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Bathymetry and sediments on the carbonate platform off western India: Significance of Halimeda bioherms in carbonate sedimentation

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Bathymetry across the carbonate platform off western India indicated small-size pinnacles and their lateral coalescence into 2 -6-m high mounds landward, and linear elongated carbonate ridges and troughs, mounds and banks up to a height of 20-m seaward of the platform. Seismic data indicated that these mounds were transparent with no rigid internal structure and can be defined as bioherms. The sediments were abundantly aragonite faecal pellets, Halimeda grains and ooids and their radiocarbon ages ranged from 11 to 7.5 ka BP. It appears that the growth of Halimeda bioherms on the platform was facilitated by intense upwelling during the early Holocene. The terrigenous sediments brought by rivers were deposited in the inner shelf and have not affected the growth of bioherms. It is estimated that the platform comprises at least 1.85 Gt of mass $CaCO_3$ accumulated during the early Holocene and comparable to those on the Great Barrier Reef. Halimeda bioherms produce abundant carbonate sediments and their growth period represents a geological carbonate sink and release of high CO_2 to the atmosphere. Detailed shallow seismic studies and sediment cores are needed to quantify the exact mass content of $CaCO_3$ and model climate change during the early Holocene.

Keywords. Halimeda bioherms; early Holocene; upwelling; carbonate platform; western India.

1. Introduction

Halimeda is a photosynthetic, reef-building calcareous green macroalgae, abundant in tropical, shallow marine environments (Hillis-Colinvaux 1980). It has many leafed-like segments and grows with the increased segments. The segments released by spontaneous disaggregation of Halimeda accumulate on the seafloor. The swift initial calcification of segments (up to 50% of new segment weight composed of $CaCO_3$ within 48 hr) and sporadic subsequent infill of inter-utricular spaces with aragonite crystals allow this alga as an important contributor of sand- to mud-size carbonate sediments (Multer 1988a). Halimeda sediments accumulate over seafloor as meadows, draperies, banks and thick mounds called bioherms (Freile 2004). The mounds grow both vertically and laterally until they coalesce laterally, or form unusual, large sediment banks. Despite Halimeda grows at water depths between 2 and 150 m (Multer 1988b), the present day Halimeda is extensive in relatively deep water (20–50 m) and forms bioherms up to a height of 15–20 m in the northern Great Barrier Reef (NGBR) (Orme *et al.* 1978; Marshall and Davies 1988), 1.5–14-m thick deposits within the Swains Reef of the southern Great Barrier Reef (Searle and Flood 1988), 20–50-m height in the Sunda shelf, Indonesia (Phipps and Roberts 1988; Roberts *et al.* 1988) and 20–30-m height (and some reaching as high as 140 m) in the southwestern Caribbean (Hine *et al.* 1988), 15-m thick deposits on the Fly River Delta, Gulf of Papua, New Guinea (Harris *et al.* 1996) and up to 55-m thick deposits on submerged carbonate platforms in the Timor Sea, northwestern Australia (Heyward *et al.* 1997). Halimeda preferentially occurs in relatively low-energy environments but reported even in the reef front, inter-reef and back reef areas. Halimeda has been discovered in many well-known atolls throughout the world, including the Grand Bahamas Bank (Hoskin *et al.* 1986), Caribbean Sea reefs (Hine *et al.* 1988) and in some atoll lagoons in the Pacific Ocean (Milliman 1974), the Great Barrier Reef (Orme and Salama 1988), Bermuda (Wefer 1980) and in the Mediterranean region (Fornos *et al.* 1992). Recent investigations on the Great Barrier Reef and other atolls showed that the Halimeda reefs cover much more area than the previously estimated (Liddell *et al.* 1988; Rees *et al.* 2005, 2007; Xu *et al.* 2015). Halimeda not only produces abundant carbonate sands and muds but are also important sources of nutrition for many herbivorous fish. Some species of parrotfish feed preferentially on Halimeda (Overholtzer and Motta 1999), but the preference is dependent on $CaCO_3$ content and algal chemical defences (Hay *et al.* 1988; Paul and van Alstyne 1988; Pennings and Paul 1992). Halimeda is highly susceptible to reduced pH and aragonite saturation state but the magnitude of these effects is species specific. Some species of Halimeda suffered net dissolution and reduction in photosynthetic capacity, while others did not calcify and alter the photophysiology in experimental treatments (Price *et al.* 2011).

The importance of understanding the Halimeda bioherms is two-fold: first, Halimeda is known to occur since the Cretaceous (Elliot 1965; Hillis-Colinvaux 1980; Hillis 1997), but does not have a rich fossil record until the Holocene. The mound building by Halimeda was first recognised in 1978 in the Great Barrier Reef (Orme *et al.* 1978), since then several occurrences of Halimeda bioherms of Holocene and recent were reported in the Indo-Pacific region (Orme *et al.* 1978; Orme 1985; Phipps *et al.* 1985; Scoffin and Tudhope 1985; Hillis-Colinvaux 1986; Roberts *et al.* 1987a, b; Hine *et al.* 1988; Marshall and Davies 1988; Roberts and Phipps 1988; Milliman 1993; Rao *et al.* 1994). Subsequently, Braga and Martin (1993) and Braga *et al.* (2015) reported the ancient Halimeda mounds of Miocene (∼6.0 Ma) in the southeastern Spain. The limited fossil record of Halimeda mounds and several Holocene occurrences hint at specific conditions (climate and environmental changes) responsible for their favoured growth and preservation. As these conditions change locally, one needs to identify the factors controlling the Halimeda bioherms precisely for each deposit. Second, Halimeda is capable of generating between 3 and 19 crops per year (Hillis 1991) and produces abundant carbonate sediments, over 2 m/1000 yr (Milliman 1993). The Halimeda bioherms thus contain much more carbonate sediment, sometimes up to four times, higher than that of the adjacent coral reef (Rees *et al.* 2007). The Halimeda bioherms at many locations are associated with coral reef carbonates and as a consequence the significance of Halimeda in the global carbonate budget, independent of coral reefs, has not yet been precisely estimated. The identification of Halimeda bioherms is usually based on bathymetric details, extensive seismic data and sediment components (Orme *et al.* 1978; Orme and Salama 1988; Phipps *et al.* 1985; Roberts *et al.* 1987a, b; Hine *et al.* 1988; Marshall and Davies 1988; Kirkland *et al.* 1993; Braga *et al.* 2015). Lateral coalescence of pinnacles and transparent internal fabric of the mounds arising from the hard bottom are characteristics of bioherms. In this paper, the extensive bathymetric data and limited shallow seismic data collected simultaneously along the east–west (E–W) profiles and components of sediment at different stations from the carbonate platform off northwestern India were used to identify the bioherms. The purpose of this paper is to better understand the factors controlling the formation of Halimeda bioherms and estimate the mass calcium carbonate accumulated during the early Holocene.

