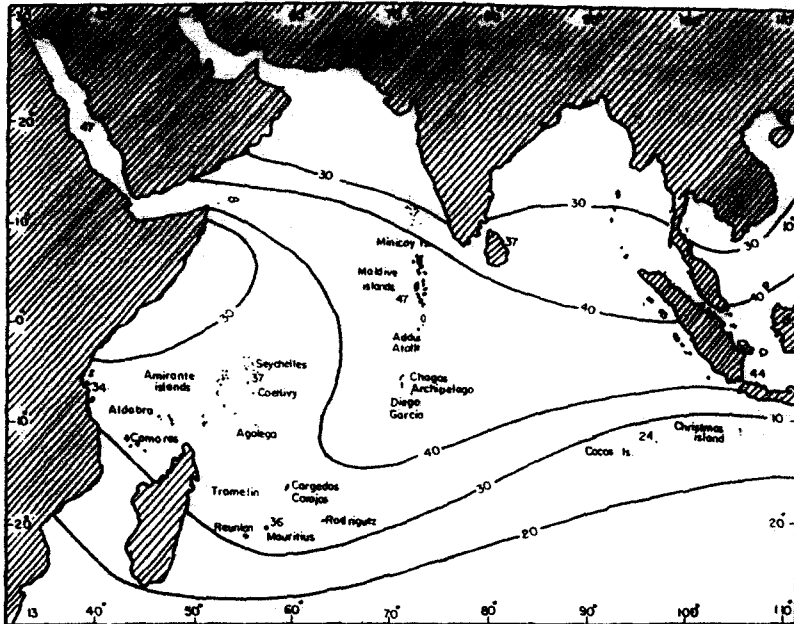
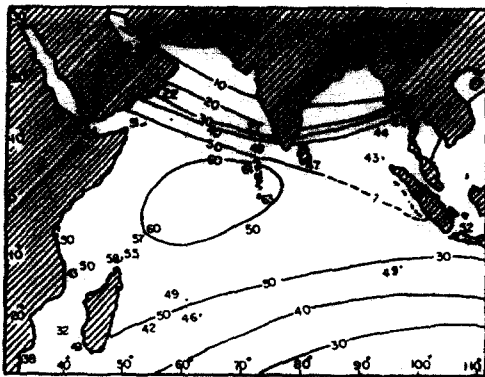


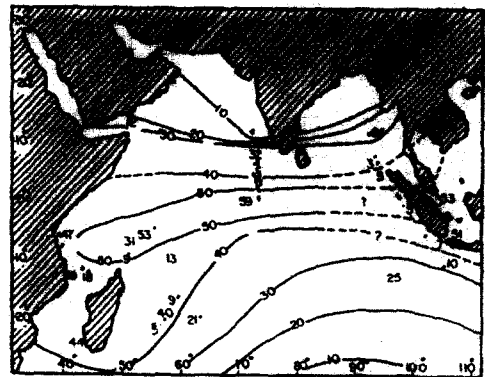
Fig.18. Map showing the biogenous deposits in the Indian Ocean.



Distribution of Indian Ocean hermatypic coral genera slightly modified after (Wells 1954)



Generic diversity of corals on Indian Ocean reefs: predicted Levels. Contours show number of coral genera (from Rosen 1971)



Generic diversity of corals on Indian Ocean reefs: actual records. Contours show number of coral genera (from Rosen 1971b)

Fig.19. Distribution of Indian Ocean hermatypic coral genera, predicted and actual generic diversity of corals on Indian Ocean reefs. (after Wells and Rosen, 1971 - from Siddiquie et al. 1979).

Recently Venkataramanugam, Santhaanam and Sukumaran (1981), studying the coral resources off Tuticorin, identified 20 species along the reefs and offshore islands. About 10,000 tonnes of lime is extracted annually from these reefs and their exploitation is already adversely affecting the islands and their local fisheries, but measures have now been taken for their conservation. There is a lack of information about the geology and potential of both the presently exploited deposits and the adjacent areas.

In the Gulf of Kutch the calcareous/shell deposits are being extensively exploited, but little information is available on their extent and reserves. Similarly, only limited exploration has been carried out around the presently mined area of the shell deposits in the backwaters of Kerala, where a detailed survey using a mud penetrator and high resolution sparker is now planned.



The bottom sediment map of the seas bordering India shows relict oolitic and biogenous sands on the middle and outer shelves (Fig.20). Along the western shelf these extend almost continuously as a wide strip from the Gulf of Kutch to the vicinity of Mangalore. On the eastern shelf, the relict sands are exposed in a discontinuous belt, and only off Visakhapatnam consist of relict carbonates (oolitic and/or biogenous sands). The relict sands occur at a depth of more than 50m on both the shelves.

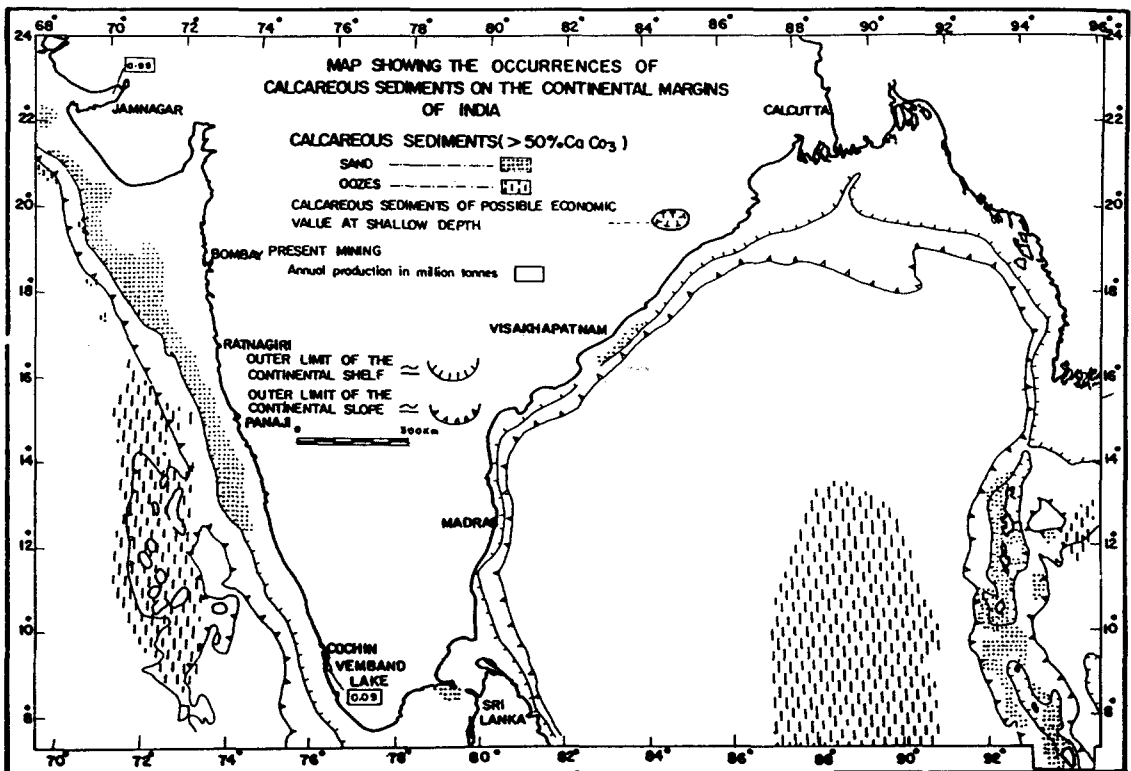


Fig.20. Map showing the occurrences of calcareous sediments on the continental margins of India (From Siddiquie *et al.* 1979).

However, deposits of coral and shell sands occurring in the shallow areas and lagoons of the Laccadive Islands, off the Andaman Islands and in the Gulf of Mannar and Palk Strait appear to be promising economically. The Laccadives are a group of coral atolls, submerged reefs and banks. Siddiquie and Mallik (1973), surveyed eleven of these lagoons in detail (1:5,000 and 1:10,000) and made a reconnaissance of four submerged reefs and banks by completing >1190 lkm of echosounding and collecting 1953 samples from the lagoons and 546 from offshore. Partial chemical analyses were carried out on 664 of these samples. These sands are of good quality and are low in silica, alumina and iron (Table 4). MgO is the only impurity and the MgO content in the sands of some of the lagoons was related to the proximity to the reef (Figs. 21 and 22). The surveys indicated that about  $288.10^6$  tonnes of calcareous sands occur in the lagoons in a 1m layer. A further  $423.10^6$  tonnes probably occur in other lagoons where no detailed surveys were undertaken. If the thickness of the sands is greater, as is to be expected, the reserves will be considerably greater (Fig.23).

The western coast of India especially the Konkan, Karnataka and Kerala coasts do not have large limestone deposits, and therefore, the deposits in the Laccadives are favourably situated for exploitation. However, before extensive mining of these deposits, particularly those in the inhabited lagoons is begun, a careful study will be needed of the impact of the removal of the sand on the reef (and on its effect on marine living resources. Ed.). The extraction of sands from the lagoons could be linked with the development of port facilities.

TABLE 4: Average percentage chemical composition of calcareous sands from the lagoons of the Laccadive Islands (Siddiquie and Rajamanickam, 1979).

LAGOON	Chetlat	Kiltan	Kadmat	Amini	Agatti	Kavaratti	Bagram
Average of number of analyses	4	4	4	3	4	3	9
SiO <sub>2</sub>	+	+	+	+	+	+	3.08
Al <sub>2</sub> O <sub>3</sub>	1.78	1.11	1.17	0.85	0.75	0.73	0.16
Fe <sub>2</sub> O <sub>3</sub>	0.13	0.25	0.18	0.05	0.12	0.08	0.19
TiO <sub>2</sub>	+	+	0.14	0.02	0.05	0.10	0.02
P <sub>2</sub> O <sub>5</sub>	0.05	0.05	0.12	0.11	0.04	0.06	0.04
CaO	50.14	50.19	49.25	49.41	49.51	49.49	51.47
MgO	0.86	0.73	2.47	2.48	2.30	2.25	1.25
Na <sub>2</sub> O	0.48	0.53	0.62	0.94	0.76	0.72	0.85
K <sub>2</sub> O	0.25	+	+	+	+	+	0.15
SO <sub>3</sub>	0.23	0.62	0.37	0.39	1.38	1.41	0.20
Loss on ignition	46.31	46.29	45.64	45.60	45.31	45.35	42.08

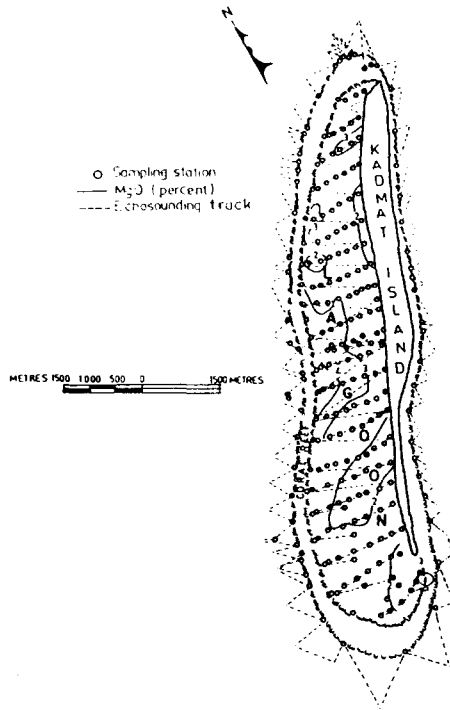


Fig.21 Base map of exploration in the lagoon and offshore area (Kidmat Island). (From Siddiquie et al. 1979).

