

MARINE GEOLOGY IN INDIA—A REVIEW

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Abstract

Marine geological studies in India date back to the late nineteenth century. These related to changes in sea level, studies of bottom samples (one of the first descriptions of barium and phosphorite nodules on the ocean floor) and topography. Similar studies were continued later by Indian Marine Survey Steamers. The organisation of studies and research in marine sciences at the Andhra University, Indian participation in the IIOE and later the establishment of the National Institute of Oceanography considerably enhanced the interest and facilities for oceanographic research in the country.

The studies in geomorphology included the interpretation of profiles of the continental shelves. These have now been extended to the preparation of geomorphological map of the western continental margin. The studies on sediments have led to the recognition of relict sediments on both the eastern and western shelves and subsequently the preparation of a bottom sediment map of the seas bordering India. Dating of the sediments from the relict zones and raised beaches have indicated lowered sea level at about 9,000 to 11,000 BP and higher levels at 6,000, 30,000 and 120,000. Considerable work has been carried out on geochemistry, the distribution of phosphate, organic matter and metals in the sediments and their partition patterns leading to the demarcation of zones of enrichment and concentration. In micropaleontology, most of the work has been carried on the taxonomy of foraminifera, and only a beginning has been made in studies of nannofossils and ostracoda. Explorations for

offshore minerals have indicated the extension offshore of heavy mineral placer deposits on the western shelf and large deposits of calcareous sands in the Laccadive lagoons. Studies on the samples of the Deep Sea Drilling Project (Site 219) have indicated that the lower part of the sequence (Palaeocene-Eocene), *i.e.* unit 5 is dominantly volcanic.

The national capability for marine geological work will be considerably enhanced when the new ship *RV Gayeshani* of the National Institute of Oceanography is available by the middle of 1975. The National Institute of Oceanography has drawn a programme of traversing the entire continental shelf and slope of the country at a uniform spacing and collection and samples on a grid pattern.

Introduction

The first works in marine geology in India date back to the last decades of the 19th century when geologists in the Geological Survey of India, analysed the ocean bottom samples (these included the descriptions of barium and phosphate concretions) collected by IMS *Investigator* and studied the changes in sea level in coastal areas. R. B. S. SEWELL, (1925-1937) Surgeon Superintendent of IMS *Investigator* studied the bottom samples and topography of the Bay of Bengal and Arabian Sea. In 1952 Andhra

University started teaching and research in marine sciences including marine geology. The International Indian Ocean Expedition accelerated the tempo of marine research and surveys in the country and a number of organisations increased their efforts in this field. The Government of India formed the Indian National Committee on Oceanic Research and the Indian Ocean Expedition Directorate was established under the Council of Scientific and Industrial Research to coordinate the activities of various organizations for the Indian Ocean Expedition. In 1966 the Directorate was re-designated as the National Institute of Oceanography. The article reviews the work carried out in marine geology in India, particularly emphasising the recent developments.

Cruises

In the absence of specially equipped vessels marine geological cruises have been carried out on naval or chartered vessels. These led to widely differing spacing of tracks and density of sampling (Fig. 1). It would be of interest to review the planning and organisation of these cruises as these form the basis for the interpretation and analyses of the data and samples collected. The earlier work in the nineteenth century was unavoidably based on stray samples. The work on the topography and sediments of the Bay of Bengal and Arabian Sea were carried out by SEWELL (1925-1937) on *IMS Investigator* and the location of the samples indicate a regular spacing and sufficient density for a regional investigation. Andhra University used naval ships for sampling and surveys; these covered a large area extending from Madras to the Swatch of No Ground but most of the sampling was carried out on a random pattern resulting in a concentration of samples in the vicinity of Visakhapatnam and a sparse distribution in other areas. During the International Indian Ocean Expedition, geological work was carried out during the 17th, 18th, 26th,

27th and 28th cruises of *INS Kistna*. Transects normal to the coast, were covered in some of the cruises; these gave a fair idea of regional variations in topography and sediments on the continental margin.

In the late 1960's the Geological Survey of India adopted a grid pattern and used this for surveys at the head of the Bay of Bengal, but off eastern Andamans due to some limitations random sampling was followed. For detailed mineral exploration in the Laccadive Islands the sampling and surveys were carried out on a close grid pattern on a scale of 1:5000 and 1:10,000. During the *INS Darshak* Oceanographic Expedition 1973-74 a grid of 15 miles was used.

Geomorphology

Coast: BLANFORD (in Ormston) 1878 noted that the submerged forest in Bombay indicates a depression or alternately a depression and elevation in recent times. FOOTE (1880) noted recent marine beds inland along the east coast and appreciated that the growth of the delta is not faster due to currents. VREDENBERG (1904) described the occurrence of oysters in (-1.5 m) Calcutta and stated that these could not have flourished much above the low water mark. The important contribution in this field has been the publication of AHMED'S (1972) text book on Geomorphology. The text book based on compilation of earlier work will be an useful reference material. The Indian Institute of Photo Interpretation and the National Institute of Oceanography have recently prepared a geomorphological map of the Goa coast based on aerial photographs and subsequent ground check. The studies indicate well defined sub-recent terraces with beach rock and conglomerate beds at heights of 5-40 m respectively. These appear to have been formed by a combination of changes in sea level and local movements. The NIO is now extending these studies to earlier aerial

photos, some of these dating back to late 1930 to decipher the recent changes in coastline and offshore features.

