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RESEARCH ARTICLES

Submarine terrace limestones from the continental slope off Saurashtra–Bombay: Evidence of Late Quaternary neotectonic activity

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Bathymetric and shallow seismic data from the continental slope off Saurashtra–Bombay indicate wide submarine terraces at 130, 145 and 170 m and reefal structures at 320–360 m water depths. 10 cm thick slabs of limestones are recovered from the 130 m depth terrace. Some of these limestones consist of thin micrite layer on the top and a sandy layer below and others are similar to calcarenites. They contain > 95% aragonite and minor high- and low-magnesium calcite. Acicular aragonite cements occur as isopachous crusts. Dissolution and clotting of aragonite needles and drusy calcite in the interstices indicate cementation of the limestones at intertidal conditions. The age of the limestones is 11,900 years BP. These imply that the 130 m depth terrace was at intertidal depths at about 12,000 years BP. The eustatic sea-level, however, was at − 90 m at 12,000 years BP. This disparity suggests neotectonic activity and subsidence by about 40 m on the Saurashtra–Bombay region some time after 12,000 years BP.

SUBMARINE terraces are important geomorphic features on the continental margins and may record former sea-levels[1]. Submarine terraces have been reported[2–4] on the western continental shelf of India between 35 and 115 m and also between 115 and 170 m water depths on the continental slope off Saurashtra–Bombay[5]. Saurashtra was tectonically unstable during the Pleistocene[6–9]. The eustatic sea-level[10] low during the Last Glacial Maxima (LGM) was only −120 m. The deeper terraces may therefore have implications to neotectonism and Quaternary sea-level changes. We report here the investigations on the limestones from a 130 m depth submarine terrace off Saurashtra–Bombay and provide evidence of Late Quaternary neotectonic activity, hitherto unknown from the western offshore.

Materials and methods

During the cruise 150 of the *R. V. Gaveshani*, bathymetric and shallow seismic data were collected from the continental shelf and slope off Saurashtra–Bombay. Sediment and limestone samples were collected with a Peterson grab (Figure 1). Mineralogy of the representative samples was determined by X-ray diffraction. Freshly broken surfaces of the limestone fragments were examined under a scanning electron microscope (JEOL T 20). Radiochemistry of the limestones was carried out at the Hydrogeology and Isotope Geochemistry Laboratory, University of Paris, Orsay. Polished and thin sections of the limestones were studied under petrographic microscope.

Results

Geomorphology

The width of the continental shelf off Saurashtra ranges from 110 to 200 km. However, in the southern part, it is about 160 km wide and the shelf break occurs at 100 m water depth. Well developed 1.5 to 2.0 km wide terraces occur at 130, 145 and 170 m water depth on the continental slope (Figure 2 *a* and *b*). Several seismic profiles across the shelf and slope off Saurashtra–Bombay indicate that these terraces are major topographic features on the upper continental slope. A 15–20 m thick acoustically transparent clayey sand layer occurs landward of the terraces and pinches out at 120 m depth (Figure 2 *a*, *b*). Terraces show strong acoustic reflections in seismic profiles, may be due to the exposure of relict carbonate sands and limestones. Further seaward 2 km wide and 25 m high massive reef was found at depths between 320 and 360 m (Figure 2 *a*).

