

Evidences of Late Quaternary neotectonic activity and sea-level changes along the western continental margin of India

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The offshore data on sea-level changes along the western margin of India have been reviewed and evidences of Late Quaternary neotectonic activity and subsidence are documented, based on the diagenetic textures of limestones from deeper submarine terraces and from the Fifty Fathom Flat off Saurashtra-Bombay, authigenic clays from the Kerala continental margin and onshore data. Offshore sea-level data relative to the eustatic sea-level show about 40 m subsidence sometime in the Holocene. Existing sea-level curves may not reflect the true sea-level changes. As there are several gaps in the data base, it is suggested that more systematically collected offshore data is an immediate requirement to chart the accurate sea-level changes and construct a regional sea-level curve for the Late Quaternary.

movements by tectonic and isostatic adjustments and geoidal variations^{1,2}. The construction of regional sea-level curve is therefore essential and important in understanding the implications of sea-level changes. Kale and Rajaguru³ and Hashimi *et al.*⁴ constructed sea-level curves for the Late Quaternary for the western continental margin of India. These curves differ distinctly from one another and also with the eustatic sea-level curve of Fairbanks⁵ (Figure 1). The authors used some estimated³ and inferred ages⁴ for making sea-level curves. Incidentally, the actual radiocarbon dates of the samples from the western offshore (outer shelf and slope) (Figure 2) are younger than those at corresponding depths on the eustatic sea-level curve (Table 1) and thus plot away from all the above curves (see Figure 1). This may be due to neotectonism which was not considered in preparing the sea-level curves. In this article we provide evidences of Late Quaternary neotectonism along the western margin of India and reassessment of existing

SEA-LEVEL change in a given area is governed by eustatic sea-level fluctuations and local factors such as land

sea-level curves and other offshore data in establishing sea-level changes.

Evidences of neotectonic activity

Deeper terrace limestones

Rao and Veerayya⁶ reported 1.5 to 2.0 km wide submarine carbonate terraces at 130, 145 and 170 m water depths on the continental slope off Saurashtra–Bombay (Figure 3). These terraces lie below the eustatic sea-level low (–120 m)⁵ during the Last Glacial Maximum (LGM). The radiocarbon dates and diagenetic textures of the limestones from 130 m terrace indicate that these sediments were cemented into limestones at intertidal conditions at about 11,890 years BP. The eustatic sea-level was, however, at –90 m at about 12,000 years BP (ref. 5). Transportation of limestones from shallow shelf

