

Late Quaternary *Halimeda* bioherms and aragonitic faecal pellet-dominated sediments on the carbonate platform of the western continental shelf of India

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Received 20 August 1993; revision accepted 6 July 1994

Abstract

The Fifty Fathom Flat is a drowned carbonate platform located on the outer continental shelf of western India. It is unique because the carbonate depositional environment prevailed until Early Holocene in spite of its proximity to a major siliciclastic tidal embayment. Study of the bathymetry, seismic and sonograph data together with the petrology, mineralogy and geochemistry of the carbonate sediments and limestones recovered from the platform resulted in (a) the discovery of Late Quaternary *Halimeda* bioherms and (b) aragonitic faecal pellet-dominated sediments.

Echograms reveal buried pinnacles between 62 and 38 m and exposed 2 to 14 m high pinnacles between 65 and 85 m on the platform. These pinnacles occur as narrow to broad mounds (bioherms) in seismic profiles and as linear ridges and massive structures in sonographs. Seismic profiles also show a prominent reflector about 25 m below the sea bed identified by boreholes as a Late Pleistocene erosion surface.

The platform consists of relict carbonate sands and limestones. Rounded and ovoid to ellipsoidal aragonite grains are predominant in the sediments. SEM studies indicate elongated parallel canals and crescent to hook-shaped canals, corresponding to faecal pellets, occur in some grains. Algal grains and pellets enclosing algal fragments are also present. The grains in the limestones are similar to those in the sediments. *Halimeda* and crustacean faecal pellets are abundant components, with minor echinoid, mollusc and benthic foraminifera. The limestones are characterised by abundant pores, dissolution cavities, relic aragonite needles, meniscus cements and drusy calcite fill the pores produced by dissolution of aragonite needles. These features indicate vadose diagenesis. The stable isotopes of the carbonate sands and limestones are almost identical and similar to isotope values of beachrocks of the Red Sea. The limestones ages (9200–8400 yr B.P.) lie within the same age limits (10,400–8300 yr B.P.) as the surficial sediments.

It appears that fluvial sediments largely accumulate in the inner shelf and did not hinder carbonate growth on the platform, lying on the outer shelf. We presume that arid climate and nutrients brought by river runoff and shelf edge currents favoured the growth of algal bioherms dominated by *Halimeda* between 13,700 (?) and 8300 yr B.P. The absence of Late Holocene and modern carbonates on the platform may be due to the combined influence of climatic change, upwelling and neo-tectonic activity at about 9000 yr B.P. The bioherms dominated by *Halimeda*, produced abundant aragonite muds. Deposit feeding crustaceans and other invertebrates subsequently excreted these muds as faecal pellets. The platform thus contains faecal pellet-dominated sediments.

1. Introduction

The study area forms the northern part of the western continental shelf of India, between the Gulf of Cambay in the north and Ratnagiri in the south (Fig. 1). The shelf reaches its maximum width (about 300 km) north of Bombay but narrows to about 100 km off Ratnagiri. The Fifty Fathom Flat, a carbonate platform, is a prominent topographic feature on the outer shelf between 80 and 90 m (Nair, 1971) covering an area of 28,336 km² extending over 4° of latitude. This platform is important for several reasons: (a) It

exists seaward of a siliciclastic-dominated major macrotidal embayment through which the Narmada and Tapti rivers presently debouching about 60×10^6 tons of sediment load annually (Rao, 1975). Carbonate buildups are totally unexpected in the vicinity of river mouths. However, it has been suggested that this platform was isolated and separated from the mainland by a huge clastic depocenter—the Dahanu depression in which extensive prodelta silts and muds were deposited since the Eocene (Basu et al., 1980). The sediment-filled depression is the present day inner shelf. (b) The carbonate depositional environment prevailed

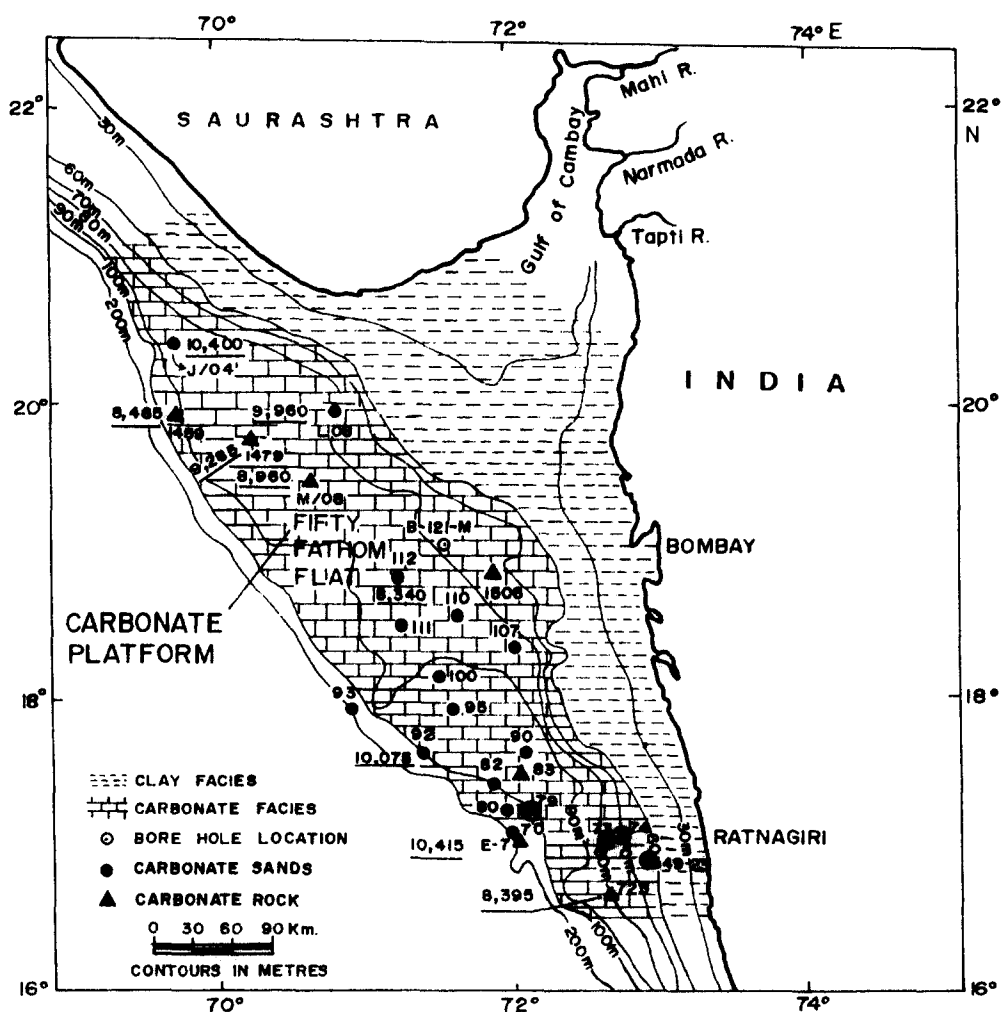


Fig. 1. Sample location on the carbonate platform of the western continental shelf of India. The numbers underlined are ¹⁴C ages.

from Eocene to Early Holocene and ceased thereafter. Furthermore, the sediments on the platform are predominantly carbonate sands and are similar to those in the modern carbonate platforms and bank margins such as Bahamas, Persian Gulf, and Shark Bay, Australia (Halley et al., 1983). Therefore, this platform may be considered their ancient analogue. (c) Petroleum occurs in the deeper Miocene strata.

Until recently, it was thought that the reefal structures in carbonate provinces were constructed only by corals (Roberts and Macintyre, 1988). However, in the year 1985, the mound building capability of *Halimeda* was brought into light and reported that this algae is forming thick bioherms in the Great Barrier Reef; the size of the biohermal structures are sometimes comparable with the coral reef structures (Roberts and Macintyre, 1988). Since then, extensive search was carried out on different modern carbonate platforms. To date, Holocene–Recent *Halimeda* bioherms were reported only from the Great Barrier Reef (Davies and Marshall, 1985; Searle and Flood, 1988), the Java Sea (Roberts et al., 1987a; Phipps and Roberts, 1988) and the Nicaraguan Rise (Roberts and Murray, 1983; Hine et al., 1988). The first part of this paper reports the discovery of relict *Halimeda* bioherms on the carbonate platform off western India.

The sediments in the study area were described by Nair and Pylee (1968), Hashimi and Nair (1976), Nair et al., (1979); Guptha (1979), Nair and Hashimi (1981) and Mohapatra et al. (1989). These studies indicate that the sediments on the inner shelf are terrigenous clays, while those on the outer shelf are relict carbonate sands. Non-skeletal grains are the most abundant on the platform; these are aragonitic, shiny with smooth surfaces and occur as rounded and ovoid to ellipsoidal forms and have been referred to as oolites (Nair and Hashimi, 1981 and references therein). In fact, most of the grains lack concentric structures and the term oolite appears to be a misnomer. Since the size, composition and external morphology of some of the grains are similar to oolites, earlier workers wrongly interpreted and the genetic interpretations thus given for these non-skeletal grains need a *re-appraisal*. In the second part of

the paper, we have described and documented these sands as faecal pellet-dominated sediments.

2. Materials and methods

Bathymetry (with 12 kHz echosounder), shallow seismic (with 3.5 kHz ORE subbottom profiler) and sonograph data (with 110 kHz SMS 960 side-scan sonar recorder) were collected on this platform along different lines across the shelf. Limestones were dredged from the mound-shaped structures. Sediment samples were collected by using Peterson grab. Thin sections of the limestones were studied under petrographic microscope. Freshly broken surfaces of the grains and limestones were examined under JEOL (T 20) scanning electron microscope (SEM). Major element geochemistry of the compact matrix and typical components within the pellets was analysed by Energy Dispersive Spectrometry (EDS Microprobe) and the average values are given in Table 1. The correlation matrix for different elements was prepared. Mineralogy of the limestones and sediments was carried out by X-ray diffraction. Radiocarbon dates and stable isotopes were determined for some limestones and carbonate sands (Fig. 1; Table 2). The GTV *Samudra Sarvekshak*, a drilling vessel of the Oil and Natural Gas Commission, India, drilled a bore hole in 75 m water depth on the outer continental shelf off Bombay (Fig. 1) to a subbottom depth of 27.5 m. Four samples from this borehole, from 2, 11, 19.5 and 26.5 m depths were examined for the sediment constituents and their X-ray mineralogy.