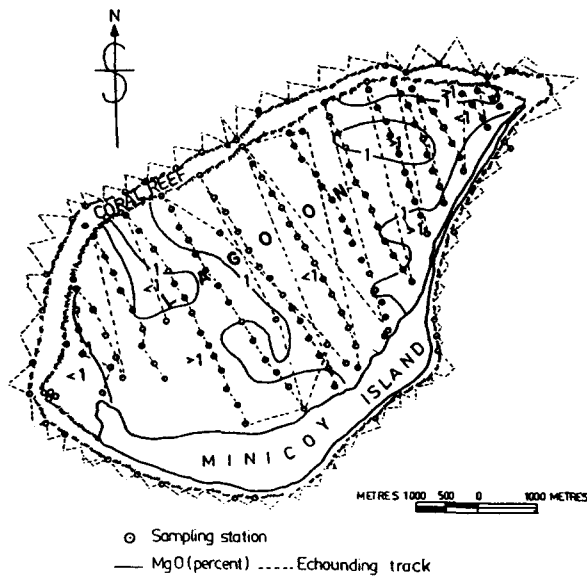


Fig.22. Base map of exploration in the lagoons and offshore area (Minicoy Island) (From Siddiquie et al. 1979).

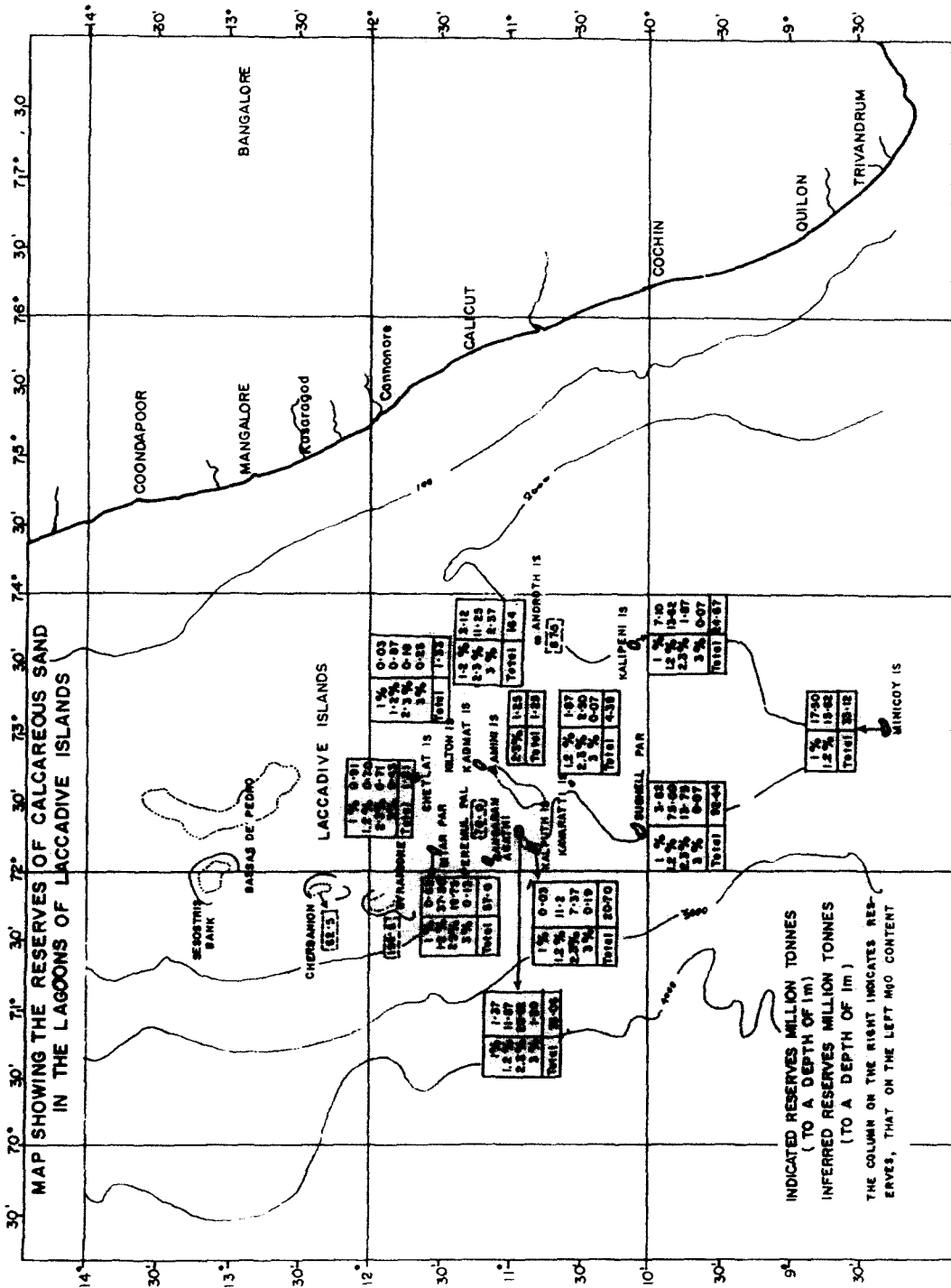


Fig.23. Map showing the reserves of calcareous sands in the lagoons of Laccadive Islands. (From Siddiquie et al, 1979).

### Ornamental and Semi-precious stones

A minor use of corals and shells is as ornamental and semi-precious stones, for which there has been a recent increase in the demand due to a rise in international tourism. Wells (1981) reviewed the international trade in ornamental corals and shells. 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 the 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 concern has been expressed regarding the depletion of their stocks and the need for their conservation. Consequently some countries have imposed a ban on exports and others are regulating the exploitation on a sustainable yield basis.

### AUTHIGENIC

#### Phosphorite

Composition: Phosphorite has been described as a sedimentary deposit composed mainly of phosphate minerals (Pettijohn 1957). Phosphatic deposits occur on the ocean floor in the form of nodules, sands, muds and consolidated beds mostly of Tertiary age. Phosphorite is composed mainly of carbonate fluorapatite, which contains in its crystal lattice some fluorine and uranium and other rare elements (Tooms, Summerhayes and Cronan, 1969).

Phosphorite nodules were first dredged from the Agulhas Bank off South Africa by HMS 'CHALLENGER'. Since then oceanographic expeditions have collected samples of phosphorites from several locations in the world oceans, at water depths ranging from few tens of metres to more than 3000m, but commonly in waters less than 1000m. Submarine phosphorites are reported from continental shelves and offshore banks and marginal plateaux. They are most abundant off the western margins of the continents but also occur on plateaux off some eastern continental margins on seamounts in association with calcareous and volcanic rocks (Baturin and Bezrukov 1979). (Fig.24).

Formation of Phosphorites: The continental margin phosphorites are commonly associated with areas of upwelling and high biological productivity. Upwelling brings large quantities of cold nutrient-rich (including phosphate) waters from intermediate depths to the surface and stimulates high biological productivity, which reflects in a large and rapid flux of organic material to deeper waters. Off the western continental margins upwelling is the result of oceanic and atmospheric circulation patterns which give rise to current divergence. Although there is an association between areas of upwelling and the occurrence of seafloor phosphorite, the age of phosphorites which occur in these areas ranges from Cretaceous to Recent. Summerhayes (1967, 1969) has suggested that in the Tertiary physicochemical and biochemical conditions in these areas were more conducive to phosphorite formation than at present.

The continental margin phosphorites are usually associated with siliceous deposits, i.e. chert, procellanite and diatomite, carbonates, glauconite and occasionally volcanic rocks, bentonites and tuffs (Gulbrandsen, 1966). Depositional features in areas of phosphorite occurrence include condensed sequences indicating slow deposition and minimum input of detrital sediment, sometimes evaporites indicating a warm arid climate (Cronan 1980). Thus the areas of upwelling and non-depositional environment appear to be a favourable locale for the formation of phosphorites on the continental margins.

The phosphorites found on seamounts have a different origin (Baturin, 1982). Many seamounts have wave-truncated tops and have relict shallow water faunas and so can be regarded as submerged islands. Extensive deposits of guano are found on the tropical islands of the Pacific, Atlantic and Indian oceans, which have phosphatised various rocks (Hutchinson, 1950; Trueman, 1965). It is possible that the phosphorites on some seamounts were formed in an analogous way.