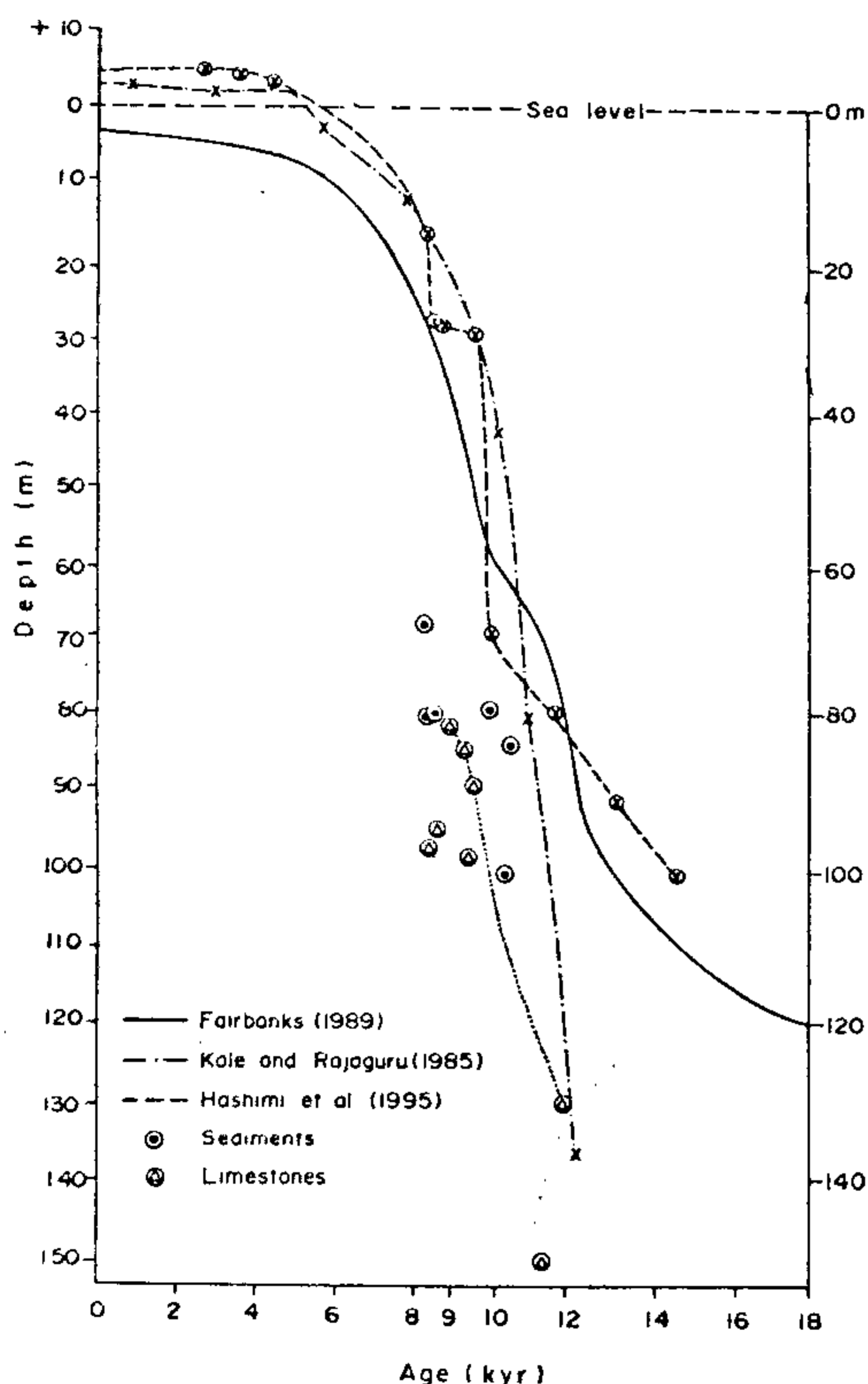


Figure 1. Sea-level curves and plot of radiocarbon dates of the samples from the western offshore. Note that the ages of the samples plot away from the curves. Fairbanks curve (ref. 5) is for the Barbados Islands; the ages of the coral samples used for the curve were corrected with the uplift data of the Barbados and for local sea water (Fairbanks sea-level curve is being used as a reference eustatic sea-level curve by several workers all over the world). The dotted line may represent sea-level change between 12,000 and 9,000 years BP.

depths can be precluded, because the terraces on landward are covered by 15–20 m thick sediments (Figure 3) and the ages of samples from the adjacent shelf are younger by about 2,000 years and nowhere else are these ages found (see Figure 2). It is therefore suggested that these deeper terraces on the Saurashtra–Bombay margin might have been positioned at water depths < 120 m during the LGM and subsided to the present position sometime after 12,000 years BP.

Evidences from the Fifty Fathom Flat (carbonate platform)

Radiocarbon dates and their comparison. The age of the aragonite sands and limestones on the carbonate platform ranges from 10,400 to 8,340 years BP and 9,200 to 8,465 years BP, respectively (see Table 1; Figure 2). There is no relationship between ages of the samples and their depth of occurrence and the sediments having younger ages occur even at greater depths. Further, the sediments and limestones with an age difference of about 2,000 years occur in the vicinity on the platform.

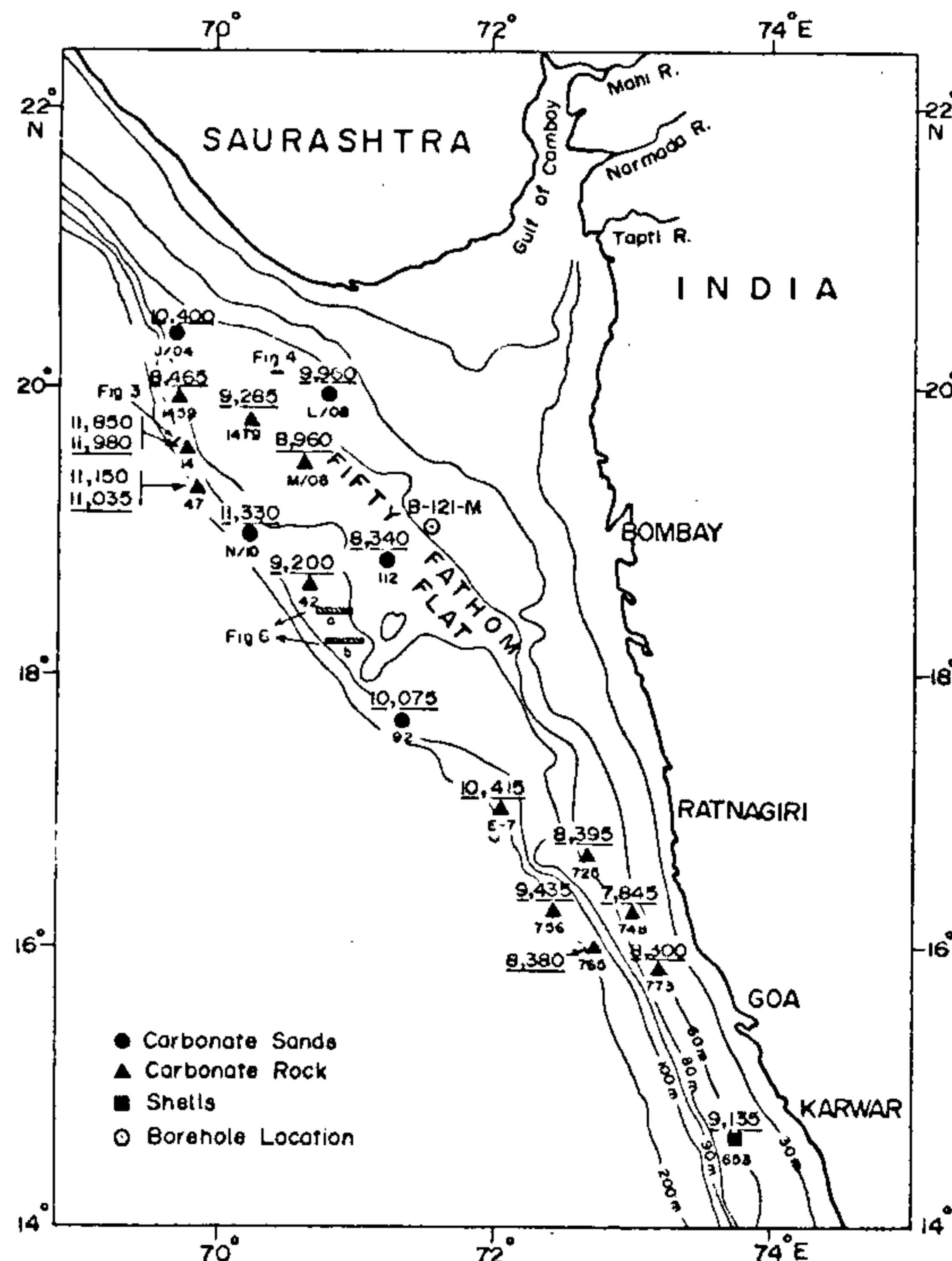


Figure 2. Sample location map of west coast of India, numbers underlined are radiocarbon ages. The location of deeper submarine terraces (Figure 3), *Halimeda* bioherms (Figure 4) and sand ridges (Figure 6) are also shown here.