Geomorphology of the shelf and slope : CARPENTER (1885) and THORPE (1905) described the topography of the Swatch of No Ground. The former compared the data with the maps of the preceding 40 years and concluded that the banks have extended further south. MALLET (1887) showed that the Barren Island volcano rises from a depth of about 1600 metres and is surrounded by a mass of volcanic ejecta. OLDHAM (1895) described the topography of the Arabian sea in the neighbourhood of the Laccadives. SEWELL (1925, 1935) described the topography of the Andaman Sea, Bay of Bengal and the Arabian Sea. He stated that the Andaman sea comprises number of small basins, the ridge has a complicated topography and traced the evolution of the islands from anticlinal folds and from the gradual sinking of the basins to the east and west. SEWELL (1935) marked that the eastern flanks of the Laccadive ridge are steeper than the western and the ridge represents part of the land mass faulted down the west coast of India. RAO (1964) described the topography of some parts of the Bay of Bengal. According to LA FOND (1954), KUKUTESWAR RAO and LA FOND (1957) the continental shelf off Waltair is about 62 km wide, has a slope of 5' and a depth at the outer edge of about 200 metres. SUBBA RAO, VENKATRAM and CHANDRA (1967) and SUBBA RAO (1971) reported that some of the canyons between Visakhapatnam and Madras are older while the others originated during Pleistocene and have been maintained since then by slumps, density flows and slow creeps. SETTY (1964) described the submarine canyons off Madras, Porto Novo and Pondicherry subsequently. VARADACHARI, NAIR and MURTHY (1967) state that the Pondicherry canyon has a maximum depth of about 580 fathoms and the Palar about 700 fathoms. NAIR (1972) noted small scale irregularities

on the outer western shelf and concluded that these are algal and oolite ridges formed during Holocene. SIDDIQUIE and RAJAMANICKAM (1974) indicate that on the western shelf the shelf break occurs between 120-145 metres. They divided the continental shelf into regions of smooth (practically no variation), uneven (about 5 m) and rugged (upto 20 m) topography. The smooth topography on the Kathiawar shelf and on the inner shelf of Bombay has probably due to the deposition of recent sediments brought down by the Indus and Cambay rivers. The rugged topography on the outer shelf appears to be relict of the period of lowered sea level and subsequently the area remained outside the influence of the Cambay and Indus sediments. The NIO is now preparing geomorphological map of the western continental shelf and slope. SIDDIQUIE (1973) described the geomorphology of the Laccadive Islands. The roughly elliptical atolls are aligned NNW-SSE and NW-SE and most of these have "storm beaches" formed by cyclones on the east and lagoon on the west. The lagoons vary considerably in size—the smallest is about a km² and the largest 150 km². The larger lagoons have a complex topography, the central part of the lagoon is usually deep and encumbered with numerous coral knolls. This is bordered by shallow sand banks on reef margin. The development of banks is dependent on the absence of openings in the reef. The first break in the profile of the seaward reef occurs at about 4-8 m followed by a number of terraces at 7-12, 15, 21-36 (prominent) and 43-47 m. The prominent terrace at 21-36 m is equivalent to the 10-fathom terrace reported from other atolls.

Mud banks and mud volcanoes : KING (1884) and OLDHAM (1884) explained that the mud banks and their smoothening effect may be due to the discharge of mud from land, presence of oily matter derived from the tertiaries and currents carrying mud.

PHILLIPS (1890) related the mud banks to mud volcanoes and churning of mud by waves and its carrying in suspension by currents. It is interesting to note that recent work supports some of these explanations (SESHAPPA, 1953; NAIR, MURTHY and VARADACHARI, 1966). JACOB and QASIM (1974) reported that the mud in mud banks ranges from 1 to 300 μ and contains high carbon and phosphorus. COGGIN BROWN (1908, 1930) observed that the submerged mud volcanoes and eruptions are situated along a N-S alignment in the shallow offshore areas of Arakans. There is no connection with volcanoes or seismicity but the alignment indicates a weak zone and shock may facilitate release of pressure.

Sediments

SURFACE SEDIMENTS

Beach sediments : PRASAD RAO and LA FOND (1954) and LA FOND and PRASAD RAO, (1954) studied the annual cycle of sea level variation and beach erosion, MAHADEVAN and PRASADA RAO (1958) the evolution, SUBBA RAO and MADHUSUDANA RAO (1970) the sedimentation during a single tidal cycle and VIJAYAN, ASWATHANARAYANA and MAHADEVAN (1960) the sediment movement, on the beach at Waltair. They observed that the foreshore is eroded during the spring tide and the eroded sand deposited on the lower fore and offshore. The cycle is completed during neap tides when the sand returns to the sea approximately to its former level. The construction of a break water disturbed the equilibrium and thereby started a new phase in beach evolution. MURTHY, NAIR, PYLEE and VARADACHARI (1966) observed a similar cycle on the west coast at Cochin. AROGYASWAMI (1955, 1958, 1962) described the formation of cross current ripples and Eolian sedimentary features and occurrence of trap pebbles on Karikal beach. He suspected the occurrence of basaltic rock within the

reach of storm waves. SIDDIQUIE (1966) stated the predominance of sillimanite in the heavy minerals of dune sand of Balasore and concluded that the sands have been transported from the Mahanadi delta by longshore currents. KIDWAI (1971) brought out textural differences between dune and beach sands of Miramar. VEERAYYA (1972) and VEERAYYA and VARADACHARI (1975) from the studies of beach and dune sands at Calangute, indicated (i) distinct seasonal variations at all sections in statistical parameters which are confirmed by student's 't' test also and (ii) student's 't' test and bivariate plots reveal significant difference in sediments of different environments.