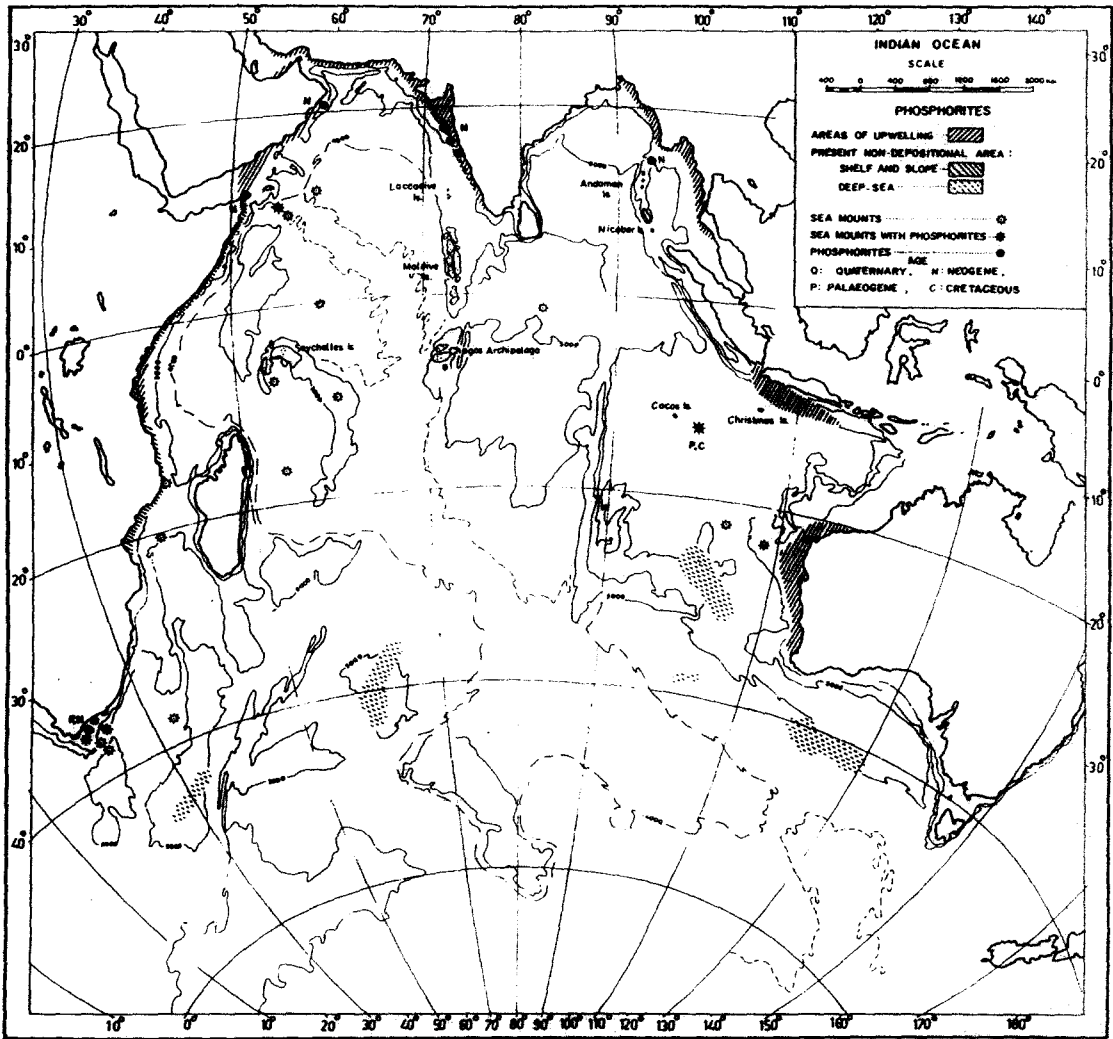


Fig.24. Map showing the phosphorite deposits in the Indian Ocean.

However, Heezen, Mathews, Catalano, Natland, Coogan, Tharp and Rawson (1973) suggested that the phosphorites were formed after the submergence of the sea mounts by metasomatic replacement of carbonate by phosphate extracted from sea water. It has also been suggested that phosphorite formation was a result of activation of volcanic and hydrothermal activity. However, no single hypothesis accounts for all the observed features of phosphorites found on seamounts but they clearly differ from those of the continental margins.

#### Occurrences in the Indian Ocean - Continental Margins

**A. Agulhas Bank:** The Agulhas Bank phosphorites are one of the largest known seabed deposits (Baturin, 1982; Parker and Siesser, 1972; Summerhayes, 1973; Parker, 1975). The deposits are spread in a belt about 600km long and 100km wide at depths of 100-500m (Fig.25). The deposit consists of phosphoritic nodules and phosphotised limestones (Tables 5 and 6). The  $P_2O_5$  content in the Fe-poor phosphatised limestone is about 15% but is lower in Fe-rich limestones. In nodules the phosphate content ranges from 15-32%. Dating of the nodules indicates that the phosphotisation took place from the Miocene to Pleiocene and ceased in the Quaternary.

The total reserves of phosphorite and phosphotised rocks ( $> 1\% P_2O_5$ ) are estimated to be  $140.10^6$  tonnes of  $P_2O_5$ , assuming a mean deposit thickness of 1m. Mechanical fractionation of some rocks can easily lead to extraction of ore containing about 16%  $P_2O_5$ . Ground phosphorites have been tested for use as fertiliser and proved to contain as much available phosphorous as commercial superphosphate. However, commercial development of the deposits awaits detailed exploration, but is unlikely as the weight of the rocks brought up during dredging varies from  $< 1 - > 100$ kg (Parker, 1975).

#### **Distribution of phosphorus in the unconsolidated sediments on Agulhas Bank ( from Summerhayes,1973)**

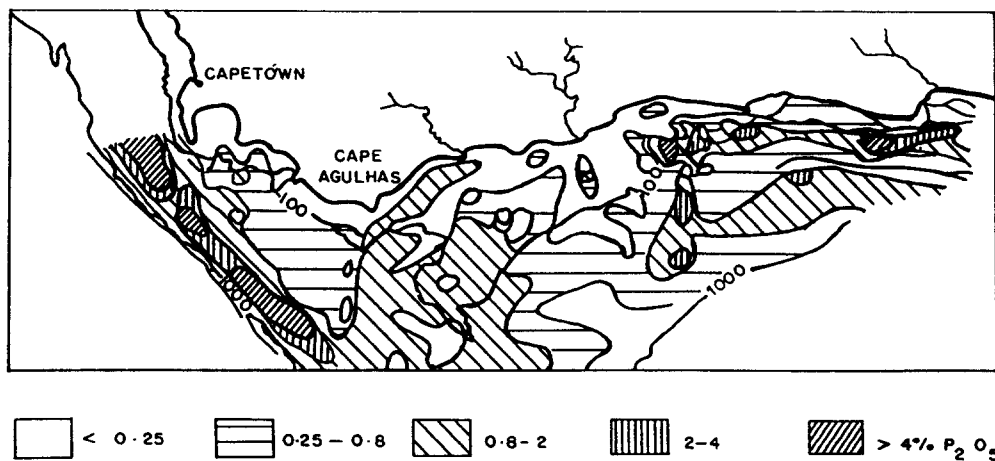


Fig.25. Distribution of phosphorus in the unconsolidated sediments Agulhas Bank (from Summerhayes, 1971).

TABLE 5: Average percentage chemical composition of phosphorites from the Indian Ocean

	1	2	3	4	5
SiO <sub>2</sub>	6.20	3.45	15.30	13.79	4.66
TiO <sub>2</sub>	0.06	0.04	0.10	0.11	-
Al <sub>2</sub> O <sub>3</sub>	1.13	0.92	2.14	2.12	2.29
Fe <sub>2</sub> O <sub>3</sub>	1.40	25.80	5.58	7.34	1.39
MnO	0.01	0.06	0.01	0.02	-
MgO	0.97	1.49	1.34	1.45	1.40
CaO	47.02	33.42	37.04	36.54	45.35
Na <sub>2</sub> O	0.62	0.34	0.78	0.73	-
K <sub>2</sub> O	0.43	0.39	1.57	1.51	-
P <sub>2</sub> O <sub>5</sub>	14.82	10.26	17.89	16.82	27.80
S	0.31	0.21	0.46	0.45	-
F	2.12	1.42	2.21	2.04	2.58
Loss on Ignition	25.52	23.24	16.15	16.89	-

1-4: Agulhas Bank, South Africa from Cronan (1980).

5: Seamount, 15°45.3'N, 99°56.4'E (Baturin and Bezrukov 1979)



TABLE 6: Ranges in percentage chemical composition of phosphorites from the submerged margin of South Africa

Rock Type	Concretions of Phosphatised Limestone	Sheets of Phosphatised Limestones	Phosphatised and Ferruginised Limestones	Glauconite-Quartz Phosphatised Sandstones	Conglomerate Phosphorites	Brecciform Phosphorites
Number of Records	8	2	4	3	15	3
P <sub>2</sub> O <sub>5</sub>	14-24	17.5-19	7.4-15.6	16.6-18.9	14.3-21.5	12.0-24.2
CaO	39-50	33-38	17.7-41.5	29.0-39.9	29.8-43.9	25.3-46.3
MgO	+1.7	0-0.7	1.0-2.3	1.3-1.7	0.9-3.0	0.95-4.2
SiO <sub>2</sub>	0-12	2.9-4.8	1.7-5.9	12.3-27.4	2.7-24.9	2.8-22.6
TiO <sub>2</sub>	0-0.15	0.12-0.16	0-0.06	0.14-0.20	0.04-0.20	0.01-0.20
Al <sub>2</sub> O <sub>3</sub>	0.9-3.5	1.5-2.5	0.6-2.9	2.0-2.5	+3.2	+1.9
Fe <sub>2</sub> O <sub>3</sub>	0.9-7.6	5.6-9.0	10.3-50.0	4.2-6.7	0.8-10.5	1.2-10.1
FeO	0-0.7	0.1-0.2	0-0.18	0.33-0.84	0.23-0.62	-
MnO	0-0.3	0.1-0.5	0-0.09	0.01	0.01-0.04	0.01
Na <sub>2</sub> O	0-0.8	0-0.7	0-0.52	0.63-0.80	0.58-0.95	-
K <sub>2</sub> O	0-0.7	0-0.7	0-0.55	1.3-2.6	0.80-2.5	-
CO <sub>2</sub>	9-22	0-5.7	6.7-22.5	3.5-10.9	4.3-12.8	-
C organic	0-0.9	0-0.3	-	-	0.5-1.0	0.5-0.9
S	0-0.8	-	0.16-0.29	0.38-0.54	0.34-0.65	-
F	0-2.3	0-2.0	0-2.1	2.1-2.4	1.8-2.9	0-2.4
Loss on ignition	1.9-28	16.8-17.2	17.6-29.9	10.5-16.9	11.0-22.3	9.0-15.9
F:P <sub>2</sub> O <sub>5</sub>	0.06-0.15	0.11	0.13-0.15	0.11-0.13	0.11-0.13	0.10

B. Andamans: Tipper (1911) reported phosphorite nodules off the northern Andamans. In the late 1960s extensive sampling for phosphorite was carried out in the same vicinity, but the results were not encouraging. Any phosphorite which does occur in this area appears to be patchily distributed.

C. Western Continental Margin of India: This upwelling area with its low sedimentation rate and non-depositional environment appeared to be a favourable area for the formation of phosphorite, but initial extensive regional exploration indicated that the phosphate content of the sediments is only 0.1-1.3% (Rao, Rajamanickam, Paropkari and Murty 1978). However, detailed surveys of the shelf between Goa and Bombay by echosounder, side-scan sonar and seismic profiling have demarcated a series of well defined NNW-SSE trending ridges, rising to a height of 2-5m above the seabed. These ridges are of algal, coral and shell limestones and extend out from the clay-sand boundary at a depth of about 50m to the shelf edge, and have been traced over a distance of over 150km along the shelf. Analysis of rocks sampled from these ridges showed that some contain up to 5% phosphate. The samples containing the phosphate were grey coloured irregular nodules (5-10cm) with protuberances and extensive irregular concentric borings which are typical of coralline algae. The X-ray diffraction showed the distinct 32.2% reflection of apatite (Nair, in press). This implies that phosphate enrichment is occurring and that richer and larger deposits may yet be discovered.