Table 1. Available radiocarbon dates on surficial carbonate samples from the western continental margin of India (see Figure 2 for sample location)

Sample no.	Nature of sample	Depth (m)	Age (years BP) and reference	Age (approx.) on the eustatic sea-level curve ⁵ for the corresponding depth
47	Algal-pelletal l.st.	150	11,150 ± 130 (refs 8, 9)	—
E-7	Algal-bryozoan l.sts.	180*	10,415 ± 250 (refs 8, 9)	—
775	Algal nodules	70–150*	11,040 ± 135 (ref. 34)	—
			7,500 ± 200 (ref. 35)	—
14	Beachrock	130	11,980 ± 185 (ref. 6)	—
			11,850 ± 210	—
42	Oolitic l.st.	98	9,200 ± 135 (refs 8–10)	12,500
M/08	Oolitic l.st.	82	8,960 ± 200 (refs 8–10)	11,850
L/08	Oolites	80	9,960 ± 160 (refs 8–10)	11,600
J/04	Oolites	80–90	10,400 ± 300 (ref. 9)	11,900
1459	Halimeda l.st.	95	8,465 ± 125 (ref. 15)	12,350
1479	Halimeda l.st.	85	9,285 ± 180 (ref. 15)	11,900
112	Pelletal sands	80	8,340 ± 185 (ref. 15)	11,600
92	Pelletal sands	100	10,075 ± 250 (ref. 15)	12,700
653	Shells	58	9,135 ± 130 (ref. 10)	9,850
725	Algal nodule	80	8,395 ± 145 (ref. 36)	11,600
773	Algal nodule	68	8,300 ± 135 (ref. 36)	11,000
			8,600 ± 080	
748	Neomorphic l.st (Original calcite is replaced, so younger ages)	60*	7,845 ± 130 (ref. 36)	10,000
756	—	90	9,435 ± 145 (ref. 36)	12,000
765	—	97	8,380 ± 140 (ref. 36)	12,900

*These points are not plotted in Figure 1.

Several samples (about 90 m depth) on the carbonate platform yielded ages of about 9,000 years BP. Contrastingly, the shells dated 9,135 years BP were collected at 58 m depth on the continental shelf, south of the carbonate platform (see Figure 2). Therefore, there is no particular trend in the data when viewed the ages of unconsolidated sediments and rocks together (Figure 2). The ages on the platform are younger than those at corresponding depths on the eustatic sea-level curve (Table 1) and with the data on the east coast of India. For example, the platform lies between 80 and 90 m depth and the sample ages range from 10,400 to 8,340 years BP. The eustatic sea-level for the corresponding ages was, however, at depths between 65 and 30 m, respectively⁵. Similarly, the ages of the terraces at 80 and 100 m water depth on the eastern shelf of India are 10,790 and 12,530 years BP⁷. The samples corresponding to these ages, however, occur at about 130–150 m water depth on the western margin (Table 1). These anomalies need to be explained based on the nature of sediments.

Constituents and topographic features. Several workers^{8–12} referred to the carbonate (aragonitic) sands and limestones on the platform as oolites and oolitic limestones. If these sands are oolites (chemical precipitates), formed during the Holocene transgression, one would expect older ages seaward and younger ages landward of the platform. This, however, is not evident in Figure 1.

There are several dates on the platform showing an age 10,000–9,000 years BP during which the eustatic sea-level rise was very rapid (23 m/1000 years)⁵. As the formation of oolitic coating is a slow chemical process¹³, it may be difficult to achieve prerequisite conditions (supersaturated aragonite in the waters and maintaining < 10 m depth) for oolite formation at this high rate of sea-level rise. Even if oolites are present at places (possibly associated with terraces or thin oolitic coating formed after 9,000 years BP), large nucleus material determines the radiocarbon ages and one has to find a suitable explanation for the origin of large homogeneous aragonitic nucleus that formed prior to the oolitic coating; this explanation, however, is lacking from the above references. So, referring to the carbonate sands on the platform as oolites does not explain the anomalous distribution of radiocarbon dates (Figure 2). Even if oolitic sediments occur locally, their ages should not be used for the construction of sea-level curve as oolites are unreliable sea-level indicators¹⁴.