BORRESWAR RAO and LA FOND (1956, 1958) discussed the process of sand sorting and heavy mineral concentration on the east coast beaches. According to them the heavy minerals are deposited on the northern side of the river confluence. MAHADEVAN and SRIRAMDAS (1954) and BORRESWAR RAO (1957) concluded that due to greater wave height and consequent greater retrogression of the beach, removal of light sands takes place resulting in the concentration of black sand. Thus deposits of black sand are formed during storms in the Bay of Bengal which generate high waves. ASWATHANARAYANA (1964) concluded that the formation of heavy mineral beach sand deposits of the south-west coast of India is the consequence of cumulative operation of lithology, structure, weathering and erosion of geological formations, geomorphic history and sea level oscillations etc.

Coastal erosion, deposition and sediment movement : MAHADEVAN and PRASAD RAO (1956, 1958), LA FOND (1956), and MAHADEVAN (1957) studied the growth of sand bars and spits at the mouth of Godavari, the development of the Kakinada Bay and erosion at Uppada. The Godavari spit non-existent a 100 years back is now a full-fledged sand spit. The growth of the spit

has been the result of increased supply of sediments due to deforestation in the Godavari Basin. OLDHAM (1903) noted that the sand hills at Chifton, Karachi are related to the dredging in the harbour and disposal of the dredged material. MAHADEVAN and ANJANEYULU (1954) concluded that a good part of the dredged material in the Visakhapatnam harbour moves shoreward by wave action and currents. VEERAYYA, MURTY and VARADACHARI (1973) in their studies of artificially dumped material on the Baina beach observed that if any foreign material with different textural characteristics is introduced on the beach it does not affect more appreciably.

KARUNAKARAN and SIDDIQUIE (1966) reviewed the petrological methods for the study of movement of near coastal sediments and stated that regional patterns of sediment drift over a long period are better studied mineralogically subject to the availability of a suitable tracer. SIDDIQUIE and SRIVASTAVA (1970) evolved a technique using Rodamine B-500, Necol clear varnish and Duco thinner for coating sand. The method avoids inflammable liquids and baking at high temperatures and is not only simpler but also cheaper than the earlier methods. SRIVASTAVA (1969) evolved a mechanism for releasing tracers at the sediment water interface. SIDDIQUIE, SRIVASTAVA and VENKATESH (1969), SRIVASTAVA and VENKATESH (1969), SRIVASTAVA (1969), VENKATESH (1969), SIDDIQUIE and SRIVASTAVA (1970), CHATTERJEE, SIDDIQUIE, SRIVASTAVA (1970), carried out a number of tracer investigations and deciphered the direction of sediment movement at Haldia, Mangalore, Paradeep, Tuticorin and the Kavarati lagoon. NAIR, VARMA and PYLEE (1972) carried out similar studies at Moplah Bay.

Ocean bottom and shelf sediments : JONES (1887, 1888) described the barium nodules collected by IMS *Investigator* in a trawl off Colombo, while TIPPER (1911) described the phosphorite concretions dredged

from the Andaman Sea. CHATTERJEE (1927) analysed samples of green mud from the Laccadive sea and the Bay of Bengal. SEWELL (1925, 1935) described the topography and bottom sediments of the Bay of Bengal and the Arabian Sea.

SIDDIQUIE (1967) stated that large area of Bay of Bengal is covered by clay; sand, silt and silty clay are confined to a narrow margin along the coast, except in the Ganges-Brahmaputra delta where silt occupies a wide area and off the west Andaman coast where silty clay covers a large area. Foraminifera and calcareous fragments increase in the central and south-eastern parts of the Bay leading to a high calcium carbonate content in the area. The distribution pattern of different heavy minerals defines a number of terrigenous mineralogical provinces. Illite, kaolinite and montmorillonite are the prominent clay minerals with minor amount of mixed layer minerals and chlorite.

MAHADEVAN (1954), POORNACHANDRA RAO and MAHADEVAN (1955), MAHADEVAN (1956), LA FOND (1957), POORNACHANDRA RAO (1957), RAO and MAHADEVAN (1959), and POORNACHANDRA RAO (1964), summarised the work carried out by the Andhra University in marine geology. The study was based on 500 samples of bottom sediments from the eastern shelf of India extending from the Ganga delta to Madras. The important results were : (1) the delineation of the shelf off Visakhapatnam into 5 zones, i.e., sand zone, clay zone, shell zone, oolite zone and the mud zone beyond the continental shelf, (2) occurrences of coarse sediments and oolites on the outer shelf and their association with shallow water benthonic foraminifera, (3) presence of black sand concentrates in the inshore sediments. SUBBA RAO (1964) delineated carbonate sediments between Puri and Kakinada and stated that the oolites and foraminiferal shells were deposited when the sea level was lower, i.e., during the Pleistocene glacia-