1.1 *Study area*

The carbonate platform is located on the outer continental shelf off northwestern margin of India and oriented in the NW–SE direction at latitudes between 17° and 21°N (figure 1). It has a maximum width of ∼110 km at the centre, tapering on either end and covering an area of ∼28,336 km^2 between 80- and 90-m depth contours. It is also known as 'Fifty Fathom Flat', but water depths on the platform vary from 75 to 115 m (Rao *et al.* 1994). The carbonate platform is unique as it constitutes only <10% terrigenous sediments (Rao *et al.*

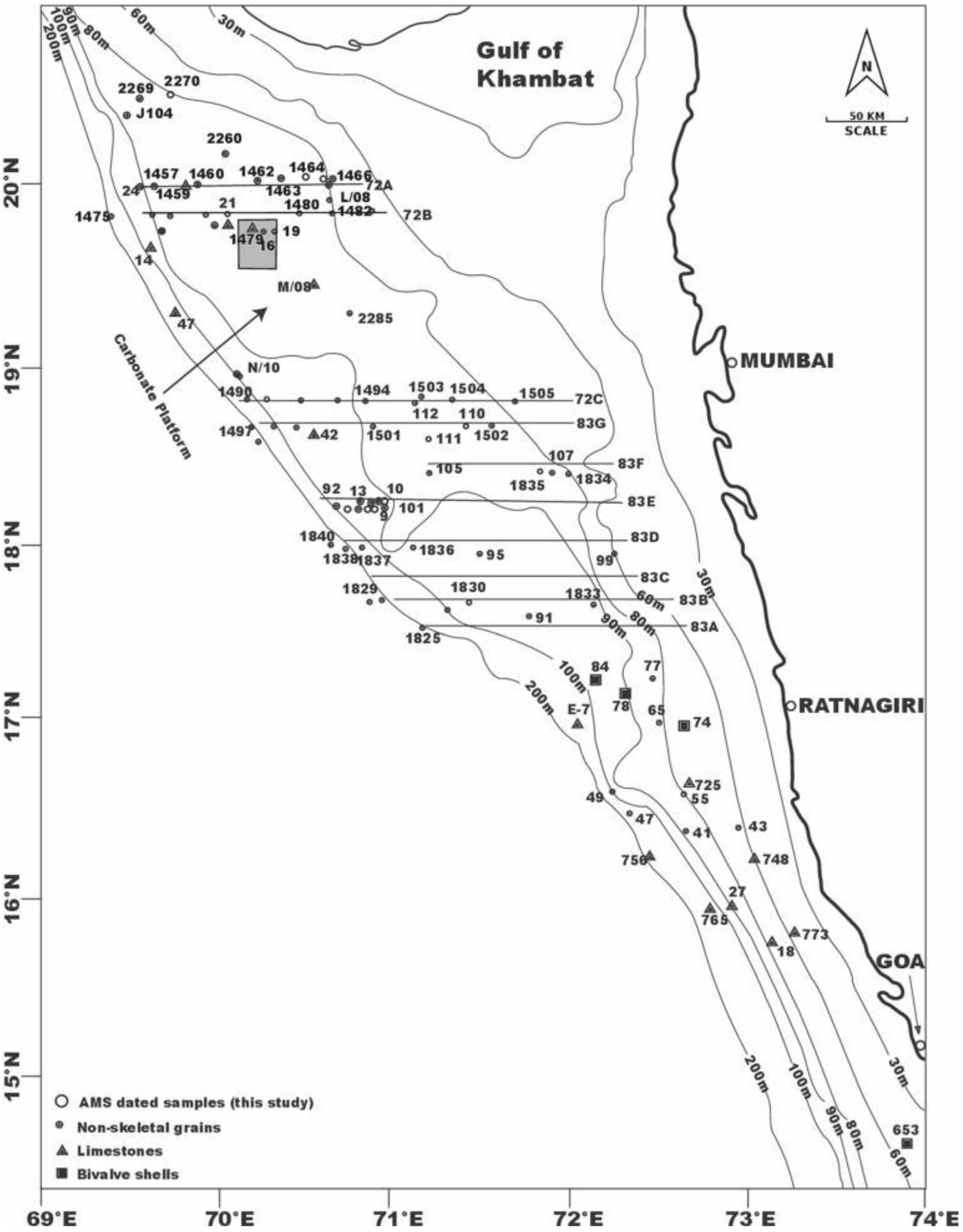

Figure 1. Location map of the carbonate platform on the western margin of India. Location of samples, bathymetric (E–W) lines, and area (box) where multibeam bathymetry was carried out are also shown.

1994) despite the major rivers being located at its proximity (figure 1). For example, on the northeast of the platform, the Narmada and Tapti rivers discharge annually ∼60 million m^3 of water and the abundant suspended sediments into the Arabian Sea (Rao 1975). Similarly, ∼400 km north of the platform, the Indus river discharges huge sediment load into the Arabian Sea and the Indus-borne sediments are known to extend 1500 km from its mouth (Nair *et al.* 1982). The limited terrigenous sediments and the abundant carbonate sediment deposition on the platform during the early Holocene make the platform amazing and invoke more understanding on the deposition of terrigenous sediments during this period. What factors influenced the carbonate growth? Investigations on bathymetry and sediments of the platform would offer valuable information on factors favouring the formation of Halimeda bioherms that developed in open, shallow marine settings.