A recent study¹⁵ based on bathymetry, seismics and side scan sonar data and on petrology of the sediments and sedimentary rocks has demonstrated the presence of Late Quaternary *Halimeda* bioherms (Figure 4) on the Fifty Fathom Flat. *Halimeda* (Figure 5A) contributed aragonite sediments to the platform. The following points have emerged^{15,16}: (i) High energy environments prevailed during the *Halimeda* growth. (ii) The aragonite muds derived from *Halimeda* were fixed in the form of faecal

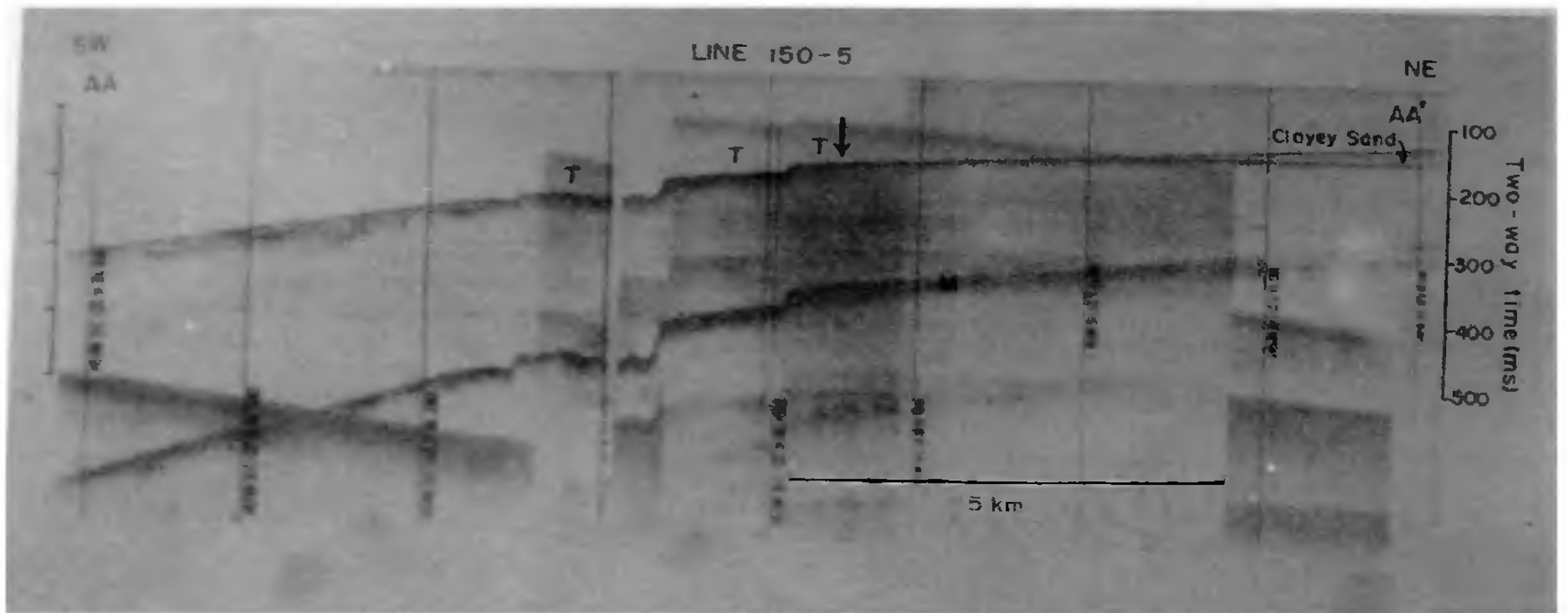


Figure 3. Deeper submarine terraces on the continental slope off Saurashtra-Bombay (see Figure 2 for location). T, terraces; M, multiple.