Part I. Late Quaternary *Halimeda* Bioherms

3. Results

3.1. Bathymetry and sub surface topography

Echograms of the western Indian continental shelf reveal that the inner shelf (up to 60 m) is smooth and featureless, while the outer shelf (60–110 m) is topographically complex with relief features (Fig. 2) from 1 to 20 m high. Buried pinnacles from 0.5 to 13 m high are present

Table 1
EDS-microprobe analyses of faecal pellets

Element	Compact matrix I (17) ^a	Calcite crystals II (1)	Algal fragment in a pellet III (1)	Globules in canals of the pellets IV (1)	External cortex of a oolite V (2)
Na ₂ O	1.67 (0.35–2.62) ^b	1.01	1.00	1.67	0.24
MgO	1.43 (0.06–2.79)	—	9.45	1.59	—
Al ₂ O ₃	1.34 (0.70–2.87)	—	—	0.93	—
SiO ₂	3.96 (1.95–6.75)	1.31	0.32	2.94	1.28
P ₂ O ₅	1.87 (0.65–4.27)	0.62	0.72	16.10	0.25
SO ₃	2.07 (0.77–3.40)	0.71	1.95	2.83	0.29
K ₂ O	0.70 (0.32–0.9)	0.49	0.38	0.68	0.57
CaO	85.16 (75.79–90.12)	95.75	84.40	72.70	96.56
FeO	1.78 (0.22–4.74)	0.12	1.24	0.56	0.81

^aAverage of number of analysis. ^bRange of values.

Table 2
Radiocarbon dates and stable isotopes of the samples of the carbonate platform

Sample number	Nature of sample	Depth (m)	Skeletal components	Non-skeletal components	Age (yr B.P)	$\delta^{18}\text{O}$ (‰)	$\delta^{13}\text{C}$ (‰)	Remarks
1459	grainstone	95	<i>Halimeda</i> , foraminifers, echinoderms	faecal pellets	8465 ± 125	0.03	3.86	this paper
1479	grainstone	85	<i>Halimeda</i> , foraminifers, echinoderms	faecal pellets	9285 ± 180	0.72	3.79	this paper
M/08	grainstone	82	<i>Halimeda</i> , foraminifers, echinoderms	faecal pellets	8960 ± 200	—	—	Nair et al. (1979)
NR2A/112	carbonate sand	80	molluscs, algae, foraminifers, echinoderms	faecal pellets	8340 ± 185	0.82	3.80	this paper
NR2A/92	carbonate sand	100	molluscs, algae, foraminifers, echinoderms	faecal pellets	10,075 ± 250	1.15	4.29	this paper
J/04	carbonate sand	80–90	molluscs, algae, foraminifers, echinoderms	faecal pellets	10,400	—	—	Nair et al. (1979)
L/08	carbonate sand	80	molluscs, algae, foraminifers, echinoderms	faecal pellets	9960	—	—	Nair et al. (1979)
B-121-M	bore hole sample at 26.5 m	75	abundant terrigenous components	faecal pellets	23,880 ± 630	1.49	4.17	this paper

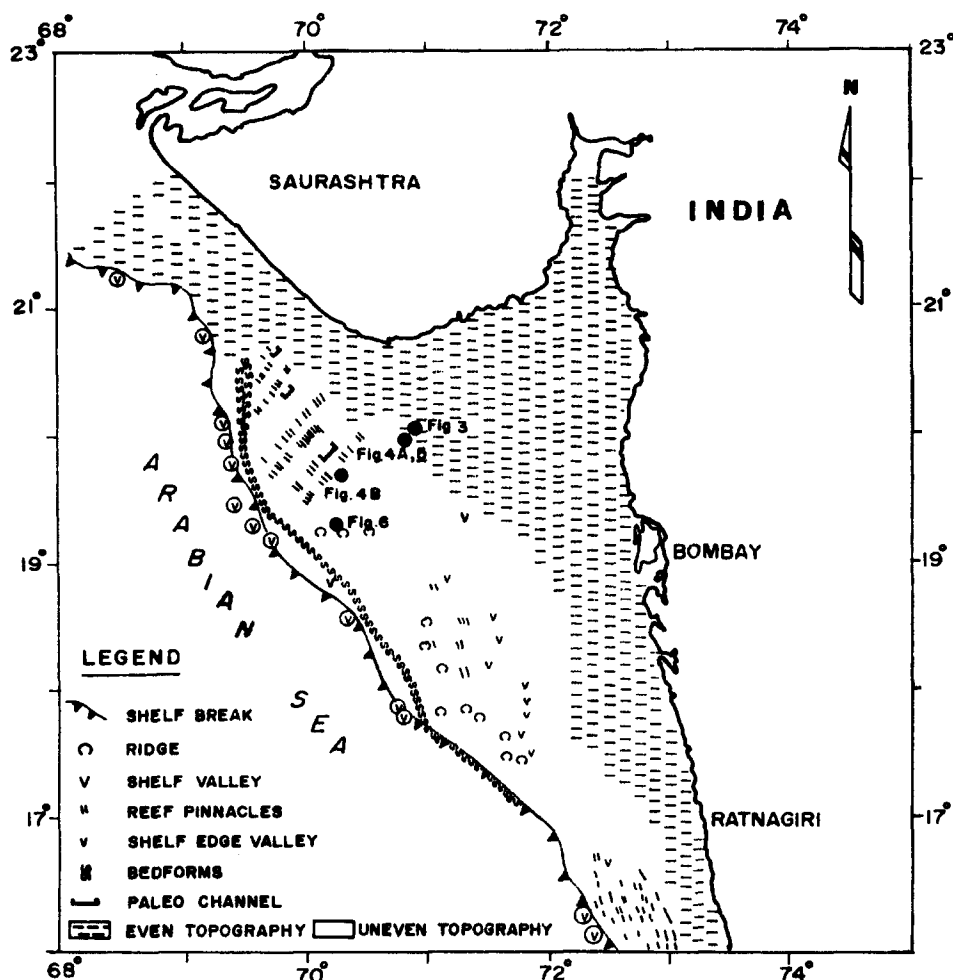


Fig. 2. Geomorphic features on the carbonate platform (after Veerayya et al., 1992; M. Veerayya et al., unpubl. data). The location of Figs. 3–6 are also shown.

between the inner and outer shelf. Larger partly exposed pinnacles are confined to the northern area close to the Gulf of Cambay (Fig. 3). To the south off Ratnagiri, the 0.5–1.0 m high pinnacles occur in 38 m water depth covered by 3 m of clay. Similar buried pinnacles were reported in 40 m water depth by Vora and Almeida (1990) on the inner continental shelf between Ratnagiri and Vengurla. Seaward of the 65–80 m isobath, 2 to 6 m high pinnacles are exposed on the outer shelf (Fig. 4A), as also shown by Nair (1975). A lagoonal-like depression 10 km wide with a maximum depth of 20 m has been observed between

80 and 85 m water depths extending longitudinally over several tens of kilometres. Pinnacles are well developed in this depression and apparently grew to a maximum height of 14 m (Fig. 4B). On the continental shelf off Bombay, another depression parallel to this reaching a maximum water depth of 10–15 m has been encountered at about 75 m water depth. Detailed bathymetric studies reveal the presence of a series of paleo-lagoonal-like depressions on the outer continental shelf off Bombay (B.G. Wagle, pers. commun.). Shelf edge pinnacles are rare off the platform but occur south of Ratnagiri.

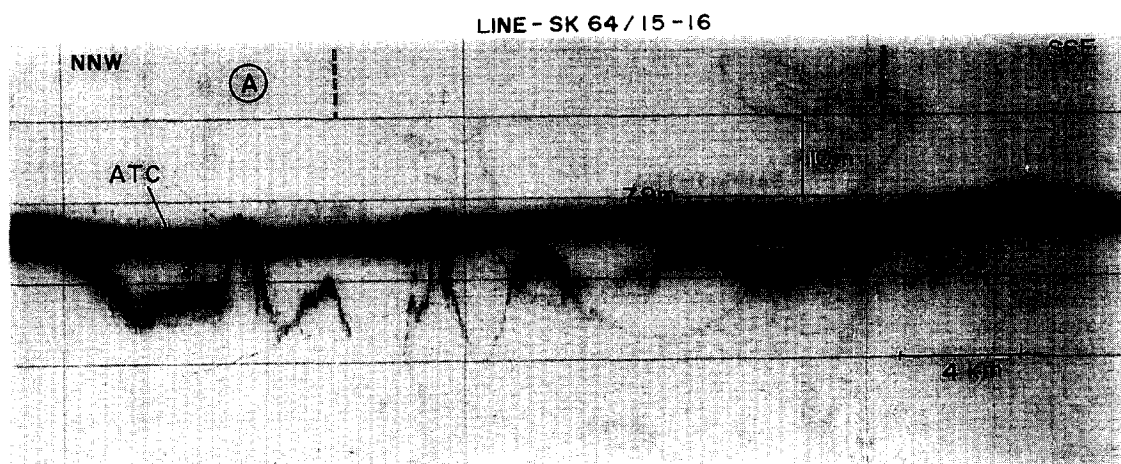


Fig. 3. Echogram showing prominent 9–12 m high pinnacles and associated mound structures which are almost buried below the acoustically transparent clays (ATC) at the landward fringe of the platform. See Fig. 2 for location.

3.2. Seismic stratigraphy

The seismic profiles across the shelf showed that the pinnacles are mound-like structures. These are isolated structures, 65–385 m across but in some places a few mounds coalesce (Fig. 5A–C). The mounds are seismically transparent and have sufficient relief above the surrounding sea floor to be termed bioherms. The mounds described are similar to modern *Halimeda* bioherms reported from Great Barrier Reef (Orme, 1985; Phipps et al., 1985; Orme and Salama, 1988; Marshall and Davies, 1988; Searle and Flood, 1988), from Kalukalukuang bank of the Java Sea (Roberts et al., 1987a; Roberts et al., 1988; Phipps and Roberts, 1988) and from Nicaraguan shelf (Roberts and Murray, 1983; Hine et al., 1988). The seismic sequences below the mounds do not show any definite structure but are characterised by homogeneous bedding concordant with the mounds suggesting a progressive upward growth (Fig. 5). The surfaces of the mounds are occasionally covered by a thin veneer of acoustically transparent sediments.

The seismic profiles display two prominent sub bottom reflectors (Fig. 5): one at 10 m, the other at about 25 m (range between 20 and 30 m) below the sea bed. The shallow reflector is prominent only in the shoreward part of the platform

(Fig. 5A). The thickness of the overlying material gradually decreases and the reflector truncates seaward at 75 m water depth. The surface of this reflector is overlain landward by acoustically transparent clays (Fig. 5A). The second reflector at about 25 m gently slopes seawards but is somewhat irregular in places. It is traced continuously across the entire shelf (Fig. 5B,C) and is regarded as a Late Pleistocene erosional surface, which is also supported by bore hole data.