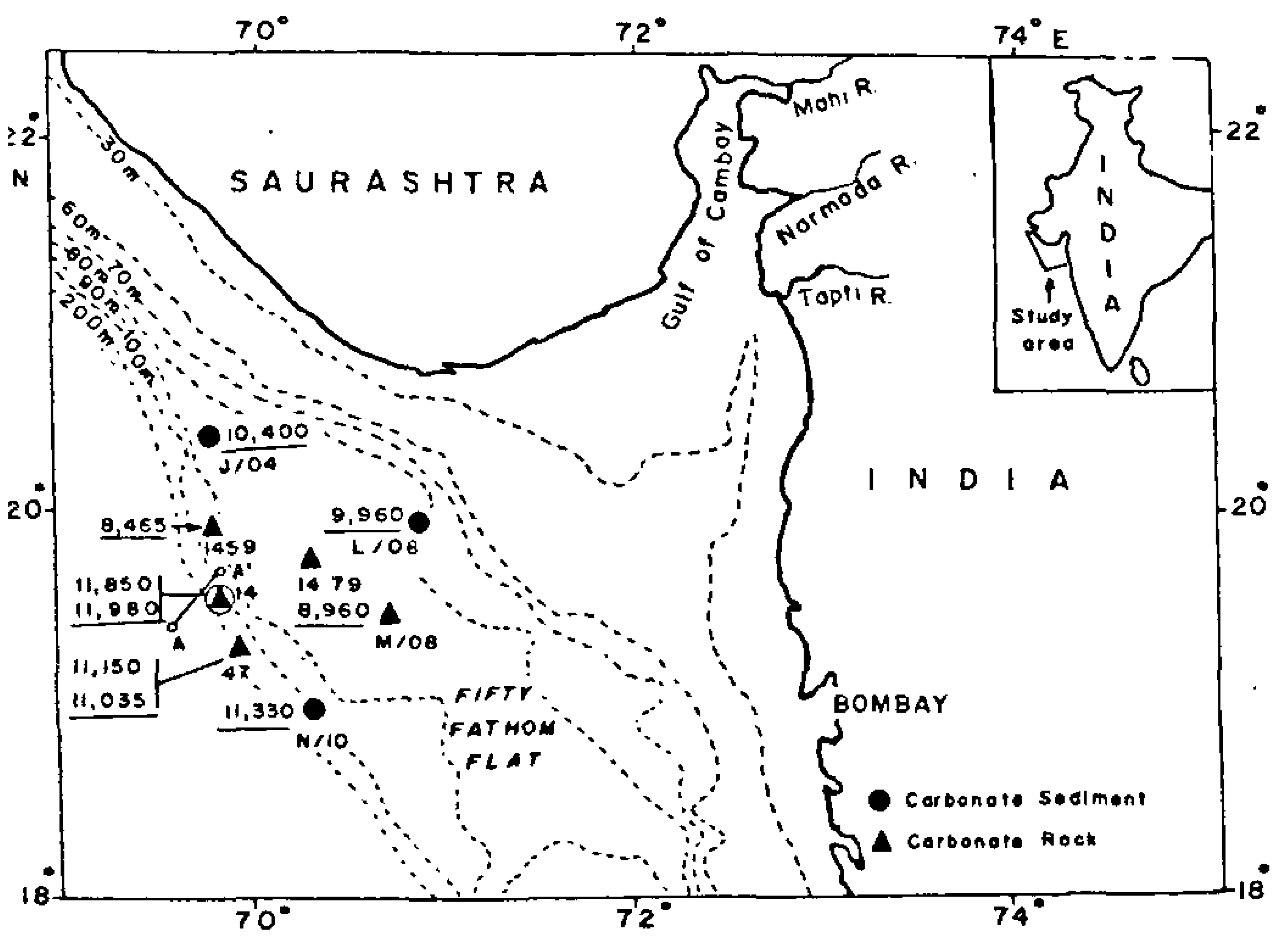

Figure 1. Sample location map (Saurashtra–Bombay). Sample collected at station 14 has been studied in this paper. Other radiocarbon dates of the samples (available in this area) are also shown and underlined. Line A–A′ indicates the position of the shallow seismic (3.5 kHz ORE subbottom) profile shown in Figure 2 *a*.