D. Seamounts: Bezrukov (1973) noted the occurrence of phosphorite on Christmas Island and so searched for phosphorites on the adjacent seamounts. During the 54th cruise of R/V 'VITYAZ' phosphorites were dredged from a seamount (13°45'S, 99°56'E; depth 3689m) on the Cocos Ridge in the west Australian basin. These consisted of phosphorite containing 22.7-32.5% of phosphate and limestone blocks with lenticular intercalations of dense white and unconsolidated brownish phosphorite. Bezrukov, Baturin and Bliskovskiy (1979) reported that the age of the coccoliths in the limestones of this seamount as Late Cretaceous and the sample included phosphatic breccias of different ages.

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

#### Projected demands and marine phosphorite resources

The estimated world resources of phosphates are about 25,732.10<sup>6</sup> tonnes; the production in 1977 was about 115.10<sup>6</sup> tonnes. The projected annual demand for 2000 is estimated to be 234.10<sup>6</sup> tonnes, so the onshore resources appear to be sufficient to meet the foreseeable requirements. The demand for phosphatic fertiliser will undoubtedly increase in the Indian Ocean countries because of their predominantly agricultural economies. The demand for phosphatic fertiliser in India (1982-83) was estimated at 1.6 10<sup>6</sup> million tonnes of phosphate whereas the production was only about a million tonnes. An effort is now being made in India to intensify exploitation of low grade land ores.

The phosphate content of many marine phosphorites is found to be <30% and include a higher percentage of metallic impurities; with enrichment the phosphorites may be upgraded to 31-33% phosphate. Land phosphate deposits contain 31-36% phosphate without enrichment. Hence, exploitation of the offshore deposits will be economically attractive only in regions where fair grade submarine phosphorite deposits of significant size are sufficiently close to local agricultural areas to offset the higher production and transport costs.

#### POLYMETALLIC NODULES

The first samples of polymetallic nodules from the Indian Ocean were collected by HMS 'CHALLENGER' (1872-1876). Wiseman (1937) described the manganese encrustations on basalts from the Carlsberg Ridge. Cronan and Tooms (1967) and Glasby (1970) carried out geochemical studies of the nodules and encrustations from the NW Indian Ocean and the Carlsberg Ridge, and found variations in the composition of morphologically similar nodules within a short distance. Cronan and Tooms (1968), found segregation of Mn-Fe oxides in the volcanic cores of manganese nodules from the southern flanks of the Carlsberg Ridge and suggested that leaching and reprecipitation of elements occurs within the volcanic cores.

and Moorby (1979) studied encrustations from seamounts from between the Carlsberg Ridge and Seychelles and Frakes and O'Brien (1980) studied the nickel-rich nodules from the south eastern Indian Ocean. Ocean-wide regional studies have been reviewed by Cronan (1980).

Frazer and Fisk (1980) observed greater enrichment of Mn, Ni, and Cu in the nodules from the equatorial radiolarian clay provinces than in the nodules from the pelagic clays and terrigenous sediments. Frazer and Fisk (1981) attributed copper enrichment to its concentration by planktonic organisms.

Mero (1965), Cronan (1972), Bezrukov and Andruschenko (1974), Siddiquie, Das Gupta, Sen Gupta, Shrivastava and Mallik (1978) and Cronan and Moorby (1981) synthesised the data on the polymetallic nodules in the Indian Ocean. Based on the distribution maps for Mn, Fe, Ni, Cu and Co they suggested that large areas in the basins east of the Chagos-Laccadive Ridge (Central Indian, West Australian and South Australian Basins) contain nodules with high percentages of manganese, nickel and copper and that the Central Indian Ocean appears promising for ore grade nodules.

The present study is based on over 800 chemical analyses from more than 300 different stations (Fig.26) in the Indian Ocean, obtained from the UNOET/SIO Data Bank (Table 7). These contain both published and unpublished data on nodule occurrences, abundance and chemical composition. Where a number of chemical analyses of nodules from a location were available the average chemical composition has been taken into account.

#### Distribution (Figs. 27-33)

The Indian Ocean has a complex structure (Sclater and Heirtzler 1977), with ten deep basins in which the water depth exceeds 4000m. The polymetallic nodules or encrustations occur in many of the deeper basins, on the upper slopes of many of the ridges and on the seamounts. Samples collected from more than 7000 locations have been used to estimate the area covered by the nodules to be 10-15.10 km<sup>2</sup>, and the total resources to be about 1.5.10<sup>10</sup> tonnes.

Bezrukov (1962) estimated that nodules cover as much as 83.2% of the sea floor in some areas which corresponds to an abundance of up to 43 kg.m<sup>-2</sup>. Glasby (1973) estimated that the distribution of nodules ranges from 5-200 nodules m<sup>-2</sup>. High abundances are generally reported from areas of low sedimentation, and Frazer and Fisk (1981) observed an inverse correlation between the nodule abundances and sedimentation rates. Cronan and Moorby (1976), Bezrukov and Andruschenko (1974) and Siddiquie *et al.* (1978) precluded the possibility of extensive nodule deposits in the Arabian Sea and the Bay of Bengal because of the high sedimentation. The sedimentation rates are lower in the Central Indian Ocean, Seychelles, Somali, Crozet, South Australian and the South Indian Basin where the nodules are most abundant. A nodule rich belt similar to the East Pacific is located in the Central Indian Basin which perhaps extends further east to the Wharton Basin.

A. Central Indian Basin: The basin ranges in depth between 4435-5399m and averages 5130m (Cronan and Moorby 1981). The sediment types are terrigenous sediments, pelagic clays, carbonate and siliceous oozes. The nodules are generally associated with siliceous oozes except in the southern area where they are associated with pelagic clays. Cronan and Moorby (1981) reported that the nodules associated with the siliceous sediments are enriched in Mn, Cu and Ni, with Cu:Ni ratios (>1.0), similar to the high grade nodules from SW of Hawaii in the Pacific Ocean (Frazer and Wilson 1980). The nodules associated with pelagic clays were depleted in manganese (15.4%, copper (0.34%, nickel (0.6%) and zinc (0.07%) but enriched in iron (12%, cobalt (0.17%) and lead (0.1%) compared to those associated with siliceous oozes. Nodules associated with terrigenous sediments are lower in Mn (14.2%), Cu (0.22%) and Ni (0.34%). All the nodules contain mainly todorkite.

Many workers (Bezrukov and Andruschenko, 1974; Siddiquie *et al.*, 1978; Cronan and Moorby 1981) have pointed out that the nodules from the Central Indian Basin generally have higher contents of Cu (0.74%), Ni (0.86%), Co (0.14%), Mn (20%) and Zn (0.1%) than those from other Indian Ocean basins and are comparable with the ore-grade nodules from the Clarion-Clipperton Zone of the Pacific. The concentrations of nodules ranges from 0.30-43.0 kg m<sup>-2</sup> (n=22).

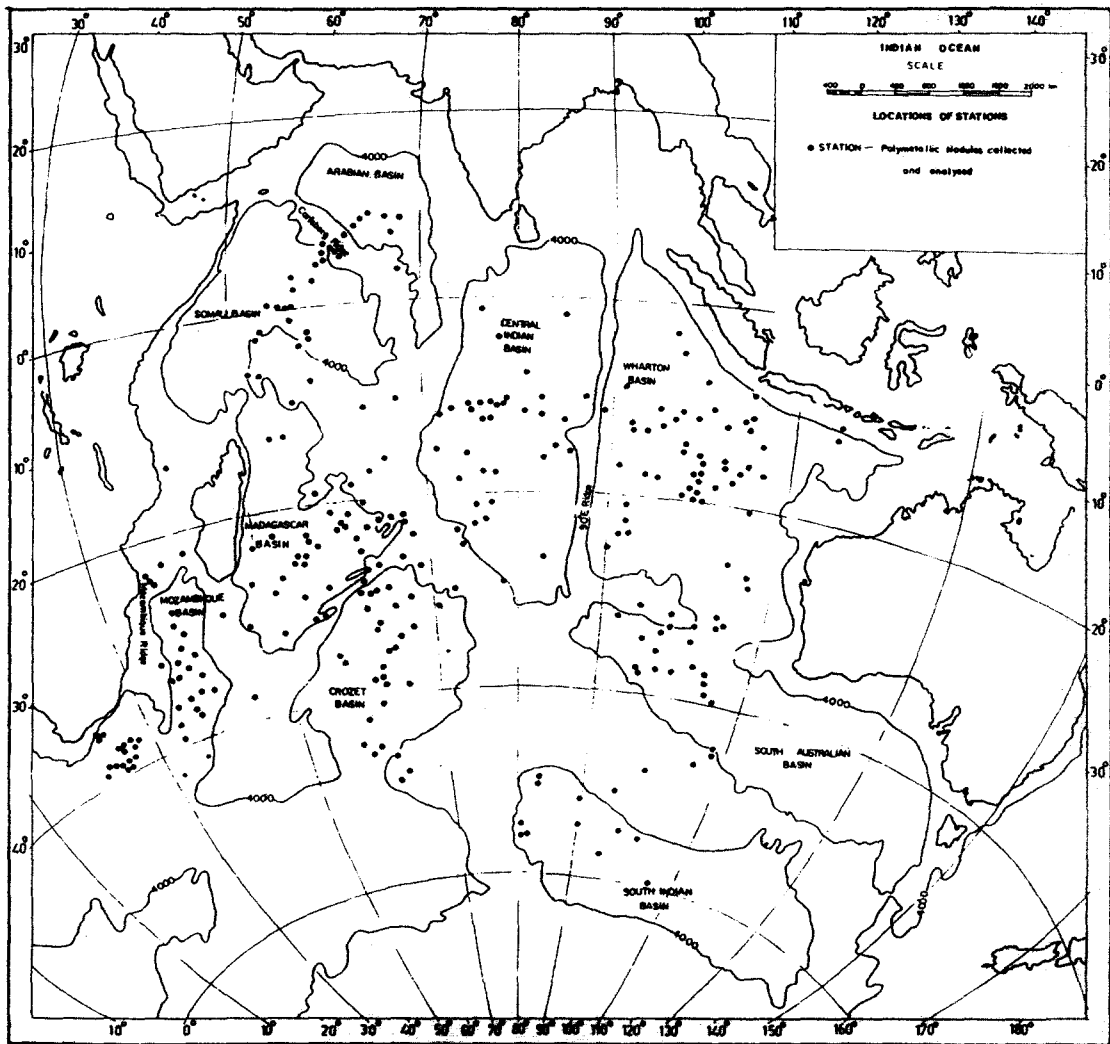


Fig.26. Map showing the locations of stations.