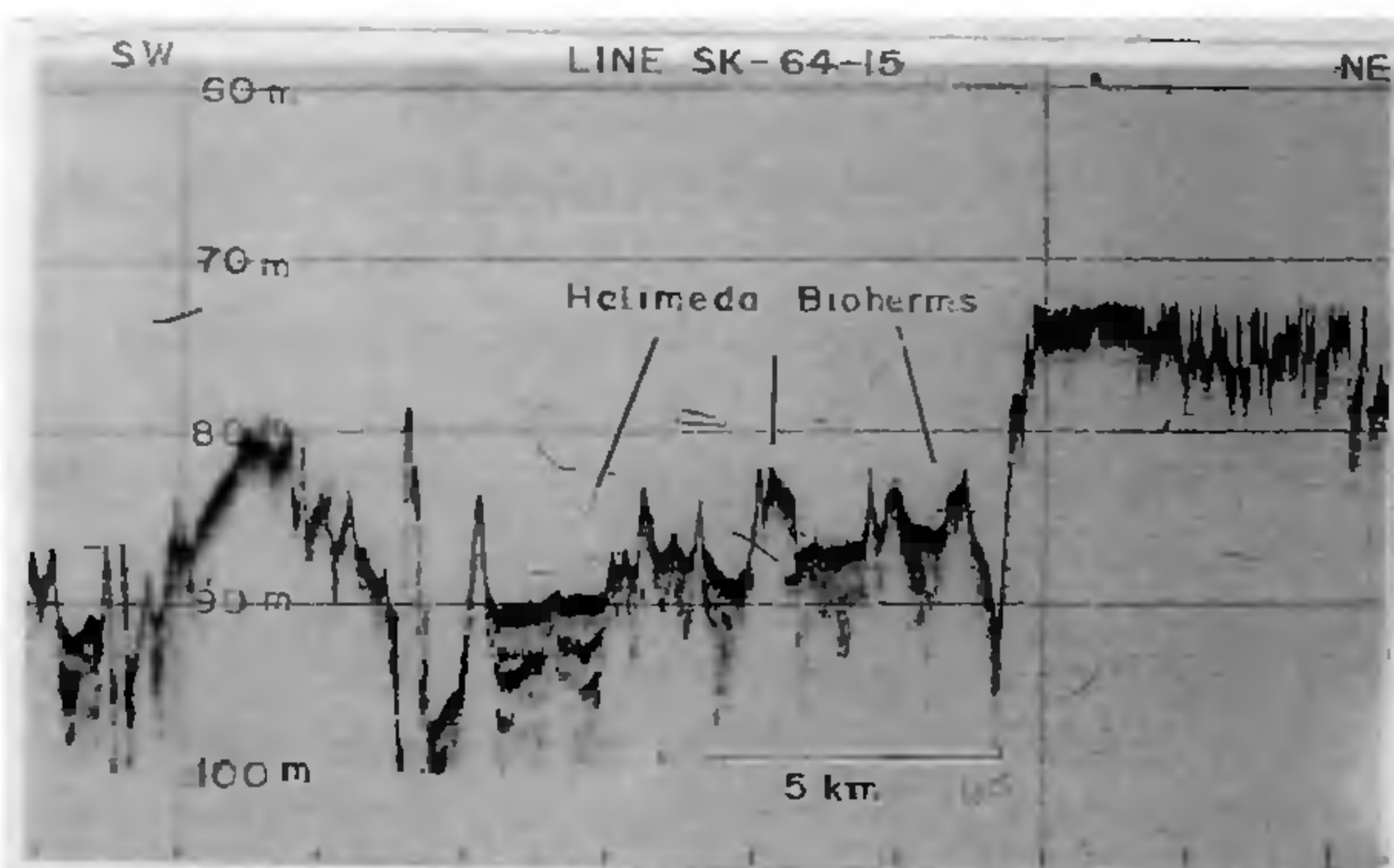


Figure 4. *Halimeda* bioherms on the Fifty Fathom Flat (see Figure 2 for location).

pellet sand (Figure 5B) mainly by Crustaceans. (iii) Reworking of aragonitic sands in high energy environments led to the exposure of older sediments at certain depths (see Figure 2). (iv) *Halimeda* growth continued locally at places until 8,300 years BP, resulting *Halimeda* limestones having younger ages at seaward edge of the platform (see Figure 2). (v) The limestones dated 9,200 years collected at 85 m depth on the platform exhibit vadose diagenetic conditions.

Well-defined submarine sand ridges have also been reported near the shelf break and on the carbonate platform where *Halimeda* bioherms profusely occur¹⁷. These ridges are 1.5 to 18 m high, 0.5 to 10 km wide, several tens of km long, a few kilometers apart and trend almost parallel to the shelf edge (Figure 6). Some broad elongated ridges are superimposed by sand waves/bed forms having heights in the order of 1–2 m

and wavelength 50–300 m. Wagle and Veerayya¹⁷ suggested that these are relict nearshore sand ridges formed in high energy environments where water depths were shallower and tidal and wave-induced currents were stronger.

Since the material that formed sand ridges is aragonite sands which comprise of abundant *Halimeda* fragments and faecal pellets, it is obvious that the *Halimeda* growth on the platform might be prior to and had continued during the sand ridges formation. Both sand ridges and *Halimeda* bioherms indicate high energy environments and the former are distinct towards the edge of the shelf (Figure 6). It is difficult to assess the depth limits for *Halimeda* bioherms, because *Halimeda* normally grew at much shallow depths (< 20 m). However, their growth at depths > 50 m towards the edge of the shelf¹⁸ and certain species of *Halimeda* at 120–150 m depths¹⁹ have also been reported. Reworking exposed older sediments at places. Therefore, the radiocarbon ages of the unconsolidated sediments from the platform may not be of much use in reporting sea-level changes. It has been suggested that all shallow water deposits are not necessarily sea-level indicators and caution be exercised in selecting the sea-level indicators^{1,2}. The depth precision of the sea-level indicators should be well defined before being used for sea-level changes.

Diagenetic textures of the limestones. *Halimeda* limestones dated 8,465 years BP occur towards shelf edge and exhibit marine cements¹⁵. These were similar to subtidal limestones²⁰, wherein pumping of sea water into the pores of the sediments results in cementation. The limestones at 85 m water depth exhibit vadose diagenetic textures, suggesting vadose conditions on the platform at about 9,200 years BP (refs 15, 16). The mineralogy

and stable isotopes¹⁵ suggest that these samples are reliable sea-level indicators. However, the eustatic sea-level was at -40 m at about 9,200 years BP. The differences in the depths thus suggest subsidence of the platform. In fact, the deeper submarine terraces (evidence 1) lie seaward of the platform (see Figure 2) and the samples both from terraces and platform support neotectonic activity. It is not known whether the neotectonic activity after 12,000 years was single or episodic. Sampling on deeper terraces from the slope and other recently described shelf terraces²¹ may yield better information.

Onshore data

There are no samples dated <8,000 years BP, yet available from the offshore. The youngest age so far reported from the calcareous deposits on the outer shelf (Figure 2) and peat/wood from the inner shelf (discussed

below) is 8,300 years BP. It is still unknown the position of the sea-level at 8,300 years BP from the offshore data. On the other hand, Patel *et al.*²² (cf. Merh²³) reported the Early Holocene high sea-level (+8 to +10 m above the present sea-level) in coastal Gujarat and Maharashtra that gradually regressed to the present position at about 6,000 years BP. Sukhtankar²⁴ reported Holocene marine terraces at 4 m above the present sea-level along Maharashtra coast. They could not indicate the exact time of high sea-level during the Early Holocene. Bruckner²⁵ identified marshy soils dated 7,600 years BP, off Gujarat, lying 1.5 m above the sea-level. Juyal *et al.*²⁶ reported oyster reefs at 1-3 m elevation whose ages range from 2,000 to 8,000 years BP, suggesting high sea-level during Early Holocene on the Saurashtra coast. The absence of data <8,000 years BP, from the offshore and the presence of corresponding (Early Holocene dated samples) data in the coastal region imply that the sea-level was already at and above present sea-level by 8,000 years BP. The eustatic sea-level was, however, at -24 m at 8,000 years BP (ref. 5). These differences in depths again indicate possible neotectonism at about this time.

