Geomorphology and surficial geology of the western continental shelf and slope of India: A review

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The geomorphology and geology of the western continental margin of India have become better known only after the International Indian Ocean Expedition (1962–1965). The continental shelf of western India is wide off the river mouths, becoming narrower south-eastwards and narrowest on the SW margin. Shelf break occurs at depths between 60 and 150 m. The Fifty Fathom Flat is a prominent feature on the outer shelf. Submarine terraces at depths between 35 and 170 m and shelf edge reefs are also present along the margin.

Coastal geology and geomorphology of the area and nearshore currents played a significant role in the distribution of placer minerals off Kerala and Maharashtra. Transport and sedimentation of fine-grained materials at places on the shelf are influenced by high-energy conditions. Clay minerals derived from the Indus, Deccan Trap basalt and Gneissic provinces are distinct along the inner shelf, but bypassed the outer shelf and got deposited on the continental slope. Relict biogenic carbonates comprising *Halimeda* litho-facies, rhodalgal-coral facies and molechfer facies, occur in the northern, central and southwestern shelf, respectively. Terrestrial limestones described as palaeo-shoreline indicators occur at mid-shelf. Several evidences exist in favour of Late Quaternary neotectonic activity and subsidence. Phosphorites and phosphatized limestones occur on the shelf and slope and phosphatization seems to be a short event in the Early Holocene. Verdine and Glaucony facies occur on the shelf and slope of the central and southwestern margin of India.

Systematic sampling/radiocarbon dating is lacking on many geomorphic features. Some coastal bays in Maharashtra are least explored for heavy minerals. Phosphorites at places could prove economic, if detailed exploration is done. Several gaps exist in the data on sea level changes during the Late Quaternary. Shelf edge exchange processes are to be studied in understanding the organic carbon distribution. Attention should be directed in solving the problems highlighted.

THE western continental margin of India shows a number of characteristic physiographic features and can be classified as stable Atlantic-type margin. There are several sedimentary basins on this margin (Figure 1) accumulating sediments since Eocene. The International Indian Ocean Expedition (IIOE – 1962–65) is an important landmark in the history of development of continental margin geology. During the IIOE, several ships participated and among them are *INS Krishna*, *Meteor*, *Vytiaz*, *Oceanographer* and *Requisite* which collected data on the continental margin along a few traverses. Subsequently, *INS Darshak* (1973–74), *RV Gaveshani* (1976–1989), *ORV Sagar Kanya* (since 1983), *RV Samudra Manthan* and *RV Samudra Shaudhikama* collected geological and geophysical data at close intervals on the entire continental shelf and upper slope. Numerous research articles were published in various journals during the last 30 years. Siddiquie[1] reviewed the status of marine geology in India in the year 1975. However, extensive research work was published only after 1975. In this article, we review the studies on geomorphology and surficial geology of the western continental shelf and upper slope of India with a view to understanding the processes operating on sediments and suggest future scientific problems to be dealt with.

Geomorphology

Heezen and Tharp[2] were the first to prepare the physiographic diagram of the Indian Ocean. The first bathymetric investigations[3–8] and broad review by Sahni[9] provided some idea on regional structures and sedimentary basins of the western margin of India. The shelf width and the depth at which shelf break occurs are variable along the western margin of India (Figure 2, Table 1). The shelf break is almost parallel to the 100–200 m depth contour and is away from the coast in the northern part (except near Saurashtra) and close to the coast in the south-western part of India. The relatively straight western coast was considered to be the result of an offshore fault believed to extend from Kanya Kumari to Karachi[10]. Some workers[11,12], however, considered rifting to be the mechanism in the evolution of the western margin of India. The Gulf of Khambat (Cambay) is a

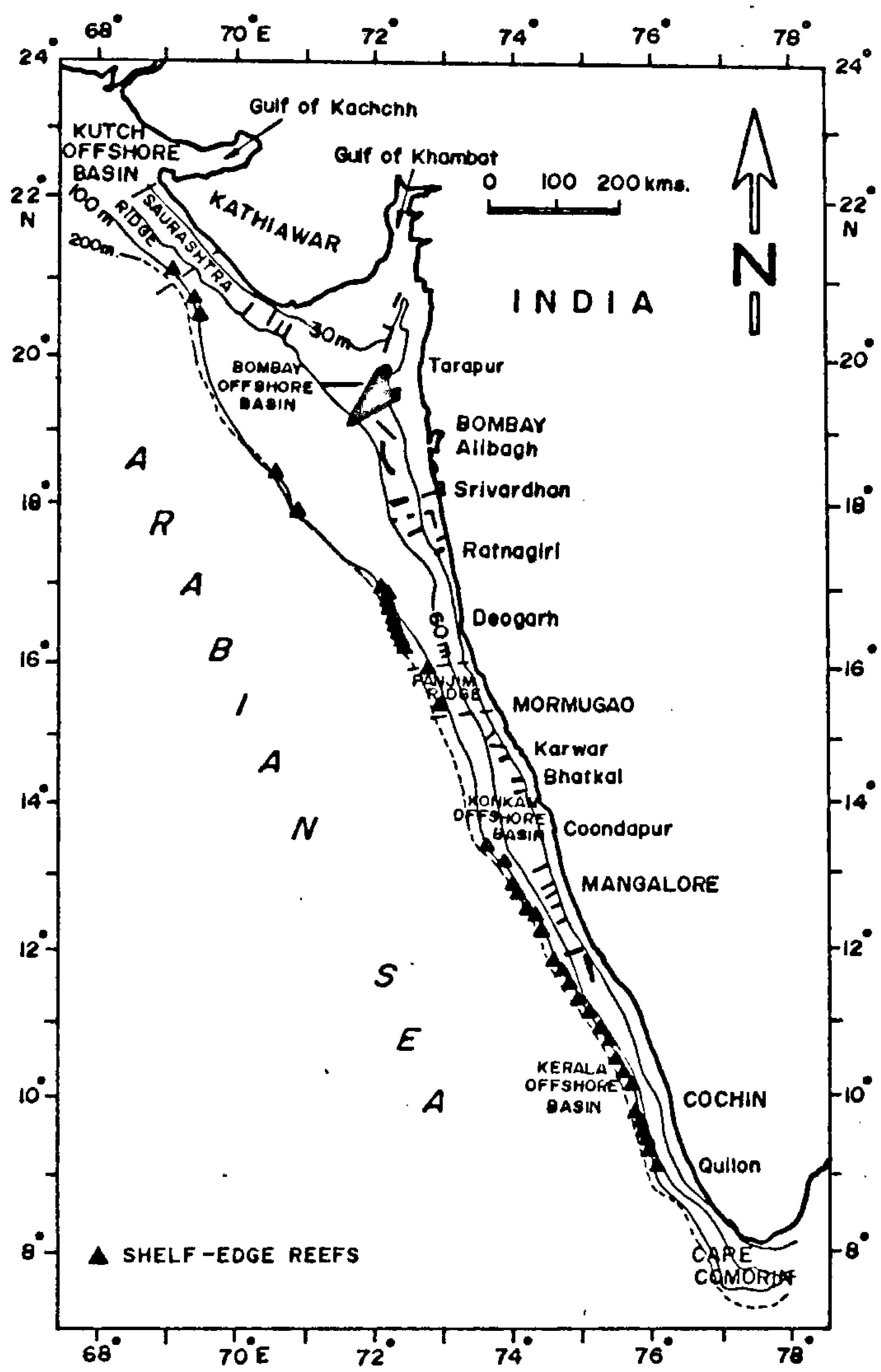

Figure 1. Major sedimentary basins and ridges along the western continental margin of India (after Ramaswamy and Rao[14]). Thickened portions of the lines denote the areas where gas-charged sediments are seen in seismic profiles (after Karisiddaiah *et al.*[149]). Location of shelf edge reefs along the western margin of India. (after Vora *et al.*[39]).

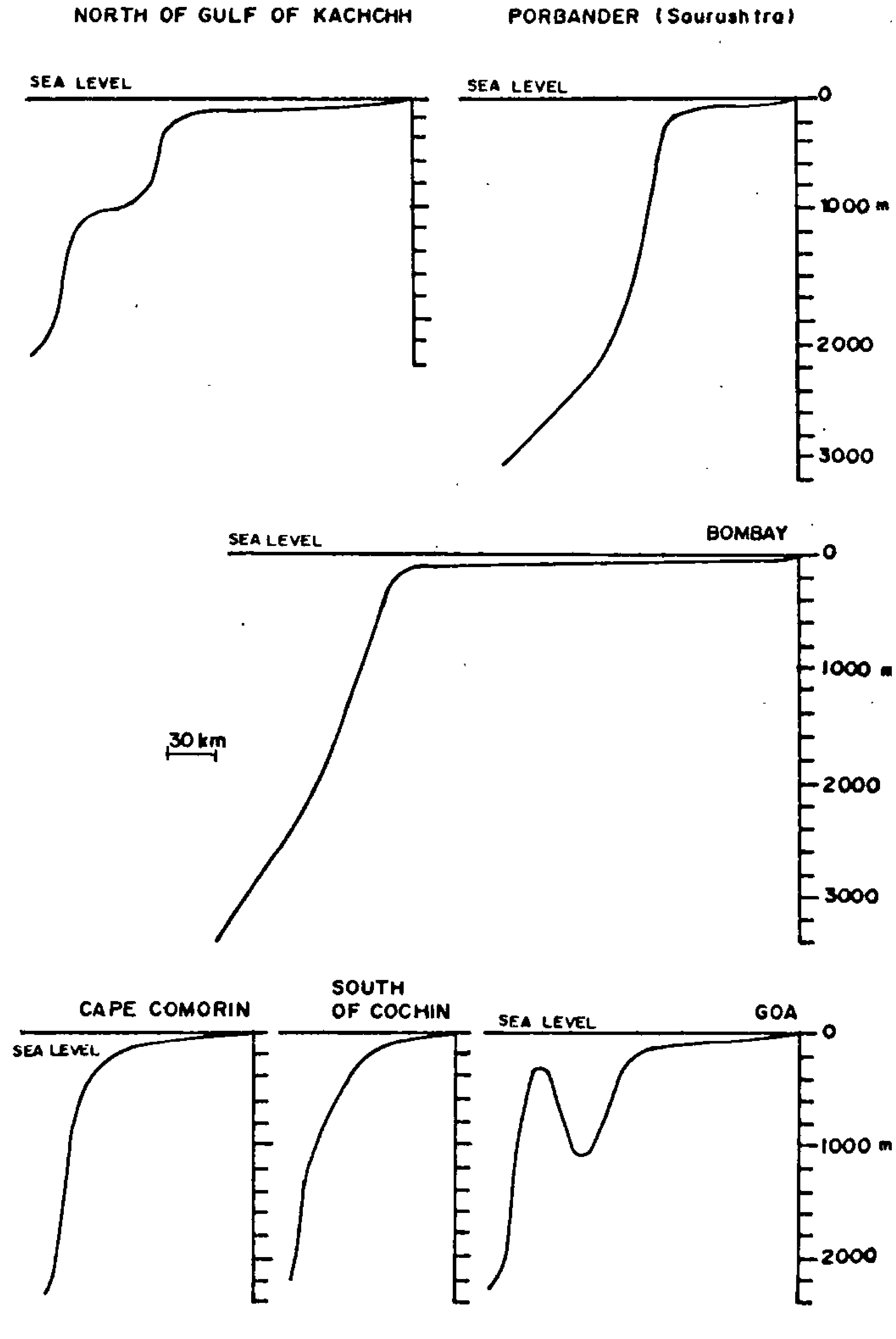

Figure 2. Topographic profiles across the shelf and slope of western India; Horizontal scale is same for all profiles.

graben filled with Tertiary sediments. Faulting is the main cause for the narrow shelf and steep slope at places off Kathiawar[13] and Alibag[14]. The most prominent feature adjacent to the western Indian margin is the Indus cone, one of the largest deep sea fans in the world.

The shelf, having an area[15] of about 310,000 km^2, is divided into two units: inner and outer shelf[13,16–18]. The inner shelf is smooth or even with gently sloping topography (gradient 1:800). This even topography occurs down to 55–60 m depth in the north and narrows down to 25 m depth off Cochin. The sediments are acoustically transparent silty clays. A prominent subsurface reflection occurs at about 35 m below the sea bed off Narmada and Tapti; this becomes shallow towards south

Table 1. Approximate shelf width and shelf break at different locations on the western margin of India

Location	Width of the shelf (km)	Water depth at shelf break (m)	Reference
Pakistan	100–150	100	Milliman *et al.*[91]
Saurashtra	70–110	80–140	Veerayya, personal communication
		122–150	Chauhan *et al.*[32].
Tarapur	345	90	Veerayya, personal communication
Bombay	–	130–140	Siddiquie and Rajamanickam[13];
	260	90	Closs *et al.*[7];
	300	95	Nair[24].
Ratnagiri	100–128	110–130	Nair[24]; Veerayya, personal communication
Goa	60–185	130–140	Nair[24].
Bhatkal	110	120	Veerayya, personal communication
Cochin	60	60	Naini[8].

and off Cochin it occurs at about 15 m below the sea bed. The age of the sediments above this reflector is considered Holocene[15]. Buried features[19–21] such as paleo-channels and wave-cut terraces have been reported between Daman and Goa. They are buried under 10–15 m thick (Holocene) sediments and presumably represent relict extensions of rivers that crossed the shelf or paleo-sea-level positions during the Late Pleistocene. Anomalous acoustic reflections related to gas-charged sediments (discussed separately) are also present. The inner continental shelf off the Gulf of Cambay consists of 6 to 13 m high sand banks (at 8 to 30 m depth)[22] and up to 4 m high sandwaves (with 100 to 400 m wave length) at 60 m depth[19,23].