Table 7: Percentage chemical composition of polymetallic nodules from the Indian Ocean (From UNOET/SIO Data Bank).

Basin/Ridge	Number of Locations	Number of Analyses	Mn	Fe	Maximum values			Ni+Cu+Co
					Ni	Cu	Co	
Central Indian Ocean	48	84	35.0	30.0	1.6	1.2	0.8	3.6
Wharton Basin	81	105	35.0	25.0	1.1	1.1	0.7	2.9
South Australian Basin	13	25	-	-	-	-	-	-
Crozet Basin	31	68	20.0	25.0	0.8	0.4	0.5	1.7
Madagascar Basin	28	64	20.0	30.0	0.8	0.3	0.5	1.6
Mozambique Basin	46	101	30.0	40.0	1.2	0.4	0.7	2.3
Seychelles/Somali Basin	37	323	30.0	30.0	0.8	0.5	1.1	2.4
Carlsberg Ridge	28	73	-	-	-	-	-	-
Average Indian Ocean	299	818	-	-	-	-	-	-

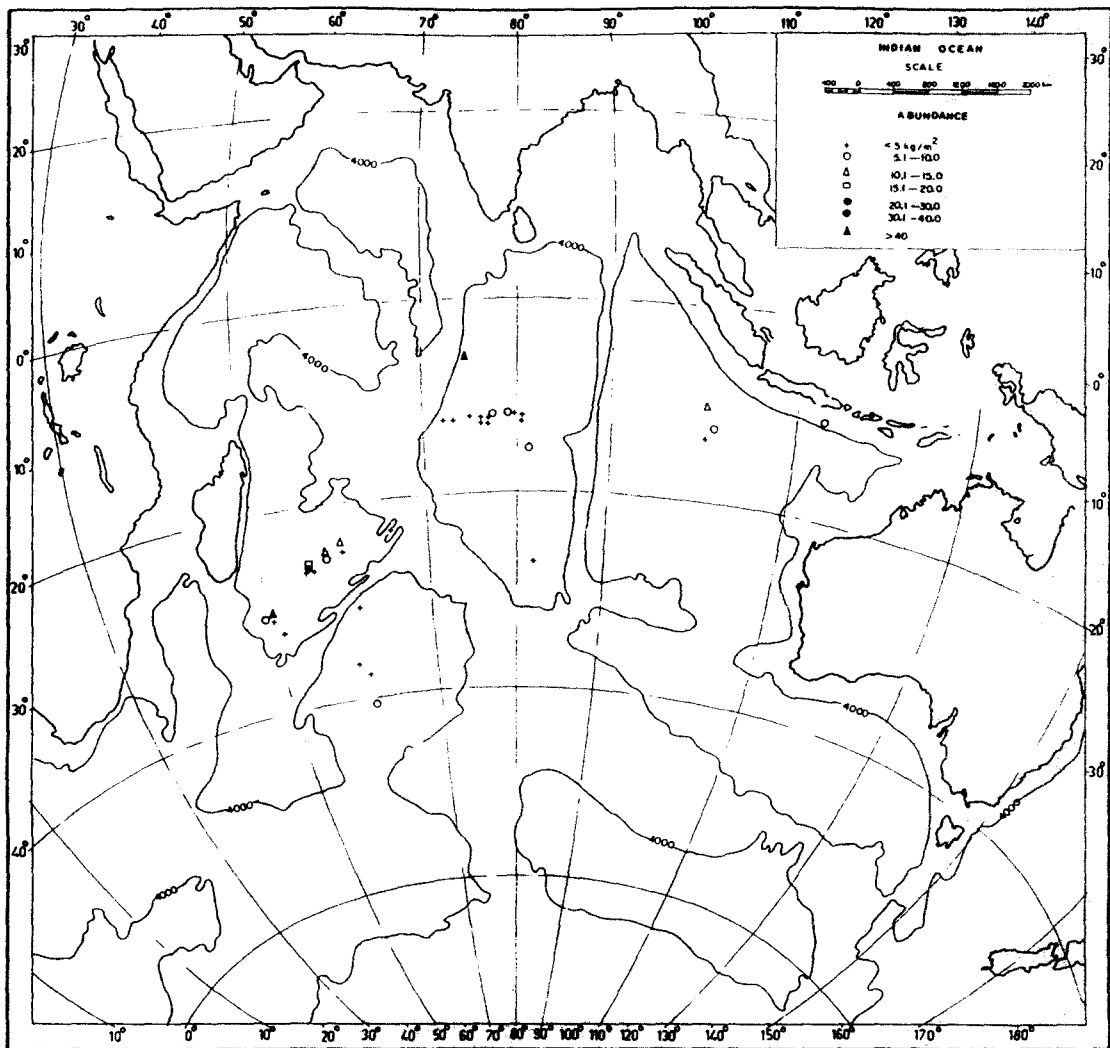


Fig.27. Map showing the abundance of polymetallic nodules

Frazer and Wilson (1980) indicated that para- and submarginal grades of nodules cover an area of  $0.7 \cdot 10^6 \text{ km}^2$  between  $10^\circ$ - $16^\circ \text{S}$  in the Central Indian Basin. 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, more detailed exploration is still necessary for the identification of a prime area and estimation of resources.

**B. Wharton Basin:** The depth in the basin is 4840-5990m and averages 5260m (Cronan and Moorby, 1981) so this basin is deeper than the Central Indian Basin. Cronan and Moorby (1981) found higher contents of Mn, Cu and Ni and lower content of Fe, Co and Pb in the nodules compared with the average contents of Indian Ocean nodules, but the variation in the chemical composition is more pronounced. Nodules associated with siliceous oozes contain higher concentrations of Mn (20.3%), Cu (0.56%), Ni (0.7%) and Zn (0.1%) and a higher Mn:Fe ratio (1.78) compared with those associated with pelagic clay (Mn 16.1%, Cu 0.26%, Ni 0.48%, Pb 0.07%, Zn 0.06%, and Mn:Fe ratio 1.4). Cronan and Moorby (1981) reported todorokite in the nodules from the Wharton Basin.

The data on the concentration of the nodules are scanty; with a range of  $<5-15 \text{ kg} \cdot \text{m}^{-2}$  ( $n=3$ ). The limited data suggest that the ore-grade nodules do not cover a large area.

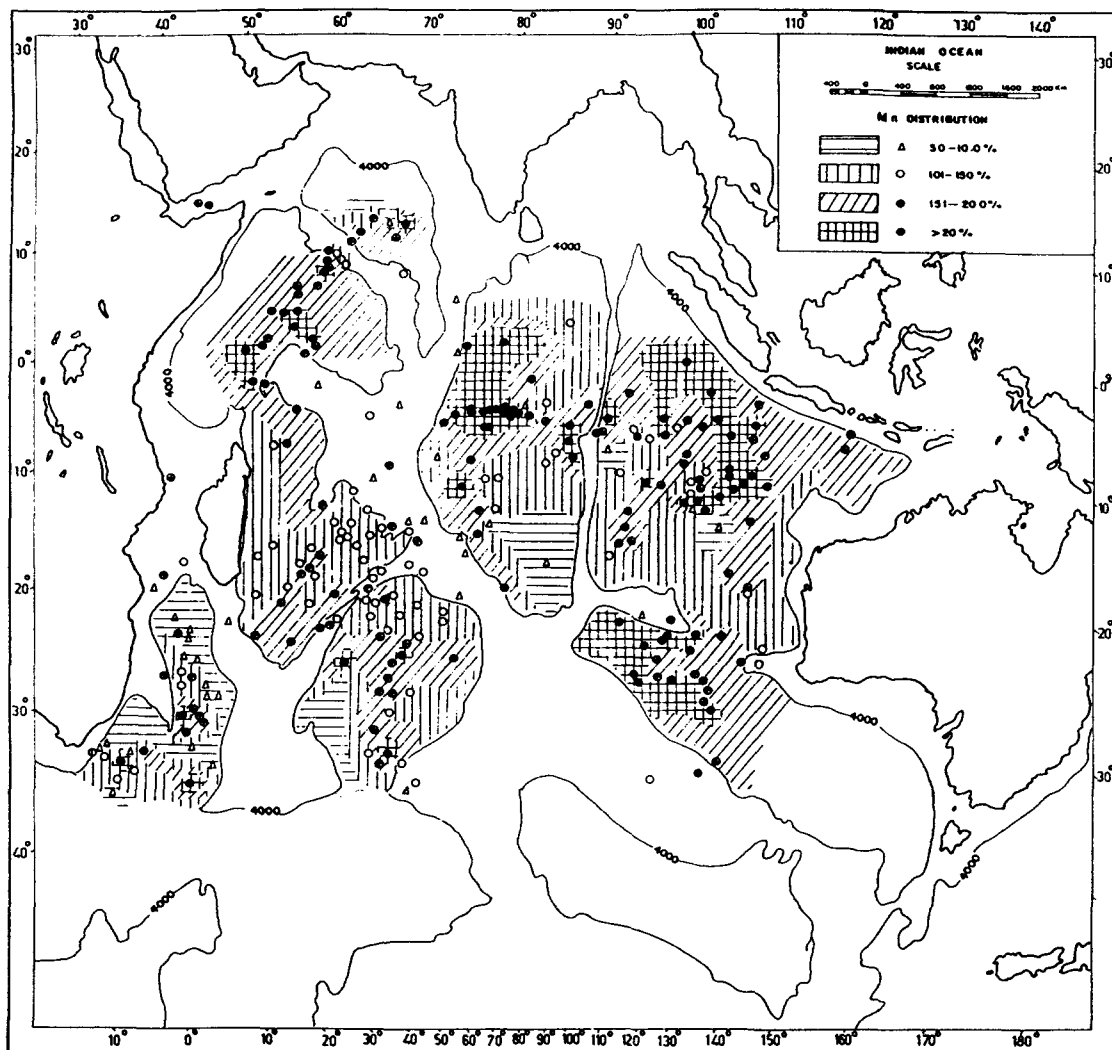


Fig.28. Map showing the distribution of manganese.

**C. South Australian Basin:** The basin depth varies from 4100-5967m, averaging 4710m (Cronan and Moorby 1981); the morphology of the basin has been described by Hayes and Conolly (1972). The sediments range from pelagic clays to carbonate oozes. The nodules in the basin have comparatively high average contents of Mn (19%), Ni (0.68%), Cu (0.34%), and Zn (0.08%) and lower Co (0.17%) and Pb (0.08%) (Cronan and Moorby, 1981). Nodules from carbonate ooze region are higher in 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 resources in the basin are submarginal (Kennett and Watkins, 1975; Frazer and Wilson, 1980).