The topography and associated sediments in a limited area of the carbonate platform were investigated by Nair and Pylee (1968), Nair (1971, 1975), Nair *et al.* (1979) and Nair and Hashimi

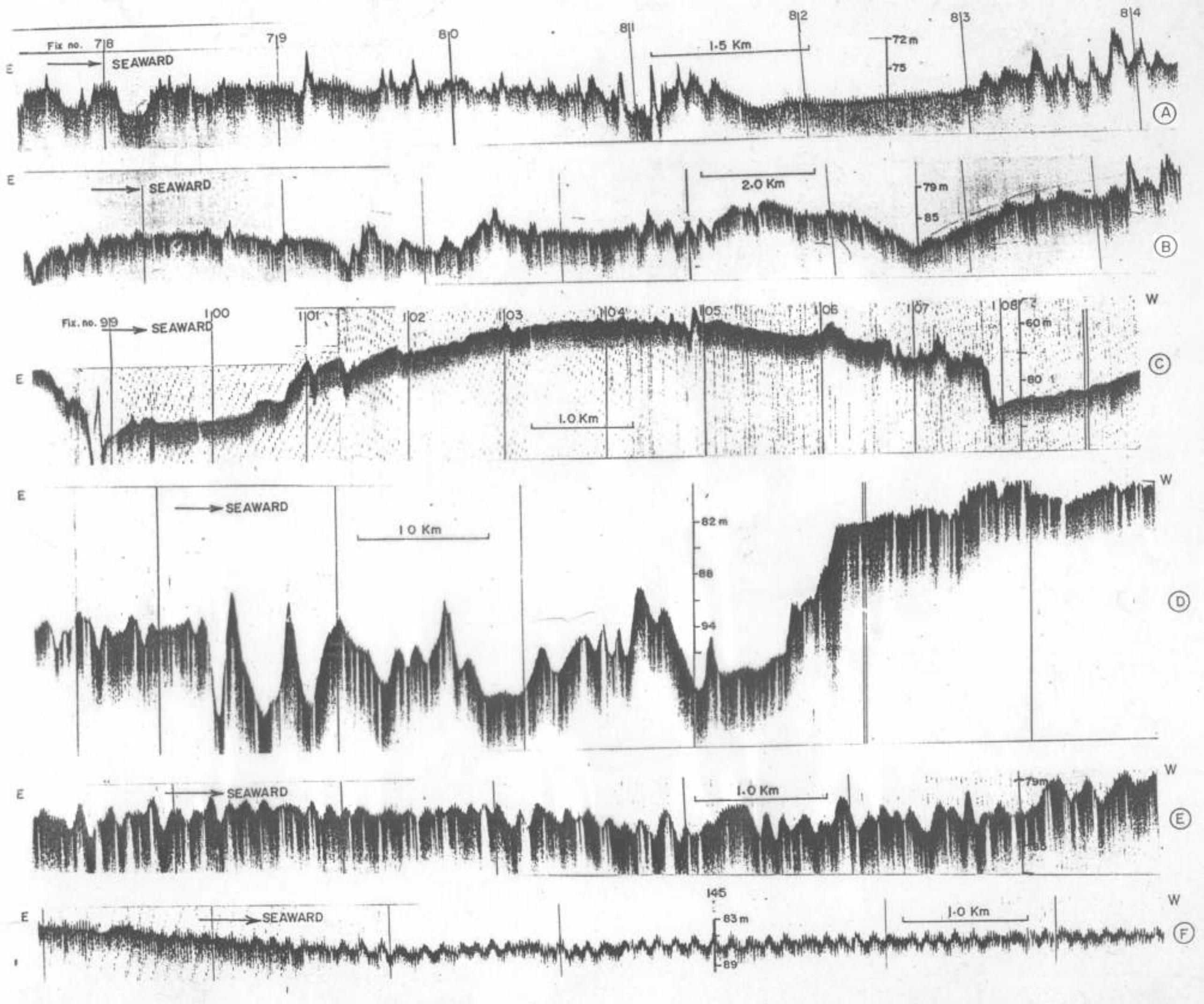

Figure 2. Bathymetry of the part of the E–W profiles of the platform along (**a**–**c**) 72A and (**d**–**f**) 72B.

(1981). Subsequently, Rao *et al.* (1994, 2003a, b), Rao and Veerayya (1996) and Rao and Milliman (2017) investigated the bathymetry, carbonate sediments and sedimentary rocks on the platform and reported Halimeda grains, ooids and faecal pellet-dominated sediments, and inferred sea level changes during the late Quaternary. The factors responsible for the formation of Halimeda bioherms and calcium carbonate budget on the platform after the last glacial maximum have not yet been attempted. This study fills the gap and details the importance of Halimeda bioherms on the platform and estimates the carbonate budget during the early Holocene.

2. Materials and methods

During the 72 and 83 cruises of R V Gaveshani, a single-beam echo-sounding (SBES) system was operated for acquiring bathymetric data along the pre-determined E–W profiles of the platform (figure 1). The SBES system onboard was Kelvin Hughes MS-45. A bar check was carried out before the commencement and after the completion of the surveys. The SBES system operates at a frequency of 30 kHz. The bathymetry data were available in the form of thermal records (figures 2–4).

Multibeam echo-sounding (MBES) system was operated for acquiring the Swath bathymetry data on the carbonate platform off Tarapur, west coast of India (see box in figure 1) during four cruises of the Coastal Research Vessel Sagar Sukti in the year 2007. The MBES system installed was the EM 1002 of Kongsberg AS, Norway, having 111 receive beams that are spaced at an interval of 2° over a 150° sector. The operating frequency of the system was 95 kHz. Using both the amplitude (inner beams) and phase (outer beams)