The middle shelf shows uneven topography with small scale topographic features or buried pinnacles under 2 to 10 m thick sediments. Several pinnacles of the order of 2 to 20 m high have been recorded on the outer shelf. Nair[24] regarded the small scale prominences (1 to 8 m high) on the shelf as erosional remnants of now submerged relict bars that formed during the Holocene transgression. *Halimeda* bioherms[25] occur as 2–14 m high pinnacles in echograms, narrow to broad mound structures in seismic profiles and linear ridges and massive structures in sonographs. A total of 7–8 rows of well-defined, broad, symmetrical submerged sand ridges were found on the middle and outer shelf between 75 and 100 m water depth over a considerable area off Bombay[26]. This suggests that they formed discretely and sequentially when sea-level rise slowed down or stopped during the Holocene. A living coral bank named as Gaveshani bank[27,28] has been reported at 80 m water depth off Malpe.

A series of submarine terraces (Figure 3) at depths between 35 and 140 m were reported[29,30]. The most prominent ones, however, occur at depths between 50 and 115 m at six distinct levels: (1) 55–60 m, (2) 65–70 m, (3) 75–80 m, (4) 85–90 m, (5) 95–100 m and (6) 110–115 m. They are quite common between 11° and 20°N but sparsely occur in the northern and southern parts of the shelf. The terraces are categorized into (a) wave-cut terraces, (b) coral/algal reef-induced terraces and (c) paleo-beach/barrier terraces and their evolution has been ascribed to reef growth, progradation and wave activity during low stands of sea level in the Late Quaternary.

The morphology of the continental slope varies from north to south. Darshak Seamount[16] and other submarine hills located just south of the Indus canyon, possibly mark the volcanic activity related to Deccan Traps. North of Kathiawar, the slope morphology is being modified by the accumulation of Indus sediments. Deeper terraces at 130, 145 and 170 m (ref. 31) and large benches[32,33] at water depths 180–230 m and 650–780 m are present on the slope off Saurashtra–Bombay. The regions between Goa and Cochin show isolated

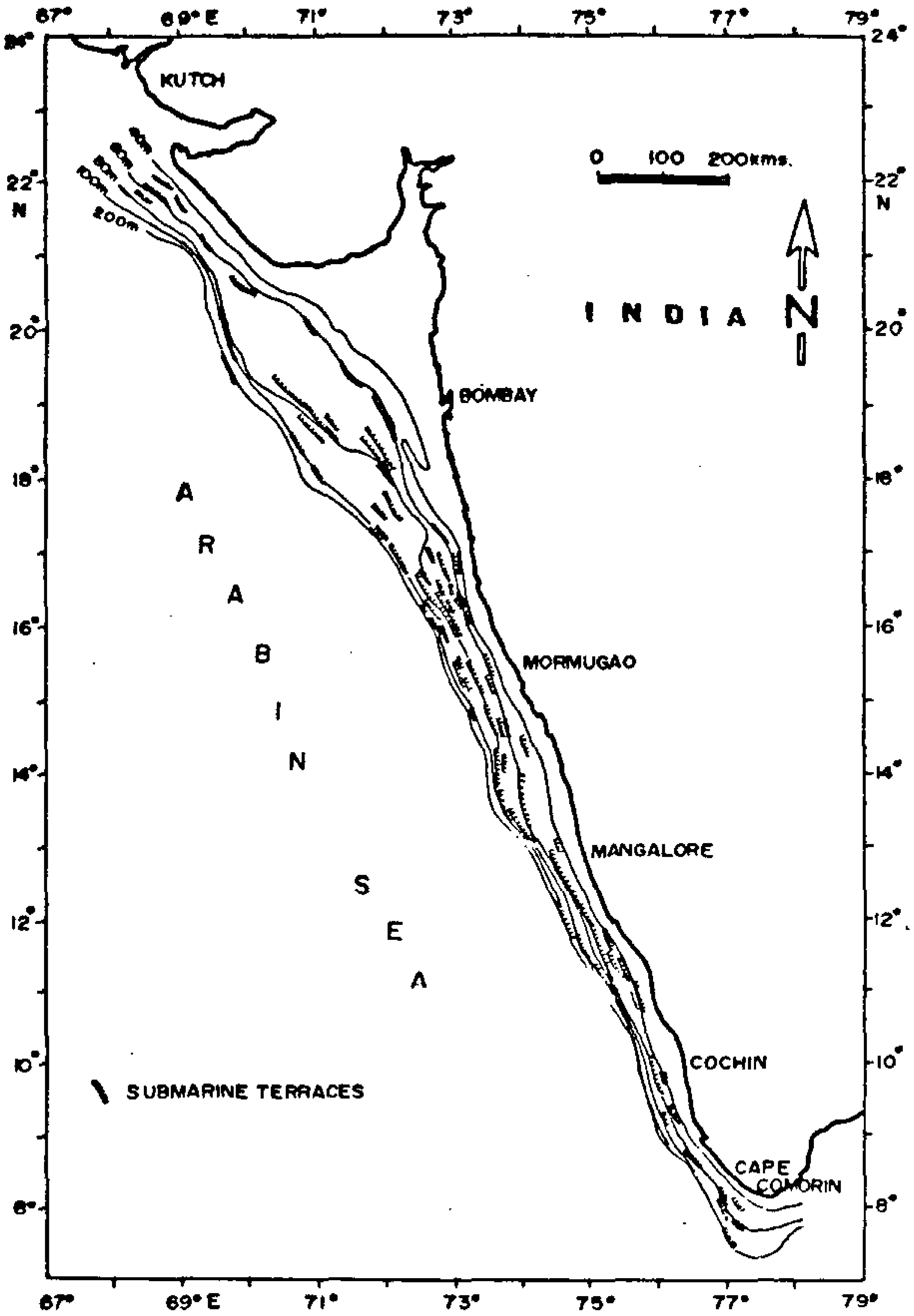

Figure 3. Locations of submarine terraces along the western continental shelf and slope of India (after Wagle *et al.*[30]).

topographic highs rising from 2,000 to 3,000 m water depth. These highs[8] are continuous and form a structural high (Pratap ridge) between 7° and 15°N. The continental slope off Ratnagiri and Goa shows the presence of sharply-defined portions indicating floors of different roughness. These may indicate portions of the slope that have been scoured by slumps and turbidity currents[34]. Turbidites transported from the shelf due to slope failure were reported in the eastern Arabian Basin[35,36].

There are several reports on algal ridges, algal knolls and reefal structures[24,29,37,38]. A scrutiny of the papers reveals that these were simply described based on underway data. Shelf edge reefs are prominent at depths between 85 and 136 m (ref. 39). This reef system is subparallel to the present day shoreline, well developed between Ratnagiri and Goa and between Coondapoor and Quilon (Figure 1), less developed between Ratnagiri and Gulf of Kachchh and absent between Quilon and Cape Comorin (latter two areas are bordered by Early Holocene carbonates). The reef growth at around

−136 m water depth at places and lack of shelf edge reefs[39] at some other places which comprise deeper terraces[31] provide clues on paleo-topography and differential subsidence that had possibly taken place on the western margin of India. Unfortunately there are no samples/radiocarbon dates on these shelf edge reefs to establish precisely the rate and time of subsidence.

Nature and distribution of surficial sediments

The surficial sediments of the western continental shelf and slope of India can be divided into terrigenous, biogenic and chemogenic sediments. Terrigenous sediments mostly occur as sands (including heavy minerals) in the nearshore (up to 10–12 m water depth) followed by a zone of silty clays on the inner shelf between Saurashtra and Quilon. Relict sandy sediments carpet the outer shelf and are predominantly biogenic between Saurashtra and Mangalore and admixture of abundant terrigenous and biogenic constituents between Mangalore and Quilon (Figure 4 *a*). Biogenic sediments are again predominant on the continental shelf between Quilon and Cape Comorin. The continental slope sediments are clayey silts with abundant carbonate tests. Chemogenic sediments are phosphorites and authigenic green clays.

Terrigenous sediments

Coarse-grained sediments

Placer minerals

Placer deposits here refer to heavy minerals concentrations. In order to better understand the controls on heavy minerals distribution in the offshore, their distribution on beaches has also been reviewed.

Placer deposits of Kerala. The Kerala coast contains placer deposits of economic importance and are being mined at several places. Several workers[40–51] reported black sands from river beds, beaches, nearshore and offshore regions of the continental shelf.

The heavy minerals occur in layers and patches along the beaches and their weight percentage varies from 0.2 to 96%. Ilmenite, monazite, zircon, sillimanite and garnet are the important minerals. Opaques (29–74%) (ilmenite, magnetite, rutile, spinel and leucoxene) dominate the heavy mineral suite and were concentrated during the formation of barrier spit and reworking of the beaches. Highest concentrations of heavy minerals occur in the beaches of south Kerala (Chavara–Manavalakuruchi) which also contain high amounts of radioactive elements[46]. Five distinct mineral assemblages representing provinces have been reported all along the beaches[47]. These provinces arise as there are variations in the composition of the rocks of the Western Ghats (from basic charnockites to intermediate and acidic charnockites), thickness of lateritic cover and the extent of Warkala coastal beds from north to south. The khondalite–migmatite complex seems to be the main source for the richest concentrations of monazites between Chavara and Manavalakuruchi[45]. There is no correlation of heavy minerals in bed loads of the rivers and those accumulated on the beaches[43,44,46,47] and the material received is being drifted northwards by powerful longshore currents generated during the southwest monsoon.

Rao[44] reported vertical distribution of heavy minerals, based on drill holes, and places of accumulation of placers, especially in the offshore between Neendakara and Kayankulam. Heavy minerals content ranges from 1 to 26% and highest concentrations are associated with medium sands and occur in stray patches. Of the heavies, 60–70% is ilmenite, 4–9% rutile, zircon and silli-

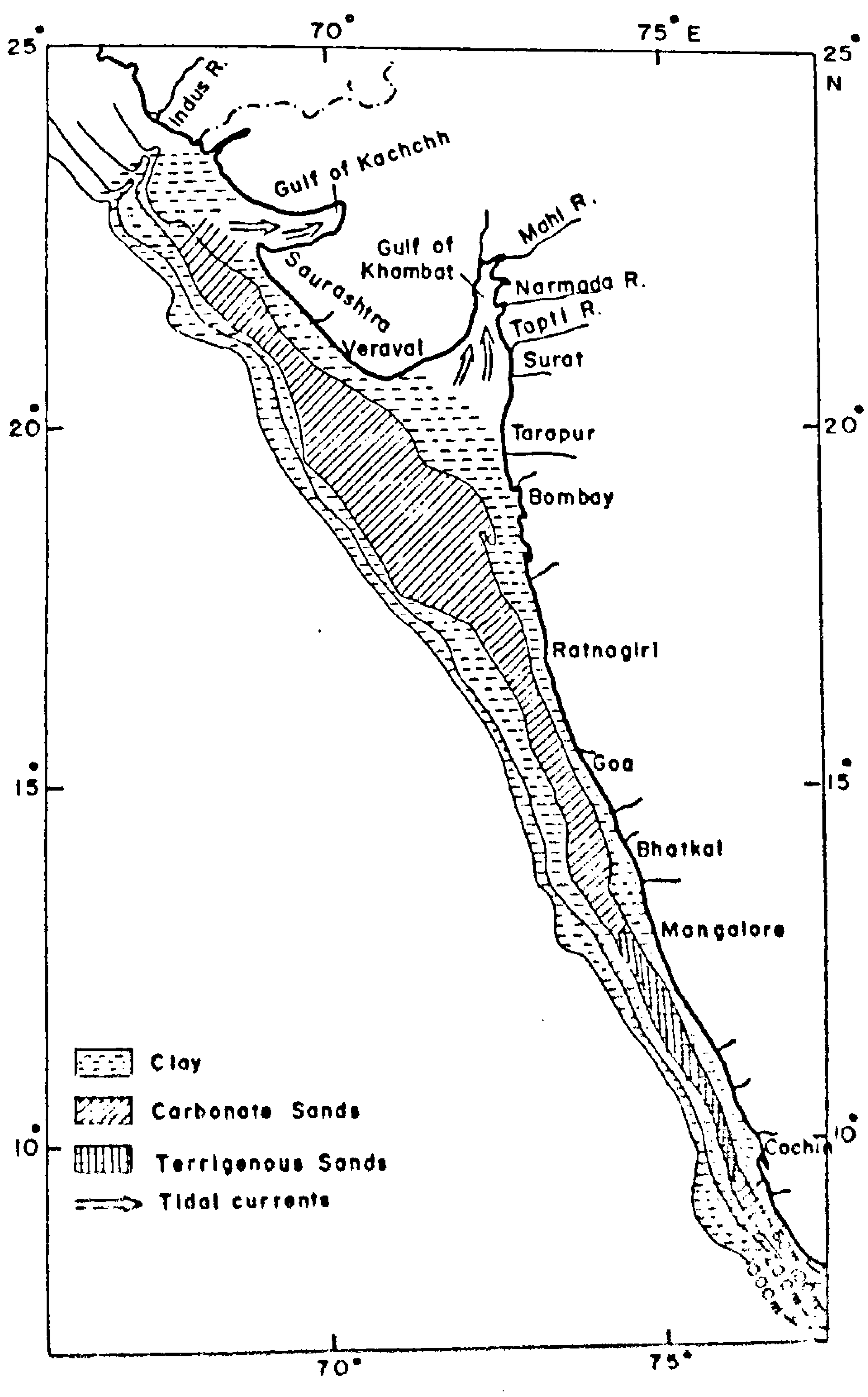

Figure 4 *a*. Sediment distribution map (prepared after Nair and Pylee[151], Stackelberg[91], Hashimi *et al.*[82]; Hashimi *et al.*[104]; Rao *et al.*[112]).