tion. MURTHY and RAO'S (1971) studies of CM patterns also indicate differences in the sediments of the two zones. RAO and MURTHY (1968) traced the extension of this oolitic zone and associated shallow water benthonic forams on the outer shelf off Madras. NAIR and PYLEE (1968) and NAIR (1969) demarcated a similar relict zone with partly phosphatised oolites on the outer western continental shelf. NAIR (1971) reported that the fifty fathoms flat off Bombay has exposures of (beach rock lime) oolitic limestone. MAHADEVAN and SUBBA RAO (1955) and SUBBA RAO (1956) studied sediments of the Kalingapatnam—Gopalpur area and divided the shelf sediments based on grain size and carbonate content and observed that the shell content increases outwards and sand decreases. The silty sands with significant amounts of biotite were derived from the Vamsadhara and Langalya rivers. SEETARAMASWAMY (1968) described the sediments of the Kistna delta and Nizampatnam Bay. MALLIK (1965, 1968) and VENKATARATNAM (1968) studied the heavy minerals in the eastern shelf sediments between the Godavari and Kistna deltas and indicated that opaque sillimanite, garnet, zircon, hornblende and hypersthene are the predominant heavy minerals. SETTY and RAJAMANICKAM'S (1972) studies of heavy minerals of shelf sediments off Madras indicate these to be characteristic of charnockitic source. They interpreted the abundance of unstable minerals like hornblende and augite at depths of 50 and 131 m and lower values further deeper as indicative of rise and fall of sea levels. SIDDIQUIE and MALLIK (1972) studied the heavy minerals of two different fractions of a number of samples from the shelf off Mangalore and suggested southerly, south-westerly and westerly directions of mineral dispersal. On further trend surface analyses (linear, quadratic and cubic), they concluded that the mineral distribution and therefore the trends are controlled by source, river flow, currents and behaviour of mineral to processes

and suggested a process response model. According to MALLIK (1972) the opaque minerals of the shelf sediment in this are magnetite, ilmenite, goethite-lepidocrosite, rutile and pyrite, off which pyrite is authigenic and occurs in the clay zones at 6-7 m depth.

DTA of clays from the deltaic region of Krishna and Godavari rivers carried out by SASTRY, POORNACHANDRA RAO and MAHADEVAN (1958) show that the clays in the Godavari delta are mainly montmorillonite, illite and kaolinite while those in the Krishna delta are montmorillonite. NAIDU (1966) noted that Na-montmorillonite is dominant in swampy areas but kaolinite is encountered in fresh waters. SUBBA RAO'S (1963) studies of clay minerals in the eastern shelf sediments show that these are mainly illite, kaolinite and montmorillonite. SWAMY, PRASADA RAO and RAO (1971) report that montmorillonite is the dominant mineral in the modern deltaic sediments of the Kistna. NAIR and MURTHY (1968) indicate kaolinite is the dominant clay mineral in mud banks with minor amounts of montmorillonite and illite.

Geochemistry

SESHAPPA (1953) studied the distribution of interstitial (7-46 ppm) and adsorbed (4-801 ppm) phosphate and phosphorus in samples of mud near Calicut in different seasons and suggested that the adsorbed phosphate has been derived from the Malabar laterites. SESHAPPA and JAYARAMAN (1956) studied the composition of bottom mud in relation to the phosphate cycle in the inshore waters of the Malabar. The total phosphorus (600 to 2000 $\mu\text{g/g}$) has seasonal trends and is highest in the monsoon period, possibly due to the rapid release of phosphate in the overlying waters and large scale mortality of bottom animals. SHENOY (1960) observed an increase of phosphate in northern and western parts and decrease in the other areas of the Kaki-

nada Bay and concluded that the enrichment in the overlying waters is not significant. MURTHY and REDDY (1968) observed that the shelf sediments in the region between Swatch of No Ground and Chilka Lake are uniformly rich in their phosphorus content while the sediments in the region between Masulipatam and Pulikkat Lake are uniformly poor. MURTHY, REDDY and VARADACHARI (1968) studied the distribution of phosphate in the western shelf sediments in 5 sections normal to the coasts (Bombay, Karwar, Mangalore, Cochin and Alleppey) and found that the sediments of Kerala coast are comparatively richer in phosphate than in other areas. SIDDIQUIE and CHOWDHURY (1968) observed that the phosphate content in the shelf sediments off Mangalore and Bombay is related to the color and size of clays and suggested that upwelling and mass mortality better explains the higher content than derivation from laterites. RAMA MURTY, SESA RAO and POORNACHANDRA RAO (1971) reported that in the eastern Bay of Bengal sediments, phosphorus increases southwards and related this to high productivity and lack of terrigenous matter.

SUBBA RAO and MAHADEVAN (1957) and SUBBA RAO (1958) indicated that only on the outer shelf off Madras and Kakinada the sediments may be classified as carbonate sediments (>50% CaCO_3). The maximum spread is off Visakhapatnam where calcium carbonate increases from 5 per cent near shore to 75-80 per cent at a depth of 60 fathoms.

SUBBA RAO'S (1960) studies indicate that the fine grained sediments of the eastern shelf are richer in organic matter than the coarser ones. The organic matter content is lower than the world average due to low plankton production and dilution of humus by inorganic detritus. VENKATARATNAM (1968) showed that organic carbon in the clays increases with depth and its distribution depends on the texture of the

sediments and rates of organic production. MURTHY, REDDY and VARADACHARI (1969) state that on the western shelf, the inner shelf and the continental slope sediments are characterised by a higher content of organic matter compared to a lower content in sediments of the intervening areas. KIDWAI and NAIR (1972) observed that the distribution of organic matter in the shelf has a terrigenous and carbonate sedimentary facies. SETTY and RAO (1972) suggest a close relationship in the distribution of phosphate, carbonate and organic matter in sediment cores off Bombay-Saurashtra and the area is probably a favourable locale for formation of phosphate. RAJAMANICKAM and SETTY (1973) report a concentration of 0.5-5% P_2O_5 and a direct relationship with organic carbon in the sediments off Goa. This they relate to the large supply of terrigenous apatite brought by rivers and organic productivity etc. GANGULY and others (1972) observed that organic matter solubilises trace elements; adsorption of Zn, Mn and Co by a coastal marine sediment is 3-30 times higher than by the same sediment freed of organic matter, whereas adsorption of alkali and alkaline earth elements did not show any difference. The above authors also observed that humus contains a large number of trace elements in ash, and alkali and alkaline earth elements such as Sr, Ba, Ra are picked up in exchangeable cationic and non-cationic forms while trivalent and heavy elements are in complex combination mostly in non-cationic forms in the humic acid.