Authigenic clays

Verdine and glaucony are two authigenic green clay mineral facies occurring in tropical shallow marine environments. Verdine occurs at depths <60 m and glaucony occurs seaward of verdine at depths²⁷ >60 m. Phyllite V and Phyllite C are the mineral phases of the verdine facies. As verdine is susceptible for alteration, it gets destroyed easily in older surficial marine sediments and therefore it has been found so far to be only of Late Quaternary age²⁷. The depth distribution of verdine and glaucony facies has been verified and used for the reconstruction of palaeogeography of the continental margins during the Late Quaternary²⁷.

The distribution of green grains on the Kerala continental shelf and slope (Figure 7) shows that verdine occurs at depths between 40 and 280 m followed by glaucony down to 420 m depth²⁸. It has been suggested that the verdine and glaucony facies on the continental

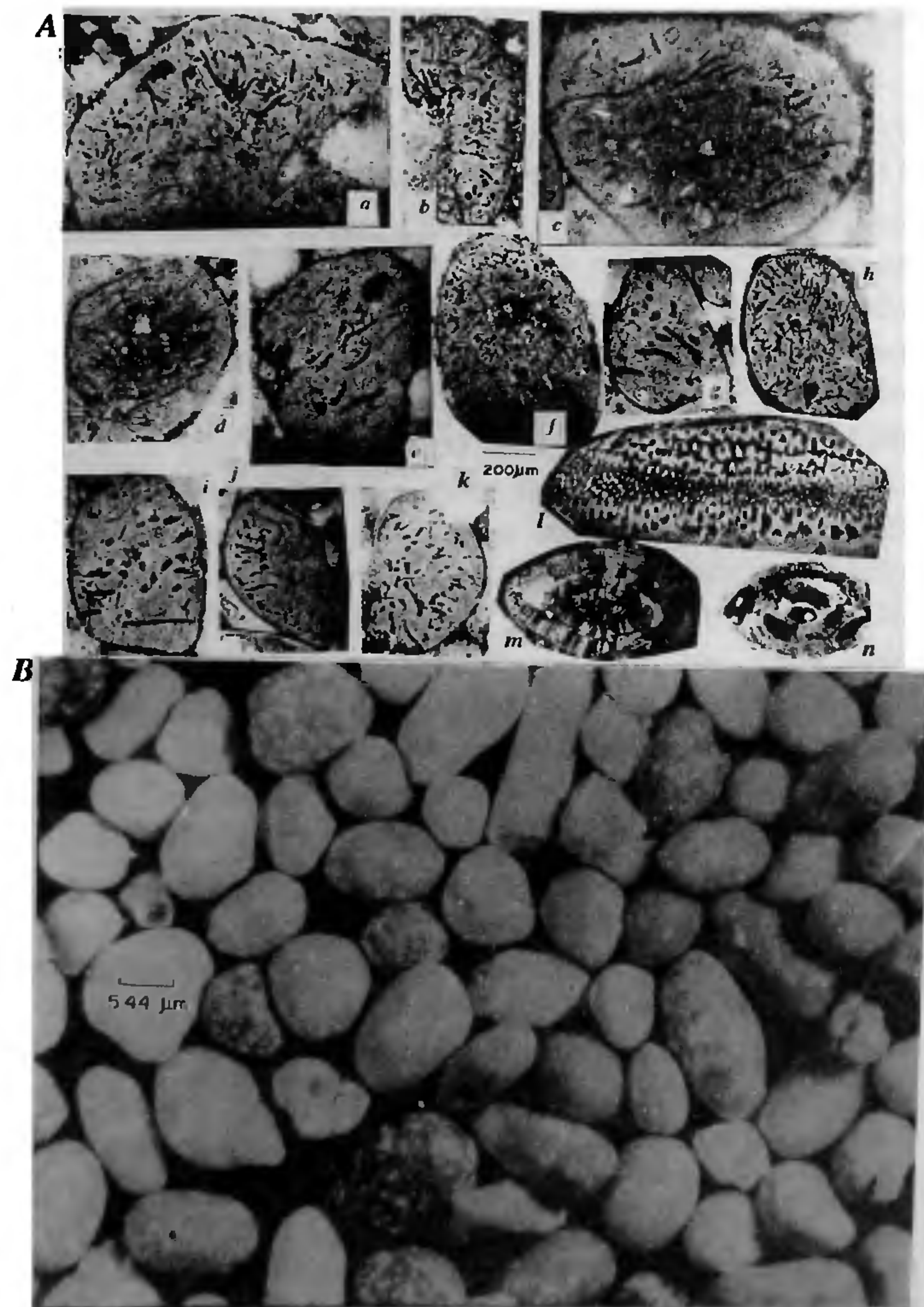


FIG. 5A

Figure 5. A, Sections of *Halimeda* (a-k), echinoderm (l) and benthic foraminifers (m & n) from the limestones of the platform. Note rounding of *Halimeda* grains. *Halimeda* is aragonitic in composition. If sections are not made, the morphology of the grains can easily be confused with the faecal pellets or oolites. B, Faecal pellet-dominated aragonite sands from the platform.