3.3. Sonographs

Side scan sonographs from the outer shelf between 65 and 90 m show strong acoustic returns from a series of linear ridges, isolated patches and vast areas of massive structures (Fig. 6) and confirms features observed on echosounder and seismic profiles. These features occur in belts trending NNW–SSE, sometimes extending over the entire width of sonographs indicating lateral continuity (Fig. 6). The massive structures are surrounded by vast areas of flat bottom (indicated by weak acoustic returns) and are interpreted to be algal ridges. This view is supported by the occurrence of *Halimeda* dominated limestones in this region (Fig. 7). The morphology of the ridges is similar to that of algal ridges off Nicaragua

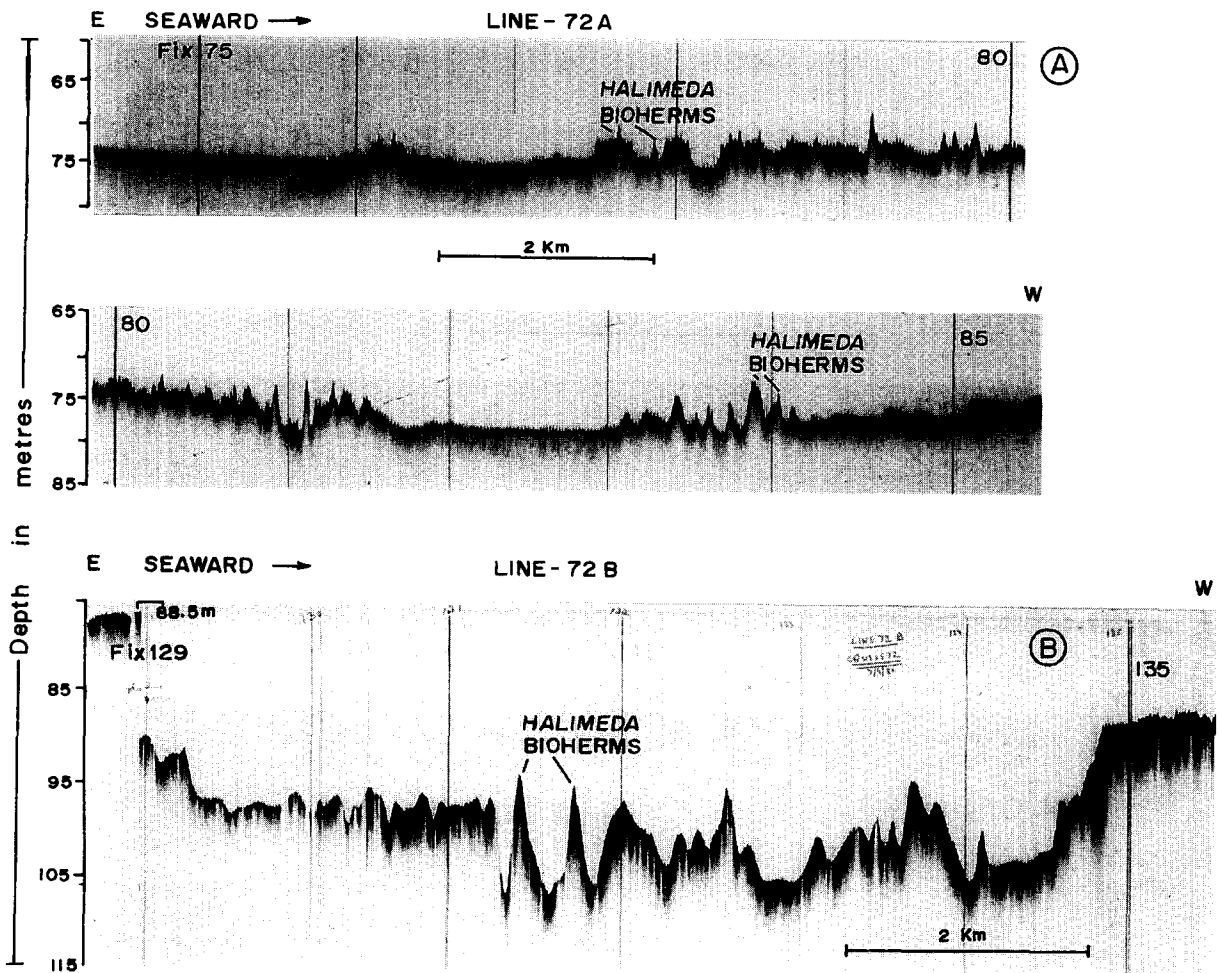


Fig. 4. A. Echogram depicts 1–6 m high pinnacles and massive mound structures (*Halimeda* bioherms) on the platform. The gently sloping even topography in the inner shelf (east) gives way to uneven to rough topography on the platform. Ponding of sediments, presumably derived from the adjoining topographic highs is clearly seen at fixes 77 and 82–83. See Fig. 2 for location. B. Echogram showing profuse pinnacles (height 14 m) and massive mounds (*Halimeda* bioherms) in and around the lagoon-like depression on the carbonate platform. See Fig. 2 for location.

(Roberts and Murray, 1983) and in the Java Sea (Roberts et al., 1987b).

3.4. Limestones (stations 1479 and 1459)

The limestones dredged from the mound-shaped structures of the platform were formed by cementation of sediments; they are 10–15 cm size irregular rocks and grey in colour. Some limestones show impregnated iron oxide layer and others show

5 mm diameter borings, characteristic of hard grounds. These are packstones–grainstones. Aragonite is the most abundant mineral in both the limestones with minor amounts of low-magnesium calcite. Thin sections show that the grains showing utricles and canals, similar to those in *Halimeda* (Fig. 7) and crustacean faecal pellets (Fig 12; described in Part II) are abundant components in these limestones. The original size of the *Halimeda* was invariably reduced in all fragments

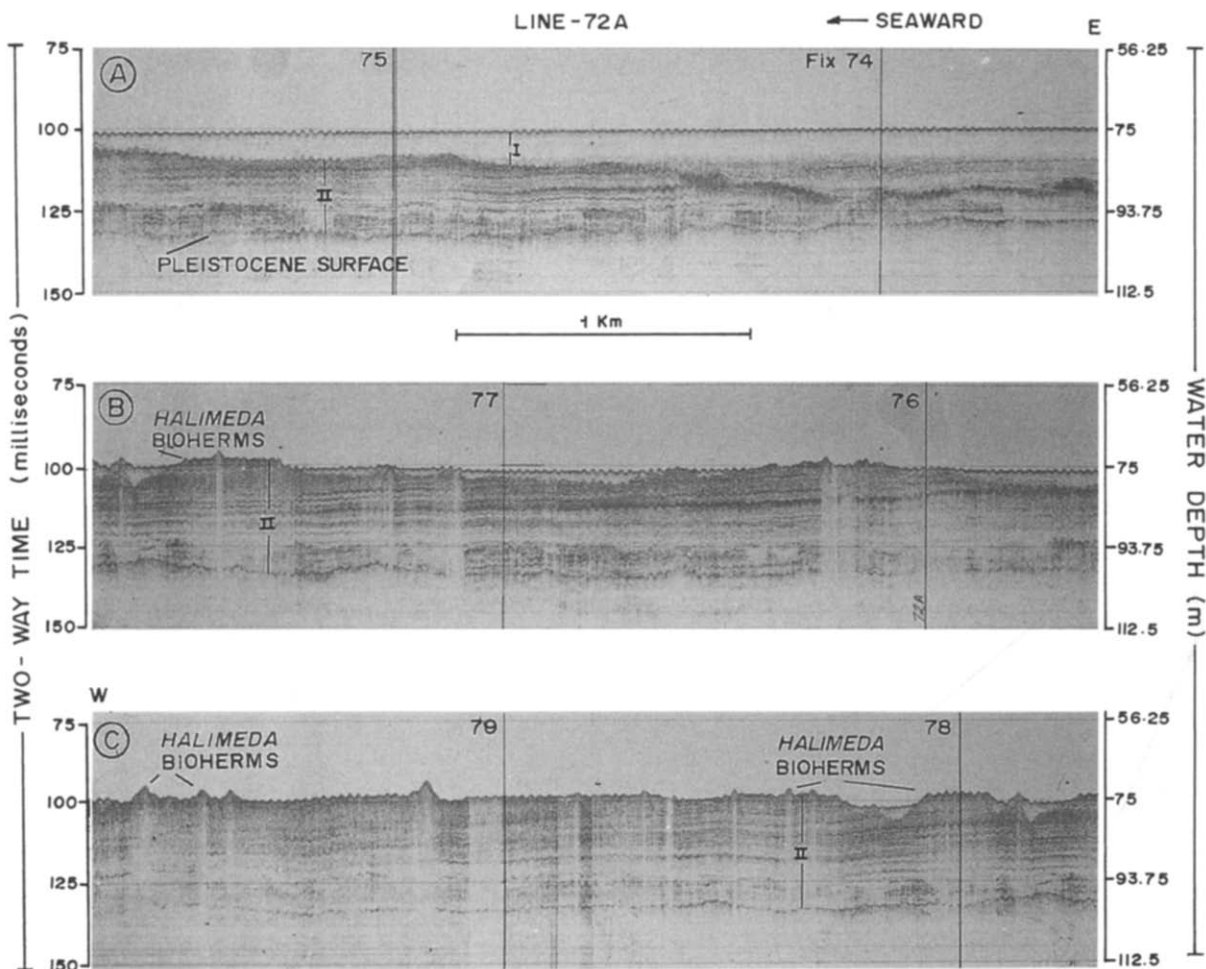


Fig. 5. Typical seismic profile of the continental shelf of Bombay depicting marked variations in seismic stratigraphy between the inner and outer shelves (platform) and the intervening transition zone (fix 76). The deepest and most prominent subbottom reflector at about 25 m (base of Unit II) continues over a large part of the shelf while the reflector at 10–12 m (fixes 75–76) (base of Unit I) truncates at the shoreward side of the carbonate platform. The base of Unit II occurs at variable depths below the surface of the platform. Some of the mounds (see B and C) are acoustically transparent indicating biohermal structures. The intervening regions of the mound/massive structures are floored by acoustically transparent sediments. See Fig. 2 for location.

(Fig. 7). Some *Halimeda* fragments were degraded and their canals were filled with sediment and thus difficult to identify them from some faecal pellets. Rough estimates indicate that sample at 95 m water depth (station 1459) shows a great number of *Halimeda* (51%) followed by crustacean faecal pellets (38%), and other skeletal components (11%) which comprises of benthic foraminifers (especially *Amphistegina*), echinoderms, mollusks and bryozoan fragments. Whereas the sample at

85 m water depth (station 1479) contains more aragonitic faecal pellets (65%), followed by *Halimeda* grains (30%), and few other skeletal fragments (5%). The radiocarbon ages of the limestones vary from 9285 to 8465 yr B.P. $\delta^{18}\text{O}$ values range from +0.03 to +1.15‰ PDB and $\delta^{13}\text{C}$ values range from +3.79 to +4.29‰ PDB (Table 2). A plot of $\delta^{18}\text{O}$ to $\delta^{13}\text{C}$ shows that all fall within the field defined by beachrocks of the Red Sea (Holail and Rashed, 1992).