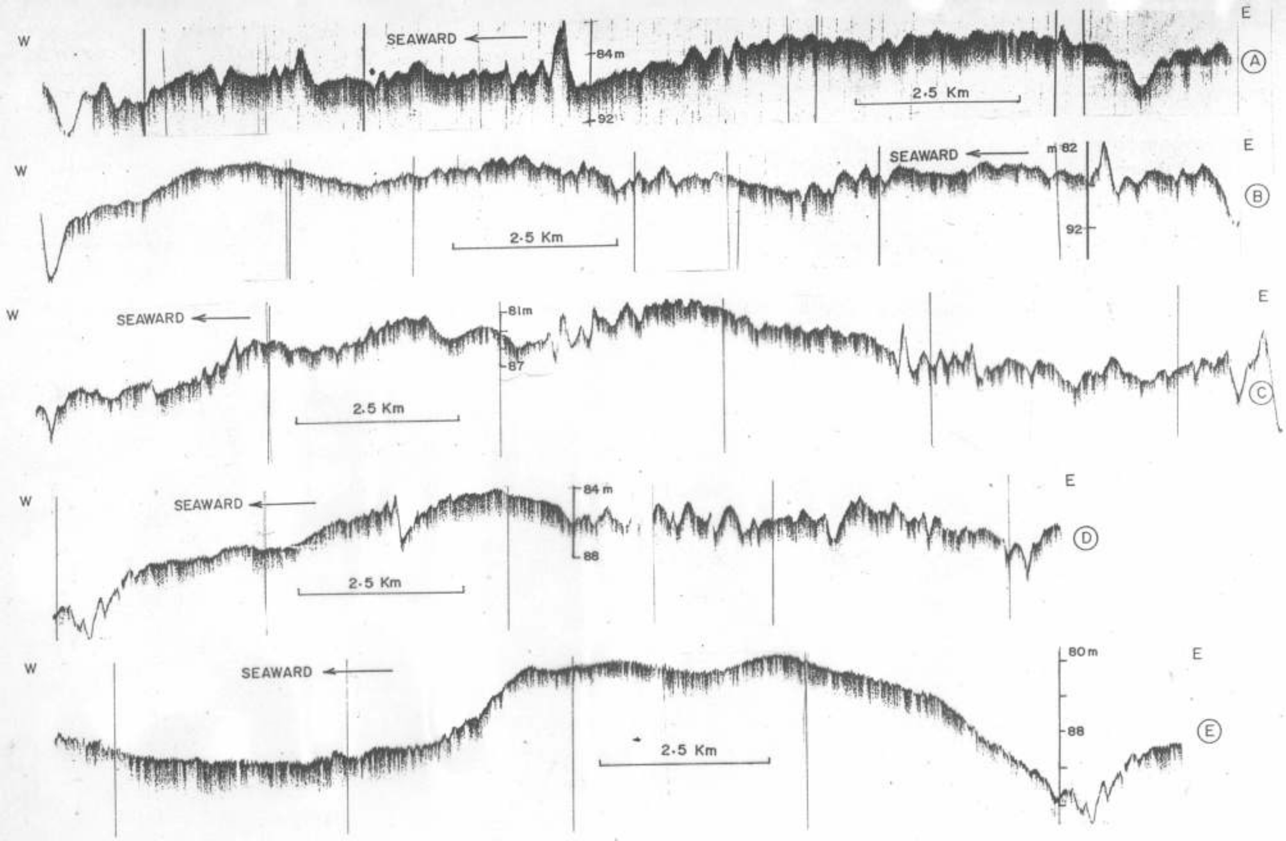

Figure 3. Bathymetry of the platform along E–W profile 83F.

detection methods, the multibeam system is capable of achieving the depth resolution (2–8 cm). Post-processing corrections include the removal of tide effects and depth outliers and gridding of the bathymetric data. Finally, three profiles were extracted along the north–south orientation from the 10-m gridded bathymetry data (figure 5), which has been depicted as one-dimensional profiles (figure 6).

High-resolution shallow seismic profiling was also carried out simultaneously with the acquisition of echo-sounding data during the 72 and 83 cruises of R V Gaveshani, using an ORE sub-bottom profiler. The system consists of an ORE Transceiver model 140 and a hull-mounted nine transducer arrays. An EPC Recorder model 3200 was used for recording a 49-cm wide dry paper (figure 7). Here, the system was operated mostly for greater penetration at 3.5 kHz and occasionally switched over to 7.0 kHz for observing the differences in sediment strata.

Surface sediments were also collected using the Van Veen Grab, during the 72 and 83 cruises of R V Gaveshani, at fixed intervals along the E–W echo-sounding profiles. The sediments collected in other cruises of *ORV Sagar Kanya* were also used (figure 1). A total number of 78 samples were investigated in this study. The sediments were wet sieved using 230 mesh sieves and coarse fraction (>63 μm) was dried and examined under a binocular microscope. Components were identified and 300 grains were counted for different components of sediments. Sediment components were abundantly non-skeletal. Halimeda grains became rounded and small in size because of dynamic environment at the seafloor and can be recognised only in thin sections. Therefore, the term non-skeletal was used to include faecal pellets, peloids, ooids and Halimeda grains. The percentage distribution of non-skeletal grains and shells and shell fragments is shown in figure 8(a and b). Faecal pellets and sections of Halimeda grains are shown in figure 9(a and b), respectively. No new samples were radiocarbon dated for the purpose of this paper. Sediment samples radiocarbon dated earlier were used and the detailed procedure for radiocarbon dating was given in Rao *et al.* (2003b) and Rao and Milliman (2017). The calibrated ages (ka BP) of samples so far dated on the platform are shown in figure 10.