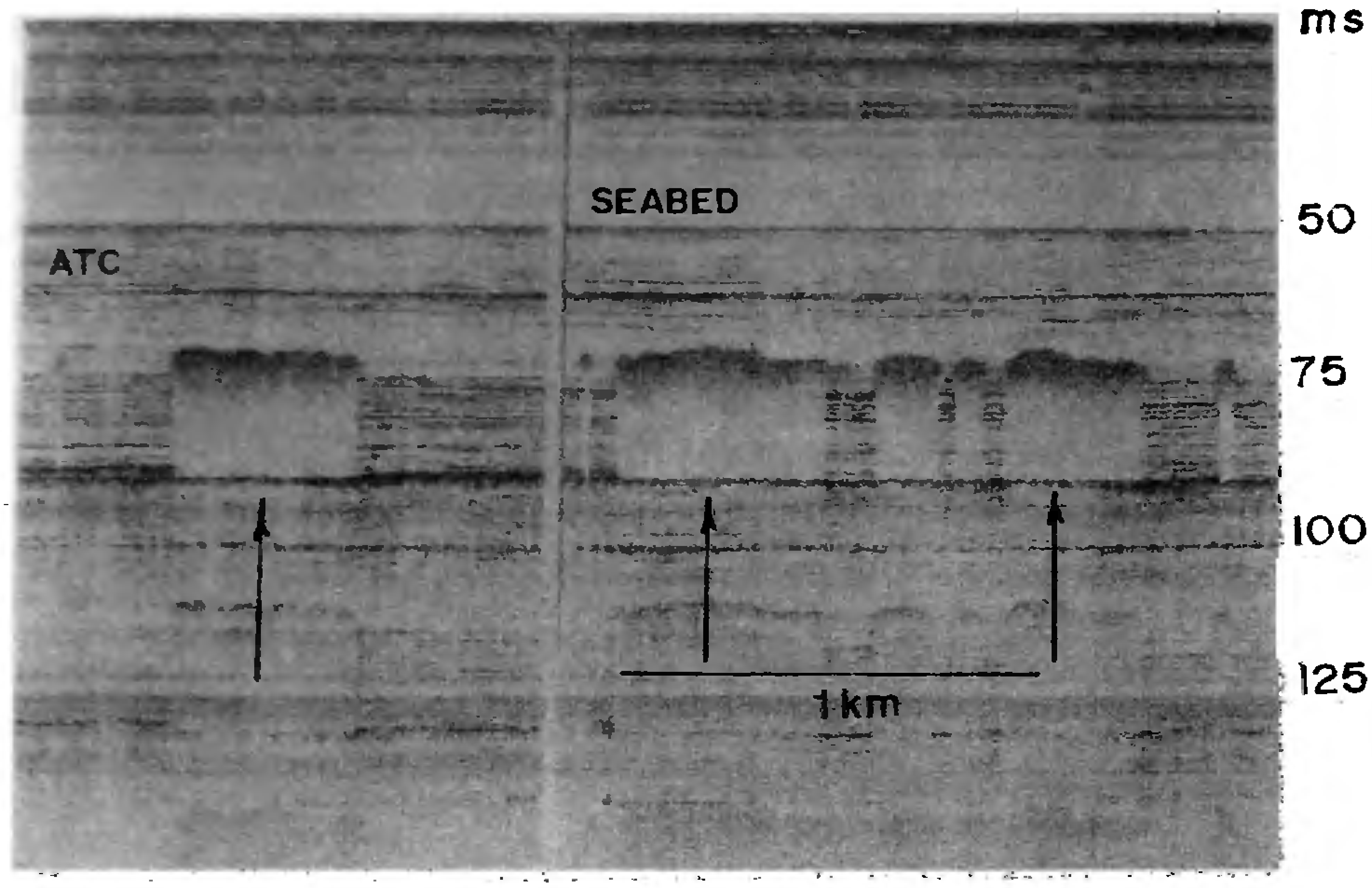

Figure 4 *b*. Anomalous seismic signatures (due to gases) in the form of well-defined reflector terminations (after Karisiddaiah *et al.*[149]).

manite and 0.5–1.0% monazite. The heavy mineral concentrations are < 10% in the shore zone off Paravur–Varkala[48]. The inferred resources up to 1 m water depth in the selected areas of Varkala are 0.33 m tons of ilmenite, 0.11 m tons of rutile, 0.02 m tons of zircon and 0.008 m tons of monazite and 0.15 m tons of sillimanite. The heavy mineral content of total sediments on the continental shelf (Quilon–Cape Comorin) varies from 0.3 to 12.5%. The decrease in the proportion of opaques and zircon in the offshore with a corresponding increase in sillimanite and hornblende has been attributed to sorting[50]. It has been estimated that the Kerala coast contains placer deposits of about 17 m tons of ilmenite, 1 m tons of rutile, 1.2 m tons of zircon, 0.12 m tons of monazite[19,40–42].

Placers of Karnataka and Goa. Heavy minerals in the beach sands between Mangalore and Cochin[52,53], Karwar[54,55], Goa[56], in the sediments off Mangalore (up to a depth of 28 m)[57,58] and in the shelf (up to a depth of 90–120 m) off Vengurla and Mangalore[59] have been reported.

The most important heavy minerals are hornblende, muscovite, tremolite–actinolite, garnet, sillimanite, kyanite, augite, zircon, monazite and opaques. Opaques are magnetite, ilmenite, hematite, goethite-lepidocrocite, rutile and pyrite[57,58]. Higher concentrations of heavy minerals occur in the 62–125 µm fraction except muscovite which occurs more in the 125–250 µm fraction[58]. The quantity of heavy minerals varies from 0.01 to 22.6% of the sediments and opaques vary from 1 to 72% of the heavies. Distributional patterns of heavies and fluorecent tracer studies indicate that the direction of dispersal of the minerals and their host sediments is towards south and southwest. The outer shelf sediments between Vengurla and Mangalore[59] consist of 1–5% of heavy minerals in the sand fraction. Of the heavies, opaques dominate (20–90%) followed by hornblende (1–30%), epidote (1–20%), garnet (0–8%), zircon (0–5%), sillimanite (1–20%) and orthopyroxene (0–11%). Mandovi–Zuari province, Kalinadi province, Netravati province and offshore relict province have been identified[59].

Placers of Maharashtra. This is an important resource region after Kerala. There are several reports on placers in the coastal[60] and offshore[61–75] (2–5 km up to a water depth of 10–12 m) areas, especially in some bays off Maharashtra.

Although heavy minerals occur all along the beaches, their higher concentrations occur between Jaigarh and Vijaydurg and highest concentrations are confined to the arcuate bays in the central part (Table 2). The Kalbadevi, Mirya and Ratnagiri bays have been investigated in detail. Heavy minerals range from 1 to 91% which includes ilmenite (1–52%), magnetite with minor quantities of augite, hornblende, diopside mostly derived from the Deccan Trap province[61]. Granitic (tourmaline, zircon) and metamorphic (kyanite, staurolite, garnet) suite of heavy minerals derived from Kaladgis and

Table 2. Heavy minerals distribution (in total sediments) in the offshore areas of several bays of Maharashtra (A. R. Gujar, personal communication)

Bay	Heavy minerals % (range)	Ilmenite %	Magnetite %
Jaigarh Bay	20–70	1–30	10–40
Ambwah Bay	5–40	3–30	1–70
Varvada Bay	15–80	10–60	1–10
Malguru Bay	0.77–83	0.3–27	0.7–38
Kalbadevi Bay	7–90	3–52	1–38
Mirya Bay	5–72	1–35	3–48
Ratnagiri Bay	2–78	1–22	0.8–59
Pavas Bay	5–80	0.2–20	0.5–40
Purnagad Bay	10–80	0.2–16	0.5–40
Vada Vetye Bay	0.6–9	0.09–10	0.08–13
Ambolgarh Bay	9–80	0.2–21	0.1–40
Rajapur Bay	10–76	2–13	5–45
Vijaydurg Bay	5–65	0.3–25	0.3–47

gneissic basement of the south Konkan coast are minor constituents[74]. Within the bays, the heavy minerals are associated with sands in the stream entrances and along the shore and with silts in the centre of the bays or offshore.

Ilmenite concentrations are the highest in the Kalbadevi and their concentration decreases in Mirya and then to Ratnagiri bay[65]. There is no correlation between grain size and heavy minerals content in the bays. The textural parameters indicate beach/barrier island/lagoon type and palimpsest environments within the bays[65]. At the stream entrances, it is found that the magnetic minerals are concentrated in the south and non-magnetic minerals in the north, apparently reflecting the drift direction wherein low specific gravity minerals were transported towards north[61]. Seismic data show the nearshore first reflector of heavy mineral sand overlain by clays in the offshore. The thickness of the heavy mineral rich sands ranges from 2 to 10 m and extends up to a depth of 20 m. More than 10 m thick beds are associated with the sediments of the river mouths and buried ancient river channels. Superposition of heavy minerals distribution map on the magnetic anomaly map showed a first order correlation between the high content of magnetic heavy minerals and longer wavelength component of the magnetic anomalies[67]. Ramana[66,68] suggested that the changes in the individual medium to high amplitude short wavelength anomalies could be due to different concentrations of heavy mineral assemblages in the sedimentary layers. Assuming an average ilmenite concentration of 10% and a minimum thickness of 1 m for ilmenite-bearing sands, the reserves are inferred to be about 12.5 m tons. Since the thickness of the ilmenite-bearing sands ranges from 2 to 10 m, the probable reserves in the area will be much more than the onshore reserves[63].

Despite basalts being the major rock types, the distributional patterns of heavy minerals significantly differ along the beaches and offshore. Wagle *et al.*[72] correlated geomorphology with heavy mineral content and divided the coast into three zones: The northern zone (Bombay–Srivardan) comprises of 3 to 30% heavies. Here, the coast is emergent type with a few rivers and low coastal relief. The central zone (Srivardan–Deogarh) contains high concentrations of heavy minerals (0.17 to 98.5%). The coast is of submergent type with several bays and bounded by plunging steep cliffs. The rivers have mostly straight courses. In the southern zone (Deogarh–Goa), the abundance of heavies decreases almost to negligible proportions. Here, the rivers run parallel to the coast due to the formation of sand spits at their mouth. Some rivers pass through mangrove swampy areas and bars at stream entrances and heavy minerals were deposited prior to the entry of the river into the sea and thus their heavy mineral content is less. Lateritic cover on the basement rocks is low in the northern part and high in the central part.

Placers of Gujarat. There are a few heavy mineral studies[76–78] in this region. The content of heavy minerals varies from 0.25 to 8.32%. The important heavy minerals are opaques (1–69%), hornblende (1–14%), clinopy-