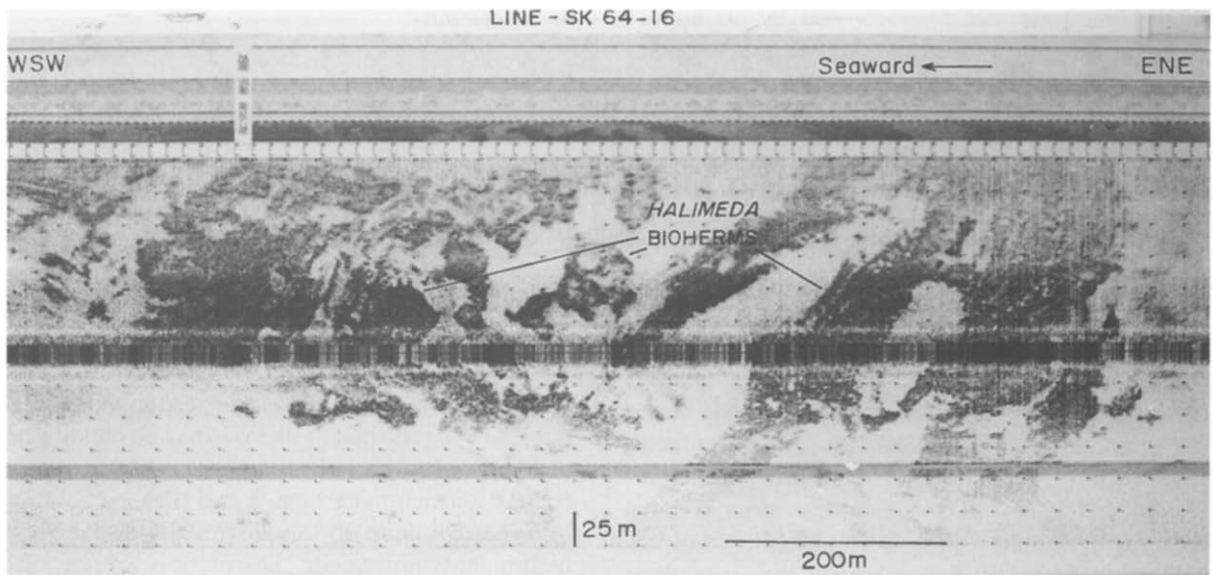


Fig. 6. Side-scan sonograph showing massive algal biohermal structure separated by sediment covered areas on the platform. See Fig. 2 for location.

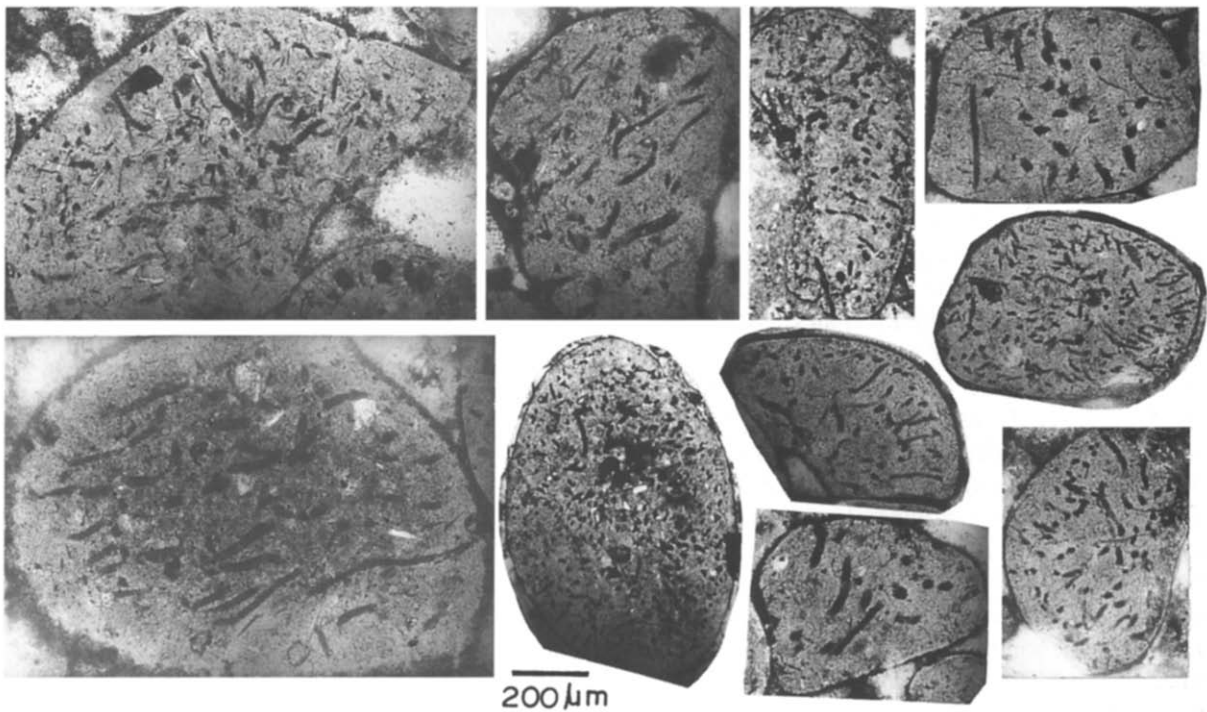


Fig. 7. *Halimeda* fragments showing utricles and canals (all are same magnification). Note different sizes and shapes of grains.

The limestones are characterised by abundant intergranular pores (Figs. 8A and 12A). Acicular aragonite needles form a cement in samples (1459) seaward of the platform. The diagenetic textures of the limestones (1479), located on the platform, were studied in detail. Thin sections show boring and dissolution features such as etching of grain boundaries (Fig. 8A) and of cements (Fig. 8B), partly dissolved aragonite needles adhered to grain boundaries (Fig. 8C) and minute calcite crystals lining pores in dissolved portions of the skeletal components (Fig. 8D). SEM studies on freshly broken surfaces of the limestones show that large pores contain cements near the grain contacts (Fig. 8E,F) resembling meniscus cements (Dunham, 1971). The aragonite needles are abruptly terminated (Fig. 8G) and the cements exhibit coalesced fabric wherein the aragonite needles are clumped together into discrete masses (Fig. 8H). Subspherical to spherical pores were apparently formed by the dissolution of aragonite cements; sometimes these pores are lined by drusy calcite (Fig. 8I). Drusy calcite also occurs together with aragonite cement and seems that it fills the pores produced by dissolution of aragonite needles (Fig. 8J,K).

3.5. Bore hole data

The sediments at 2 and 11 m are sandy. Rounded and ovoid to ellipsoidal grains are abundant in the coarse fraction and are similar to those in the surficial sediments. Echinid spines, foraminifers and molluscs are minor components. The sample at 19.5 m is largely aragonitic mud with a few algal grains and faecal pellets. In contrast, the sample at 26.5 m depth largely consists of terrigenous grains dominated by mica, quartz and few aragonite grains. X-ray mineralogy shows that the samples at 2 and 11 m are largely aragonitic, while the sample at 19.5 m contains both aragonite and low-magnesium calcite in near equal proportions. However, the sample at 26.5 m consists of calcite, mica, quartz, feldspar and aragonite in approximate order of abundance. The ^{14}C age of the sample at 26.5 m is $23,880 \pm 630$ yr B.P.

4. Discussion

4.1. Inferred environmental conditions during cementation of sediments

The diagenetic fabrics of the limestones reflect two diagenetic environments. The grains were originally cemented by aragonite precipitated under shallow marine conditions. The dissolution of aragonitic skeletal and non-skeletal components and cements apparently took place immediately after. Aragonite and high-magnesium calcite are stable and their alteration to low-magnesium calcite has not yet been reported in shallow marine conditions. However, meteoric waters are undersaturated with respect to calcium carbonate and their percolation into the sediments locally dissolves aragonite and high-magnesium calcite. Dissolution fabrics such as abundant empty pores (Figs. 8A,B and 12A), relic and abruptly terminated aragonite needles (Fig. 8C,F–H) and the clotted fabric of aragonite needles (Fig. 8H) provide evidence of vadose conditions. The meniscus bridges (Fig. 8E,F) at grain contacts and drusy calcite filling the pore spaces (Fig. 8I–K) suggest vadose cementation. Similar diagenetic fabrics has been reported in beachrocks (Taylor and Illings, 1969; Land, 1970; Meyers, 1987; Strasser et al., 1989; Rao and Nair, 1992). Therefore, the diagenetic processes can be related to initial cementation and emergence. Hence, the limestones may either represent beachrocks or low sea-level conditions after marine cements were formed.

Marine cements (aragonite and high-magnesium calcite) in shallow water environments include heavy stable isotopes $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values are $+3\%$ and $3.5 \pm 1.5\%$ PDB, respectively (Milliman, 1974; Hudson, 1977). The $\delta^{13}\text{C}$ values of our samples (Table 2) lie within the range of marine cements whereas $\delta^{18}\text{O}$ values are considerably less than marine cements but within the domain of shallow water limestones reported by Milliman (1974). Since the limestones exhibit vadose features similar to those in beachrocks, their stable isotopic values were compared with the beachrocks. The $\delta^{18}\text{O}$ values (0.03 – 1.15%) of our samples are within the limits of the $\delta^{18}\text{O}$ values of the beachrock cements of the Red Sea (-0.1 to