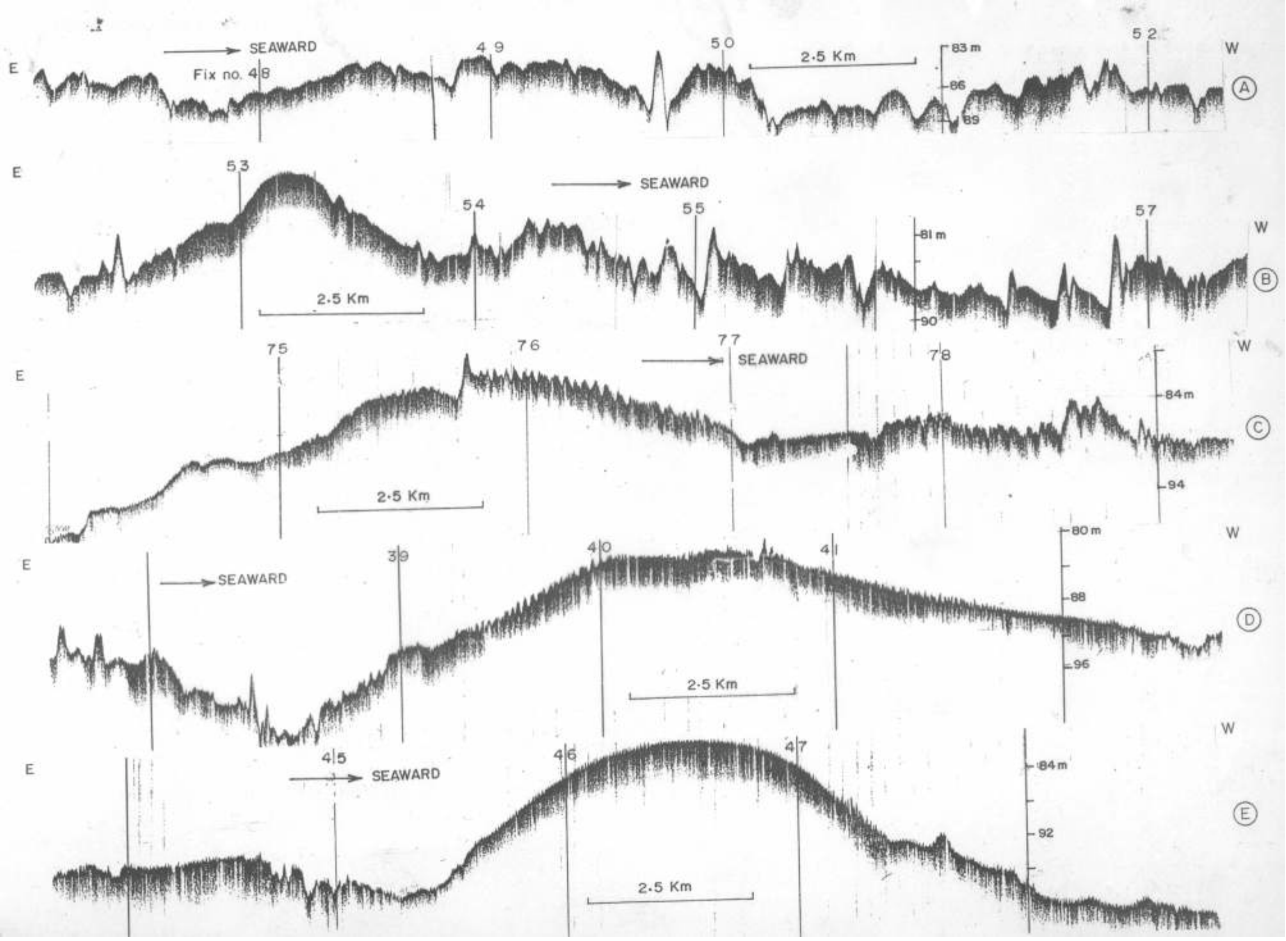

Figure 4. Bathymetry of the part of the E–W profiles of the platform along (**a**–**c**) 83D, (**d**) 83E and (**e**) G.

3. Results

3.1 *Bathymetry*

The bathymetry data are available along the 11 E–W profiles across the platform (figure 1) and important profiles are shown in figures 2–4. The platform, in general, exhibits rugged, sea floor topography with low relief (∼2–6 m) features in the eastern part (72A, B and C) and the high relief features (15–20 m) in the western part (83D, E, F and G). The slope of the platform along its western edge was gentle in the northern part, but abruptly steep in the southern part. Buried pinnacles of 6–8-m high have been reported at the eastern edge of the platform (Rao *et al.* 1994) and at the transition between terrigenous clays and carbonate sediments.

The bathymetric features in the northern profiles (figure 2a) showed pinnacles or coalesced pinnacles of ∼2–6-m height, separated by flat floors. The pinnacles were smaller at landward but larger and laterally coalesced into mounds seaward. Parallel profiles indicated that the position of a broad and well-developed mound at seaward in profile 72A (figure 2c) corresponds to a depression with the well-defined individual and coalesced mounds in profile 72B (figure 2d). The individual mounds were ∼1-km wide and 6-m high, whereas the coalesced mounds ranged from 3 to 7 km in width and up to 25 m in height (figure 2c). A series of shoals with the well-defined mounds were also found in profile 72B. The seafloor becomes smoother and smoother with small-scale ripples as one proceeds seaward, closer to the western edge of the platform (figure 2e and f).

A continuous bathymetric profile of 83F (figure 3) and part of the profiles at seaward sections in profiles 83D, E and G (figure 4) show distinct surface expressions of the mounds. In profile 83F, the mounds were developed on wide tracts. From figure 3(a and b), it appears that the mounds were initially thinner and relatively less wide landward and their size and complexity