According to SUBBA RAO (1962) the manganese content of sediments (0.018-0.108%) on the eastern shelf decreases seaward and away from the coast. DURGA PRASAD RAO and POORNA CHANDRA RAO (1971) studied the distribution of Fe, Ti, Mn, Na and K and concluded that Mn is incorporated in the sediments by adsorption and precipitation. NAIDU, KRISHNA RAO and BORRESWARA RAO (1967) concluded that Mn is being fixed in clay-sized

sediments of the Godavari delta as ferri-manganic hydrate and decrease in Mn with increase of organic matter may be related to a progressive fall in oxidation potential. MURTHY, RAO and REDDY (1968) studied the distribution of manganese on the western shelf and observed a similar seaward decrease but reported a slight enrichment in the slope sediments which may be due to volcanism, chemical precipitation or biological extraction. DURGA PRASAD RAO, RAMAMURTY and POORNACHANDRA RAO (1970) studied the distribution in the sediments of the eastern part of the Bay of Bengal and concluded that in the distribution of manganese the amount of river discharge played a more important role than the prevailing environment. KRISHNASWAMY (1972) analysed the possibility of using Mn nodules for studying the rates of authigenic removal of trace elements to the ocean floor.

VENKATARATNAM and TILAK (1968) reported a comparatively higher content of Cu, Ni (particularly in the dark green clays) and Co in the sediments of Visakhapatnam region than other areas on eastern shelf. MURTHY, RAO and REDDY (1970) report that the fine grained sediments in the inner shelf and those on the slope contain higher nickel than the sediments of the outer shelf. Nickel co-varies with manganese and iron and a negative relationship is noticed between nickel, calcium carbonate and depth. GOGATE, SASTRY, KRISHNAMURTY and VISWANATHAN'S (1970) studies show that sediments with high potassium show higher values of manganese, calcium, cobalt, zinc, and copper which indicates that the elements are associated with a potassium bearing clay rather than carbonate. SITARAMASWAMY and MADHUSUDANA RAO'S (1971) studies indicate that in the recent sediments of Kistna delta the boron content increases from fresh water to estuarine and offshore region. RAO, MURTHY and REDDY (1972) observed a higher titanium content in the inner shelf and southern western shelf sedi-

ments and a general decrease towards the slope which they related to dominant lithogenous contribution. MURTHY, RAO and REDDY (1972), RAO, MURTHY and REDDY (1974) studied the partition of iron, manganese, nickel, cobalt and copper in the shelf sediments. They indicated that (i) concentration of elements in the total sediment samples of inner shelf region as well as their lithogenous and non-lithogenous fractions are relatively higher than those associated with their counterparts on the outer shelf and slope regions, and (ii) contributions made by the lithogenous fraction to the concentrations in the total sediment sample in the inner shelf region are higher than those in the outer shelf and slope region. Copper was found to have both a lithogenous and non-lithogenous component in the sediments. DURGA PRASAD RAO and POORNACHANDRA RAO (1973) indicate the abundance of most trace elements in the inner shelf sediments compared to the outer shelf suggesting different rates of detrital supplies of trace elements to the two areas. The trace elements in the shelf clays are primarily derived from the source detrital material. The concentration of Ge, Sn and to a lesser extent Ga and Pb are influenced by co-precipitation or absorption by organic matter.

Radioactivity: According to MAHADEVAN and ASWATHANARAYANA (1954) and Mahadevan, Sastry and Aswathanarayana (1957) low radioactivity in the shelf sediments generally corresponds to a high carbonate content and the deltaic sediments of the Ganga and the Mahanadi show higher radioactivity than the Godavari and Pennar sediments. The radioactive content is related to the mineralogy and environmental conditions. SRIKUMARAN (1964) studied the distribution of uranium (1.3-3.1 microgram/gram dry weight of sediments) in the sediments of the western shelf. Gross alpha radioactivity determinations indicated the existence of radioactive non-equilibrium between uranium-thorium and their

daughter products.

Chronology: PETERS (1955) suggested the possibility of using cosmic ray produced isotope Be^{10} for dating and subsequently KHARKAR, LAL, NARASAPPAYYA and PETERS (1957) reviewed the Be_{10} method for dating ocean sediments. LAL *et al.* (1960) detected the presence of Si_{32} in the spicules from silicious sponges. GOEL, KHARKAR, LAL, NARASAPPAYYA, PETERS and YATIRAJAM, (1957) studied the distribution of Be_{10} in a 15m core of sediments from the Pacific and gave a sedimentation rate of 5 mm/100 years. KHARKAR (1964) studied the distribution of Be_7 and Si_{32} in sea water and silicious sponges to determine rates of large scale circulation and rates of sedimentation. MOORE and KRISHNASWAMI (1972) described R^{228}/Pb^{210} methods for measuring coral growth rates; the former is applicable for the last 30 years and the latter for the last 100 years.