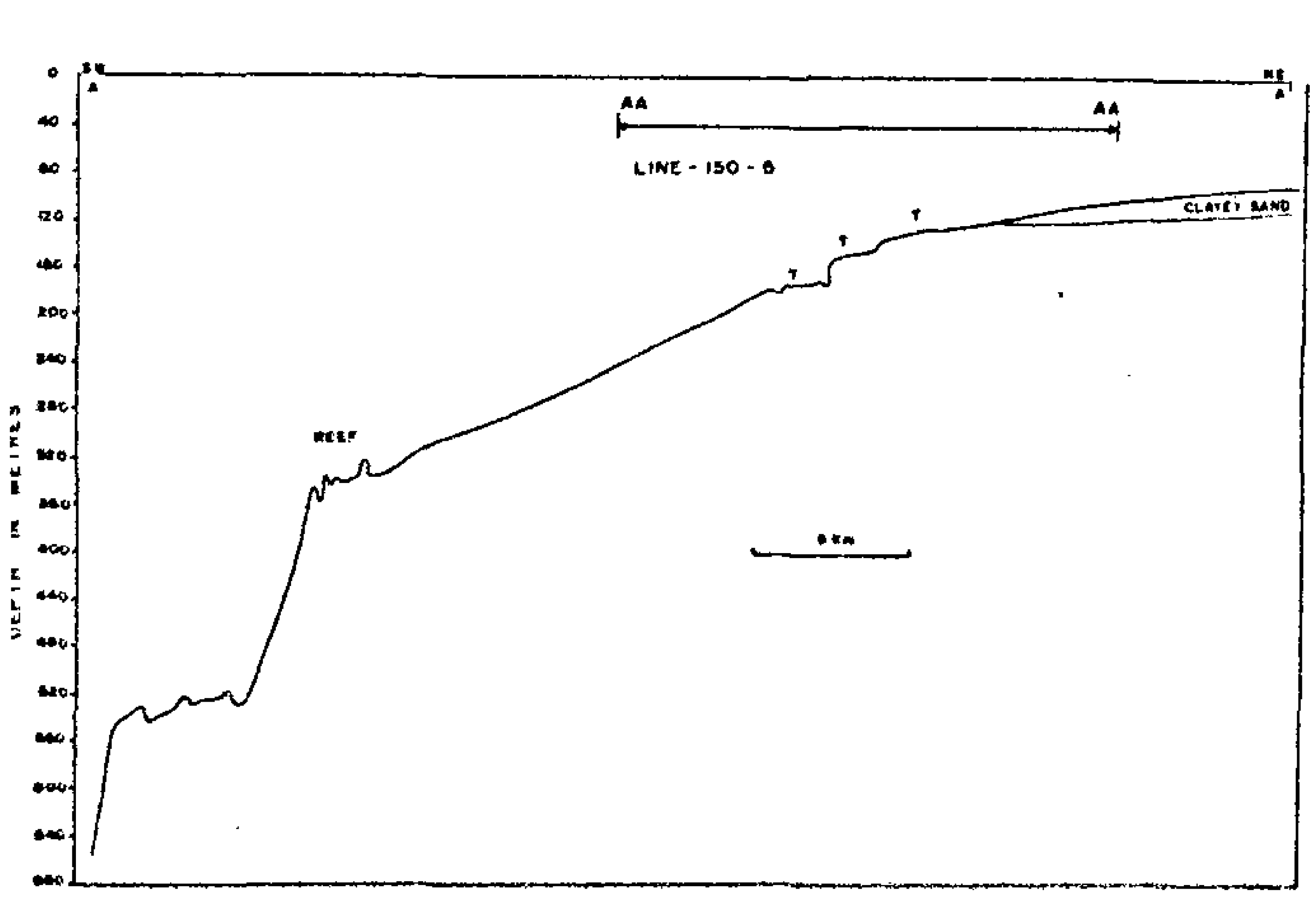

Figure 2 *a*. Seismic profile at the shelf break-upper continental slope showing the terraces (T) with terrigenous clayey sand zone on landward and reefal structures on seaward (see Figure 1 for location A–A′).

Mineralogy and radiochemistry of the limestones

The limestones recovered from 130 m depth terrace are 10 cm thick slabs; their lower surfaces are flat and light brown and upper surfaces contain 1 cm diameter macroborings, serpulid encrustations (Figure 3 *a*) and ferruginized coatings. Associated sediments consist of 1–5 cm size pelecypod shells, limestone fragments and a few coral pieces. The limestones contain > 95% aragonite and minor high and low-magnesium calcite. The radiocarbon ages of the micrite-dominated and pellet-rich limestones are 11,980 ± 185 BP and 11,850 ± 210 BP and $\delta^{13}C$ and $\delta^{18}O$ values of these two limestones are + 4.03‰ and + 3.75‰ and + 1.66‰ and + 1.64‰, respectively.

Petrology of the limestones

Polished sections of some limestones show large borings filled with fine-grained carbonate mud (Figure 3 *b*) and in others dense and loosely cemented areas leading to different textures (Figure 3 *c*). Some other limestones contain abundant shell fragments in their upper portions. The limestones can be divided into micrite-dominated and pellet-rich types.

Micrite-dominated limestones consist of thin micrite-dominated layer on the top and sandy layer below. The micrite layer is laterally discontinuous and consists of trapped carbonate debris, partly to completely micritized algae (Figure 4 *a*, *b*) and a few pellets. Pellets are abundant in the sandy layer and cement is again micrite. Patches of micrite (Figure 4 *c*) consisting of oolite aggregates, cemented intraclasts and terrigenous particles are present. Pellet-rich limestones are calcarenites. Pellets (Figure 4 *d*) are the most abundant constituents followed by oolites, shell fragments, algal fragments with minor echinoids and benthic foraminifers. Many are mature oolites with several well developed concentric laminae. The nuclei are mainly pellets, sometimes skeletal fragments. Some oolites are bored and infected by microbial activity and their concentric laminae are riddled with a discontinuous zone of sparry calcite (Figure 4 *e*).