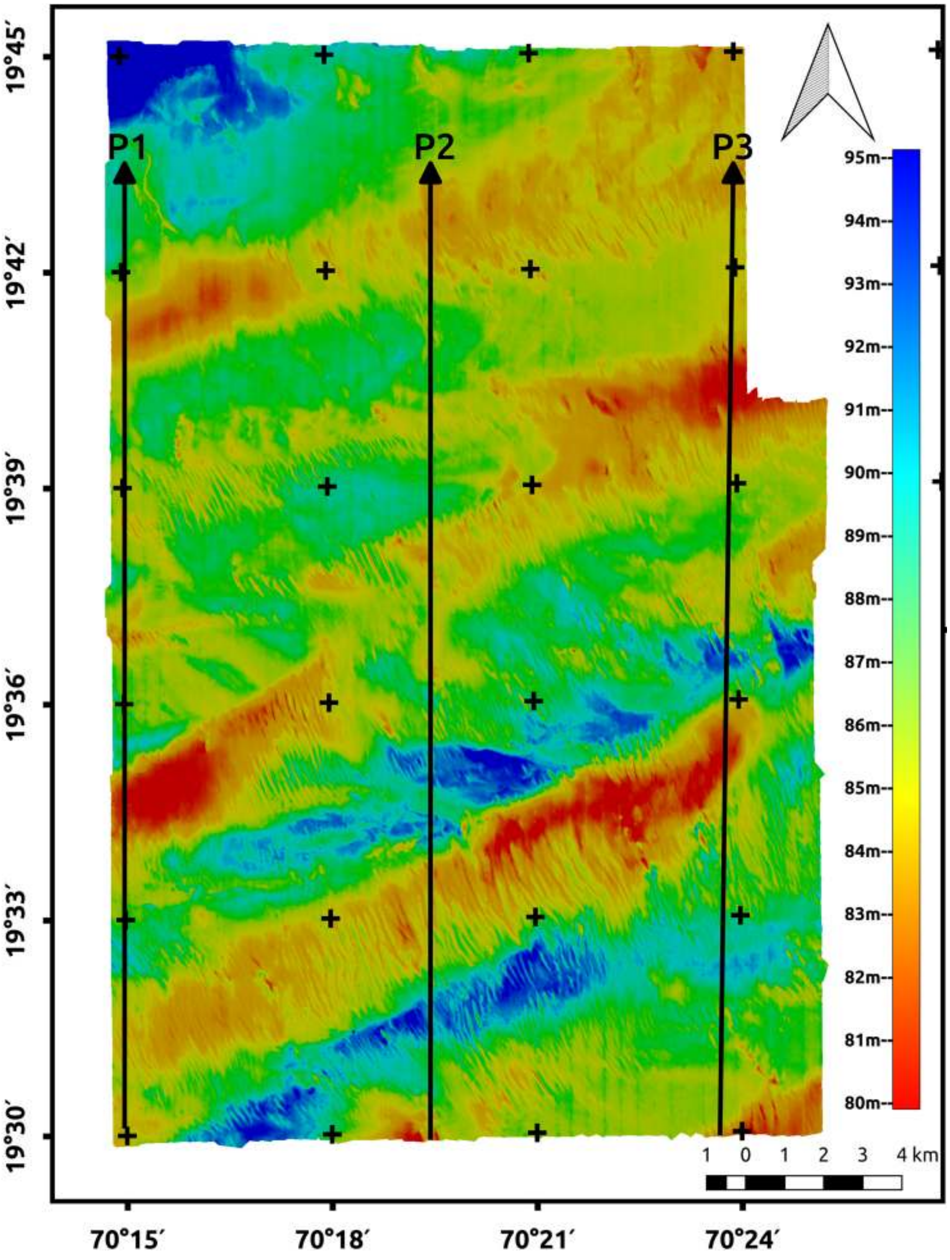

Figure 5. Multibeam bathymetry of the area (box) shown in figure 1.

increase offshore; the mounds coalesced into large composite mounds with maximum thickness at the centre (see figure 3c and d). It is evident that the tops of the mounds are not at same depths as one proceeds offshore. The smaller mounds on the eastern end were 3-km wide, whereas those on the western end were coalesced and ∼5–7-km wide and 15–20 m in height with smoother top surfaces (figure 3e). Figure 4(a and b) shows the part of the profile starting from the eastern end in profile 83G, and figure 4(c, d and e) shows small portions at the western end in profiles 83D and 83E. The crest portions of some mounds were smooth but showed well-preserved, small symmetrical ripples either on their western flanks or eastern flanks. The mounds were asymmetric on seaward flanks in profile 83D (figure 4c).

Detailed multibeam bathymetry carried out in a small area on the platform (see box in figure 1) showed the linear algal ridges and troughs parallel to one another in the east–west direction and their coalescence at places across the platform (figure 5). The ridges raised from 85 m water depth to 95 m along their length. The width of the ridges also varied and much wider when coalesced. The north–south profiles in the same area showed

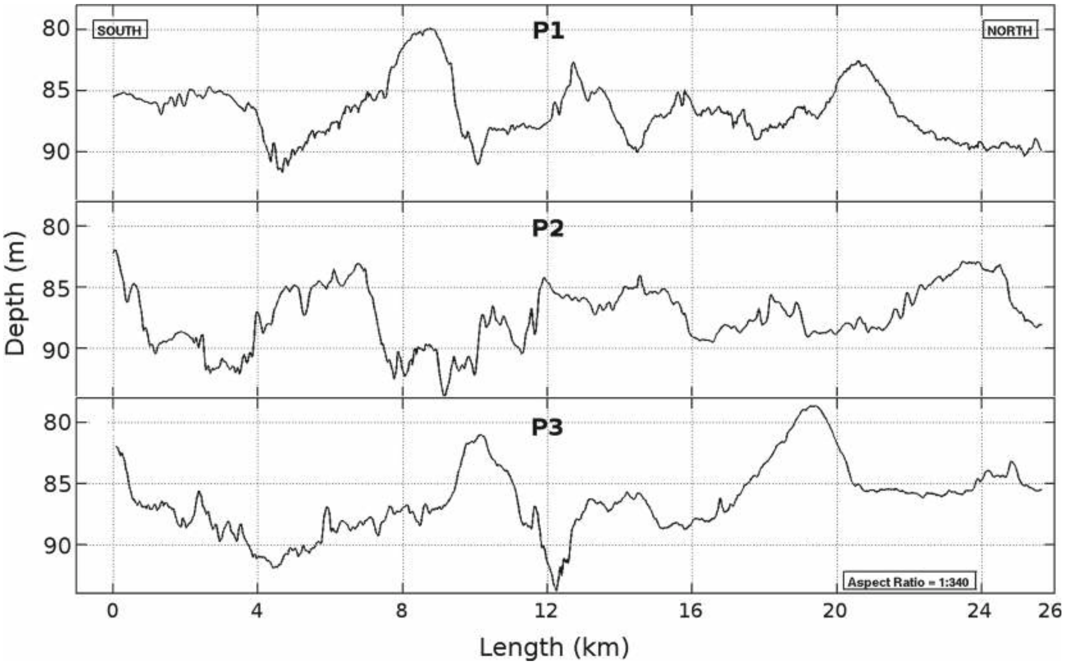

Figure 6. Bathymetry of the N–S profiles (P1, P2 and P3) shown in multibeam image.