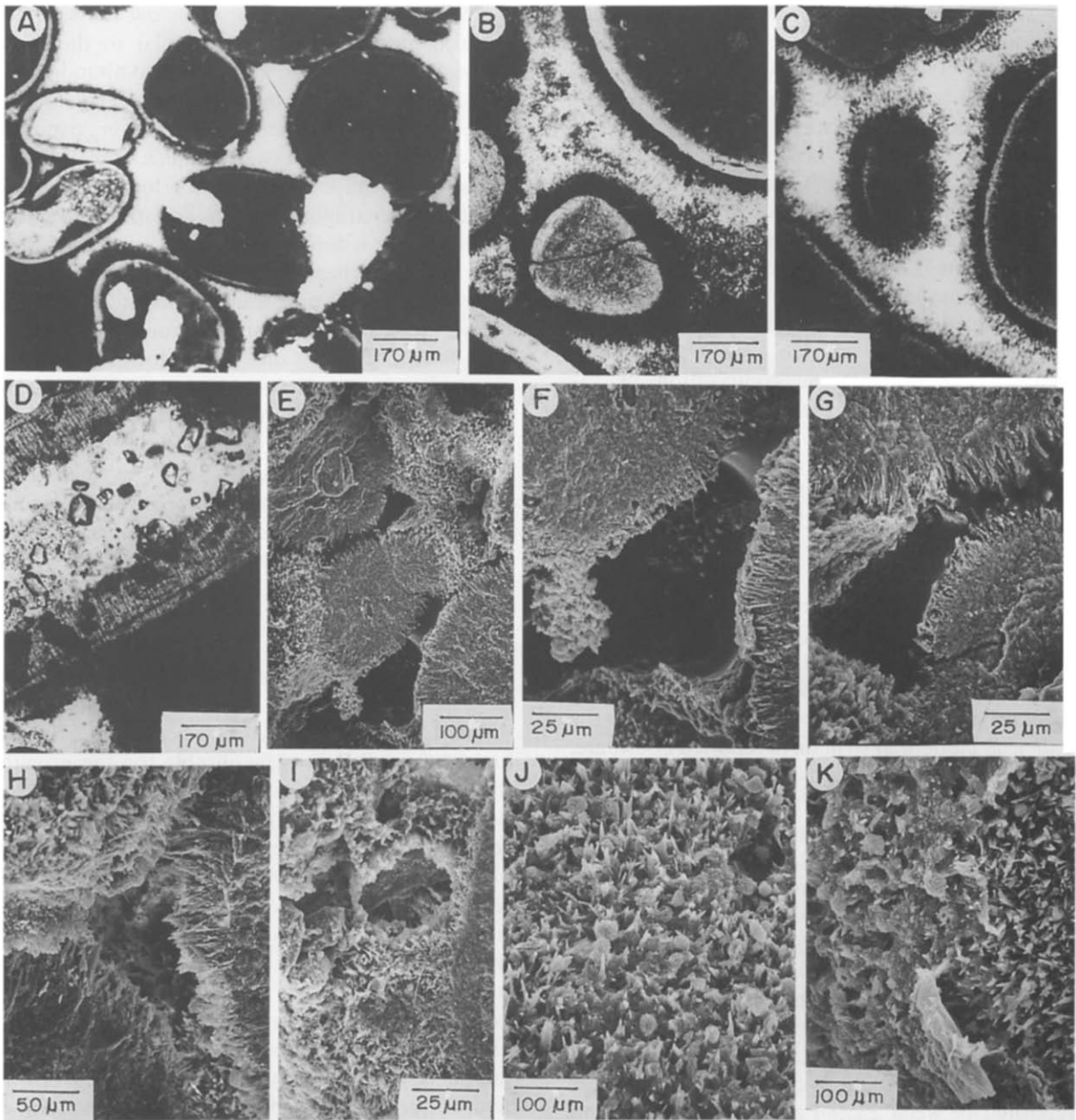


Fig. 8. Diagenetic textures of the limestones: (A)–(D) photomicrographs, (A) porous fabric of the limestones showing etching of grain boundaries and pores resulting from boring and from dissolution of cements; (B) cement around grain boundaries and dissolved cements in the pores; (C) relic aragonite needles and empty pore spaces; (D) dissolution of skeletal fragment, the resulting pore is lined by minute calcite crystals. (E)–(K) SEM photographs, (E) at low magnification showing grains bound by aragonite needles and different sizes of empty pores; (F) and (G) are details of (E): (F) curved outlines of cement at grain contacts resembling meniscus cement; (G) pores showing abruptly terminated aragonite needles and undissolved aragonite needles in the adjacent pore; (H) clumping of aragonite needles into discrete masses in pore; (I) cavity formed by dissolution, drusy calcite can also be seen around the cavity; (J) and (K) dissolution of aragonite needles and pore filling drusy calcite.

+1.2‰) (Holail and Rashed, 1992) and Israel coast (about –0.1‰) (Magaritz et al., 1979). However, $\delta^{13}\text{C}$ values (3.79–4.29‰) of our limestones differ and are within the range of values of Red Sea beachrock cements (+2.1–4.5‰) but higher than beachrock cements of Israel coast (0.5–2.6‰). The higher $\delta^{13}\text{C}$ values in our samples relative to the Israel beachrock cements may be due to the carbonate species derived from meteoric water cements is small compared to the carbonate derived from solution of marine cements and marine constituents; this results higher values of $\delta^{13}\text{C}$ in accord with marine cements. This also suggests that the isotopic composition of the beachrock is similar to the isotopic values of the cement formed in marine diagenetic environments. Since stable isotope values of our limestones agree with the beachrocks of the Red Sea, it may be that arid and high salinity conditions prevailed at the time of their formation.

4.2. Growth period of *Halimeda* bioherms

The bathymetry, seismic and sonograph data show the presence of mound-shaped structures on the carbonate platform which resemble the *Halimeda* biohermal structures reported elsewhere. Moreover, *Halimeda* grains are most abundant in the limestones recovered from the mounds. The ages of the limestones and surface sediments (Table 2; Fig. 1) suggest that the algal bioherms were relict and the ages represent the youngest ages of bioherms on the platform. However, the presence of 25 m thick bioherm-like structures (further confirmed by bore hole data) suggests that the *Halimeda* growth on the platform must have started much earlier than 8300 yr B.P. The age of the bore hole sample at 26.5 m is about 23,880 yr B.P. This implies that 26.5 m of sediment were deposited between 23,880 and 8300 yr B.P. This period, however, includes the Last Glacial Maximum (18,000 yr B.P.) wherein sea level fell to 120 m below the present; this would have exposed the shelf to subaerial conditions. With only one radiocarbon date from the bore hole, it is difficult to determine the thickness of the carbonate sediment deposited after the Glacial Maxima. Nevertheless, we have tentatively inferred the age of the other bore hole samples.

The samples at 2 and 11 m below the sea bed are aragonitic sands and are similar to those on the surface. Aragonitic muds are also abundant in the sample at 19.5 m but terrigenous clays occur at 26.5 m. If the sediments at 19.5 m were exposed to subaerial conditions, the mineralogy of the muds must have changed to low-magnesium calcite. Since aragonite muds are still dominant, the bore hole sediment level at 19.5 m may represent the time when the platform was submerged. In order to get the time frame at about 20 m depth below the sea bed, we should know the rate of algal growth which is unknown. However, highest accumulation rate so far reported for open ocean bioherms is 5.9 m/1000 yr (Roberts et al., 1987a). Even if we assume this accumulation rate (5.9 m/1000 yr) for our bioherms, the 20 m thick algal facies on the platform might have started growing around 3300 years before the sediments of the present day sea bed (10,400–8300 yr B.P.) about 13,700 (?) yr B.P.

4.3. Growth conditions of *Halimeda*

The Late Quaternary period between 13,700 (?) and 8300 yr B.P. was favourable for the growth for algal bioherms. The diagenetic textures of the limestones indicate that the sediments were cemented at intertidal conditions. Skeletal components (other than *Halimeda*) in limestones and in sediments are indicative of shallow water conditions (Guptha, 1979; Nair et al., 1979). It may be that the biohermal growth on the platform started during low sea levels and their upward growth kept pace with the rising sea level during the Holocene transgression. The most important factors responsible for their formation, apart from temperature, salinity, light, rate of sedimentation and grazing, are the antecedent topography and availability of nutrients (Hallock and Schlager, 1986; Roberts and Macintyre, 1988). Seismic profiles show that the topographic irregularities are minor on Pleistocene erosional surface which is almost flat with only a gentle slope. Therefore, it is difficult to determine whether the sea floor relief is an important prerequisite for the biohermal development.

Upwelling in the Arabian Sea is seasonal and dependent on the intensity of the summer monsoon. Moreover, an arid climate with weak monsoon conditions (and weak upwelling) prevailed between 18,000 and 9000 yr B.P. (Luther et al., 1989; Prell et al., 1989), the growth period of *Halimeda* on the platform. Therefore, upwelling might have not been a major supplier of nutrients for the growth of *Halimeda* bioherms.

The thick pile of siliciclastic sediments in the Dahanu depression (present day inner shelf) and the prevalence of carbonate depositional environment until early Holocene on the platform lying on the outer shelf suggest that the fluvial sediments largely accumulated in the depression and thus leaving carbonate growth on the platform unhindered. However, the acid-insoluble residue of the sediments of the platform is about 10% (Hashimi and Nair, 1976). Microprobe analyses (Table 1; see Part II) reveal that a small terrigenous component is incorporated in the faecal pellets. It is likely that a small quantity of the terrigenous sediments reach the carbonate platform and probably acted as a nutrients source for the *Halimeda* growth.

The platform is a windward facing margin feature and well developed biohermal structures are present in the lagoons close to the shelf edge (Fig. 4). The high tidal and internal wave generated currents associated with the shelf break (Shenoi et al., 1988) might have provided some nutrients to the algal bioherms. Searle and Flood (1988) suggested that shelf edge currents were the source for bioherms of the Great Barrier Reef. Mankiewicz (1988) suggested that *Halimeda* flourished on the sedimentary wedges of proximal slope facies during low stands of sea level.

Unlike the biohermal sediments at the Great Barrier Reef, and at the Java Sea (Marshall and Davies, 1988; Phipps and Roberts, 1988), the surface as well as bore hole sediments of the carbonate platform off western India are sandy; Furthermore, *Halimeda* segments were reduced to sand size and the fine sediments abraded from *Halimeda* were absent on the platform. This may indicate that (a) high energy environment prevailed during the growth of *Halimeda* and (b) the fine-grained material brought on to the platform (terrigenous flux) and/or generated on the platform

itself (by abrasion of *Halimeda* segments) were either simultaneously modified into faecal pellets (see Part II) and/or advected to the deep sea.

The shallow sea-level conditions during the Late Quaternary associated with arid climate and nutrients from river runoff and shelf edge currents were probably responsible for the growth of algal bioherms, dominated by *Halimeda*; this resulted an accumulation of huge carbonate buildups (25 m thick) on the platform between 13,700 (?) and 8300 yr B.P. Why carbonate bioherms stopped growing after about 8300 yr B.P. is unknown. The presence of Early Holocene carbonate buildups and their absence during the Late Holocene–Recent on the platform appear conspicuous because some platforms (Campeche Bank, eastern Australian shelf, parts of Indonesian reef belt) were drowned and others (Bahama Banks and Caribbean platforms) lost some ground material during the Early Holocene as they could not keep pace with the rapid rise of sea level (see Schlager, 1981, 1991). However, shallow water carbonates of Late Holocene age occur on these platforms and suggested that this growth is due to slower rates of sea level rise during this period. The absence of Late Holocene–Recent carbonates on the platform is quite intriguing. Possible causes of platform drowning include (1) reduction of benthic growth due to environmental stress and (2) rapid pulses of relative sea level (Schlager, 1981).