Boring cavities often impart a porous fabric to the rock (Figure 4 *d*). Some of the cavities are filled with terrigenous clay. Carbonate intraclasts and/or quartz and clay aggregates (Figure 4 *e*) commonly occur in the intergranular spaces. Acicular aragonite forms dense isopachous crusts around grains (Figure 4 *f*). Aragonite

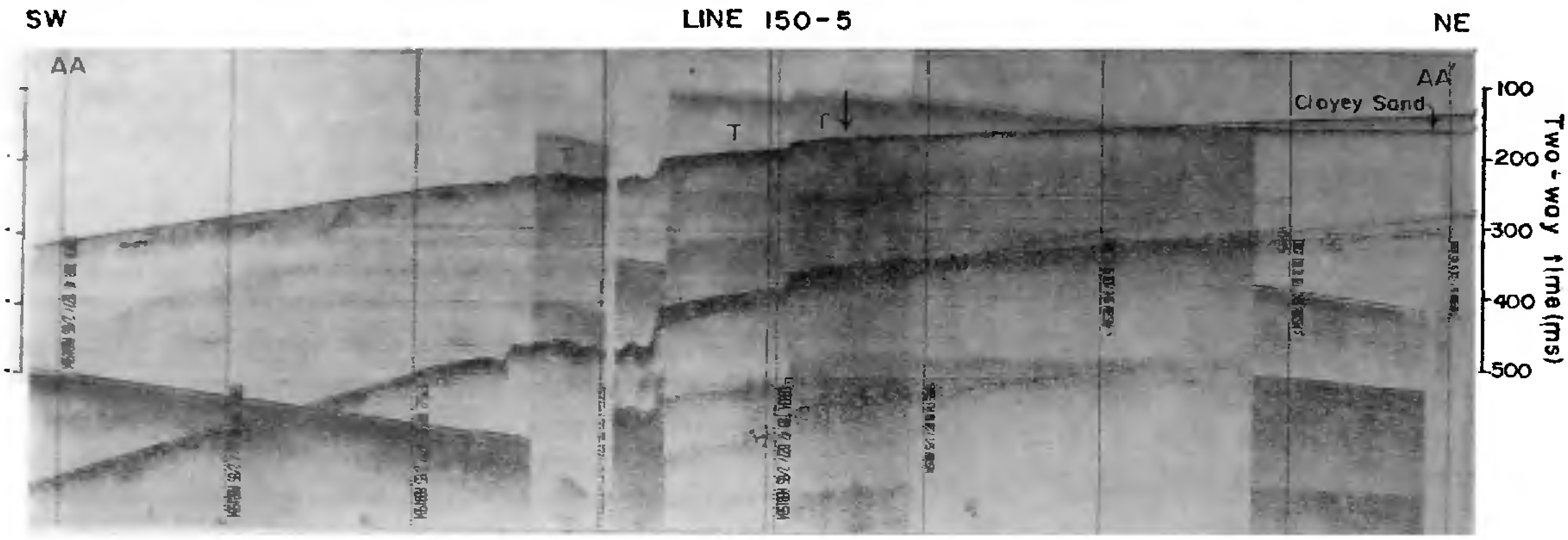

Figure 2 *b*. Seismic profile showing submarine terraces (T) and pinching out of clayey sand zone on landward of the terrace from the upper continental slope off Saurashtra-Bombay. Arrow indicates approximate location of the limestone sample on the terrace which is 1.5 km south of the profile. M-multiple, (see Figure 2 *a* for location AA–AA").