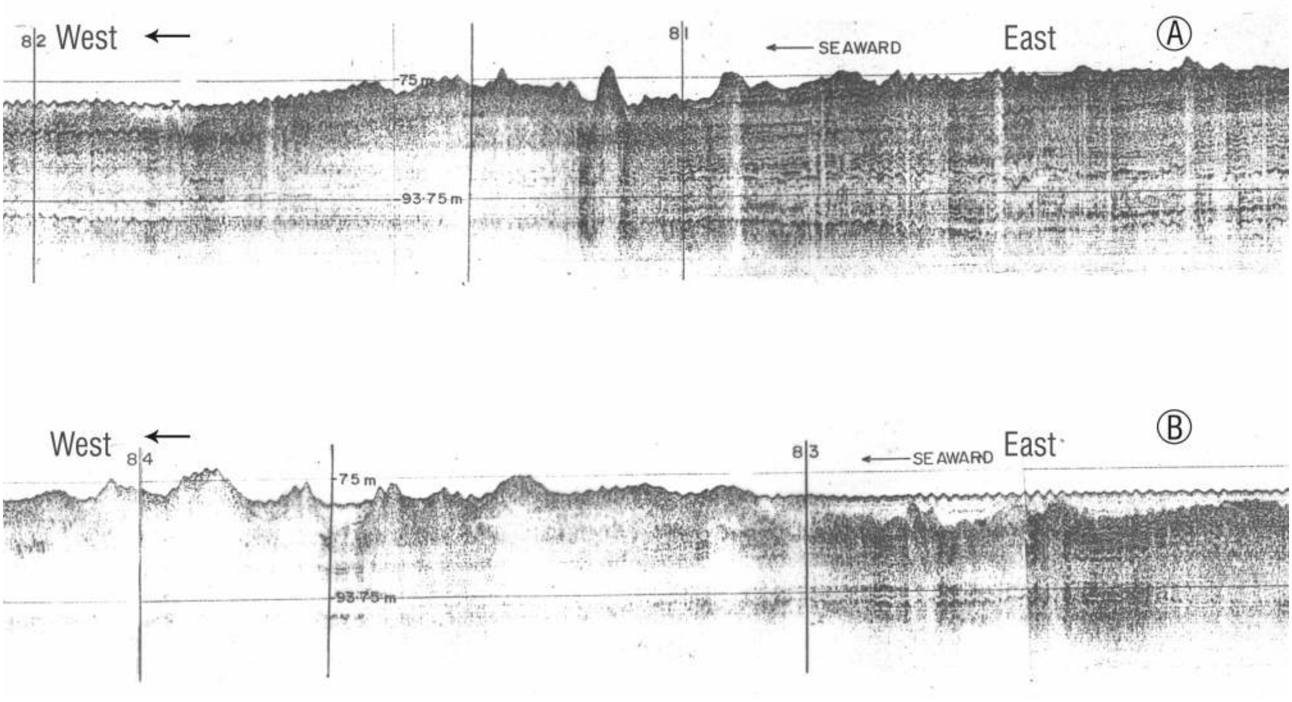

Figure 7. Seismic profiles showing transparent mounds.

mounds and coalesced mounds (figure 6). The individual mounds were up to 12 m in height and 5–7 m in height when coalesced. The limited seismic data were available. The pinnacles and coalesced pinnacles were represented by transparent mounds in the seismic profiles and do not exhibit a clear internal framework (figure 7a and b).

3.2 *Sediments*

The platform consisted of abundant carbonate-dominated (up to 90%) sandy sediments. The sediment samples everywhere on the platform composed of non-skeletal grains, shells and shell fragments. The percentage of non-skeletal grains increased seaward while that of shells and shell

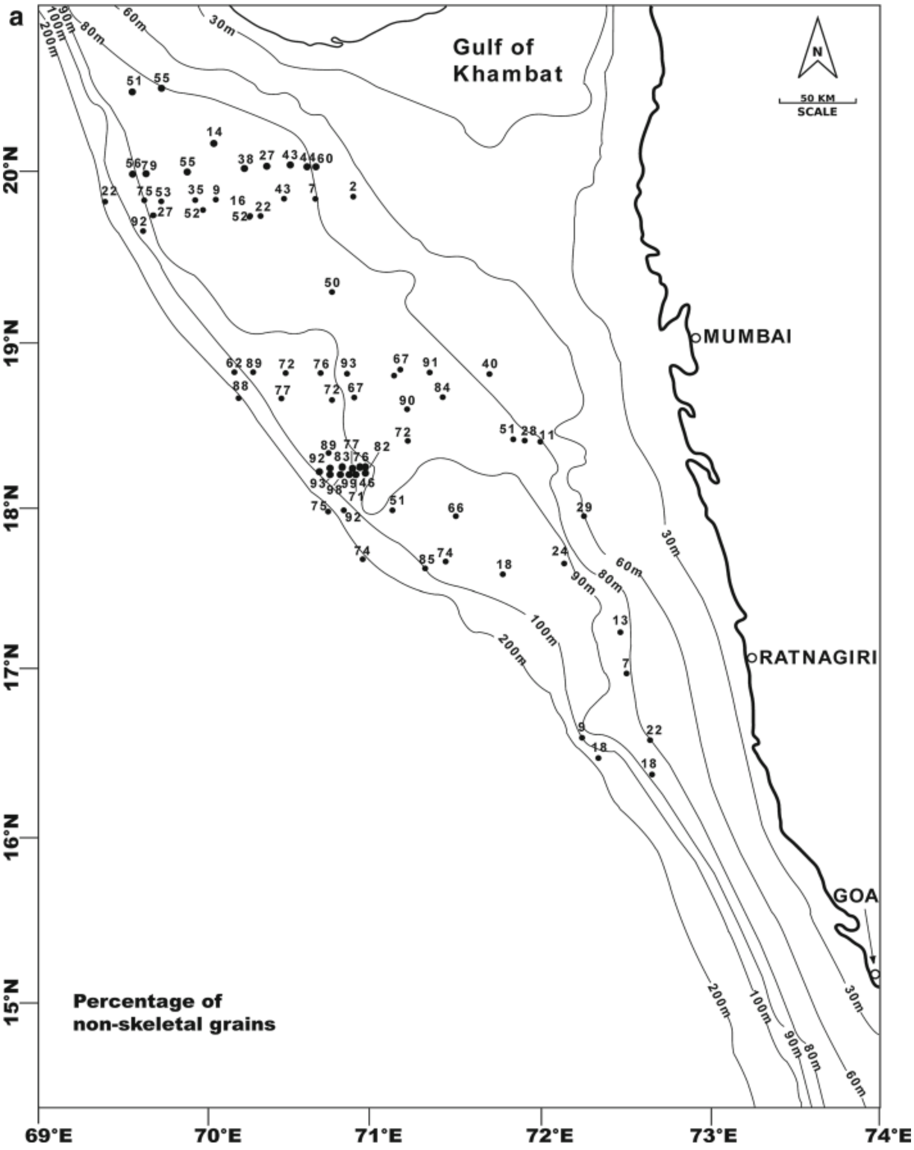

Figure 8(a). The distribution of non-skeletal grains.

fragments increased (up to 36%) landward of the platform (figure 8a and b). Thin sections of the non-skeletal grains indicated the abundant crustacean faecal pellets, followed by Halimeda grains and ooids (figure 9a and b). Boring cavities are extensive on many particles. The calibrated radiocarbon ages of carbonate samples on the platform ranged from 11 to 7.56 ka BP. The samples from the slope and a few samples from the platform showed radiocarbon ages between 12.33 and 13.28 ka BP and 21.04 ka BP (figure 10).