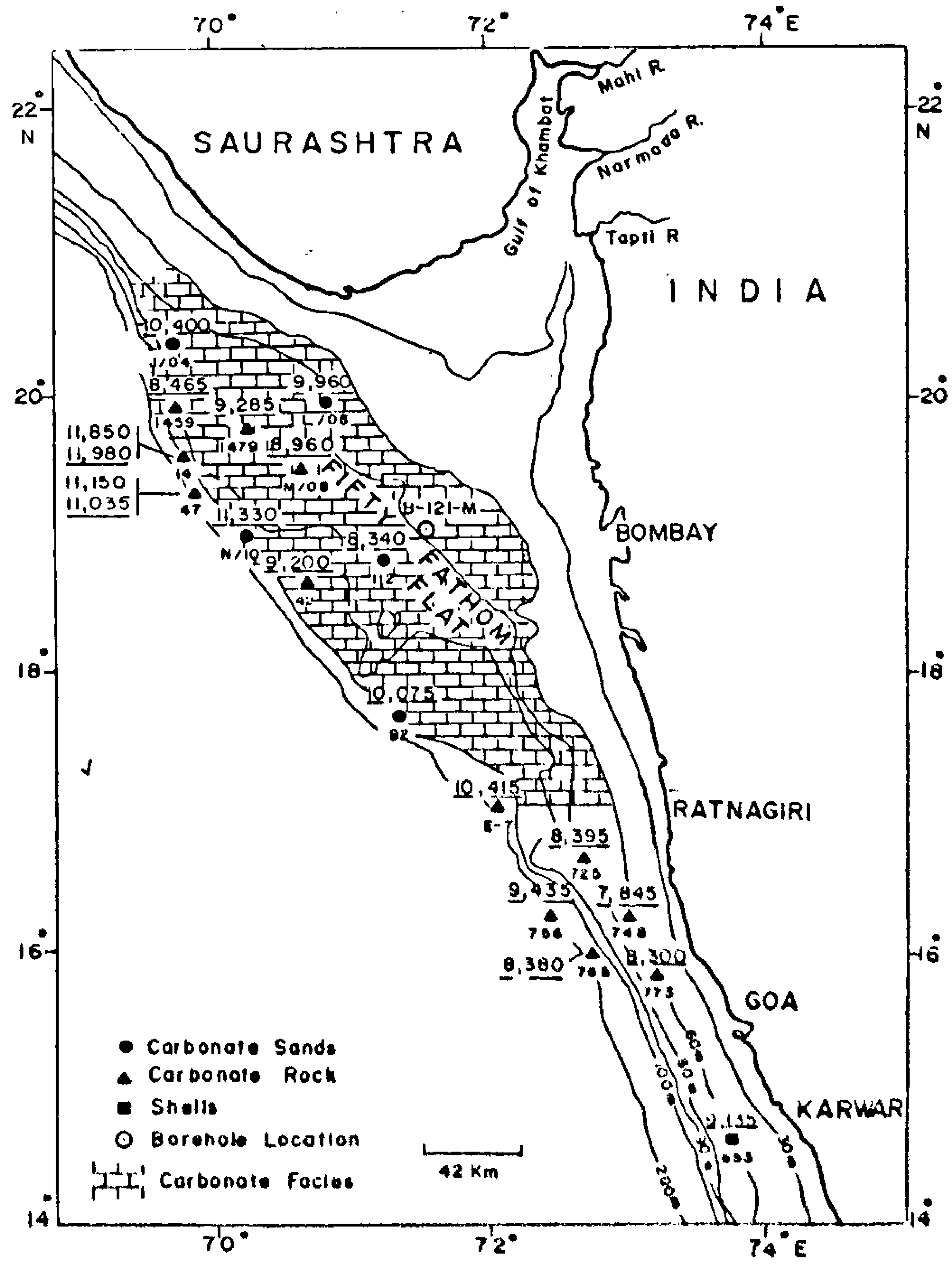

Figure 5 *a*. Radiocarbon dates (underlined) of carbonate sediments, sedimentary rocks on the western shelf of India (after Nair and Hashimi[155] and Rao *et al.*[25]).

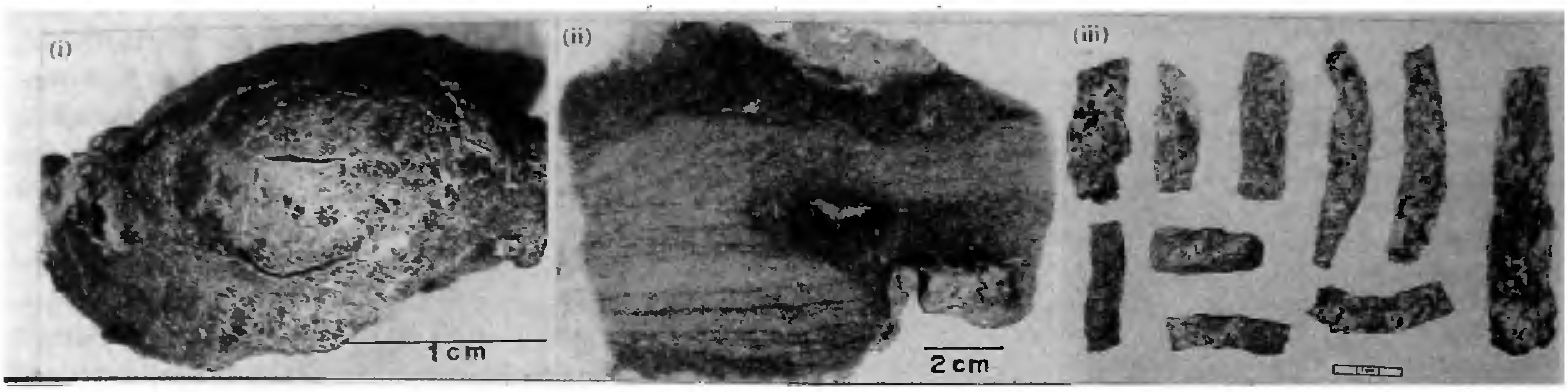

Figure 5 *b*. Terrestrial limestones (i) caliche pisolite, (ii) dune associated calcrete and (iii) rhizoliths on the continental shelf of India (after Rao[162] and Rao and Thamban[165]).

roxene (0–25%), monazite (1–26%), zircon (1–20%), epidote (0–18%), muscovite (0–32%) and chlorite (1–29%) (ref. 77). Magnetite is predominant amongst the opaques. Four distinct provinces have been identified[77]: (a) Indus Province characterized by muscovite, biotite and chlorite, (b) Offshore province characterized by clinopyroxene, hornblende and some garnet, (c) Cambay province with high amount of epidote, monazite, pyroxene and some muscovite and (d) Bombay–Daman province with opaques, pyroxene, zircon and garnet. Heavy minerals suite reported at the intertidal zone off Hazira, Gujarat[78] is same as those in the Cambay province. The mineral assemblage suggests a mixed igneous and metamorphic source.

Light minerals

Stewart *et al.*[76] reported 20% quartz and 20% mica in the shelf sediments off the Indus. These high concentrations of quartz and mica continue to be present as far as north of the Gulf of Kachchh. In the shelf south of Gulf of Kachchh, quartz and mica contents are significantly low (5%) due to the barrier effect of tidal streams operating at the Gulf of Kachchh[79,80]. Quartz and feldspar contents range from 20 to 75% in the sediments of the Gulf of Kachchh. Subangular frosted variety of quartz, transported by winds from the inland sources during the northeast monsoon, also occurs in this region[79]. About 20% quartz was reported in the inner shelf sediments off Bombay[81]. Quartz (68–98%) followed by minor orthoclase, plagioclase, muscovite and rock fragments occur in the sediments (< 28 m water depth) off Mangalore[57]. Between Vengurla and Mangalore, light minerals content is higher (50–70%) in the inner shelf than in the outer shelf sediments (10–50%) (ref. 82). The outer shelf sediments contain iron-stained quartz (5–20%) and unstained quartz occurs in the inner shelf sediments[81].

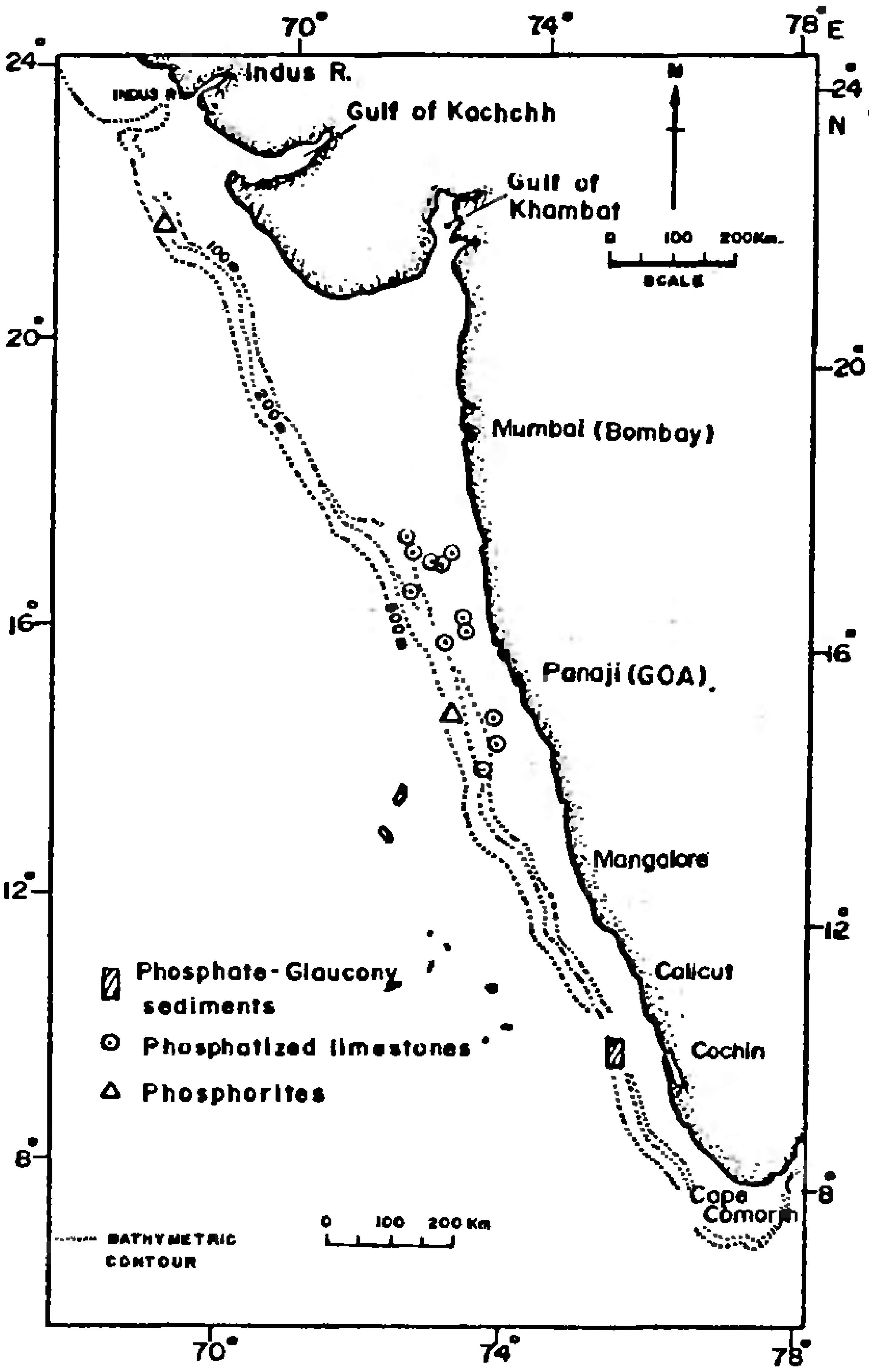

Figure 6 *a*. Location of phosphate-glaucony sediments, phosphatized limestones and phosphorites (after Baturin[193], Rao *et al.*[199], Rao and Lamboy[173], Vaz *et al.*[202]).

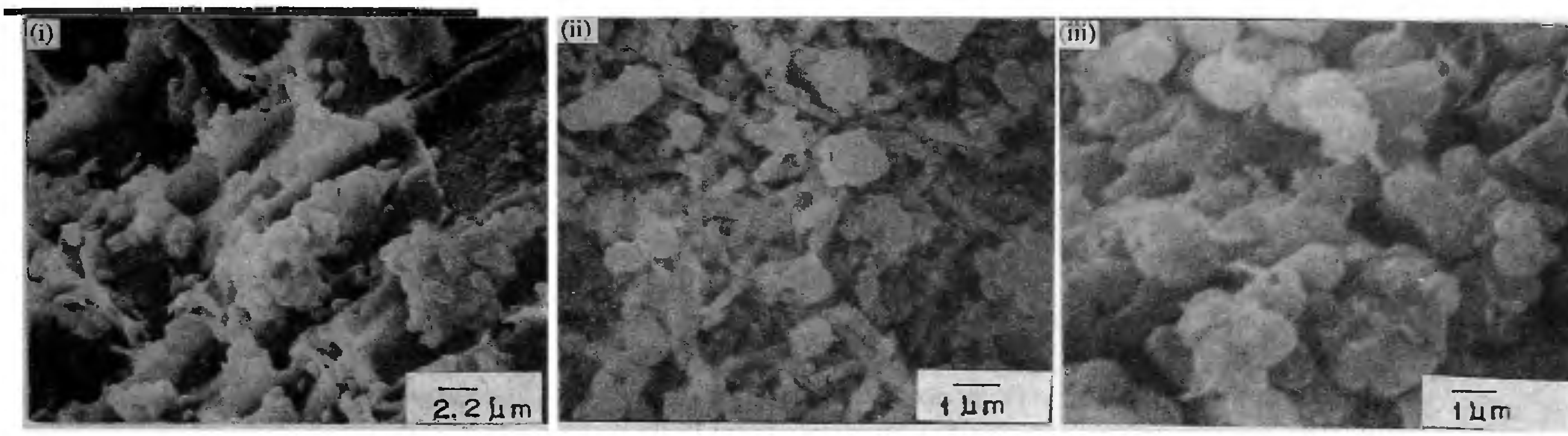

Figure 6 *b*. Apatite micro particles (i) within the cellular structure of coralline algae and in the interseptal cavities of corals (ii) and (iii) resembling phosphatized bacteria (Rao and Nair[197] and Rao and Lamboy[173]).

Sedimentological studies indicate that the outer shelf represents paleobeach environment[83]. It could be that the iron-stained quartz is a relict representing paleobeach environment, while the unstained quartz in the inner shelf is of Holocene age. Relict terrigenous sediments in the outer shelf between Mangalore and Cochin (Figure 4 *a*) implies that, unlike in the northern part, the Holocene sedimentation to the outer shelf is minimal and has been unable to cover the Late Pleistocene sediments. This is further confirmed by the exposure of terrestrial carbonates such as calcretes and paleosols of Pleistocene age at 50–60 m water depth (see biogenic sediments).