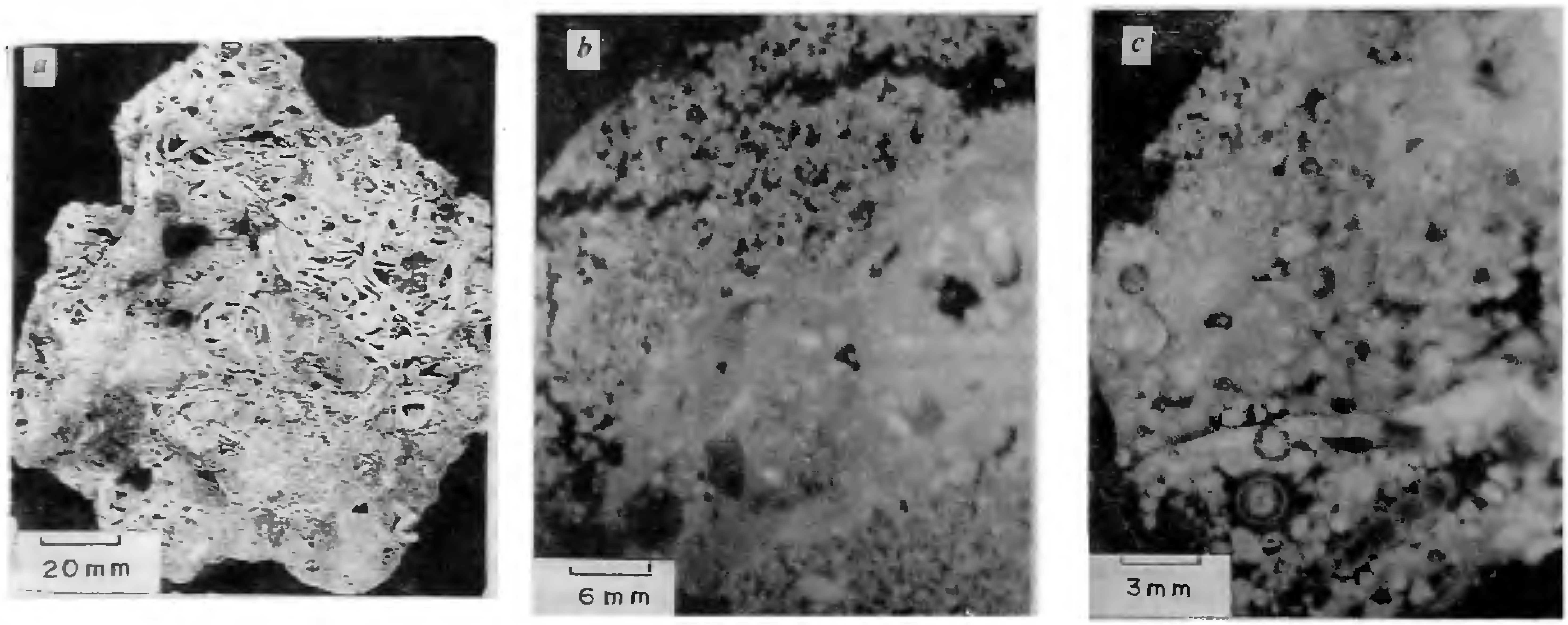

Figure 3 *a*. Hand specimen of a limestone showing boring cavities and thickly encrusted serpulid worm tubes; (*b*, *c*) polished sections: *b*, the boring cavity filled with aragonite muds; *c*, dense and loosely cemented patches in the limestones, leading to different textures.

cements are locally dissolved and replaced by the development of calcite spar and their growth was apparently terminated before the introduction of clay in the pores (Figure 4 *f*). Peloidal micrite cements are rare.

SEM studies on limestone fragments indicate that micrite is an aggregate of 1–2 μm globular carbonate particles (Figure 5 *a*). Needle aragonite fringe cements (Figure 5 *b*) are abundant. Matting of aragonite needles leading to drusy calcite (Figure 5 *c*), dissolution of aragonite needles and the formation of calcite aggregates (Figure 5 *d*), peloids consisting of mixture of micrite and aragonite needles and spherical aggregates of micrite are present. Globular aggregates of calcite occur within the boring cavities (Figure 5 *e*) and sometimes attached to microbial filaments within the interstices (Figure 5 *f*).