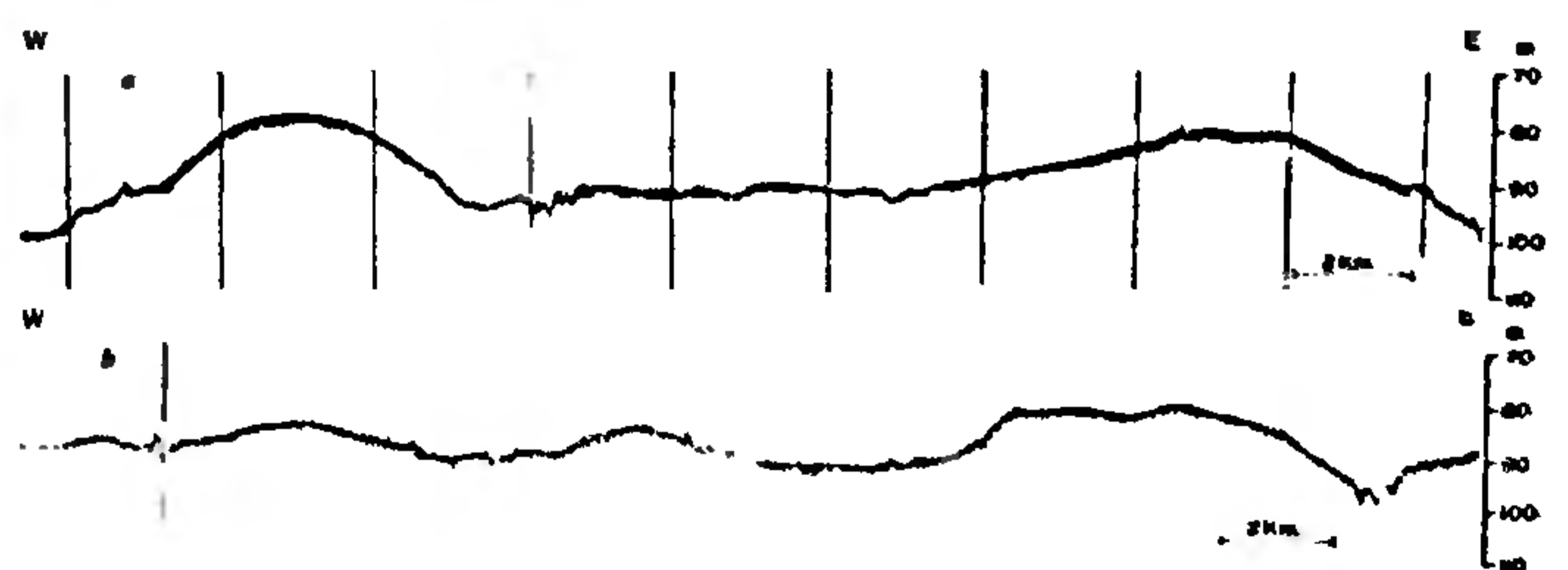


Figure 6. Sand ridges on the continental shelf off Bombay (see Figure 2 for location).