Hashimi and Nair[84] showed that the feldspar contents are low in the inner shelf and relatively high (quantified by X-ray diffraction method) in the outer shelf sediments, between Goa and Mangalore and interpreted these differences in terms of paleoclimate and suggested that arid conditions prevailed during the Late Pleistocene/Early Holocene and humid tropical conditions in the present day. The inner shelf sediments are predominantly clayey, whereas the outer shelf are sandy and represent paleobeach environment. In other words, the authors compared feldspar content in predominant sands of the outer shelf with the predominant clays in the inner shelf. Moreover, plagioclase feldspars weather more easily than alkali feldspars and thus the former associate with clayey sediments[85]. The differences in feldspar content thus found appears obvious and may not be true reflectors of climate.

Fine-grained sediments

A characteristic feature on the west coast of India is the occurrence of clastic sediment zone along the inner continental shelf from Saurashtra to Cochin (see Figure 4 *a*). The sediments are silty clays and this zone is widest on the continental shelf off Narmada and Tapti and narrows down to the south. It is 40 km wide off Saurashtra, 175 km off Tarapur, 80 km off Bombay, 40 km off Ratnagiri, 45 km off Goa and Bhatkal and 25 km off Cochin. This zone extends up to 60 m water depth off the major rivers and narrows down to 25 m in the south-western part. The organic carbon content, ranges from 1 to 4% (ref. 86), is lower than the world average (2.5%) for the nearshore sediments. The carbonate content is about 8–10% and rarely exceeds 20%. The coarse fraction content is < 10% and is dominated by shallow water foraminifers and molluscs. The peat/carbonized wood apparently transported from land occurs as intercalated layers in the sediments between Vengurla and Taingapatnam[87–89]. Some workers[90,91] suggested that the inner shelf sediments are repeatedly reworked by currents running parallel to the coast that resulted in good sorting and sediment layering without bioturbation.

Influence of hydrodynamic conditions on clay sedimentation: Examples from the nearshore and from the continental shelf

The Indus, Narmada and Tapti are the major rivers situated on the north-western margin and contribute enormous sediment load to the Arabian Sea[92–94]. Moreover, the Indus cone has a volume of sediments in the range of $0.21 \times 10^6\,km^3$, (ref. 9) and Indus sediments cover huge area in the Arabian Sea and were recorded up to a distance of 1500 km from its mouth. Besides, there are several minor and seasonal rivers contributing sediments to the shelf. Obviously one would expect their sediments in the immediate shelf. Sedimentation at places on the shelf is influenced by intense hydrodynamic conditions and examples are given below.

Macro-tidal environment at the Gulf of Kachchh. Macro-tides of the order of 4 m high at the mouth of the Gulf of Kachchh and 7 m in the inner Gulf and high speed surface currents (1.5 to 4.5 knots) within the Gulf[95] have been reported. The physiography and sediments of the Gulf[79,80,96–100] indicate that a large area, extending from mouth of the Gulf to the centre, consists of numerous topographic irregularities (with 10 m high pinnacles). The floor at the centre is covered with rock fragments, algal limestones, sandstones and dead corals. The southern shore of the gulf is relatively smooth and is covered by tidal flats with patches of corals. These features attest that the tidal influence is more rigorous at the centre of the Gulf.

The river Indus is located 100 km north from the Gulf (see Figure 1). The Indus-borne sediments largely accumulate on the entire shelf to the north of the Gulf of Kachchh and as a result the shelf is smooth and featureless and 20 and 50 m isobaths are shifted towards offshore. On the shelf south of the Gulf of Kachchh (Saurashtra), these isobaths occur very close to the coast and even small scale topographic features of 3 m high are not covered by sediments on the outer shelf[80] due to lack of sediments. Similarly, the distribution of mica, carbonate constituents, quartz and feldspar[79,100], heavy minerals[77] and abundance and type of various clay minerals[80,100,101] showed distinct differences suggesting two distinct sediments types (the Indus sediments and sediments from the arid Saurashtra peninsula) on the shelf on either side of the Gulf of Kachchh.

The results suggest that alongshore transport of the Indus-borne sediments across the Gulf are affected by E–W flowing macro-tidal currents which are intense at its mouth. The net sediment transport in the inner shelf off the Gulf of Kachchh appears to be an interplay of tidal currents with south-eastward (alongshore) currents which flow from Indus to this area. Along-shelf movement takes place during ebb-flood cycles, slack periods at mid-tide and during the weakening of the E–W flows. Factors such as uneven topography and a frictional drag applied by sizable shoals and the bifurcation of these flows[79,100] significantly weaken the tidal currents towards offshore. The presence of Indus sediments on the slope off Saurashtra and to some extent on the outer shelf indicate that the macrotidal influence is more on the inner shelf and decreases offshorewards and insignificant on the continental slope[101].

Macro-tidal environment at the Gulf of Khambat. The Gulf of Khambat (Cambay) (Figure 1) receives drainage and large sediment flux from Narmada, Tapti, Purna, Ambica and Damanganga rivers. The tides are about 10 m high at Bhavnagar and 5 m at Daman. Surface currents speed up to 2.5 knots. Due to intense hydrodynamic conditions at the Gulf, terrigenous sands (mainly quartz and feldspar) are predominant in the Gulf and extend much further offshore up to a depth of 17 m in the eastern side. The asymmetric and symmetrical sand waves reported in the vicinity of Eastern Sand Bank[23] are manifested by strong tidal currents operating at the Gulf. Furthermore, the fine-grained sediments discharged into the Gulf largely accumulate in the inner shelf from 17 m to 60 m water depth and up to a distance of 175 km from the shore and form a thick (35 m) modern terrigenous silty clay zone.

High energy conditions on the Fifty Fathom Flat. The Fifty Fathom Flat lies on the outer shelf and off the Gulf of Khambat. (a) The sediments on the platform are predominantly carbonate sands (90%) with < 10% siliciclastic flux[102], despite the Narmada and Tapti contributing enormous sediment through the Gulf; (b) Surficial sediment constituents record high energy shallow water conditions and are of Early Holocene age[103]; (c) Sediments on the platform are reworked[25]. These imply that high-energy conditions (generated by shelf edge currents) prevailed on the platform during the Early Holocene and, siliciclastic sediments transported through the Gulf either did not reach the platform or due to high-energy conditions these sediments must have been transported further offshore (see section on biogenic sediments).

No-clay zone on the south-western shelf (Quilon–Cape Comorin). The continental shelf between Quilon and Cape Comorin does not contain clay zone unlike the rest of the inner shelf (between Saurashtra and Quilon) (see Figure 4 *a*). It consists of biogenic carbonate sands. Within the Kerala coast, seasonal mud banks are a characteristic feature between Allepy and Quilon (northern Kerala) but are absent further south between Quilon and Cape Comorin. Characteristics of the shelf sediments have been studied and the absence of clay zone has been attributed to the scarcity of estuaries[104–106]. It has been suggested that north of Quilon, there are a large number of estuaries which trap coarse sediments and transport fine-grained sediments to the inner shelf. South of Quilon, the scarcity of estuaries result in the deposition of calcareous sediments[105].

The rivers such as Karmana, Neyyar and Tambrapani bring sediment to the shelf between Quilon and Cape Comorin. Therefore sediment filtering in the estuaries[105] does not convincingly explain the absence of clay zone on the shelf. Two possibilities may be considered: (a) The coastal region between Quilon and Alleppy consists of a wide belt of Recent alluvium and Warkala beds and between Quilon and Cape Comorin this belt is, however, narrow and Precambrian khondalites occur very close to the coast[10]. It is, therefore, likely that the rivers draining between Allepy and Quilon supply large sediment flux to the shelf while the rivers between Quilon and Cape Comorin supply less sediment to the shelf, as they drain through hard formations; less sediment supply probably favoured carbonate growth; (b) Just south of Quilon (at Neendakara rocky headland) the coastal orientation changes from N70°W to N10°W. Wave height ranges between 1 and 2 m at Trivandrum while at Allepy it ranges between 0.6 and 0.9 m (ref. 107). South of Quilon, the shelf width is either narrow (with steep gradient) or wide with flat shallow bottom (Wedge bank). The southwest monsoon waves approach from S70°W which make a more oblique angle to the coast at Neendakara rocky headland, thereby creating a longshore transport southward leading to the removal of sediments brought by earlier cycles. Moreover, alongshore currents show a seasonal reversal trend in the southern part. The no-clay zone in the south-western shelf may therefore be due to coastal rock formations and hydrodynamic factors influenced by coastal configuration.

Detrital clay minerals on the continental shelf and slope

Stewart *et al.*[76] were the first to report the clay minerals in the sediments off Saurashtra. Mattiat *et al.*[108] reported clay minerals on the basis of a few widely-spaced traverses and Nair *et al.*[109] from the inner shelf sediments. Besides, there are local and regional studies such as clay mineralogy of the sediments of the mud banks[110,111], continental shelf and slope off Kerala[112,113], Bombay – Saurashtra[114], Gulf of Kachchh[100,101,109], and on the outer shelf from Bombay to Cochin[115], particulate matter in the sediment traps[116,117] and clay minerals in the suspended and bed loads of the rivers[118,119]. A better understanding has been achieved by the studies of Rao and Rao[120] based on 156 sample analyses from the shelf and slope. Several workers[121–129] have reported distribution of quartz and clay minerals in the Indian Ocean which includes several samples from the Arabian Sea Basin.

Mattiat *et al.*[108] indicated that illite, illite–montmorillonite, montmorillonite and montmorillonite mixed layers are important clay minerals in the sediments off Karachi, Saurashtra, Bombay and between Vengurla and Cochin, respectively. Four distinct clay mineral provinces in the inner shelf sediments[109] are i) the montmorillonite(M)–kaolinite(K)–illite–chlorite zone (M/K 2–3.5) off the Gulf of Kachchh; ii) the montmorillonite-rich zone (M/K > 3.5) between the Gulf of Cambay and Ratnagiri; iii) the transition zone (M/K 1.5–2) from Ratnagiri to Bhatkal and iv) the montmorillonite-poor –(M/K 1.5) gibbsite zone from Bhatkal to Quilon. Degraded illite, mixed layer minerals and kaolinite along with high montmorillonite are present in the shelf sediments of Bombay and Saurashtra[114]. Clay mineral assemblages of the Indus province, the Deccan Trap basaltic province and Western Ghats Gneissic province are distinct on the continental shelf in the north of the Gulf of Kachchh, the inner shelf from Saurashtra to Goa, and from Goa to Cochin, respectively[120].

A few studies[115,116] have indicated the abundance of illite, kaolinite and chlorite with minor amounts of montmorillonite in the outer shelf sediments. These are in contrast with the inner shelf sediments which consist of montmorillonite, kaolinite, illite and chlorite in order of abundance[109]. Based on these differences, Ramaswamy and Nair[115] suggested that there is no cross shelf transport and attributed the outer shelf clays as a product of Indus river discharge. If there is no cross shelf transport, the clay minerals in the sediments of the outer shelf and adjacent slope are expected to be similar. The clay minerals on the adjacent continental slope (Saurashtra–Goa), however, are admixture of minerals derived from Indus province and Deccan trap province[120]. Sedimentation rates (by excess Pb method) show present day clay accumulation on the continental slope[130]. These imply that there is a cross shelf transport. On the other hand, several workers[100,101,120] showed that the clay content itself is less on the outer shelf between Saurashtra and Goa (as is dominated by carbonates); wherever clay is present the illite dominates over smectite in the northern part (off Saurashtra) or smectite dominates over illite in the southern part (off Ratnagiri–Goa). The outer shelf being a high-energy environment (as also revealed by tracer studies[131]), the clay minerals mostly bypass the outer shelf and settle in the low-energy slope environment[120]. These points suggest cross shelf transport of clays.

The decrease in abundance of Indus-borne clay minerals from north to south with a corresponding increase of clay minerals derived from the Deccan trap basaltic province along the continental slope suggests decreasing influence of Indus sediments carried by SW monsoon currents[120]. Influence of organic carbon and depositional environment on the accumulation of clay minerals and propensity of individual clay minerals for transport (abundant montmorillonite in clayey sediments and relatively high illite in sandy sediments) have been reported in the shelf sediments on either side of India[100,120,132,133].

The outer shelf and slope sediments off Goa–Cochin are smectite and kaolinite dominated with characteristic gibbsite and minor illite. The illite content increases together with kaolinite and gibbsite towards offshore. In view of the composition of the Ghats (composed of Precambrian granites, gneisses, schists and charnockites) and high seasonal rainfall (3000 mm/year), one would expect some residual clay minerals like illite and chlorite in the inner shelf sediments. Despite appreciable amounts of mica in the coarse fraction[57], illite content is low in finer sediments of the inner shelf which needs explanation. Narrow shelf, high surface runoff and offshore transport of surface water during the SW monsoon must have effectively transported illite and chlorite farther from the coast and accumulated in the outer shelf and slope[120]. Western India experiences semi-arid climate in the northern part and humid tropical climate in the central and southern parts. Clay minerals so far reported are confined to only group levels. Investigations on identifying the specific clay minerals of the group may not only enhance our understanding the influence of climate on source rocks but also will help delineate the mineral provinences and their distributional patterns more precisely. For example, the NE monsoon is active and intense on the southeast peninsula. As there is an underwater current characteristic of Bay of Bengal waters on the continental slope of the west coast of India[134], clay minerals transported by this current can very well be studied.