Discussion

Environmental conditions during sediment accumulation and cementation

Abundant shell fragments and pellet-rich sediments with some oolites in some limestones indicate high energy conditions prevailed during sediment accumulation. Colonization of both algae and lichens can produce laminated crusts on the upper surfaces of the rocks. Lichen produced crusts are, however, amorphous[11]. The laminated micrite crusts with trapped detritus and algal material (Figure 4 *a*, *b*) may therefore suggest algal colonization by trapping and binding activity and their subsequent calcification to micrite. Algally formed micrite laminations in

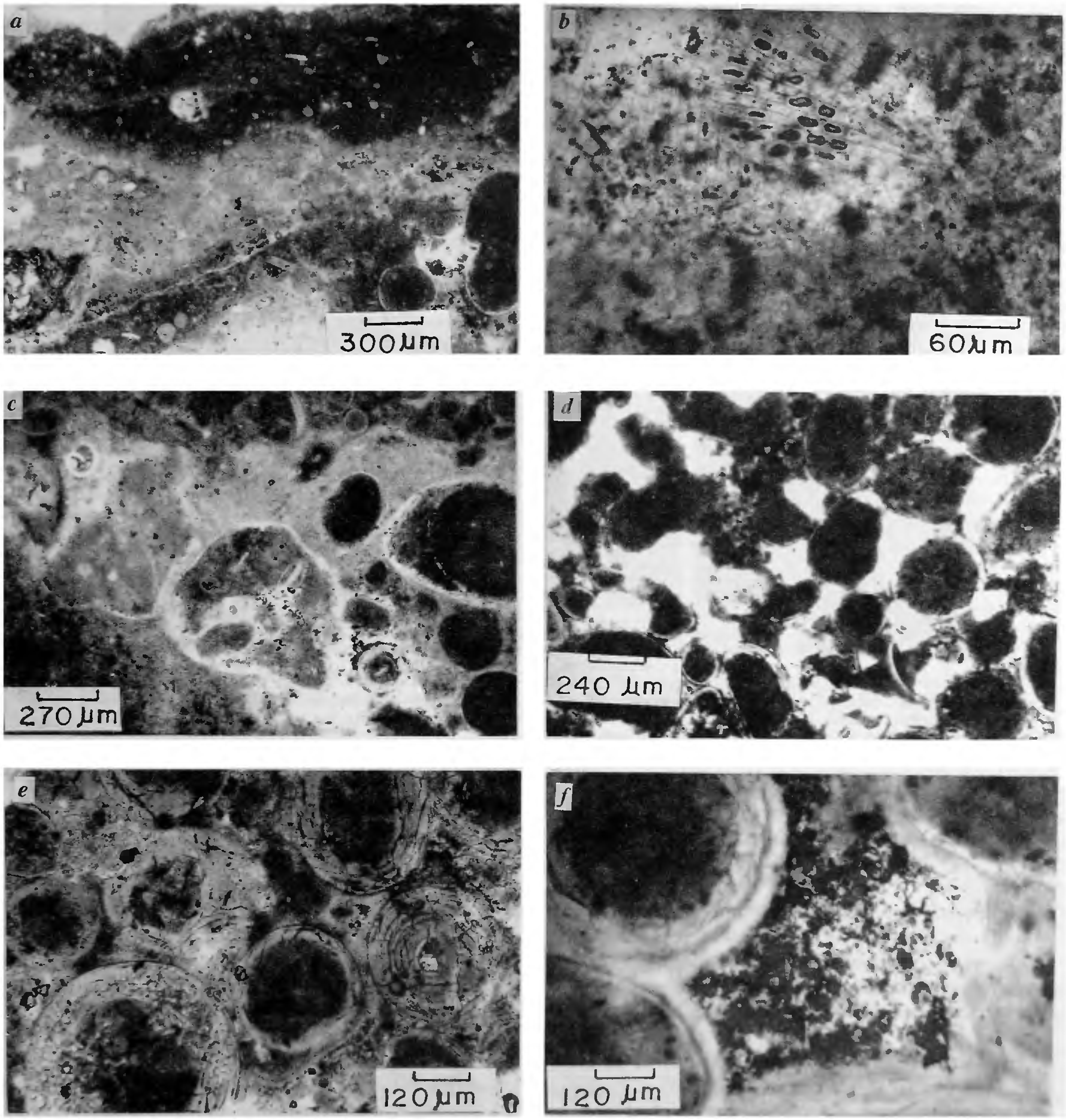

Figure 4 *a–c*. Photomicrographs (plane polarized light) from micrite-dominated limestone. ***a***, showing distinct ferruginised micrite-dominated layer on the top and light brown micrite layer below; ***b***, partly micritized algal body; ***c***, a micrite patch with cemented intraclasts; ***d–f***, photomicrographs from pellet-rich limestones (plane polarized light); ***d***, pelletal grains in aragonite cements, porous fabric is due to the boring activity of algae; ***e***, oolites which are infected by microbial activity showing obscured laminae; ***f***, aragonitic isopachous rim cements, porefilling aragonite cements are being replaced by calcite mosaics and terrigenous clays and quartz in the interstices.