NAIDU (1968) reported a date of 10,800 \pm 155 years BP for the oolite occurring at a depth of 70 fathoms off the east coast. The deposition of recent deltaic sediments of the Godavari river was initiated around this period. RAO (1968) indicated a date 6,120 \pm 110 to 5,470 \pm 115 BP for the mud flats on which the rich heavy mineral sands of the barrier beaches were deposited. Based on C_{14} dating of *Ostrea Virginea* VENKATARATNAM (1970) surmised that the Chilka lake began forming about 3,750 \pm 250 years BP. NAIR (1974) reported an age of 9000-11,000 years BP for oolitic rocks from the outer western continental shelf. The sea level vs. depth curve for the western continental shelf shows apparent but no definitive similarities to global Holocene sea level fluctuations. GUPTA (1972, 1974) dated the unrecrystallised fossil corals occurring at 2-6 m above the present mean low tide level, on the Saurashtra coast (Western India) by $230Th/234U$ and $234U/238U$ methods. The measured ages fall in three groups of 6,000, 30,000 and 120,000 years

BP and represent high sea level strands in the Holocene and Quaternary.

Fauna

THEOBOLD (1872) stated that in raised beaches *O. cucullata* may indicate elevation from high water mark and creek oyster from low water mark. SEWELL (1935) studied the corals and coral formations in Indian waters. CHANDRA (1965) described the bryozoan in the bottom sediments collected from the eastern shelf. SUBBA RAO (1970) stated that the bryozoan population in the outer shelf indicate relict admixture.

BHATIA (1956), BHATIA and BHALLA (1959) and BHALLA (1968) described foraminifera from the beach samples of the western and eastern coasts of India. The assemblage on the west coast beach was regarded as characteristic of Indo-Pacific types, while the assemblage at Visakhapatnam includes elements of both Indo-Pacific and East African provinces and this was explained as due to intermixing of waters of the two regions. GHOSH (1966) described two species of *Asterorotalla trispinosa* from the Digha beach. GNANAMUTHU (1943) and DANIEL (1949) described the foraminifera from the Krusadi islands and reported 47 species. VENKATA RAO and SUBBA RAO (1971) studied the monthly variation in foraminiferal population from a tidal estuary. KAMESWARA RAO (1974) noted poor representation of living foraminifera in the lower reaches of Mandovi and Zuari estuaries and high species diversity in the Zuari estuary. On the basis of living to total population ratio, he suggested a rapid rate of sedimentation in the Mandovi and Zuari estuaries. GUPTA (1973) identified benthic forams from the Kavarathi lagoon.

GANAPATI and SATHYAVATI (1958) studied foraminifera from the shelf sediments off the east coast of India, identified 65 genera and 100 species mainly belonging to the families

Rotalidae, *Laginidae*, *Globigerinidae*, *Milliolidae* and *Buliminidae* etc. GANAPATI and SAROJINI (1959) studied the ecology of foraminifera of the Visakhapatnam coast. CHANDRA (1967) identified over 60 species of forams from eastern shelf sediments. SUBBA RAO and VEDANTAM (1968) and VEDANTAM and SUBBA RAO (1970, 1971) studied the foraminifera in the eastern shelf sediments and inferred that the fauna of outer shelf also contain shallow water fauna of periods of lowered sea levels. They also compared the fauna in surface and in cores to evaluate the extent of relict fauna in the outer shelf sediments. BHATT (1969) reported the occurrences of cold water planktonic foraminiferal species from the outer shelf of the east coast which he explained as due to glacial advance during the Pleistocene times and mixing due to the oceanic currents.

ALMEIDA and SETTY (1972) described agglutinated foraminifera from the eastern shelf and marked their particular abundance in fine sands at depths of 55-74 m. SETTY and ALMEIDA (1972) reported aberrant foraminifera from the eastern shelf.

KAMESWAR RAO (1970 and 1971) noted similarities in the foraminiferal assemblage of the Gulf of Cambay and the north-eastern part of the Arabian Sea. SETTY (1972, 1974) reported 22 species of planktonic and 32 species of benthonic foraminifera from the shelf sediments of Kerala. GUPTHA (1973) reported a mixture of recent and relict foraminiferal fauna on the outer shelf off Cochin. SETTY and GUPTHA (1972) identified *Globigerina pachyderma* in sediments off Karwar and Mangalore which they infer as an indication of influx of Antarctic cold water current. Subsequently SETTY (1974) discussed in detail the occurrence of the different forms of this species in the north Indian Ocean. KAMESWAR RAO (1972, 1973) compared the fauna of the Bay of Bengal and the Arabian Sea and noted a diversity of species in Arabian

Sea which he attributed to increased salinity which in the Arabian sea, and explained the mixing of high and middle latitude fauna due to the influx of Antarctic cold water and also to the spread of Red Sea water. ANTONY (1968), CHATTERJEE, GURURAJA (1968), SETHULAKSHMI AMMA (1958), described the foraminifera from the various localities on the western continental shelf. GUPTHA (1974) initiated microscopic and electron microscopic studies of nanno fossil in the sediments from the eastern Arabian Sea.