A few workers[122,124] suggested that the clay minerals follow a latitudinal zonation while others[121,123,125–129] indicated the detrital nature of the clay minerals. Later authors suggested that the clay minerals distribution in the ocean is influenced not only by the continental climate and geology but also by oceanic circulation patterns and varying processes of sediment transport. These workers[125–129] reported high smectite zone both in the Bay of Bengal and Arabian Sea bordering the Indian margins derived from the Deccan province. Nair *et al.*[135] reported large lithogenic flux to the central Arabian Sea. Clay mineral assemblages in the dust plumes[136] from the continents bordering the Arabian Sea show significant differences between the Holocene and Glacial accumulation rates of wind-transported clay minerals in the Arabian Sea related to the intensity of monsoon winds.

Sedimentation rates

The sediment accumulation rates in a given area depend on the current circulation patterns and environmental conditions at the site of deposition. There are a few publications reporting clay accumulation rates, determined by either excess Pb method[130,137–142] or computed from the radiocarbon ages of the peat occurring at different depth intervals in the sediment cores of the inner shelf[87,88] or by biostratigraphic method[142]. The clay accumulation rate is 19 mm/yr at the mouth of the Narmada and Tapi rivers. It is about 5–7 mm/yr in the nearshore region at 20–36 m water depth[137], and about 1.8–2.5 mm/yr in the offshore region of Bombay at about 50–52 m water depth[137,141]. Towards south, the rates obtained by excess Pb method are low and vary from 0.56 to 0.72 mm/yr in the inner shelf sediments off Mangalore (at 35 to 45 m depth), 0.72 mm/yr off Mulki (at 50 m depth), 0.44 to 0.89 mm/yr off Karwar and 2.6 mm/yr off Kalinadi (at 20 m depth)[140]. The high sedimentation rates in the north corroborate the high sediment flux derived from larger rivers and lesser sedimentation in the central and SW part suggest less sediment discharge to the shelf. The sedimentation rates computed by using radiocarbon ages of the peats in the sediment cores off Taingapatnam, Ponnani, Karwar and Vengurla range from 0.11 mm/yr to 1.0 mm/yr and are lower than those determined by Pb method. A perusal of the data[87] shows that the peat dated 9,630 years BP occurs at 420–438 cm depth interval of the sediment core collected at shallow water (25 m depth), whereas the peat dated 8,620 years BP occurs at 578–580 cm depth interval of the core collected slightly offshore (34 m). This suggests reworking which placed the older age peat relatively at shallow depth intervals in the core (at 25 m depth) and younger age peat at deeper depth interval in the core collected at deeper depth (34 m). In other words, the sedimentation rates are not uniform and the rates estimated by ^{14}C ages of the peat, therefore, may not be useful. A rate of about 3.8 mm/yr (by excess Pb method) at 350 m depth on the continental slope sediments off Saurashtra[130], 12 cm/1000 yr (ref. 143) at 1230 m depth and 2–3 cm/1000 yr (ref. 144) on the lower slope at 2188 m depth has been reported. Based on biostratigraphy[142], a rate of 1–2 cm/1000 yrs has been suggested for the continental slope sediments. The cores collected in the region off 10°N at 2523 m (ref. 145), and Laccadive Trough at 1724 m depth[146] showed mean sedimentation rates of 2.2 cm/1000 yr and 3.84 cm/1000 yr, respectively.

Methane-associated sediments

High resolution seismic reflection studies on the inner continental shelf between Bombay and Cochin show weakly stratified and acoustically transparent clays which contain anomalous seismic signatures in the form of acoustic maskings (Figure 4 *b*) and are interpreted as gas-charged sediments[147,148]. Subsequently several workers[149–152] reported widespread occurrence of similar reflectors over the areas of the inner shelf from the Gulf of Kachchh to Cochin (Figure 1). Siddiquie *et al.*[148] identified turbidity within the clays resembling inverted U-like features extending from an unidentified reflector, which is usually a sand. These acoustic maskings extend continuously for a distance of 50–60 km on some tracks off Bombay. A sediment core collected in the area showed bubbles at about 3.5 m depth in the core and fissures below 4 m. The gases associated with the sediments are methane-rich (11.15%) followed by minor pentane, hexane and heptane[148]. The methane enrichment may be due to the bio-degradation of organic matter or thermocatalytic cracking of more complex compounds. It has been proposed that the acoustic maskings on the outer shelf and on the inner shelf off

Bombay are of different origin. It has also been estimated[150] that the potential sub-surface methane in the gas-charged sediments is 2.6 Tg CH_4. Its contribution to the atmosphere with an annual flux of 0.039 Tg/yr appears quite significant[151]. This may diffuse into the overlying waters in the event of destabilization of the reservoir due to neotectonic activity.

Biogenic sediments

Biogenic sediments on the western margin of India are mainly carbonates. Dolomite occurs as well-rounded grains in the shelf sediments off Saurashtra[76] transported from the adjacent rocks and from pre-existing sediments. Nair and Pylee[153] reported grain size and carbonate content along a few traverses and Stackelberg[91] delineated relict carbonate facies on the entire margin. A pioneering work was done by Nair and his colleagues[25,29,31,153–165].

Sediment constituents

Carbonate-dominated sediments predominantly occur on the outer continental shelf off Saurashtra–Mangalore and on the shelf between Quilon and Cape Comorin (see Figure 4 *a*).

Saurashtra–Mangalore

Major part of the outer shelf in this region is occupied by the Fifty Fathom Flat, a unique carbonate platform lying off the Narmada and Tapti Rivers (Figure 5 *a*). The sediments are aragonite sands (90%) which predominantly (80–90%) comprise non-skeletal grains referred to as oolites and pelletoids[91,102,153]. Other constituents are molluscs and benthic foraminifers. Benthic foraminifers such as Amphistegina, Ammonia, miliolids and several agglutinated forms are associated with them, suggesting a shallow marine environment during the Holocene[103,159]. *Halimeda* fragments and abundant aragonite faecal pellets[25] corresponding to the crustaceans were reported. The mean size of the non-skeletal grains decreases from north to south (0.3 mm off Bombay, 0.08 mm off Karwar and 0.06 mm off Mangalore)[166]. The radiocarbon dates of the sands range from 10,400 to 8,300 years BP (see Figure 5 *a*). The content of oolites increases in the sediments and sedimentary rocks associated with submarine terraces[31]. Grapestones are aggregates of grains cemented by microbial filaments. Their content increases towards the southern part of the platform[102]. A shell zone comprising large Chama shells occurs at places off Ratnagiri and Goa. Relict sediments off Karwar are represented by ferruginous coarse sands and shells associated with angular basalt fragments, laterite pebbles and silicified wood[153]. Aragonite content (up to 99%) decreases southwards and is replaced by calcite; this is due to the decrease of non-skeletal grains in the sediments south of Bombay. High-magnesium calcite ranges in abundance from 4.6 to 38.9% and mole percent of $MgCO_3$ varies from 5.5 to 16% (ref. 156). The following problems require attention.

Where did the riverine sediments accumulate during the Holocene?

The Fifty Fathom Flat mostly lies between 80 and 90 m water depth and the surficial carbonate sediment ages range from 10,400 to 8,300 years BP (see Figure 5 *a*). The glacio-eustatic sea level was at –70 m at about 10,500 years BP[167]. This implies that the platform was at depths between 10 and 20 m and shoreline was close to the platform. If normal shelf gradient (1:800) existed, one would expect the deposition of siliciclastic flux (transported through the Gulf) directly on to the platform and complete inhibition of carbonate growth during 10,400–8,300 yrs BP. On the contrary, the carbonate depositional environment prevailed during this time with <10% siliciclastic flux accumulation on the platform, suggesting that the topographic conditions on the inner and outer shelf were abnormal. This means that the platform (outer shelf) and inner shelf were at different elevations (or tectonic settings) (see neotectonic activity); this probably prevented terrigenous flux to the platform and favoured carbonate growth. It could be that the riverine sediments discharged through the Gulf of Khambat most probably were directed south-eastwards or were still filling the Dahanu depression on the inner shelf.

Climatic conditions during the Holocene

Nair and Hashimi[155] predicted arid climate during the Early Holocene based on sediment constituents (carbonate and quartz) of the western margin of India. On the contrary, Van Campo[168], based on the sediment cores from the continental slope of western India, reported that the SW monsoon reactivated about 11,500 years BP and intensified monsoon existed at about 9,000 years BP suggesting humid conditions during Early Holocene. Other independent studies in the Arabian Sea sediments[169,172] are in agreement with Van Campo[168]. Furthermore, it is not yet known as to why carbonates growth ceased on the western margin of India after 8,300 years BP. The corals and coralline algal limestones dated 8,000 ± 250 years BP consist of abundant siliciclastic flux (which filled the interstices of corals and were trapped between algal laminations), suggesting that increased terrigenous flux at about this time[173] could have caused the demise of carbonate growth. The increased flux may be due to climate or sea level change. Since no climatic change was reported at about 8,000 years BP, sea level change may be responsible (see neotectonic activity). Detailed study in this direction would provide valuable information.

Lime muds off Saurashtra–Bombay

The continental slope off Saurashtra–Bombay at depths between 150 and 500 m consists of lime muds which occur either as surficial deposits or are covered by thin layers of clayey sediments derived from the Indus[174,175]. These muds are creamy white, soft, homogeneous and composed of worn-out skeletal fragments, pelletal grains and mud aggregates. It consists of abundant aragonite with minor calcite. SEM studies show the presence of minute skeletal fragments, stumpy aragonite crystalline aggregates and slender aragonite needles[176]. These characteristics suggest detrital origin of muds. On the other hand, investigations on the adjacent shelf indicate the presence of *Halimeda* bioherms of Early Holocene age. *Halimeda* is an aragonitic alga and gets easily disintegrated upon diagenesis. It is evident from the size and shape of the *Halimeda* grains[25] that the original *Halimeda* plates have been disintegrated and aragonite muds derived from them were not retained on the shelf (as the shelf was composed of abundant aragonite sands). These points suggest that the lime muds which originated from *Halimeda* bioherms must have been transported and got accumulated on the slope during the low stands of sea-level. The results on $CaCO_3$ content of the sediments in the gravity cores collected from the continental slope indicate aeolian carbonate derived from Saurashtra miliolites and a 200 yr periodicity in $CaCO_3$ deposition[177]. Detailed studies on identifying and ascertaining the relative importance of the sources of carbonates (biogenic, detrital and aeolian) in the sediment cores may help us to segregate the arid and humid periods more precisely and associated sedimentary processes during the Quaternary.

Quilon–Cape Comorin

Carbonate sediments on this shelf are dominated by molluscs (20–55%) and benthic foraminifers (33–69%), echinoderms (up to 6%) and other constituents (6 to 16%) such as ostracods, bryozoans, sponge specules, serpulids and algal and coral fragments and rock fragments. Most of the skeletal constituents are brownish to dirty white and white, broken, rounded, worn and coated with secondary carbonates suggesting oxidizing and agitating conditions during their formation[104]. Aragonite is the dominant mineral where molluscs are significant components in the sediments and high-magnesium calcite is dominant where benthic foraminifers are the main constituents. The age of the carbonates is not known.

The type of carbonate litho-facies varies from north to south. For example, on the carbonate platform (in the north) algal litho-facies, related predominantly to *Halimeda* bioherms (Early Holocene) and its byproducts, is common[25]. In the central part, coral and rhodoalgal litho-facies is abundant and phosphatization took place in these limestones during the Early Holocene[173]. Towards south, especially between Quilon and Cape Comorin, the carbonate litho-facies is dominated by molechfor litho-facies consisting of abundant molluscs, benthic foraminifers, echinoderms and bryozoa[104]. Although the age of the latter litho-facies is unknown, the change in carbonate litho-facies from north to south is seemingly related to latitude, depth, water temperature and other similar factors. Carbonate litho-facies as paleolatitude indicators, has been reported from Brazilian middle-outer shelf and Mediterranean Sea (see ref. 178) and aided in the interpretation of the paleoenvironmental conditions during their formation. This type of studies are absent from this margin.

The Carbonate platform covers an area of 28,336 km^2, extending over 4° latitude[25] Bombay High Oil field is located on the carbonate platform and at present oil is being extracted from Miocene beds of the platform. The surficial and subsurface sediments (at least up to a depth of 26 m) are carbonate-rich (90%) (ref. 25) and thus serve as good reserves for lime deposits.

Sedimentary rocks and paleo-sea levels

Several types such as algal, oolitic, shelly, pelletal limestones and sandstones[102,154] occur at depths between 60 and 150 m mostly confined to the north-western shelf of India (Figure 5 *a*). Based on mineralogy, diagenetic textures, radiocarbon dates and stable isotope data, these limestones have been classified into Holocene and Pleistocene limestones. Within the Holocene limestones subtidal, intertidal and vadose diagenetic limestones were identified. Limestones recovered from the 130 m depth terrace showed intertidal conditions at about 11,890 years BP[31]. Subtidal and vadose diagenetic limestones were recovered from the carbonate platform[25,163]. The age of the limestones on the platform ranges from 9,200 to 8,430 years BP. Terrestrial limestones such as caliche pisolites[162], limestones with marine fauna and neomorphic meteoric cement fabrics[163], dune-associated calcretes, rhizoliths, and paleosols[165] (Figure 5 *b*) have been recovered from 50 to 60 m water depth along the shelf between Ratnagiri and Cochin and suggested to be Pleistocene shoreline indicators.