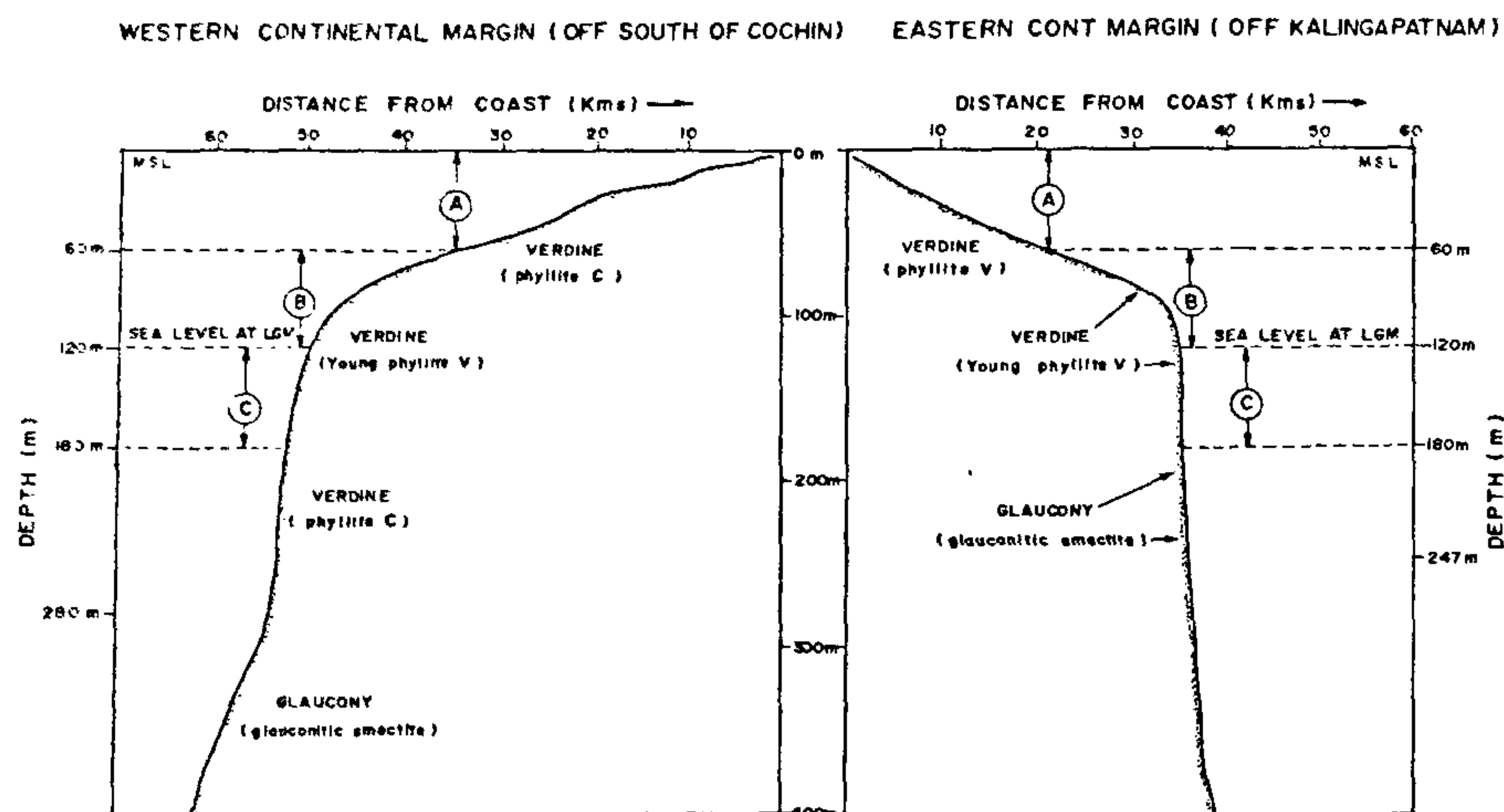


Figure 7. Distribution of green grains on the eastern and western continental margin of India. Zone A is the depth range (0–60 m) for the formation of Present day verdine, zone B is the depth range (61–120 m) for verdine formed during Holocene transgression and zone C (120–180 m) is the depth range for verdine formed during the Last Glacial Maximum.

margin are diachronous and slope facies formed during LGM, when the sea-level was at -120 m, and shelf facies formed during the Holocene transgression²⁷. So the expected depth ranges for verdine and glaucony facies on the slope during the LGM are 120 to 180 (120 + 60) m and >180 m, respectively. However, on the continental slope of Kerala verdine occurs down to a depth of 280 m. Verdine mineral at 100–205 m (phyllite V) and at 280 m (phyllite C) are different and rules out the possibility of lateral transport. So the distribution of verdine and glaucony facies on the continental margin off Kerala does not coincide with the suggested depth range. On the other hand, verdine facies occur at depths between 18 and 170 m followed by glaucony down to 247 m on the east coast of India²⁹. The range of green grain facies from verdine to glaucony at 170 m depth on the continental slope of the east coast of India (Figure 7) is well in agreement with the suggested depth ranges of these facies during the LGM, and also their distribution is similar to that on Senegalese and French Guinea margins²⁷. The distribution of verdine and glaucony on the west coast therefore appears anomalous and suggests that the paleogeography of the west coast was different during the Late Quaternary, pointing to the possible neotectonic activity. As these authigenic clays form in wide depth range, quantitative aspect of sea-level changes cannot be deciphered from them.

Reassessment of offshore data and sea-level curves

1. There is a paucity of data on sea-level changes for the periods between 18,000 and 12,000 years BP and

8,300 years BP to Present from the offshore region.

2. Although one should appreciate the efforts of earlier workers for attempting sea-level curves for the western margin of India with limited data, these curves may not work as they^{3,4} have used oolite ages and some estimated and inferred ages based on the presumption of oolites which are unreliable sea-level indicators¹⁴. They⁴ have also used radiocarbon ages (range from 9,630 to 8,300 years BP) of carbonized wood/peat^{30,31} from the inner shelf clays. (i) The peat dates are higher as it has been established that mangroves started growing on the tropical shelves world wide during Mid-Holocene and the Holocene peats are nowhere older than 7,000–5,000 years BP (ref. 32). (ii) It has been observed that the age of the peat layer from a core collected at 29 m depth is 9,630 years BP and another peat layer from a core collected deeper offshore at 40 m depth is 8,620 years BP (ref. 31). These dates should have been exactly opposite if peat is sedentary (a sea-level indicator) and if one is to trace the course of Holocene transgression on the western shelf. (iii) The peat ages on the inner shelf and ages of the carbonate deposits on the outer shelf (see Figure 2) are similar suggesting that one of them is allochthonous. The carbonate deposits are extensive on the platform, derived from the *Halimeda* bioherms and thus were not transported. The above points suggest that the peat in the inner shelf clays is most probably allochthonous similar to the peat reported by Mascarenhas *et al.*³³ in the inner shelf sediments off Karnataka and their ages thus do not qualify for the construction of sea-level curve.

3. There are several radiocarbon dates on algal limestones^{8,9,34–36} (Table 1). Unless the specific algae-forming

limestones are identified³⁷, these limestones alone cannot be considered as reliable sea-level indicators³⁸.

4. Since the diagenetic textures have been investigated for the limestones having ages between 12,000 and 9,000 years BP, this part of the curve is constructed and shown in Figure 1. A comparison of this with eustatic sea-level curve of Fairbanks⁵ reveals about 40 m subsidence on this margin sometime after 12,000 years BP. The rate of subsidence and timing of the Holocene neotectonic activity are yet to be established.

5. Practically little radiocarbon ages data exist for the SW continental margin of India.

Despite there were two international efforts (IGCP Projects 200 and 274) for obtaining sea-level data, the Indian continental margins have received very little attention and the construction of sea-level curve for this region is still at its infancy. Sea-level data is of crucial importance, because it provides knowledge on the past sea-level stands based on which we can accurately model and estimate the impact of sea-level rise as a consequence of global warming. More serious and concerted efforts by geomorphologists, sedimentologists and radiochemists are required and would be useful in obtaining this important information.

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