About 9000 yr B.P. climate changed from hot and dry (arid) to hot and wet (humid) conditions (Prell et al., 1989). This climatic change is associated with heavy monsoons in the Indian Ocean and also in many parts of the world (Kutzbach, 1983); this results in an enormous terrigenous influx, high nutrients, drop in salinity and turbid conditions which affect the carbonate growth. Buried biohermal structures landward of the platform (Fig. 3) may be an evidence of this phenomenon. On the other hand, the surface sediments of the platform are still sandy suggesting that little clastic fine-grained sediments have accumulated after 8300 yr B.P. presumably due to strong currents (Anonymous, 1976; Veerayya and Nath, 1994). Apparently, high energy environment continued on this platform even after 8300 yr B.P. and therefore the fine fraction brought on to the

platform winnowed to the deep sea. There is a relative increase in the intensity of monsoons and upwelling after 9000 yr B.P. (Luther et al., 1989); obviously this brings relatively excess nutrient recycling which may cause the demise of carbonate growth (Hallock and Schlager, 1986; Hallock et al., 1988). The slower rates of sea level rise during the Late Holocene (Fairbanks, 1989) might have affected the carbonate growth. Several workers (Patel et al., 1984; Merh, 1987; Patel, 1991) reported neo-tectonic activity in the coastal areas of this platform and documented that the sea level was at about +8 to +10 m above the present sea level during the Early Holocene. If this is true, light penetration, temperature, salinity of the waters would adversely affect the *Halimeda* growth and cause the cessation of bioherm growth. Why *Halimeda* bioherms have grown with the exclusion of coral reefs on the platform is not known but high concentrations of nutrients in the waters of the rivers passing over the platform are probably detrimental (Hallock et al., 1988) and inhibited the coral growth.

Part II. Aragonitic faecal pellet-dominated sediments

5. Results

The distribution of sediments and their coarse fraction constituents on the carbonate platform were reported (Nair and Hashimi, 1981, and references therein). Rounded and ovoid to ellipsoidal non-skeletal grains referred to as oolites are abundant and constitute >80% of the coarse fraction on the platform but vary from 30 to 90% on the outer shelf with lower values towards the south (Hashimi and Nair, 1976). Benthic foraminifers, echinoderms, molluscs and bryozoan fragments are minor constituents. Detailed investigations and a re-appraisal of the non-skeletal grains are as follows.

5.1. External morphology of grains

The grains (maximum diameter 2 mm) (Fig. 9A) are aragonitic and may be light yellow to tan, grey

or white; light yellow are most abundant but all become light yellow to tan when treated with hydrogen peroxide indicating that the grey colouring is probably due to organic matter. Most are ovoids, rods, ellipsoids or cylindrical (Fig. 9B–M). Crescent-shaped grains (Fig. 9N), rods with transverse constrictions (Fig. 9P) and tube-like grains (Fig. 9O) are also present. Many have smooth surfaces but a few show moderate to intense surface borings (Fig. 9Q). The branching pattern of some borings may indicate formation by fungi (Fig. 9R).

5.2. Internal structure of grains as revealed from SEM studies

Freshly broken surfaces of grains under SEM indicate that peripheral borings extend deep within (Fig. 10A). Many grains are compact and composed of homogeneous muds (Fig. 10C–E). Moderately compacted areas show an admixture of needle-like aragonite crystals and muds (Fig. 10E). Long, thin and straight canals parallel to each other traverse the grains (Fig. 10H,I). Under high magnification, these contain acicular aragonites and globular structures resembling bacteria (Fig. 10J). Some canals are crescent or hook-shaped (Fig. 10G). The interior of some pellets (Fig. 10B) has been dissolved and a cement of calcite crystals is present. Some pellets contain algal fragments (Fig. 10F).

Some grains show algal structures (Fig. 11A,B). Some others are also algal but mostly show compact internal structure (Fig. 11C,D). Of 350 grains studied, only two show thick coating around nuclei like ooliths (Fig. 11E,G). Radial aragonite occurs as coating in one grain (Fig. 11F) and in the other (Fig. 11H), the coating appears to be diagenetic accretions of aragonite.

5.3. Internal structure of the grains as revealed from thin sections of the limestones

The size and shape of the grains in the limestones are similar to those in the associated sediments. Thin sections show that there are abundant *Halimeda* segments, which attained rounded to ovoid shape (Fig. 8); Other skeletal components

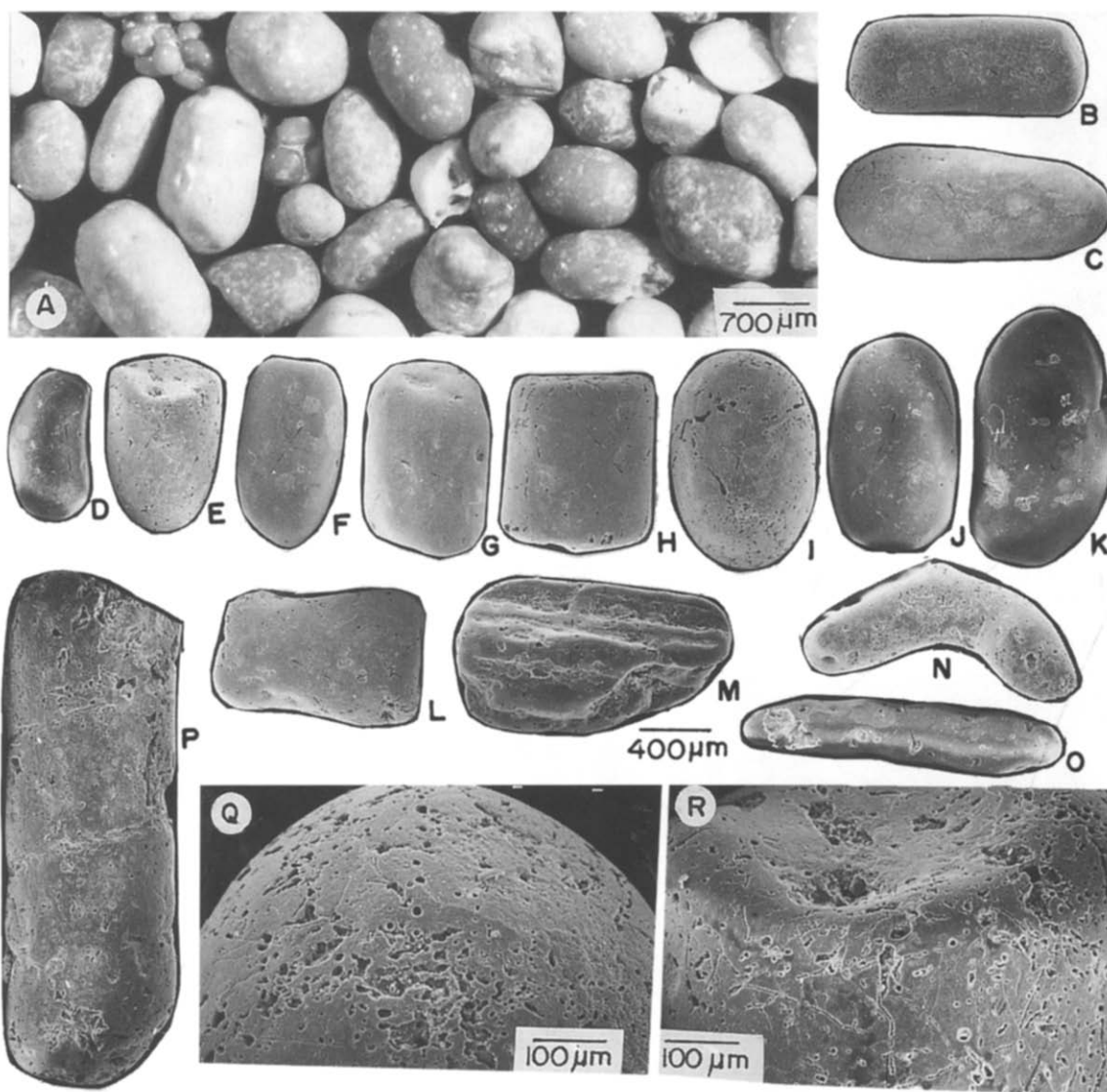


Fig. 9. (A) Light yellow to tan non-skeletal carbonate grains (photomicrograph); (B)–(P) SEM photographs showing variation in morphology of grains (all are same magnification); (Q)–(R) (SEM photographs) detail of the part of the grain surfaces showing borings; the branched pattern (R) of the borings indicate that they may be due to fungi.

are echinoids, benthic foraminifers and bryozoan fragments. Some other ovoid to ellipsoidal grains show distinct internal structures (Fig. 12) characteristic of some known crustacean faecal pellets (Moore, 1932, 1975; Parejas, 1948; Hantzschel et al., 1968; Cu villier et al., 1969; Brönnimann, 1976; Brönnimann and Norton, 1960; Brönnimann et al., 1972).

Crustacean faecal pellets are pierced by longitudinal canals; the number, size and the morphology of these canals, in transverse sections, are the most diagnostic features for their identification. Longitudinal sections (Fig. 12E) show that these canals run parallel to each other on the long axis. Some oblique cuts (Fig. 12C,D,G) give a discontinuous canal appearance. The transverse or near