**D. Crozet Basin:** The basin ranges in depth from 4050-5270m, averaging 4570m (Cronan and Moorby, 1981). The sediments include siliceous oozes, pelagic clays and carbonates, and the nodules associated with each sediment type show marked differences in the composition and mineralogy. Their average Fe, Co, Pb and Zn contents are comparable to the Indian Ocean averages, but their Mn:Fe ratio (0.79) is lower.

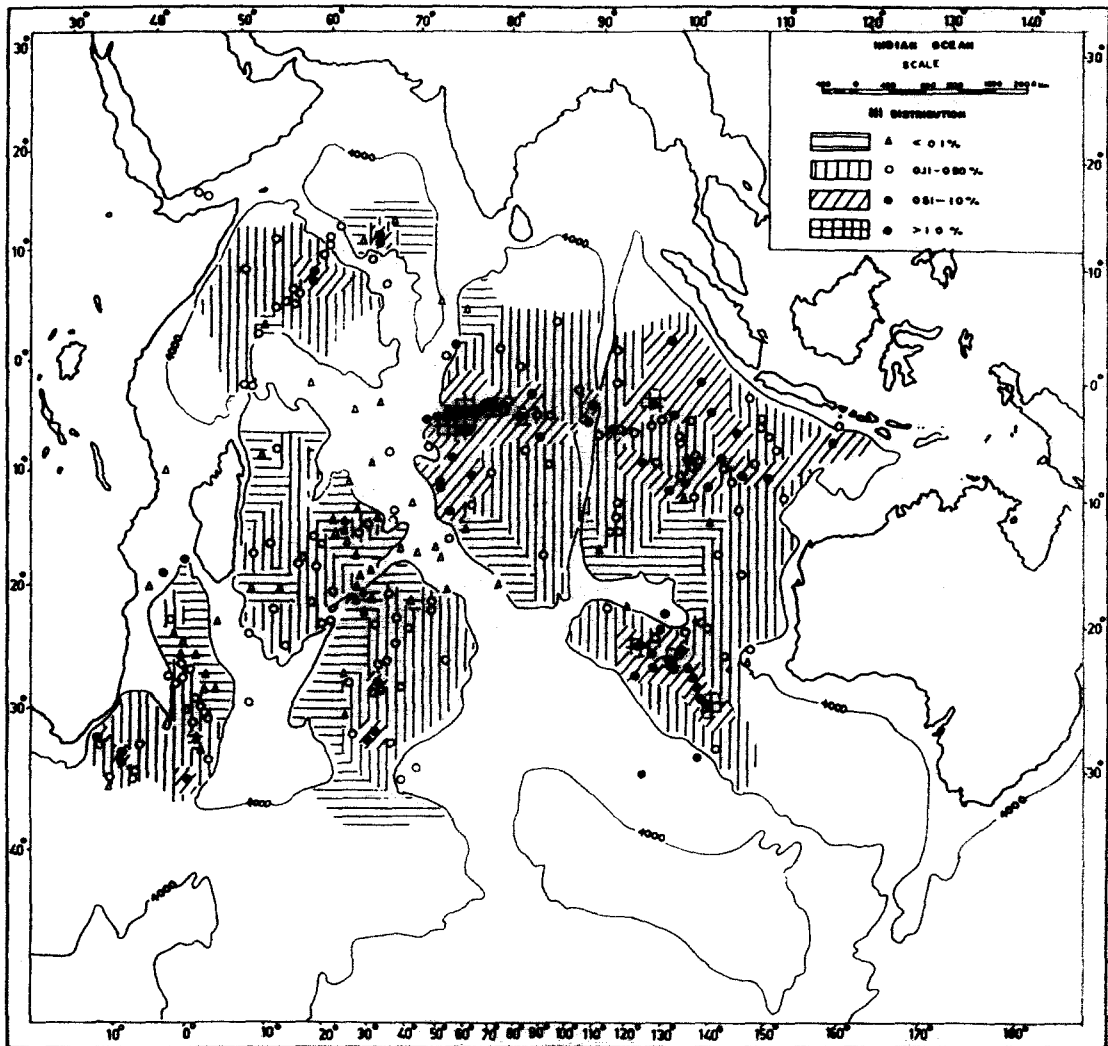


Fig.29. Map showing the distribution of nickel

The nodules from siliceous ooze have lower contents of Fe (9.4%) and Co (0.11%) but higher contents of Mn (14.2%), Cu (0.22%) and Ni (0.69%) which are also lower than nodules associated with similar sediments in the Central Indian Basin. The lower Mn and Mn:Fe ratio is attributed to the lower biological productivity in the basin (Koblentz-Mishke, Volkovionksy and Kabanova, 1970; Parsons, Takahashi and Hargrave, 1977). The average Ni values are near to that of the Wharton Basin and the Central Indian basin. Compared with the nodules associated with pelagic clays from the Central Indian Basin, the average contents of Mn(12.2%)

Cu (0.18%) and Ni (0.32%) are lower whereas the contents of Fe (15.6%) and Co (0.25%) are higher. Nodules associated with the carbonate oozes have higher Mn (13.6%), Co (0.18%) and Pb (0.1%) and lower Cu (0.11%) and Ni (0.38%).

Leclaire and Perseil (1978) found todorokite the predominant mineral in the nodules from the basin but in the nodules associated with pelagic clays the principal mineral is  $\delta$  MnO<sub>2</sub> and in those associated with carbonate oozes are vernadite and birnessite. The available limited data indicate that concentrations vary from >5-10 kg m<sup>-2</sup>



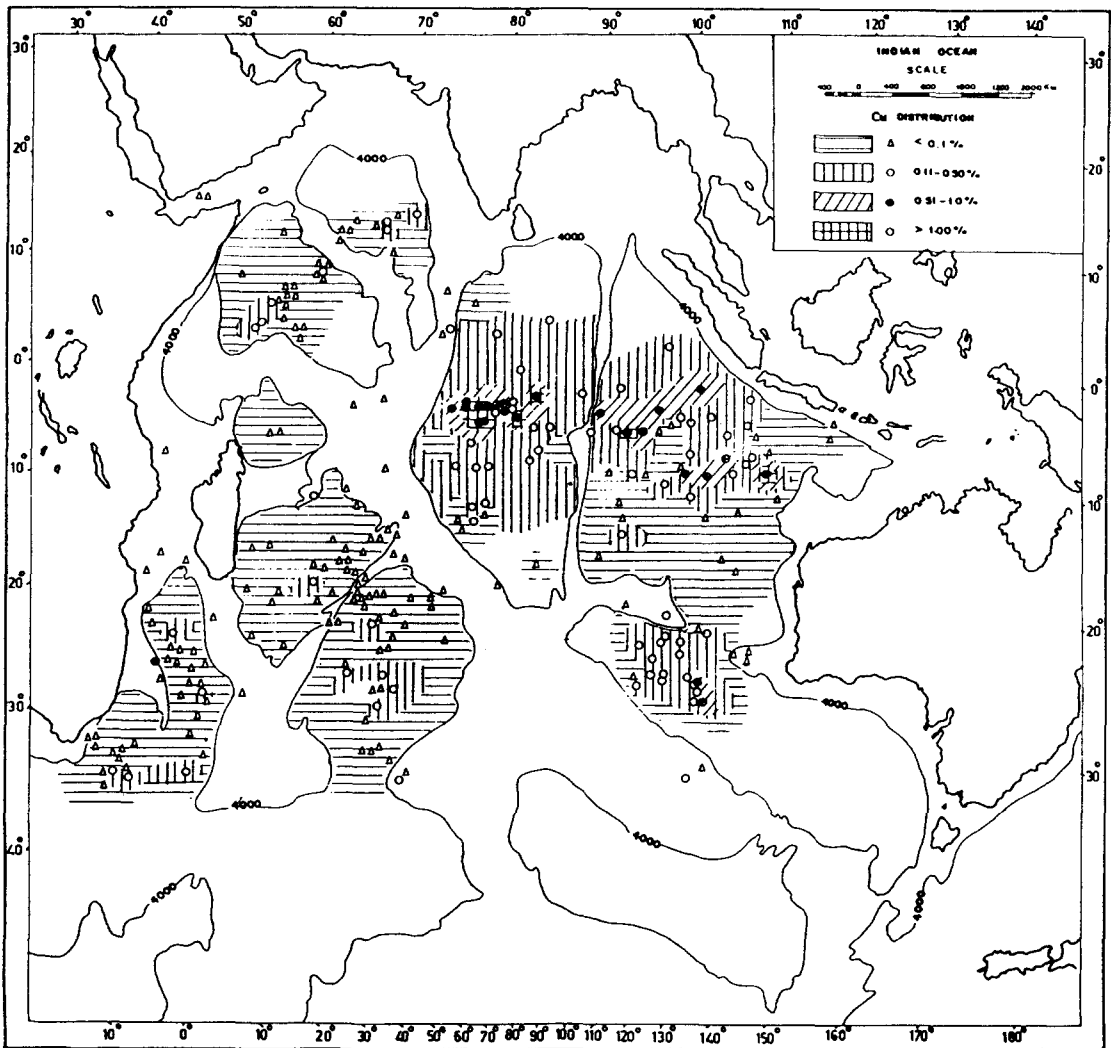


Fig.30. Map showing the distribution of copper.

**E. Madagascar Basin:** The basin depth ranges from 3967-5209m averaging 4620m (Cronan and Moorby, 1981). The nodules in the basin are characterised by low average contents of Mn (12.3%), Ni (0.21%), Cu (0.12%) and Zn (0.05%), but high Fe (16.4%) and Co (0.27%), whereas Mn:Fe ratio (0.75) is intermediate between the nodules of the mid-ocean ridges and seamounts and aseismic ridges, generally the composition is similar to mid-ocean ridge samples. The low Mn, Ni, Cu, and Zn values are similar to those of seamount nodules.

The sediments in the basin are carbonate oozes and pelagic clays and the nodules associated with these sediments show no significant compositional variations except for Co (0.31%) and Pb (0.12%) which are comparatively higher in the nodules associated with the carbonates. Koblentz-Mishke *et al* (1970) reported higher biological activity which is perhaps reflected in the higher Mn:Fe ratio (1.1).  $\delta \text{MnO}_2$  is common in the nodules from seamounts within the basin. The limited data suggest that concentrations vary from  $<5 - >40 \text{ kg m}^{-2}$  (n=12).