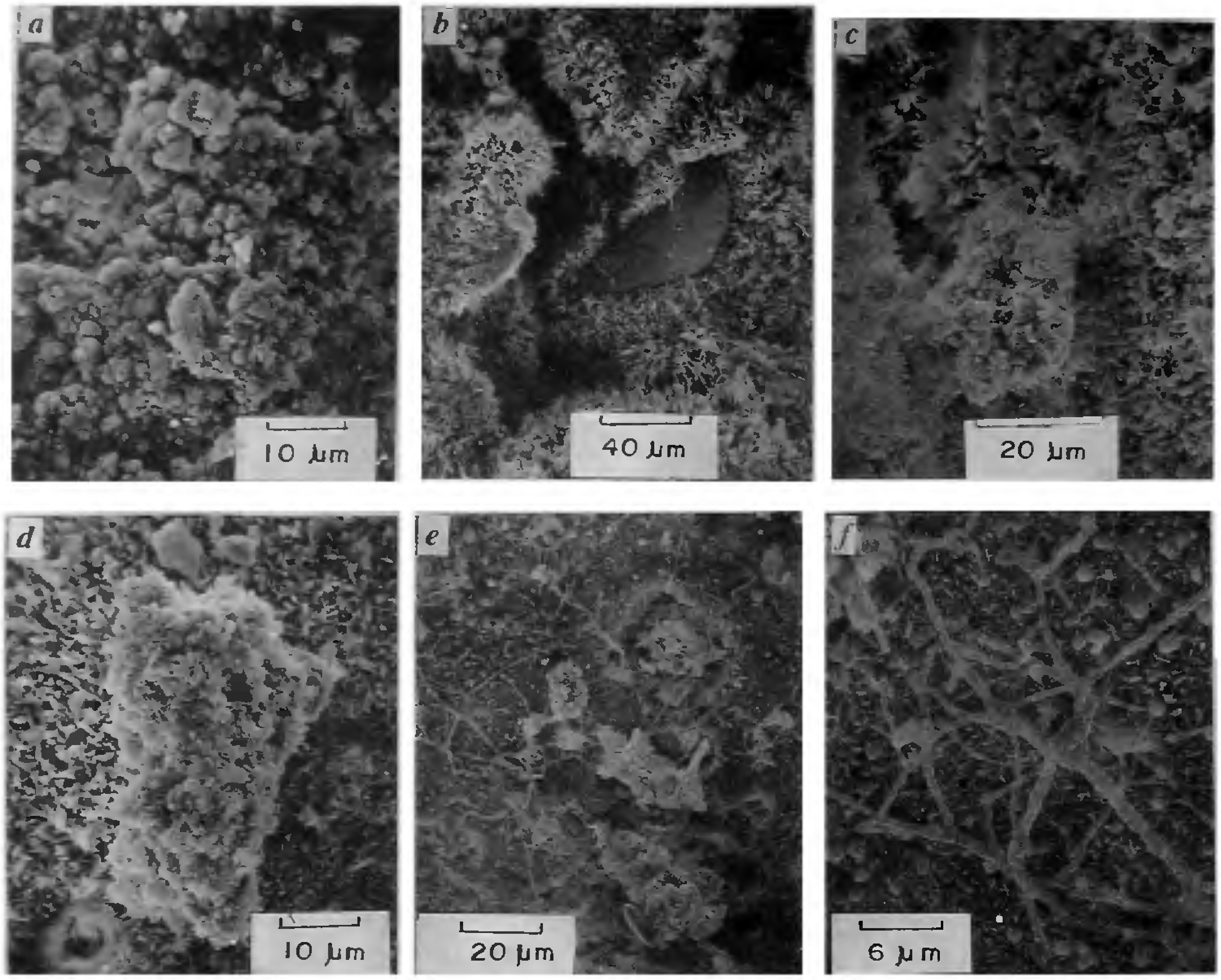

Figure 5 ***a–e.*** ***a,*** **Micrite matrix showing that it is an aggregate of 1–2 µm size globular particles;** ***b,*** **acicular aragonitic fringe cements;** ***c,*** **clotted aragonite needles;** ***d,*** **a globular calcite aggregate on top of aragonite needles;** ***e,*** **globular calcite in boring cavities, several fungal filaments on aragonite matrix can also be seen;** ***f,*** **enlarged portion of 'e' showing filaments which are irregularly branched.**

supratidal limestones are thicker and laterally more continuous than those in intertidal conditions[12]. So the thin, laterally discontinuous micrite laminations (Figure 4 *a*) in some limestones and intraclasts, shell and pellet-dominated sediments with mature oolites in others probably suggest that the sediments were accumulated in intertidal conditions. Detrital material (Figure 4 *f*) most probably washed onto these sands and subsequently filtered down into the pores under agitating conditions.