Sub-surface geology

The above review shows that most of the work on the marine geology of the continental shelf and slope was based on grab samples and short cores (about 5 m). These samples are not more than a hundred thousand years of the geological history of the shelf out of an estimated 175 million years. The lack of sub-surface data was in a large measure also due to the absence of a geophysical survey and lack of exploratory drilling on the continental shelf. One of the interesting features of the western continental margin has been the alignment of the Laccadive Islands and the likely continuation of this trend on the shelf and the shield. The interpretations varied from geologist to geologist (KRISHNAN, 1956; EREMENKO, 1966; EREMENKO and DATTA, 1968; HARI NARAIN, KAILA and VARMA, 1968). EREMENKO and DATTA (1968) indicated that the Indian shield extends as far west as the Laccadive Islands and western slope of the Laccadive ridge forms the transition between the oceanic and continental crusts. During Leg. 23 the DV *Glomar Challenger* drilled (Site 219) north of the Minicoy Island in the 9° channel. The site provides an interesting opportunity to study the geological history of this ridge (Initial reports of the Deep Sea Drilling Project). The detailed mineralogical, sedimentological and geochemical studies of this 411 m sequence carried out at the NIO (SIDDIQUIE, MURTHY, REDDY, RAO and VEERAYYA,) are briefly reported

here. The lower formations, *i.e.*, the Palaeocene and Eocene contain significant amounts of volcanic tuff which probably represents the early phases of Deccan trap volcanic activity. Some of these tuffs occurring with calcareous sediments like micarb chalk and oozes are evidently re-worked, while others are essentially tuffs directly deposited. The heavy minerals in these sediments are hornblende, garnet, sillimanite, kyanite and anatase indicating that at least part of the sediments have been derived from metamorphic rocks of the Indian shield. The clay minerals of the sediments specially in the lower parts (Unit 4 and 5) almost entirely consist of montmorillonite. The occurrence of montmorillonite, volcanic tuffs and associated anatase support a volcanic origin for the lower part of the sequence. The western continental shelf of India is a well known area of upwelling but the analyses for P_2O_5 indicate only low values excepting in Core 26 in lower Eocene. The occurrence supports the existence of upwelling in this area since at least the lower Eocene but the condition for formation of phosphate were only favourable when the terrigenous source was out off, biogenic sedimentation was low and the site was briefly at the continental shelf edge. The site started subsiding in the lower Eocene and finally by the end of Eocene, it was well in the deep waters. The distribution of other elements indicate that organic carbon has been fairly uniformly distributed throughout the entire column, while Mn, Fe and Ti increases appreciably in unit 5 in the volcanic material. The distribution of Fe and Ti broadly follow the variation in detrital material while Mn does not follow—indicating a possible different source.

Mineral Exploration

CHATTERJEE, KARUNAKARAN and SIDDIQUIE, (1968) presented a programme for exploration of the continental margin of India and an appraisal of the existing data.

MAHADEVAN and POORNACHANDRA RAO (1953, 1955) discussed the economic potentialities of the sediments of the east coast of India, NAIR (1971) reviewed the mineral potentialities of the western shelf and considered the outer shelf favourable for occurrence of unconsolidated deposits.

Terrigenous deposits : Occurrences of heavy mineral sands along the Kerala coast are the most important and best known (TIPPER, 1914; BROWN AND DEY, 1955). In the black sands occurring in an area extending from Quilon to Cape Comorin, the deposit is estimated to contain 17 million tonnes of ilmenite, 1 million tonnes of rutile, 1.2 million tonnes of zircon and 0.12 million tonnes of monazite. Similarly beach sand deposits with varying proportions of monazite, ilmenite, zircon and garnet have been described from the Ratnagiri (KRISHNAN and ROY, 1945; and ROY, 1958), Tinnavalli, Ramnad and Tanjore districts of Tamilnadu (JACOB, 1956), Visakhapatnam, Yarada, Waltair, Bhimuniapatnam areas of Andhra (MAHADEVAN and SRIRAMDAS, 1954; MAHADEVAN and RAO 1958; MAHADEVAN and RAO, 1950) and the coastal areas of Orissa (officer of GSI, 1949). The occurrence of heavy mineral placers on the coast is the most important clue for the search of submerged placers in offshore areas. PRABHAKAR RAO (1968) reported the extension of some of the heavy mineral placers to shallow offshore areas of Kerala. Recent work at the National Institute of Oceanography (SIDDIQUIE, VICTOR RAJAMANICKAM and ALMEIDA, 1974) has indicated that samples of sand from offshore areas of Ratnagiri show significant enrichment of ilmenite (1.7-9 per cent).

Biogenous deposits : Deposits of sea shells, corals and calcareous sands occurring in coastal areas have been utilised on a small scale from early historical times for making whitening and lime for local construction of houses. The best known deposits are in the Gulf of Kutch and in the Vembanad Lake, Kerala. The present pro-

duction from the deposits is about two million tonnes. The deposit in the Vembanad Lake has a reserve of 17 to 25 million tonnes. Another 0.4 to 0.5 million tonnes of lime shell are reported to occur in the Kadarundi and a million tonnes in the lower reaches of Pullet and Thatapalli rivers. SIDDIQUIE and MALLIK (1973) carried out a detailed survey of the lagoons and shallow offshore areas of the Laccadive Islands. The surveys indicated the occurrence of 288 million tonnes of calcareous sands in the lagoons to a depth of about 1 metre below the lagoon floor. The inferred reserves in some lagoons where no detailed surveys could be carried out are of the order of 423 million tonnes to a depth of 1 metre. The reserves at greater depth are expected to be many times more and the inferred reserves in the lagoons between 1-2 metre below the lagoon floor are about 712 million tonnes. These sands are of good quality and contain low silica, alumina and iron. MgO is the only impurity and it is interesting to note that the MgO content in the lagoon sands is related to the proximity to the reef. The sands can be utilised for cement, lime, glass, paper and chemical industries.