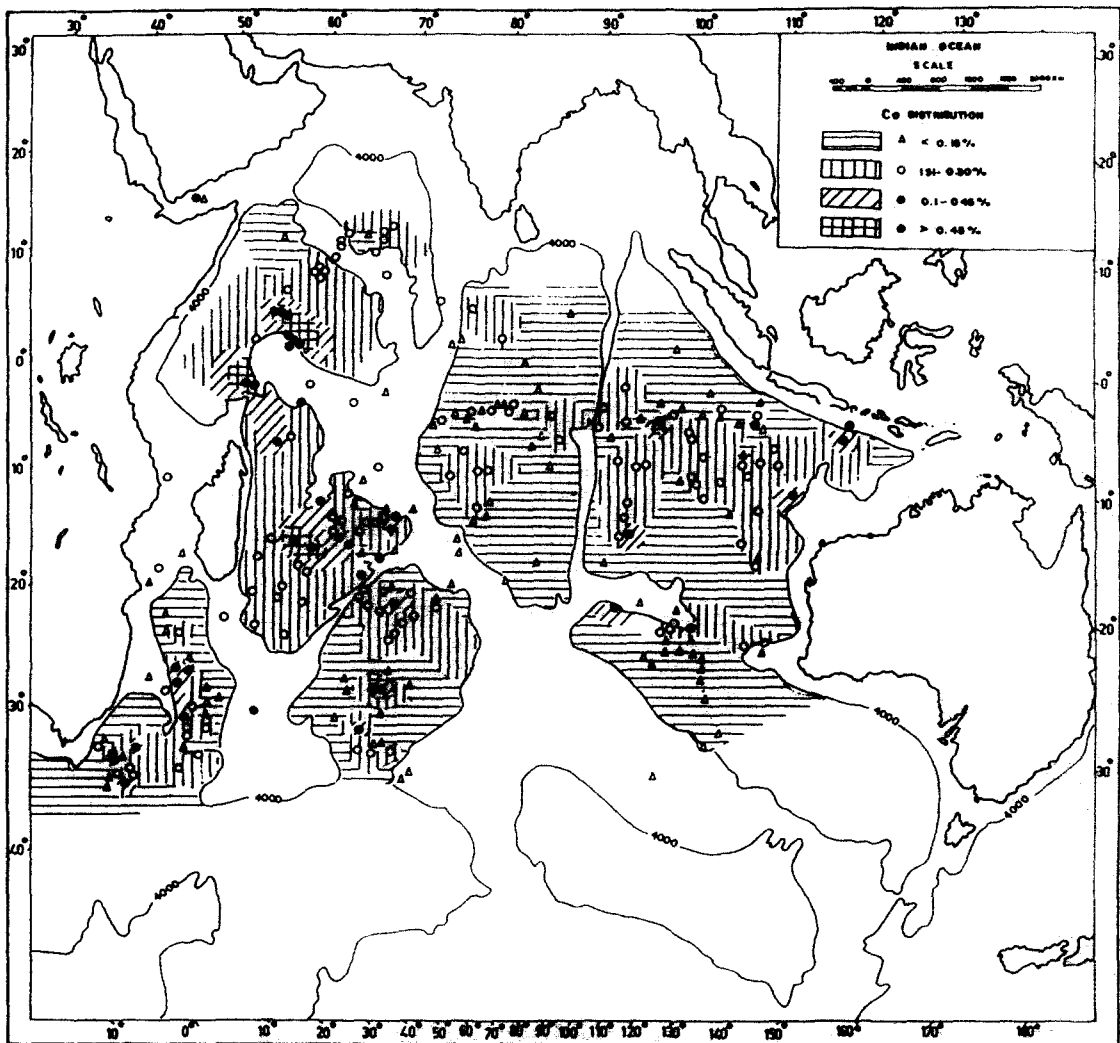


Fig.31. Map showing the distribution of cobalt.

**F. MOZAMBIQUE BASIN:** The basin depth varies from 4960-5450m averaging 4880m (Cronan and Moorby 1981). Vincent's (1972) limited data suggested that nodules are not widespread in the basin.

The nodules are characterised by large variation in Mn and Fe and the Mn:Fe ratios range from 1.0 (Mozambique Channel) to 1.21 (Mozambique Ridge). 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.

The nodules in the basin are associated with carbonate oozes and terrigenous sediments. The latter are higher in average Mn (11.9%), Fe (14.4%), Cu (0.19%), Ni (0.3%), Co (0.13%), Pb (0.12%) and Zn (0.06%) as compared to the nodules from carbonate oozes i.e. Mn (9.8%), Fe (13.2%), Cu (0.13%), Ni (0.2%), Co (0.12%), Pb (0.08%) and Zn (0.04%).

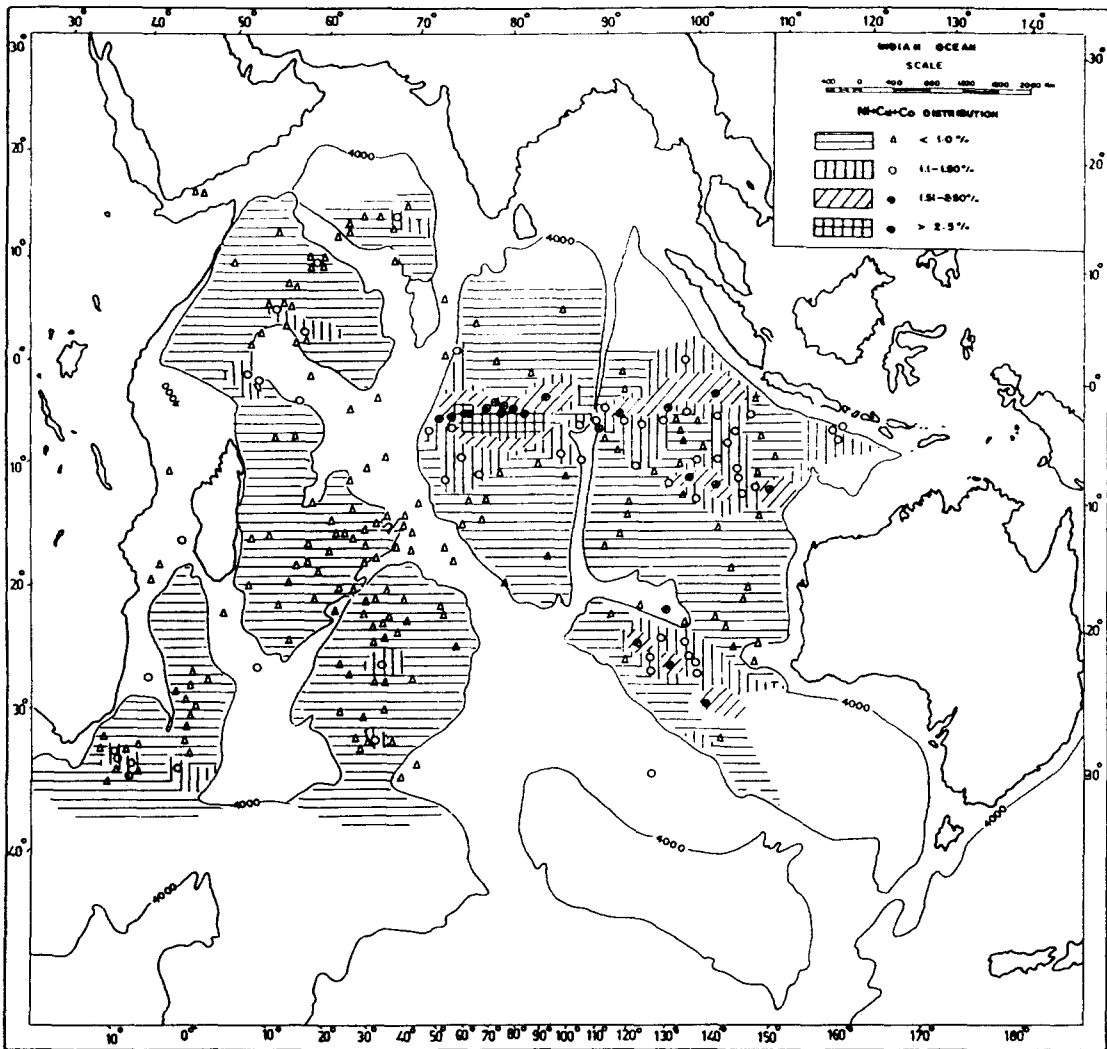


Fig.32. Map showing the distribution of nickel + copper + cobalt.

**G. SEYCHELLES-SOMALI BASIN:** The basin depth varies from 4190-4727m and averages 4500m. Cronan and Moorby (1981) reported average module contents of Mn (16%), Cu (0.22%) and Ni (0.41%) and Mn:Fe ratio (1.17), higher than reported for the Crozet, Madagascar and Mozambique Basins. Encrustations on seamounts in the northeastern part of the basin are enriched in cobalt (averaging 0.45%).

Carbonate ooze and pelagic clay are reported in the basin. Cu is higher (0.28%) in the nodules from pelagic clays whereas other elements are enriched in the nodules from the carbonate ooze. Cronan and Moorby (1981) reported todorokite in the nodules associated with different sediments.