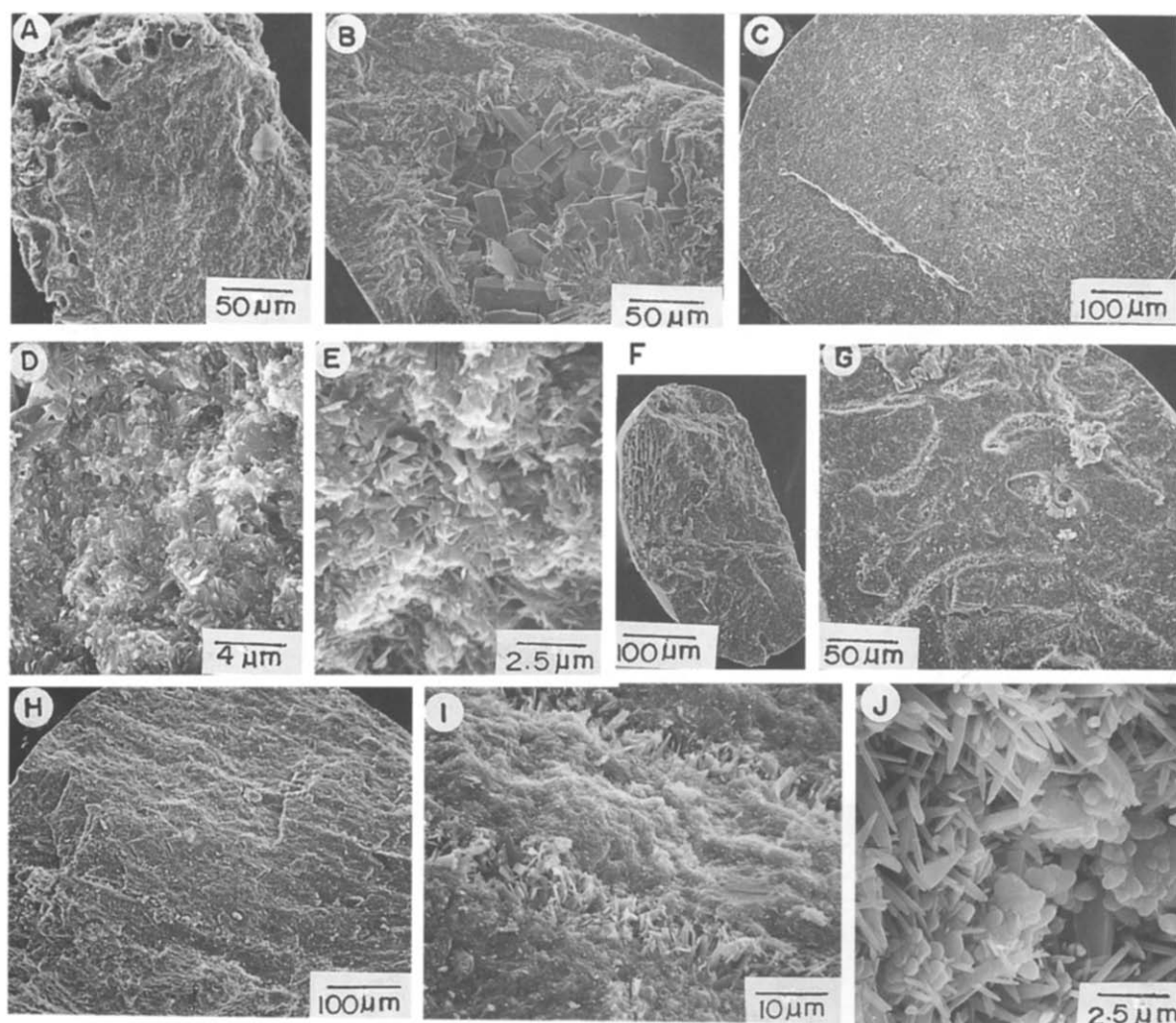


Fig. 10. Broken surfaces of the carbonate grains (SEM photographs). (A) grain showing peripheral boring and compact internal matrix; (B) a pellet showing pore filling calcite in the central part; (C) a grain showing homogeneous compact matrix; (D) and (E) detail of (C) in the central part showing aragonite muds and tiny aragonite needles, respectively; (F) pellet consisting of algal fragment; (G) grain showing crescent to hook-shaped canals; (H) grain showing elongated parallel canals; (I) detail of the canals; (J) detail of one canal showing acicular aragonite and submicron-sized coalesced globules resembling bacteria.

transverse sections (Fig. 12F,H–N) showed 10 canals, arranged in two groups of five each bilaterally symmetrical. In each group, 3 canals are inner (near the symmetrical plane) and 2 are outer. Oblique sections also show this disposition (Fig. 12F,H–N). The best sections (Fig. 12H–K,M) show the crescent to hook-shaped canals. The convex side of crescent is pointed towards outside. All these characters

(number, arrangement and morphology) correspond to the *Palaxius* genus of Thalassinidea tribe described by Brönnimann and Norton (1960). According to these authors, two species could be identified: *P. habanensis* with simple crescent shaped canals (Fig. 12F,J,N), and *P. decum lunulatus* (Perejas) with more curved crescents and enlarged tips (Fig. 12H,I,K,M). But in numerous sections crescent-shaped canals are more or less

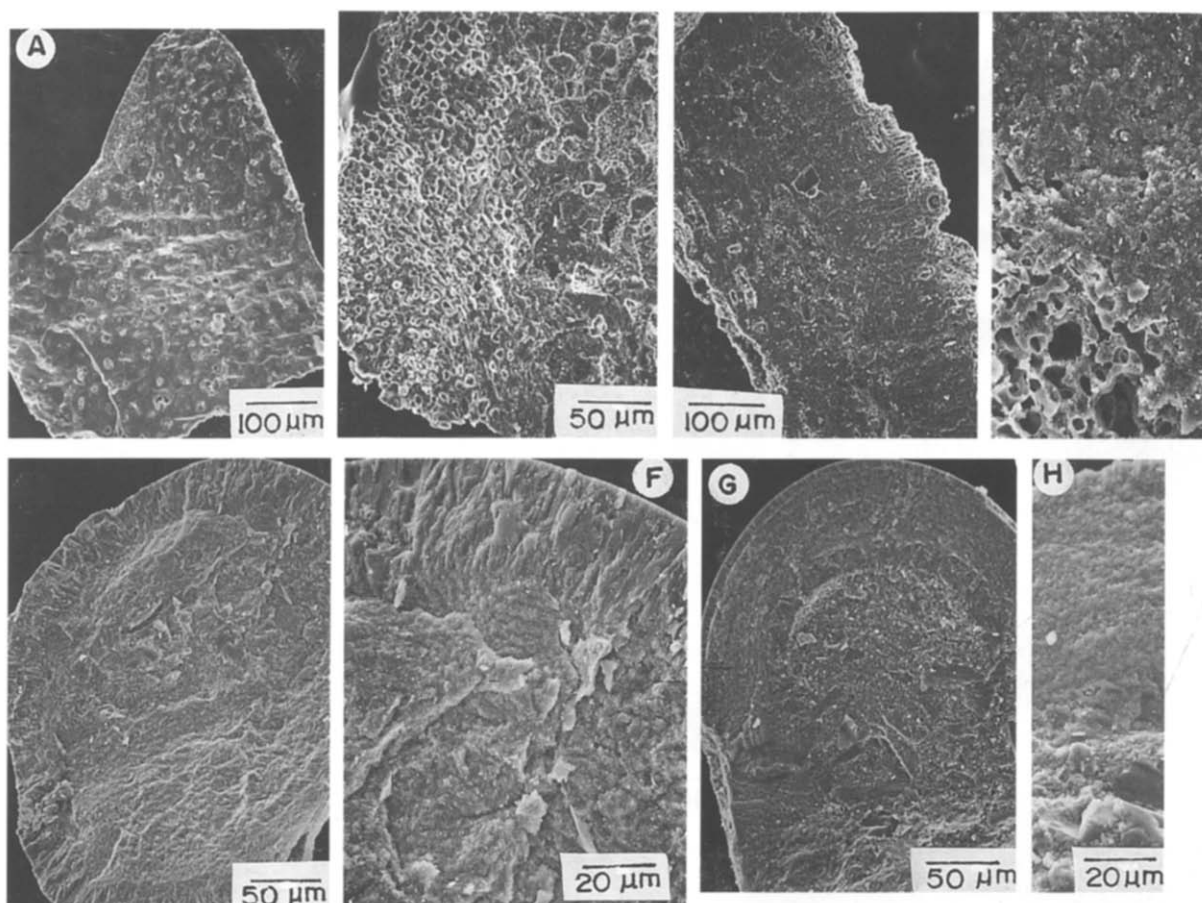


Fig. 11. Broken surfaces of other type of grains: (A and B) grains showing algal structure; (C) algal grain with compact internal structure; (D) detail of (C) at the edge; (E) grain coated by radial aragonite; (F) detail of (E) at the cortex; (G) another grain similar to oolite; (H) detail of (G) at the cortex showing that the layering is due to diagenetic accretion.

clearly curved and may be *habanensis*, a junior synonym of *decem lunulatus*.

There are also rare specimens which show fifty canals in transverse section (Fig. 12O). The number of canals and their arrangement in two symmetrical groups correspond exactly to the description of *Upogebia* (*Gebiopsis*) *deltura* (of Thalassinid tribe) by Moore (1932). Some other sections may correspond to other species (Fig. 12Q) but the conservation is not good enough to determine them with precision.

Finally, some other grains are probably faecal pellets of other organisms. Some do not exhibit internal canal system (Fig. 12P) and others are

long tube-like (Fig. 12R). Foraminifers (Fig. 12T) or echinoid remains (Fig. 12U) and detrital fragments (Fig. 12S) can be recognised in some faecal pellets.

Some sections show a transparent envelope around faecal pellets (Fig. 12Q,T,R,U); based on this envelope these grains were interpreted as oolites (Hashimi and Nair, 1976). In fact, it does not seem to be oolitic coating, and we interpret this transparent envelope as a possible organic coating often present in faecal pellet sections. Furthermore, Brönnimann (1976) reported some specimens of *Favreina salevensis* with a similar thick coating.

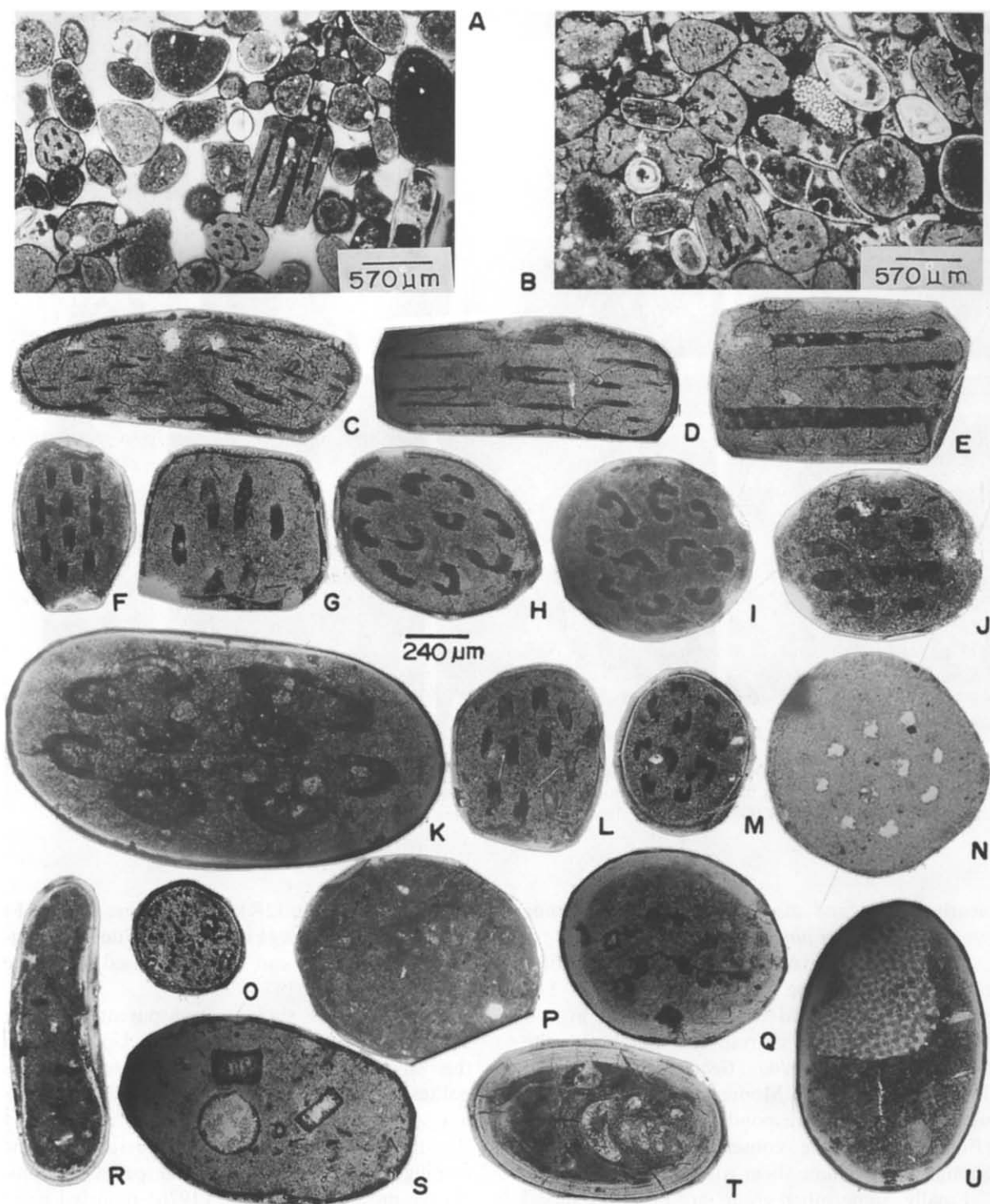


Fig. 12. Non-skeletal grains from the limestones: (A) and (B) low magnification photomicrographs of the samples at stations 1479 and 1459, respectively. (C)–(O) Crustacean coprolites: (C,E,G) longitudinal and oblique sections, (F) and (H–N) transverse or near transverse sections of *Palaxius* genus, (O) transverse section of *Upogebia* (*Gebiopsis*) *deltura*, (P)–(U) unidentified faecal pellets, some show transparent envelope (Q,R,T,U).