Evidences of neotectonic activity

Nair[29] reported five radiocarbon ages of the samples from the submerged terraces at –92, –85 and –75 and

–55 m off Bombay and Karwar and suggested that the terraces at –92, –85 and –75 m may correspond to global sea level stillstands during the Holocene. A mid-Holocene strandline deposit was reported on the inner shelf off Cochin[179]. A few[180,181] attempted sea level curves for the Late Quaternary. Actual radiocarbon dates of the samples, however, fall away from these curves and also from the glacio-eustatic sea level curve[167]. A review by Rao *et al.*[164] documented several evidences in favour of Late Quaternary neotectonic activity, using glacio-eustatic sea level curve[167] as a reference. These are (a) the presence of submarine terraces off Saurashtra–Bombay at 130, 145 and 170 m water depths which lie below the glacio-eustatic sea level low (–120 m); (b) the intertidal limestones dated 11,980 years BP occur at 130 m depth terrace. In contrast, the glacio-eustatic sea level for the corresponding age was at –90 m; (c) The radiocarbon ages of samples from the Fifty Fathom Flat are younger (by 2,000 years) than at the corresponding depth on the glacio-eustatic sea level curve; (d) Occurrence of vadose diagenetic limestones dated 9,200 yrs BP on the Fifty Fathom Flat at 85 m water depth. The eustatic sea level for the corresponding age was, however, at –40 m; (e) *Halimeda* bioherms grew on the carbonate platform until 8,300 years BP and ceased thereafter; (f) Absence of data younger than 8,300 years BP from the offshore and presence of corresponding data (Early Holocene –8000 to 2000 years dated marine samples) from the coastal regions[182]; (g) Depth distribution of verdine and glaucony facies on the Kerala continental shelf and slope which appear anomalous when compared with the distribution of verdine and glaucony facies in the eastern margin of India (Figure 7 *b*), Senegal and French Guinea margins.

Rao *et al.*[164] showed subsidence by about 40 m on the north-western margin some time in the Early Holocene. The time and rate of subsidence during the Holocene are yet to be determined precisely. Subramanya[183] reported evidences of buckling of landmass along east-west line close to 13°N resulting submergence in the north and emergence in the south and uplift of southern Karnataka during Holocene. Whiting *et al.*[184] found 'excess' subsidence on the west Indian margin mainly due to Indus Fan sediment deposition and fan loading. They proposed that the flexural deformation influenced in such a way that the areas closer to the subsidence are depressed and far from the load experience uplift, exposing the larger portions of the shelf of Saurashtra during the Quaternary. Moreover, the Kachchh area consists of a series of parallel E–W trending gentle folds cut by E–W strike faults that possibly extend into the sea[185]. Valdiya[186] has also shown geomorphic, structural and geodetic evidences indicating repeated and fast movements in the Pleistocene and Holocene on faults and thrusts in the Himalayas. He indicated in his talk at the international symposium[186] that the stresses and tensions developed due to thrusting of the Himalayas should be released elsewhere and continental margins could be the probable areas that get affected by these stresses. There thus appears some correspondence between the uplift of Himalayas and observed neotectonic activity in the northwestern shelf of India during the Holocene.

Chemogenic sediments

Phosphatic sediments, phosphatized limestones and phosphorites

Phosphate content in the sediments off Mangalore and Bombay to Ratnagiri[187], in phosphatized oolites at 70–120 m depth off Bombay-Ratnagiri[166] and from a

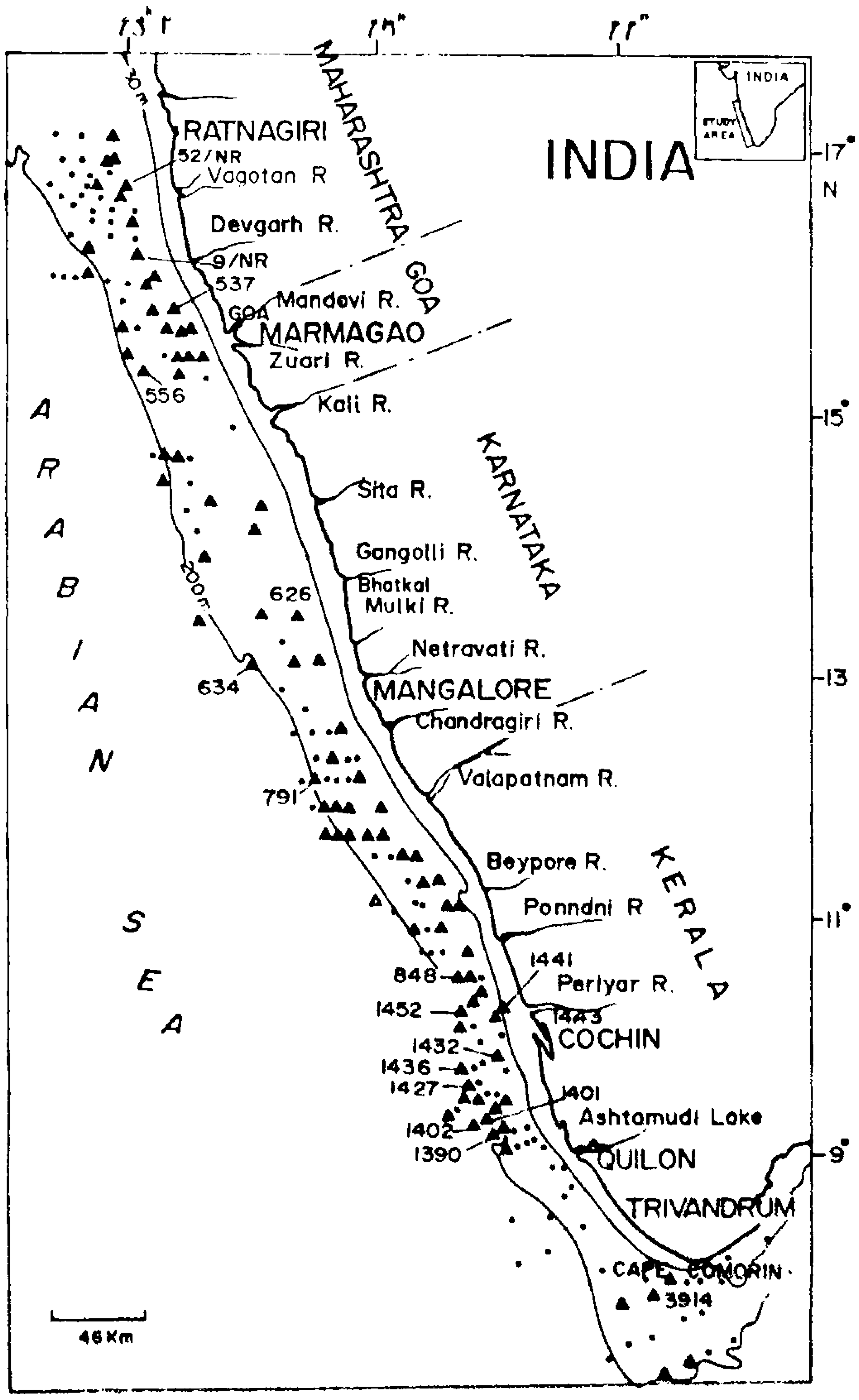

Figure 7 *a*. Location of authigenic green grains along the central and southwestern shelf of India. Triangles indicate more than 5% green grains in the coarse fraction. (prepared after Rao *et al.*[194] and Thamban and Rao[217]).

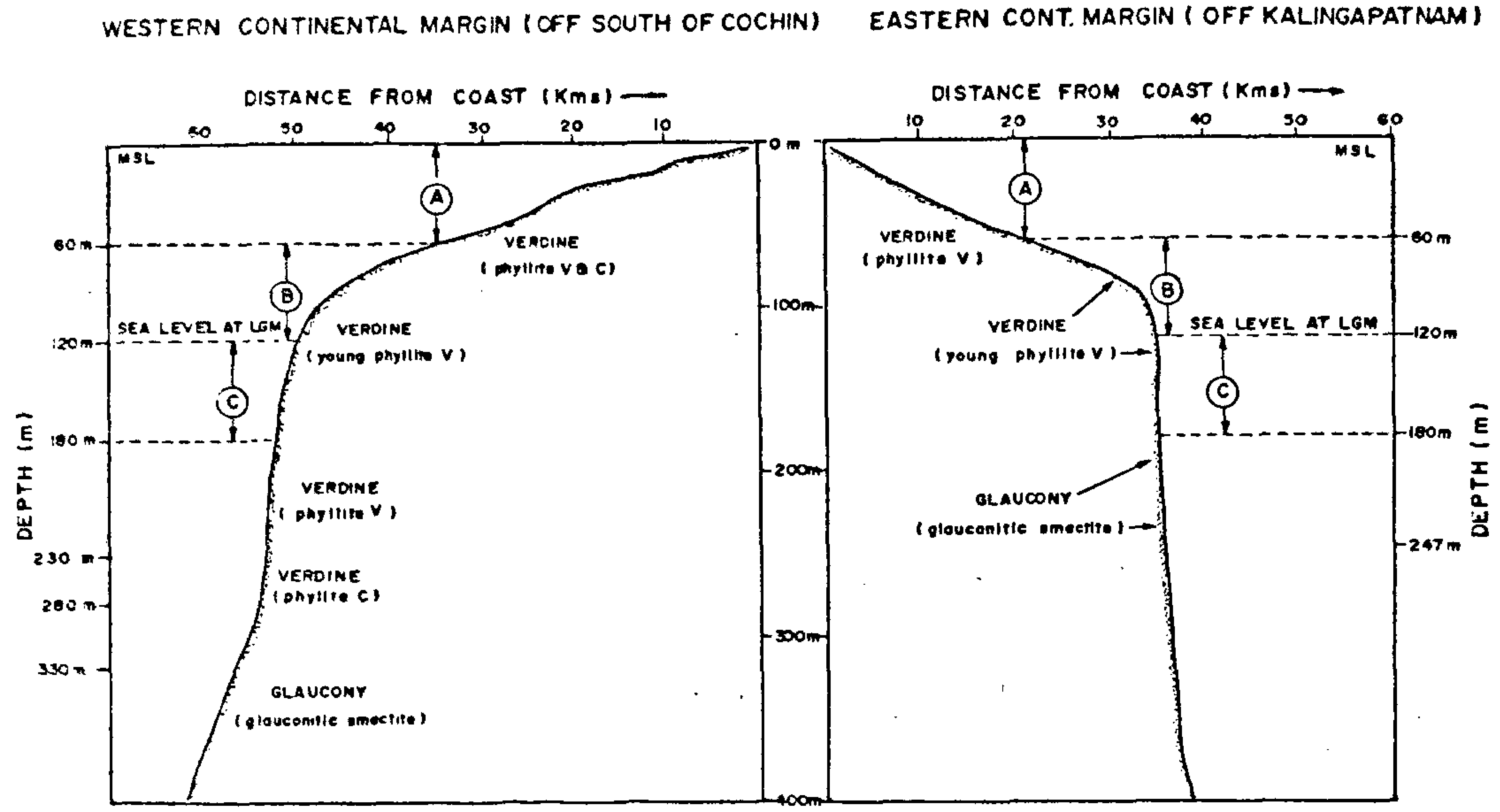

Figure 7 *b*. Comparison of verdine and glaucony distribution on the Kerala coast with those on the east coast of India. A, Depth range suggested for present-day verdine formation; B, Verdine formed during the Holocene transgression; C, Depth range suggested for verdine during the Last Glacial Maximum (prepared after Rao *et al.*[199,218]).

few transects across the continental margin between Cochin and Karachi[188] have been reported. Subsequent workers[189–192] made detailed studies on the distribution of phosphate from the entire shelf and upper continental slope. Various types of Holocene phosphatized limestones and phosphate–glaucony sediments, and Pleistocene phosphorites have been reported from the continental shelf and slope of India (Figure 6 *a*)[173,193–202].

The P_2O_5 content ranges from 0.03 to 1.19% (av. 0.48%) in the inner shelf sediments, 0.02 to 0.45% (av. 0.16%) in the outer shelf and 0.26 to 0.54% (av. 0.36%) in the upper continental slope[190]. P_2O_5 shows a positive correlation with Al_2O_3 ($r = 0.59$) and also with Fe_2O_3 ($r = 0.63$) indicating its presence in the form of ferric phosphate or being adsorbed onto hydrous Fe-oxides[192]. On carbonate-free basis, the P_2O_5 content in the southern part reaches up to 1.53 wt%. The correlation between organic carbon and P_2O_5 ($r = 0.34$) is weak. The P_2O_5 content of these sediments is relatively low[192] compared to the sediments of Peru–Chile[203].

The phosphorus content of the oolites is 700 µg/g and 1096 µg/g in the samples off Bombay and Karwar, respectively[166]. Baturin[193] reported 7% P_2O_5 in fossilized tubular structures on the 330 m depth terrace off Cochin. The P_2O_5 content of different types of limestones (algal nodules, coralline limestones and pelletal limestones) range from 2 to 11%, being highest in the algal nodules[194,195]. Uranium content of the phosphatized limestones ranges from 22 to 124 ppm and their age measured by ^{14}C and $^{230}Th/^{234}U$ methods range from 14 to 7.5 kyrs. Thin section, SEM tied EDAX studies of the limestones showed that apatite is in the form of rods, ovoids and dumb-bell shaped microparticles or their coalesced/aggregate forms (Figure 6 *b*) or microbial filaments[173,197]. These particles resemble fossilized bacteria reported by several workers[204–210]. Microprobe studies showed that phosphate is associated with siliciclastic material[198]. There seems to be a sudden increase in the sediment flux to the shelf in the early Holocene that filled the interstices of corals or got trapped between algal laminations. Phosphatization of limestones on the shelf appears to be a short-lived event in the Early Holocene, influenced by microbial processes.