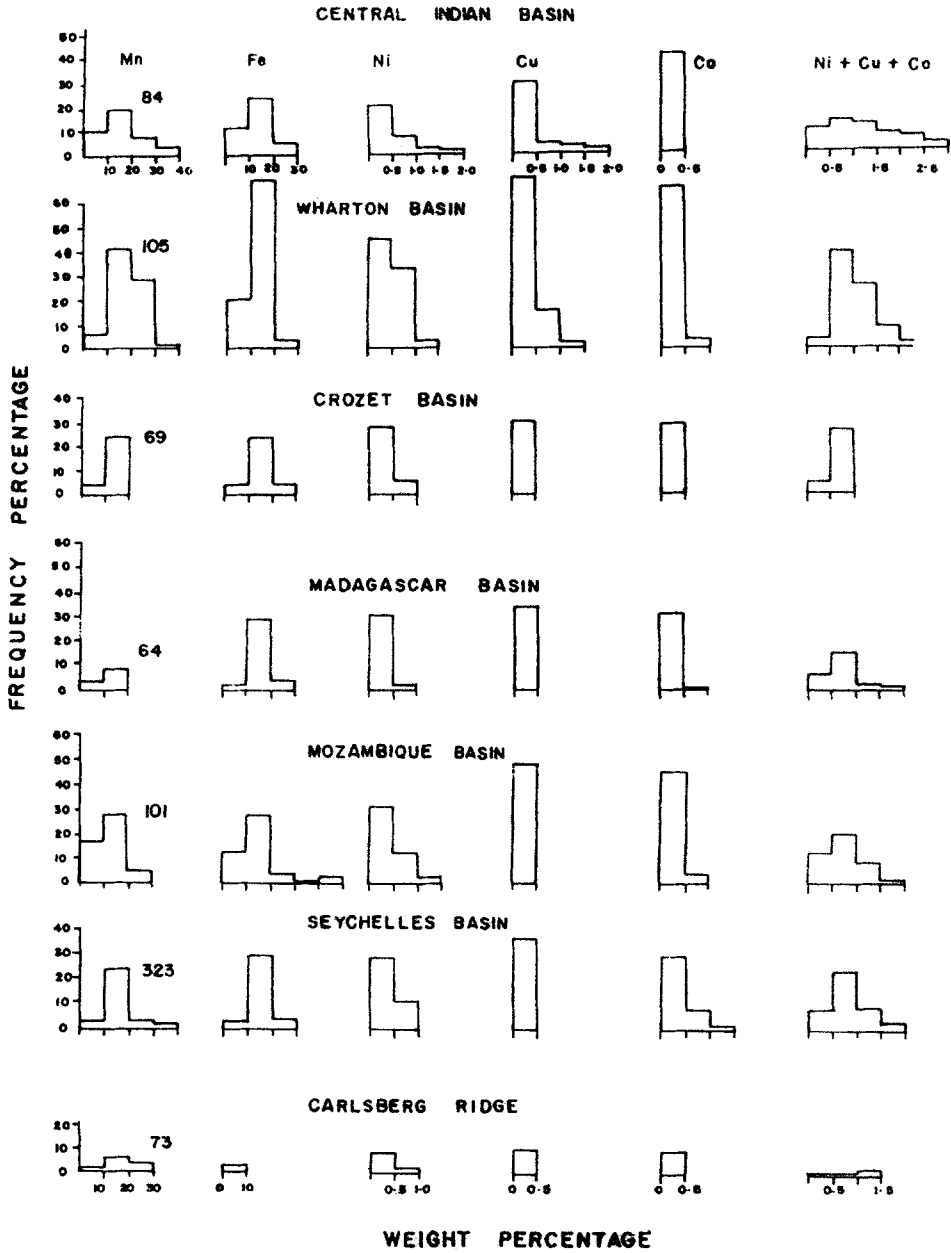


Fig.33. Frequency distribution of manganese, nickel, copper, cobalt and grade (Ni+Cu+Co).

## PROSPECTS FOR EXPLOITATION

Terrigenous deposits

Heavy mineral placers are reported from a number of localities on the beaches of the Indian Ocean. Placers of ilmenite, zircon and monazite are reported from the east coast of South Africa, ilmenite, zircon, rutile and monazite from the Mozambique and ilmenite, zircon and magnetite from Tanzania. Of these, only the offshore placers off Zambezi, Mozambique have been explored and the reserves are estimated at about  $55.10^6$  tonnes. In the north-western Indian Ocean, the climate is arid, the river runoff is low and the major rivers bringing the sediments are affected by large tidal ranges (in the Gulf), low wave and current activity and thus the environment is not conducive for the formation of placers. The beaches on the western shelf of India have placers of ilmenite, rutile, zircon, magnetite, ilmenite, zircon and garnet. The onshore reserves of ilmenite are estimated at  $138.10^6$  tonnes. The offshore extension of the placers on the western shelf has been explored and the deposits in some of the areas are many times larger than the onshore deposits. However very little exploration has been carried out on the eastern shelf. The beaches of Sri Lanka are well known for the placers of ilmenite, rutile, monazite, zircon and garnet and the reserves are estimated at  $4.10^6$  tonnes. Recently some detailed exploration has been carried out to map their offshore extension.

The beaches and estuaries of Burma, Malaysia and Indonesia have large placers of tin and these contribute substantially to the world production. Exploration has also confirmed the extension of these deposits to the offshore. The deposits in shallow areas are already being exploited but exploitation of deeper deposits would require development of technology. The west coast of Australia has large placer deposits (about  $108.10^6$  tonnes) of rutile, ilmenite, zircon, and monazite. The exploration of the deposits to the offshore has also been carried out and low grade (0.2-0.22% of rutile and zircon) deposits are estimated at  $375-500.10^6$  tonnes.

The heavy mineral placers on the beaches and offshore areas of the Indian Ocean are perhaps far more widespread and richer than on the beaches of other oceans. This is perhaps related to the source 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 volume of sediments by the large rivers. The heavy minerals are initially deposited as the rivers enter the sea and on the beaches where these are further sorted and concentrated by the 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 of the onshore placers have been explored but large offshore areas still remain to be explored. Exploration is undoubtedly necessary to assess the potential of the offshore deposits. A study of the quaternary history of the continental shelves, the rise of the sea level, distribution of sediments, especially the relict sediments is also necessary in areas where the placers occur. This would not only provide the data on the mineral potential of the shelf, but also a conceptual framework for the exploration for offshore placers.

Biogenous Deposits

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

In some islands in the Indian Ocean whose economies are largely dependent on tourism, restraint would have to be exercised for their exploitation. The exploitation of calcareous deposits is only possible in certain favourable areas, i.e. where there is a demand for cement or chemical grade limestones and the higher cost of offshore mining is offset by longer distances of transport or higher cost of imports. The pragmatic approach would be to work out the rate of regeneration of the sand on the reefs or lagoons or sustainable

yields of the shells and corals so as to regulate the exploitation to commensurate with the turnover rates. The scientific studies (biology, ecology and sustainable yields) of the reefs, lagoons, corals and shells would provide basic data and also lead to a regulation of their exploitation and their scientific management.

### Authigenic Deposits

**Phosphorites:** The favourable environmental conditions for the formation of phosphorites are upwelling, and non-depositional environment or minimal sedimentation. The continental margins of East Africa, Southern Arabia, Western India and the Andamans are marked by upwelling and some of these areas also coincide with non-depositional environments. These areas thus appear to be favourable for the exploration of phosphorites. The occurrence of phosphorites in some of these areas has also been confirmed, but systematic exploration has only been carried out on the continental margins of South Africa and India. The upwelling and non-depositional environments particularly off the Somali and the Arabian Coasts should be explored, and other areas where phosphorites are already known (western shelf of India and the Andaman Islands) need to be studied in detail to estimate the potential of deposits and investigate their origin and formation. The Indian Ocean has a number of seamounts and only a few (Eastern Indian Ocean and Error seamounts) have yet been explored.

**Polymetallic Nodules:** Polymetallic nodules in the Indian Ocean cover an area of  $10-15.10^6 \text{ km}^2$  and the resources are estimated at  $1.5.10^{11}$  tonnes. Both in terms of the area covered and the estimated resources the Indian Ocean is second only to the Pacific Ocean.

Analyses of the available data show that in most of the basins the nodules (concentrations  $> 5 \text{ kg m}^{-2}$  and grade  $\text{Ni}+\text{Cu}+\text{Co} > 2.47\%$ ) do not meet the requirements for first generation mine sites except perhaps in the Central Indian Ocean. The local requirements for metals, especially Mn, Ni, Cu and Co are small because of the low level of industrial activity in the region, but may rise in the future with increased industrialisation.

Most of the exploration for minerals even on the continental margins of the Indian Ocean has been carried out by the developed countries from outside the region and little work has been carried out by countries within the region. The development of capabilities within the region for exploration for mineral resources should receive a priority. The exploration and exploitation of the mineral deposits in the Indian Ocean will not only add to an inventory of its marine resources, but also lead to a greater understanding of the formation and development of marine mineral deposits.

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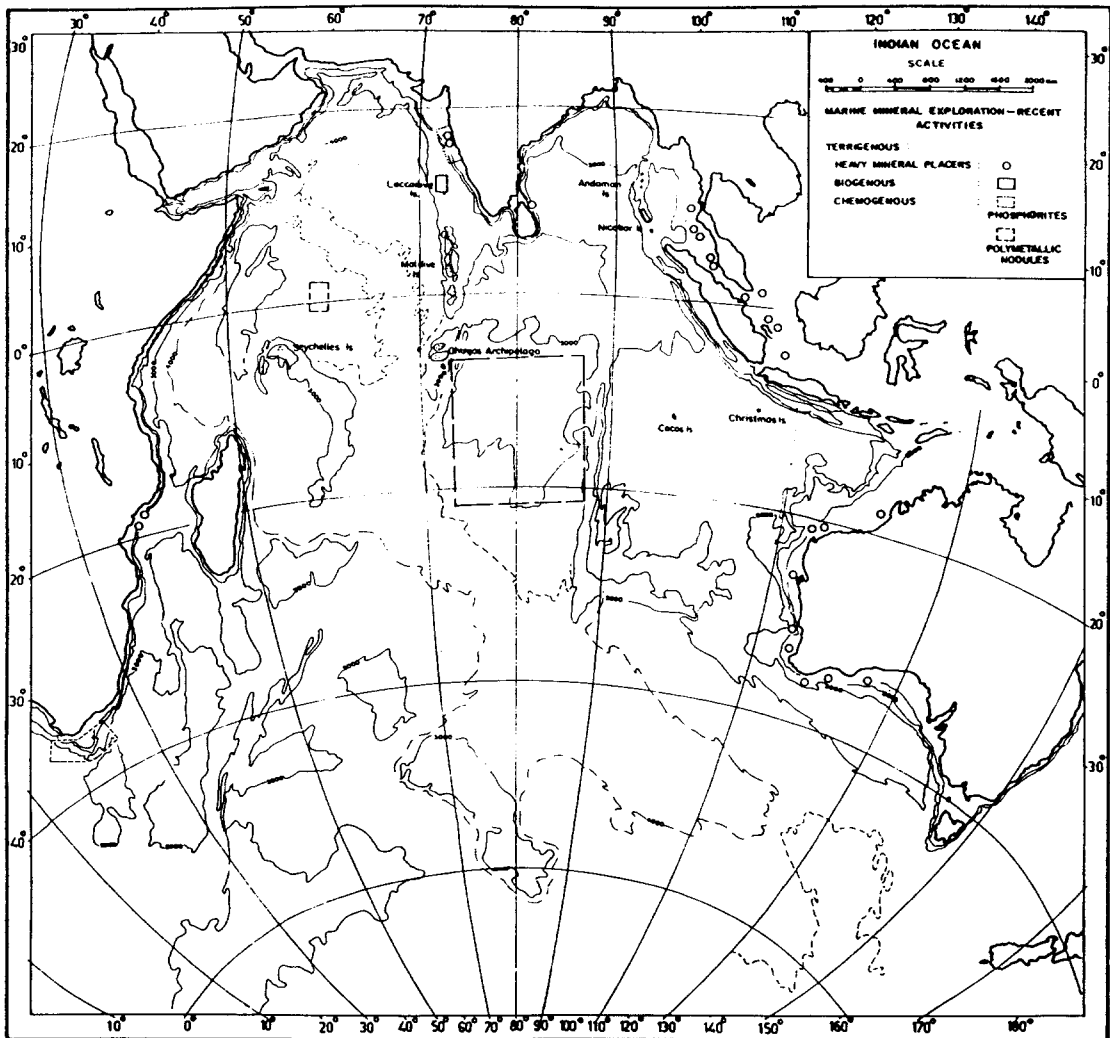


Fig.34. Marine mineral exploration/recent activities.

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