5.4. Mineralogy and microprobe geochemistry

X-ray mineralogy shows that rounded and ovoid to ellipsoidal grains consist of aragonite. The major element chemistry of the internal compact matrix of these grains from different stations (Table 1) indicates that calcium is the most abundant element and CaO values range from 75 to 90%. This is followed by SiO₂ which ranges from 2 to 6.75%. Other major elements vary from 1 to 2% (column I, Table 1). Inter-element correlation indicates that Al₂O₃ is positively correlated with SiO₂, MgO, K₂O, Na₂O, P₂O₅ and SO₃, while CaO is negatively correlated. Both biogenic and lithogenic components are present, the former being the most abundant. The lithogenic component may correspond to detrital clays (magnesium aluminium silicates with a little iron), derived from weathering of the Deccan trap basalts in the hinterland. Most of the calcium is biogenic, probably derived from the mechanical disintegration of algal fragments (see discussion). SO₃ does not correlate with FeO but shows a strong positive correlation with P₂O₅. The sulfur may be incorporated within the phosphate phase. The phosphate is in the form of bacteria-like structures. The relationship between S, P and Fe indicates that there may have been mild reducing conditions within the grain sufficient for bacteria to assimilate phosphate either from organic matter and/or from phosphate adsorbed on lithogenic platelets.

Other typical structures within the pellets were also analysed. The calcite cement (Fig. 10B) in pellets are enriched with CaO (column II, Table 1). Mg and Al are not detected in these pellets. The algal fragment enclosed in the pellet (Fig. 10F) is rich in magnesium (column III, Table 1). The cell-like structures (Fig. 10J; column IV, Table 1) are enriched with phosphate. The thick cortex of the oolitic grains (Fig. 11H) are also enriched with CaO (column V, Table 1).

6. Discussion

Halimeda fragments and crustacean faecal pellets are the dominant components in the limestones

(Figs. 7 and 12). The grains showing parallel canals and hook-shaped structures, under SEM (Fig. 10), may correspond to faecal pellet internal features. Some other grains show an algal structure (Fig. 11). Earlier workers have reported neither *Halimeda* nor faecal pellets. They wrongly interpreted these grains as oolites because of the similarities in composition, size and external shape of the grains. This study, on the other hand, clearly shows that the rounded and ovoid to ellipsoidal grains are *Halimeda* fragments and faecal pellets; oolites are rare components. Since faecal pellets are abundant on the platform, these sediments may be classified as faecal pellet-dominated sediments.

The faecal pellets consist of aragonite muds and tiny aragonitic needles. A few biogenic and lithogenic detrital fragments are associated with them. This indicates that (a) there was an abundant supply of aragonitic mud and (b) the crustaceans and other invertebrates concerned utilised these muds as a food source material. How did the aragonitic muds originate?

6.1. Source and production of aragonite muds

Possible sources of aragonitic muds lie in mechanical breakdown or abrasion of skeletal constituents, and in chemical precipitation. Since there are a few oolites, pure chemical precipitation appears to be insignificant in this region. Coral reefs do not seem to be the main source because (a) there are no fragments derived from coral reefs in either the unconsolidated sediments or in the limestones, (b) the mechanical production of silt and clay size sediment from coral reefs is generally small (<2%) (Milliman, 1974).

Mound-shaped structures on the platform are probably built by *Halimeda*, whose fragments are also abundant in the limestones (see Part I). (a) *Halimeda* is aragonitic and has been recognised as significant contributor to carbonate sediments. A *Halimeda* plant can produce one segment per day per branch which lead to the production of 50 g/m²/year (Wefer, 1980). (b) The *Halimeda* grains (Fig. 7) observed here range from 0.5 mm to about 2 mm, and are smaller than the average original

plate (5 mm) (Neumann and Land, 1975). This suggests that *Halimeda* produces both sand and mud size particles upon disintegration. Sand size *Halimeda* grains were reported by several workers (Basan, 1973; Orme, 1977; Alexandersson and Milliman, 1981; Harris et al., 1990; Shinn et al., 1990) who suggested that *Halimeda* segments furnish abundant debris ranging in size from almost whole segments to silt and clay particles. Faecal pellets containing algal fragments (Fig. 10F) provide evidence that animals were feeding on algal plant detritus and organic matter derived from these plants. Other skeletal like molluscs probably contributed some aragonite. It is therefore suggested that the sources of aragonite muds were largely from algal bioherms dominated by *Halimeda* and a little from other skeletal components.

6.2. Production of faecal pellets

It appears that the algal bioherms supplied abundant aragonitic muds. Crustaceans and other deposit feeding invertebrates obtain their food by sifting through sediment for microscopic animals. The faecal pellets are produced once the animal has passed the sediment through its digestive tract (Weimer and Hoyt, 1964). Faecal pellet production by these organisms is volumetrically important. Pryor (1975) reported that *Callianassa major* is capable of removing and pelletising approximately 12×10^6 tons of suspended material per square kilometre per year and of depositing faecal pellet muds as thick as 4.5 mm/yr in shallow water environments. In tidal flats and in shoreface environments *Callianassa major* produces an average of 2480 pellets per day. In protected environments, *Callianassa* can pelletise nearly 618×10^6 tons of suspended solid/square kilometre/year, enough to cover each square meter with 141 mm of faecal pellets each year. Verwey (1952) estimated that *Mytilus* alone annually extracts and deposits from 20,000 to $175,000 \times 10^6$ tons of suspended solids. The abundant supply of aragonitic muds in shallow water conditions probably favoured crustaceans to produce abundant faecal pellets.

6.3. Preservation aspects of faecal pellets and their comparison with other faecal pellets

The faecal pellets studied here are small, compact and associated with shallow water conditions. The original constituents are still retained. The internal canals are distinct although they contain diagenetic acicular aragonite and phosphatic globular structures resembling bacteria. It appears that they must have indurated by rapid early diagenetic processes which were promoted by microbial organisms. Rao et al. (1993) reported faecal pellets which acted as substrate for verdine and glaucony on the SW continental margin of India. Nair (1969) reported phosphatised ooids (may be faecal pellets) off Ratnagiri. The size of the faecal pellets in all the three regions is same, but the aragonitic faecal pellets are much more abundant than the other pellets. There are no recent faecal pellets reported from this margin. It implies that (a) Early Holocene conditions were favourable for faecal pellet production and (b) their preservation was probably determined by the consistency and initial constituents of the faecal pellets. For example, aragonite faecal pellets are compact while the others are porous and therefore the latter were modified by subsequent authigenic–diagenetic processes. Since the size of the pellets is same, it may be that the animal concerned utilised different food material and produced pellets of different initial composition, or different animals with a different feeding habit produced similar size faecal pellets. It appears that crustacean faecal pellets are better preserved than those produced by any other animals in marine sediments. Illings (1954) reported Recent aragonite faecal pellets from Bahamas and suggested that rapid diagenetic processes were responsible for their preservation. Kornicker and Purdy (1957) reported extremely fragile faecal pellets of gastropods (*Batillaria minima*) from the same region, which consist of silt-sized carbonate particles embedded in organic matter mucus. Ginsburg (1957) reported Recent faecal pellets of burrowing worms, chitons and crustaceans in the oceanic muds off Florida. Recent gastropod pellets consisting of about 50–90% organic matter with the rest carbonate were reported in beach sedi-

ments of Alacran reef complex, Mexico (Folk and Robles, 1964).

7. Summary and conclusions

The carbonate platform lies on the outer continental shelf off the Gulf of Cambay through which the Narmada and Tapti rivers discharge their sediment load. The sediment load carried by the rivers largely deposited in the inner shelf, which was a huge depression got filled with sediments since Eocene, and thus uninhibited the carbonate growth on the platform. Bathymetry on the platform shows buried and partly exposed pinnacles which reflected as parallel ridges and massive structures in the sonographs. Seismic profiles indicate mound-shaped structures resembling bioherms and a prominent sub bottom reflector at about 25 m depth, considered as Late Pleistocene erosional surface, which is also supported by bore hole data. *Halimeda* fragments and aragonitic faecal pellets are abundant in the limestones. It appears that the algal bioherms dominated by *Halimeda* grew on the platform between 13,700 (?) and 8300 yr B.P. under warm shallow-water conditions, nutrients brought by river runoff and shelf edge currents. The factors for their demise during Late Holocene are unknown but may be due to the combined influence of climatic change, relative increase in nutrient discharge by river runoff and by upwelling and local neo-tectonic activity at about 9000 yr B.P.

Rounded and ovoid to ellipsoidal grains are abundant on the platform. SEM studies indicate that these grains are *Halimeda* fragments and aragonite faecal pellets. *Halimeda* provided abundant aragonitic muds to the sediments. Crustaceans and other invertebrates produced faecal pellets. As faecal pellets are dominant on the platform, the sediments may be referred as faecal pellet-dominated sediments. They indurated by rapid early diagenetic processes mediated by bacteria. Crustacean coprolites were better preserved in the geological history may be due to their compactness and smaller size.

Acknowledgements

We thank the Director, National Institute of Oceanography for the encouragement. Mr. K. Venkateswera Rao kindly provided bore hole samples. We also thank Mr. Shyam Prasad and Dr. Ratin Sharma for the help in sample preparation. Part of the work was carried out when the senior author was in France on a CEC Post doctoral fellowship offered by the Department of Science and Technology (India) and the Commission of the European Communities (Brussels). The late Prof. J.Ch. Fontes (Paris-Sud University, Orsay, France) for all the isotopic analysis, Prof. J.P. Masse (Marseille University) and Breton (Le Havre, Museum) for providing information and papers on crustacean coprolites. We thank Profs. C.J.R. Braithwaite, A.C. Hine for their constructive reviews, and D.A. McManus and Michael Arthur for their valuable suggestions which improved the manuscript. Mr. V.M. Date and Shaik Ali Karim helped in photography.

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