(i) Endolithic algae/fungal activity is evident in these limestones by the porous fabric (Figure 4 *d*), microbially infected oolitic laminations (Figure 4 *e*), algal borings and fungal filaments (Figure 5 *e*, *f*). Endolithic algae are abundantly photosynthetic and they bore intensively in nearshore zones[13].

(ii) Although micrite is abundant in both subtidal and intertidal limestones[14,15], it is mostly high-magnesium calcite in submarine cemented limestones[16]. The micrite reported here, however, is aragonite.

(iii) Four types of cements exist: thinly laminated micrites (Figure 4 *a*), dense patches of micrite (Figure 4 *c*), acicular aragonite (Figures 4 *f*, 5 *b*) and peloidal cements. These cements are further complicated by subsequent superposition of other cements. Replacement of pore filling aragonites by calcite (Figure 4 *f*), clotted aragonite needles (Figure 5 *c*) and calcite aggregates on top of aragonite needles (Figure 5 *d*) indicate that initially formed aragonitic cements were subsequently replaced by drusy calcites. Similar cement fabrics were reported[17–19] in intertidal limestones and beachrocks. The formation of clotted aragonites and drusy calcites perched on aragonites was attributed to the high degree of super saturation in the pores of sands at intertidal conditions[17]. Micrite patches enclosing terrigenous particles suggest that allochthonous micrite filled the boring cavities. These four types of cements cause different textures in the rock (Figure 3 *b*, *c*), a feature generally observed in beachrocks.

(iv) Submarine cemented limestones consist of aragonite skeletal components replaced by high-magnesium calcite and abundant peloidal high-magnesium calcite cements[16,20-22]. In contrast, the limestones studied here contain minor high-magnesium calcite, rare peloidal cements and unaltered skeletal aragonites. In view of (i) to (iv) we suggest that these limestones were cemented at intertidal conditions.

Relationship of terrace limestones with sea-level changes

The age and depth relationship of the limestones suggest that intertidal conditions existed at 130 m depth terrace at about 11,900 years BP. Contrastingly, the glacio-eustatic sea-level[10] was at −90 m at about 12,000 years BP. Three possibilities exist to explain this disparity:

(i) The limestones might have been transported from shallow shelf. This is unlikely as a terrigenous clayey sand zone (15–20 m thick) exists landward of the terrace (Figure 2 *a*, *b*). The clay in the interstitial pores of the limestones (Figure 4 *f*) may have originated from this clayey sand zone. Moreover, the limestones are from a wide terrace and the constituents in limestones and in unconsolidated sediments of the terrace are similar.

(ii) Incorporation of modern carbon and replacement of aragonite by calcite may give younger ages of limestones than the actual. This is also unlikely as the dates given here were corrected for modern industrial carbon and, calcite content (low and high-magnesium calcites) is < 5% and low-magnesium calcite that replaced the aragonite is a small part within the 5% which may not have major influence on the given dates.

(iii) This part of the continental margin may have subsided after the limestones were formed. It is more likely as the terraces occur at depths more than 120 m (eustatic sea-level low during the LGM − 18,000 years BP). Vadose diagenetic limestones of Holocene age on the Fifty Fathom Flat[23,24], missing data for the period younger than 8,300 years BP from the offshore and tidal mud flats of Early Holocene age at + 8 to + 10 m above the present sea-level in the coastal Gujarat and Maharashtra[25,26] probably support neotectonic activity in this region.

The sea-level rise after 11,900 years BP was 130 m on this margin. The eustatic sea-level rise[10] after 12,000 years BP was only 90 m. This suggests that some time after 11,900 years BP, the margin may have subsided by about 40 m. This subsidence could be due to the overburden of Indus-borne sediments accumulated on the continental slope and in the adjacent Arabian Basin as also suggested by Whiting *et al.*[27].

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