Chemogenous deposits: The chemogenous deposits reported from the ocean floor in the vicinity of the country are barium nodules described by JONES (1887 and 1888) and phosphate nodules described by TIPPER (1911) off north-Andamans. There is not likely to be large interest in exploration for barium nodules in the near future because it is a low priced commodity. In the late 1960's a number of organizations carried out sampling for phosphorites on the continental shelf of the country, particularly in the vicinity of the reported occurrence of north-Andamans, but the results have been negative. Mn-nodules cover a large area in the Indian Ocean next only to the Pacific. Mn nodules collected by Soviet and United States research vessels from the Indian Ocean were studied in detail by SIDDIQUIE and others (being submitted).

The studies included microscopic, DTA, X-Ray and analyses for major and minor elements. In polished sections the nodules show characteristic colloidal texture around a central nucleus with intervening beds of gangue. Its texture is better defined in the inner layers than the outer ones. The DTA curves of the samples from different stations and also from different parts of the nodules are similar with an endothermic at 120-130°. With the increase in the rate of heating the peak temperature also decreases and in inert atmosphere the peak is delayed and compressed. The curves are similar to those of delta MnO₂.

Processing of data

KARUNAKARAN and SIDDIQUIE (1971) prepared a format of an edge notched card for marine geological data. Recently the National Institute of Oceanography using the earlier format has processed the ship-board geological data collected during the INS *Darshak* 1973-74 cruises.

Synthesis of data

With the increase in work, there is a considerable scope for synthesising of the data and preparation of maps depicting various geological features of ocean floor. SEWELL (1925-1927) showed the sediment distribution in the Bay of Bengal and the Arabian Sea, on a small map. More recently the Geological Survey of India (SIDDIQUIE, SRIVASTAVA, MALLIK, VENKATESH and RAY, 1972) compiled a bottom sediment map of the seas bordering India (1 : 2 million). The map shows bottom composition based on 15,000 bottom notations from navigational charts substantiated by description of 3,200 bottom samples. In addition it also shows mineral occurrences classified as terrigenous, biogenous and chemogenous. The age of the sample with the height and depth above or below sea level and in case of cores the horizon has been shown. The method of dating C¹⁴, Th²¹³

or U^{234} is also depicted. Besides depicting the general distribution of sediments, rock and coral on sea floor the map brought out the following interesting features: Occurrence of an extensive sand zone (Pleistocene) of relict sediments on the outer western shelf. A similar zone of relict sediments is shown on the eastern shelf but this has been largely covered by clayey sediments brought down by the rivers. The extensive occurrence of rock and corals on the western shelf indicates low terrigenous sedimentation. The occurrence of corals on the outer western shelf and in some cases the occurrence of decayed coral indicates an ancient reef which probably thrived at a period of lowered sea level. Possibly the reef acted as peripheral sediment dam on the outer shelf. RAO (1972) prepared an accompanying map (1:5 million) showing the coastal land forms of India.

With the expanding activities in offshore exploration and marine geology, it was felt necessary that the scales and projections for offshore geological maps should be standardised. The Working Group on Offshore Mineral Exploration adopted a scale of 1 : 1 million and 1:250,000 for regional and detailed maps. Based on the interpretation of the geology of land areas KRISHNAN (1968) and AHMED (1968) discussed the evolution of the Indian coastline and the origin of the Indian Ocean. KRISHNAN (1968) concluded that the peninsula acquired its shape during the upper Jurassic to Cretaceous. The separation of India from Madagascar in the upper Cretaceous led to the intermingling of the Mediterranean and Indo-Pacific faunas. The fracture which was responsible for this separation apparently extended north to the Gulf of Cambay and beyond in the early Eocene. A marine regression in the Oligocene was followed by a transgression in the Miocene. The west coast was finally faulted down in the late Pliocene with simultaneous uplift of the southern part of the peninsula. AHMED (1968) concluded that the earliest

break came in the Triassic in the SE Africa-Tasmania-Victoria land region. It was followed by a break of India-Australia-Antarctica from Africa in the Cretaceous and the former block soon started rotating anticlockwise; immediately after this, Australia-Antarctica broke away from India.

Future

The above review has shown, though marine geological work in India dates back to the nineteenth century but the progress has been slow and much remains to be done. The main reason for the lack of progress was the non-availability of suitably equipped ships for marine geological work. Most of the work was carried out from naval ships or chartered vessels. With the acquisition of a multi-disciplinary oceanographic research vessel by the National Institute of Oceanography, the situation will change fast. It is expected that with coordinated efforts of a number of organizations in this field a reconnaissance of the geology of the continental margin can be completed within the next 4 to 5 years. The Institute's research vessel *RV Gaveshani* (Sanskrit 'Research') is undergoing refit in the Garden Reach Workshop, Calcutta and is likely to be operational by mid-1975. The vessel is 68 metre long, 12 m broad and has provision for 13 scientists and 6 technicians. The vessel will have a number of laboratories for physical, biological, geological, geophysical and chemical work. The vessel will be equipped with satellite positioning, sub-bottom profiling, magnetometer and facilities for coring and dredging. Provision is also being made for installation of a suitable light drill for drilling in hard rocks. The proposed programme of the NIO for geological and geophysical work (Fig. 2) envisages traversing the entire continental margin of India at tracks spaced at 20 km so that the spacing is sufficient for incorporation of data on the existing 1:2 million maps of India. This programme will involve cruising over 75,000 line-km, collec-

tion of 5,000 samples and about 22 months ship time.

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