High-grade phosphorites with 33% P_2O_5 have been reported in the gravity cores collected on the topographic highs off Goa[200,201]. They occur at different levels below 110 cm from the core tops. Absence of allogenic material, unique mineralogy and chemistry and presence of fish bones in these phosphorites are not convincing that these are diagenetic precipitates in the sediments[201], but suggest that these are fish coprolites phosphatized at low rates of sedimentation during the Pleistocene[199].

The central and south-western margin is known for intense seasonal upwelling and high productivity[211]. Oxygen minimum conditions exist between 150 and 1500 m depth. The organic carbon content reaches up to 8% in the slope sediments[212–214]. Though these conditions are comparable with those of Peru margin where present day phosphogenesis is taking place, present day apatite formation has not yet been reported. This may be due to lack of systematic exploration or some other factors inhibiting apatite formation.

Authigenic green clays

Verdine and glaucony are two granular green clay facies usually reported from the shallow submerged margins. Verdine is a newly distinguished facies. It has been reported to occur at depths < 60 m followed seaward by glaucony. Earlier workers[77,215] reported green grains on the western shelf of India at depths < 50 m and referred to them as glauconite without analysing their mineralogy. Verdine facies as separate green grain facies was known only in the year 1985 (see ref. 216). Subsequently, detailed studies[199,217] were carried out on the green grains from the Kerala continental shelf and slope and on the shelf from Ratnagiri to Cape Comorin.

A total of 195 samples have been examined for the green grains occurring at depths between 40 and 330 m and between Ratnagiri and Cape Comorin. Of these, 116 samples showed the presence of green pigment (Figure 7 *a*). The green grain content ranges from 2.4 to 51.2% of the coarse fraction of the sediment. The green grains are abundant in the sediments off the river mouths and in association with skeletal constituents. The green grains occur as irregular dark green grains, dark green glossy and light green rugose pellets and internal molds of skeletal constituents. Detailed mineralogical studies on 19 samples indicate that all the green grains studied here are a mixture of predominant authigenic green clay and detrital clay minerals and are altered. Both phyllite V and phyllite C (verdine minerals) associated green grains occur on the continental shelf. Phyllite C associated grains occur off the river mouths and in the transition zone between inner and outer shelf where there is some contribution of fine-grained material. Phyllite V associated grains are found with relict reefal sediments and terrigenous sands of the outer shelf. On the continental slope, phyllite V occurs at depths between 100 and 205 m followed by phyllite C at about 280 m depth on the continental slope. Glauconitic smectite of the glaucony facies occurs in association with phosphate facies at 330 m water depth[199]. Major element composition of the green grains slightly deviates from that of the green grains that contain pure authigenic clay.

The results[217] indicate that (a) verdine facies occur over an area of about 100,000 km^2 representing the largest sedimentary basin in the world associated with low fluvial input; (b) The size of the verdine deposit is related to the influx of iron rather than the amount of fluvial discharge; (c) The colour of the grains does not reflect the authigenic mineral or its evolution and (d) Green grains on this margin formed at different times when the sea level was at different depths during the late Quaternary; (e) Comparative studies on the distribution of the green grains from the Kerala shelf and slope with those on the continental shelf and slope of the east coast of India (Figure 7 *b*) indicate that the verdine facies occur up to 280 m depth followed by glaucony facies on the Kerala coast. Whereas on the east coast of India, verdine facies occur up to 170 m depth followed by glaucony facies[218] which is in agreement with Senegal and French Guinea margins[216]. The contrasting distribution on either side of the Indian margins has been attributed to the differences in paleogeography of the margins and as an evidence of Late Quaternary neotectonic activity on the west coast of India.

Organic-rich sediments

The amount and type of organic matter in marine sediments reflect the supply and preservation of organic materials from marine and terrestrial sources. Organic-rich sediments occur as laminated sediments on the continental slope of the west coast of India[91] and black shales in east coast of India[219]. These are important indicators of palaeo-oceanography. Several workers reported the distribution of organic carbon in sediments along the western margin of India and also the adjacent Arabian Sea[86,91,192,212,213,220–230].

Organic carbon (OC) content in the inner shelf sediments[212] along the west coast of India ranges from 1 to 4% and is associated with clayey sediments. High C/N ratios (10–30) indicate that it is mainly of terrestrial nature. On the outer shelf, OC values are low (<1%) and associated with relict sandy sediments. OC values are relatively high (>2%) on the continental slope except the slope between Indus mouth and Porbandar and a small portion of the anoxic slope along the southern Indian tip. Moreover, organic carbon-rich (4–16.7%) band[213] and laminated organic-rich sediments[91] occur on mid-slope, intersecting the oxygen minimum, continuously between Bombay and the southern tip of India and is relatively wide between Ratnagiri and Mangalore. C/N ratios and $\delta^{13}C$ values[143,227] indicate that the OC is mostly of marine origin. Higher levels of OC in the slope sediments are still a matter of debate. As there is mis-match in the productivity-associated zones and organic-rich zones on the continental slopes, some[213] consider that OC-rich sediments have accumulated due to preferential preservation of deposited organic matter in anoxic conditions and thus considered that the Arabian Sea is a modern analogue for the environment of formation of organic-rich sedimentary facies. Hydrogen indices (HI) values[226] for the sediments in the oxygen minimum are higher than that of sediments above and below the oxygen minimum zone and higher HI values are indicative of preservation. The poor supply of organic matter[228] from the Indus may be responsible for

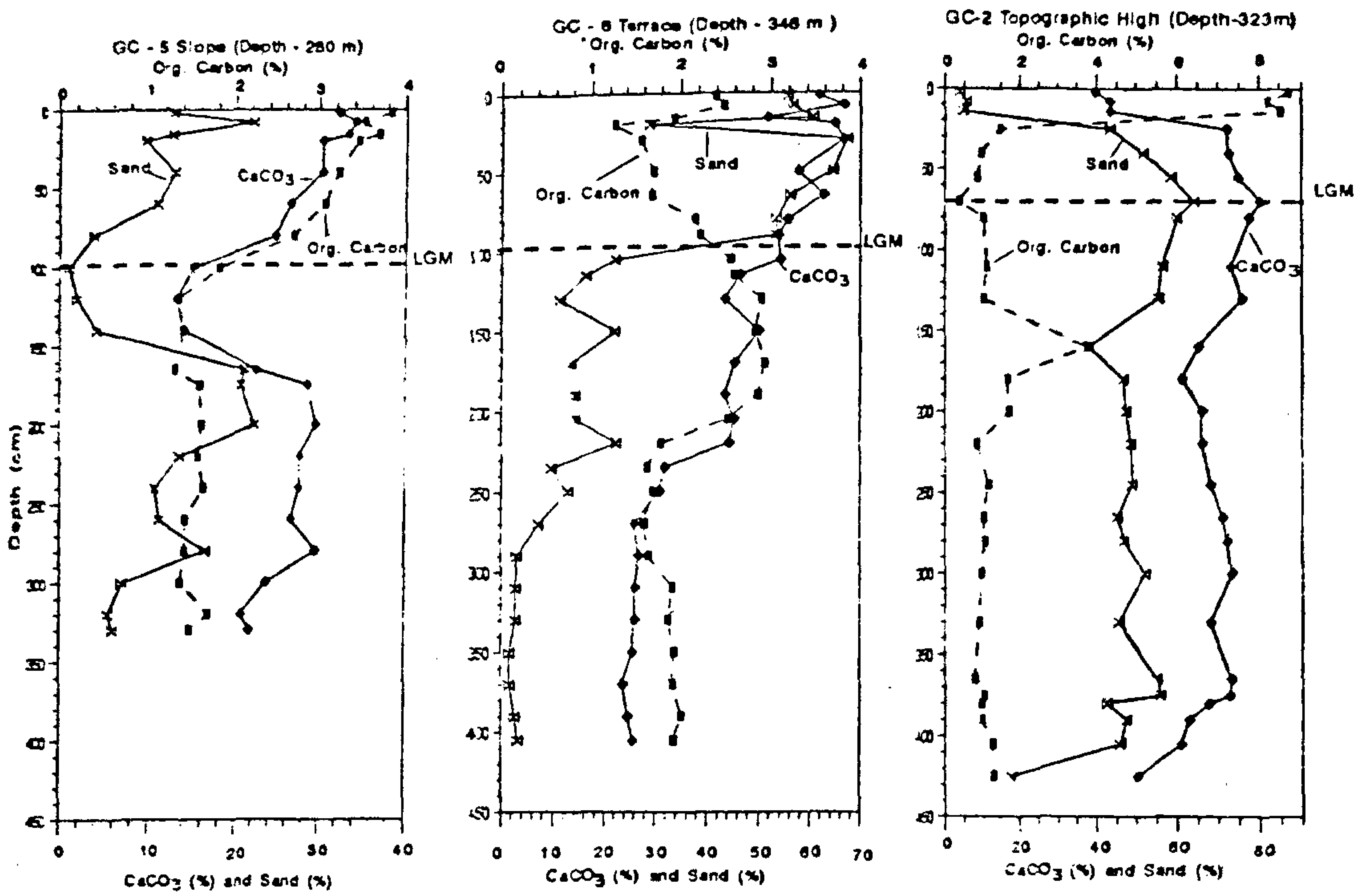

Figure 8. Distribution of organic carbon (OC), $CaCO_3$ and sand fraction in sediment cores from three physiographic settings (after Thamban *et al.*[214]).

the low OC in the slope sediments of the northeastern part of the Arabian Sea.

Several others[227,229,230] have reported that organic carbon maximum on the western margin of India extends over a larger depth range than the oxygen minimum and hydrogen indices of the sediments are similar in the sediments accumulating within and outside the oxygen minimum zone. These authors suggest that hydrogen richness in the sediments is not related to bottom water oxygen concentration but is controlled by sediment reworking. They found low HI values for the OC in coarser sediments and high HI values for the OC in finer sediments. These authors suggest that the distribution of OC is controlled by the variations in surface productivity, dilution by other sedimentary components and texture of the sediments and conclude that the bottom water oxygen concentration cannot be the primary factor determining the organic content and its preservation in continental slope sediments. Since surficial sediments on the western continental margin of India are being modified by depositional and mass transport processes from the adjacent shelf[231], the investigations in the sediment cores may be useful in resolving this problem. In fact a core collected off Pakistan showed OC variations in relation to productivity[229].

Detailed studies (texture, OC and $CaCO_3$ contents, rock-eval pyrolysis, coarse fraction studies and radiocarbon dates) were carried out on sediments in the gravity cores collected from three physiographic settings (upper continental slope, topographic highs and terrace), within the oxygen minimum zone at depths ranging from 280 and 350 m (ref. 214). These studies indicate that the OC, $CaCO_3$ and sand contents (Figure 8) are high at core tops and the values decrease with increasing depth in the Holocene and Upper Pleistocene sediments of the continental slope. OC shows strong positive correlation with $CaCO_3$ and sand content of the sediments of the slope and strong negative correlation with those of the topographic highs. On the terrace, it shows negative correlation in the sediments closer to the Last Glacial Maxima (LGM) and then positive correlation at the core tops. The OC content is lower in all Pleistocene sediments and its relationship with $CaCO_3$ content is diverse. The OC is immature and marine or a mixture of both marine and terrestrial in the Holocene sediments and is mostly terrestrial in the Pleistocene sediments. The influence of reworking, winnowing and texture of the sediments varies in each physiographic setting. It has been suggested that OC in the Holocene sediments is mainly controlled by primary productivity. Texture and reworking are also responsible for the OC variations. Data on stable isotopes are required to substantiate the findings.

Some important research problems to be investigated

Marine geological studies on the western continental margin of India have progressed for the last 30 years and a fairly good understanding has been achieved on surficial geology. The following are some important research problems to be investigated: (a) Precise sampling and dating of submarine terraces, shelf edge reefs and drilling on reefal sediments may provide important clues on paleo-oceanography; (b) Exploration for placer deposits in several less studied coastal bays in Maharashtra and those associated with former shorelines and river valleys on the continental shelf may be helpful in discovering the placers of economic potential; (c) There is no reliable sea level curve for the continental margins of India. A systematic study is essential to generate reliable database on sea level changes and for the construction of a regional sea level curve for the Late Quaternary. This area of study, which has received less attention so far, should be given high priority in order to model and better estimate the rise of sea level by greenhouse gases and by subsidence; (d) Recent studies have merely described acoustic maskings based on shallow seismics. Actual measurements for confirmation and estimation of methane in waters as well as in sediments should be investigated; (e) Detailed exploration for phosphorites are required at least in three areas (off Saurashtra, Goa and Kerala); (f) Stable isotope studies on sediment cores are required to understand the palaeo-oceanography of the organic-rich sediments; (g) Studies on shelf edge exchange processes may allow the identification of the mechanisms of sediment transport; (h) Data on sediment accumulation rates on the shelf and slope are sparse and scattered and more areas have to be investigated systematically; (i) As the clays on the inner shelf are carbonate-poor and organic-rich, studies may be initiated for the utility of these clays for ceramics.

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