4. Discussion

Carbonate reefs, mounds and build-ups are important components of the sedimentary rock record and occur both in deep (up to 1000 m) and shallow marine settings (Henriet *et al.* 2011). They are formed by a variety of organisms such as corals, stromatophorids, sponges, bryozoans, crinoids, algae and rudists (Riding 2002). Besides, mud mounds as rigid framework reefs produced by *in-situ* organisms (degradation of delicate skeletons, microbial production) and formed by an inorganic accumulation of mud have also been reported (Pratt 1995; Wood 2001). Carbonate mounds provide unique archives, and the understanding of the entire architecture of a mound is fundamental in the identification of past environmental changes. Recent carbonate mounds stand as natural laboratories to link the build-up history and architecture to high-resolution sequence stratigraphy. High-energy conditions and the

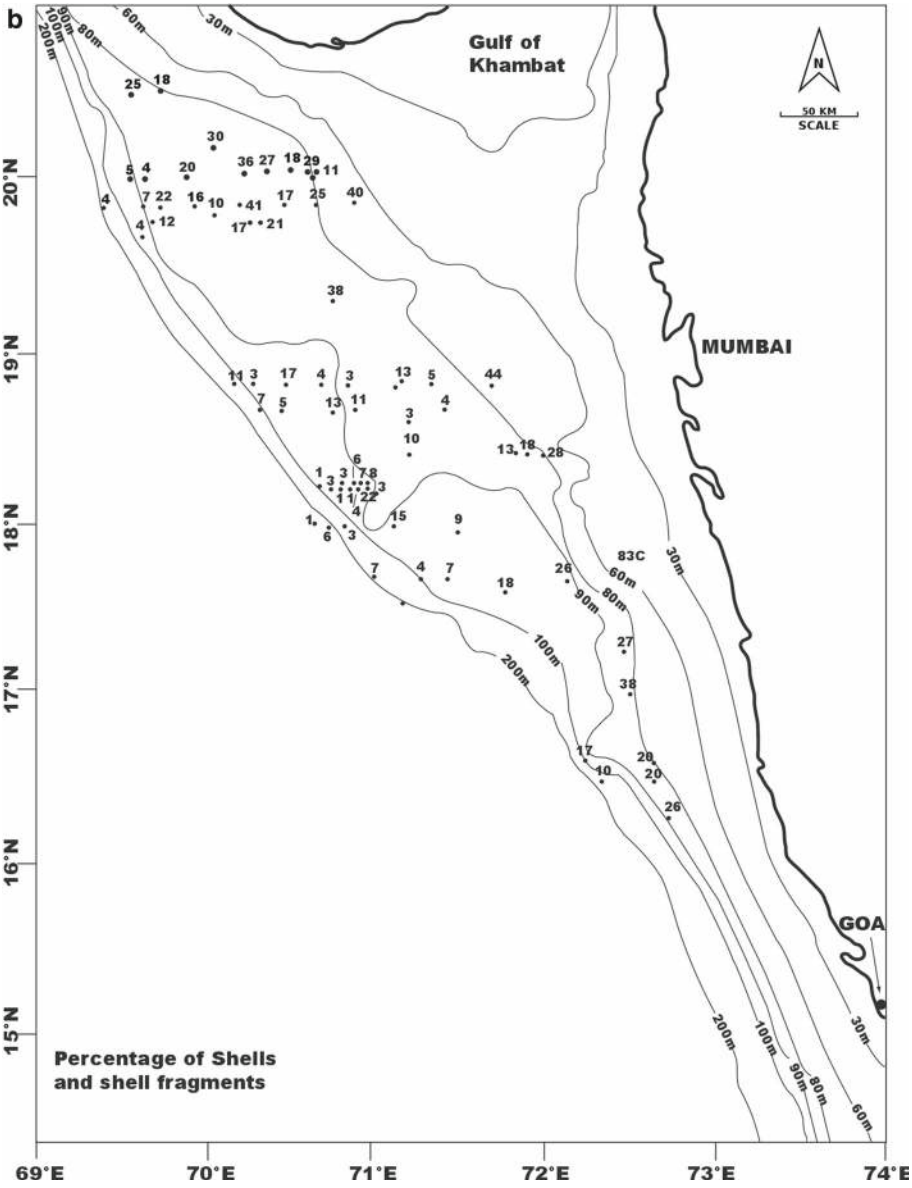

Figure 8(b). The distribution of shells and shell fragments on the carbonate platform.

presence of organisms in mounds would be distinctive indicators for the origin of shallow water mounds.

4.1 *Environmental settings inferred from bathymetric features*

The bathymetric features comprising pinnacles, elongate carbonate ridges and troughs, mounds and banks occur on the platform (figures 2–6). The width and height of these geomorphic features vary spatially. Roberts *et al.* (1988) defined bioherms as mounds that have relief above the seafloor, but do not exhibit a clear, internal framework. In one E–W profile (figure 2), one can see individual pinnacles and their coalescence with the neighbouring pinnacles initially as small mounds of 2–4-km wide and then into large lens-shaped mound seaward (figure 2c). In another profile, mounds are thickest at the centre and the small individual and adjacent mounds frequently merge to form 10–15-m high mound (figure 3). In other words, large mounds are probably the final product formed by fusing of the individual mounds (figure 3). In seismic profiles, mounds are transparent with no rigid internal structure (figure 7) and therefore can be defined as bioherms. Such features have been reported previously and attributed to Halimeda bioherms. For example, Orme *et al.* (1978) and Orme and Salama (1988) reported

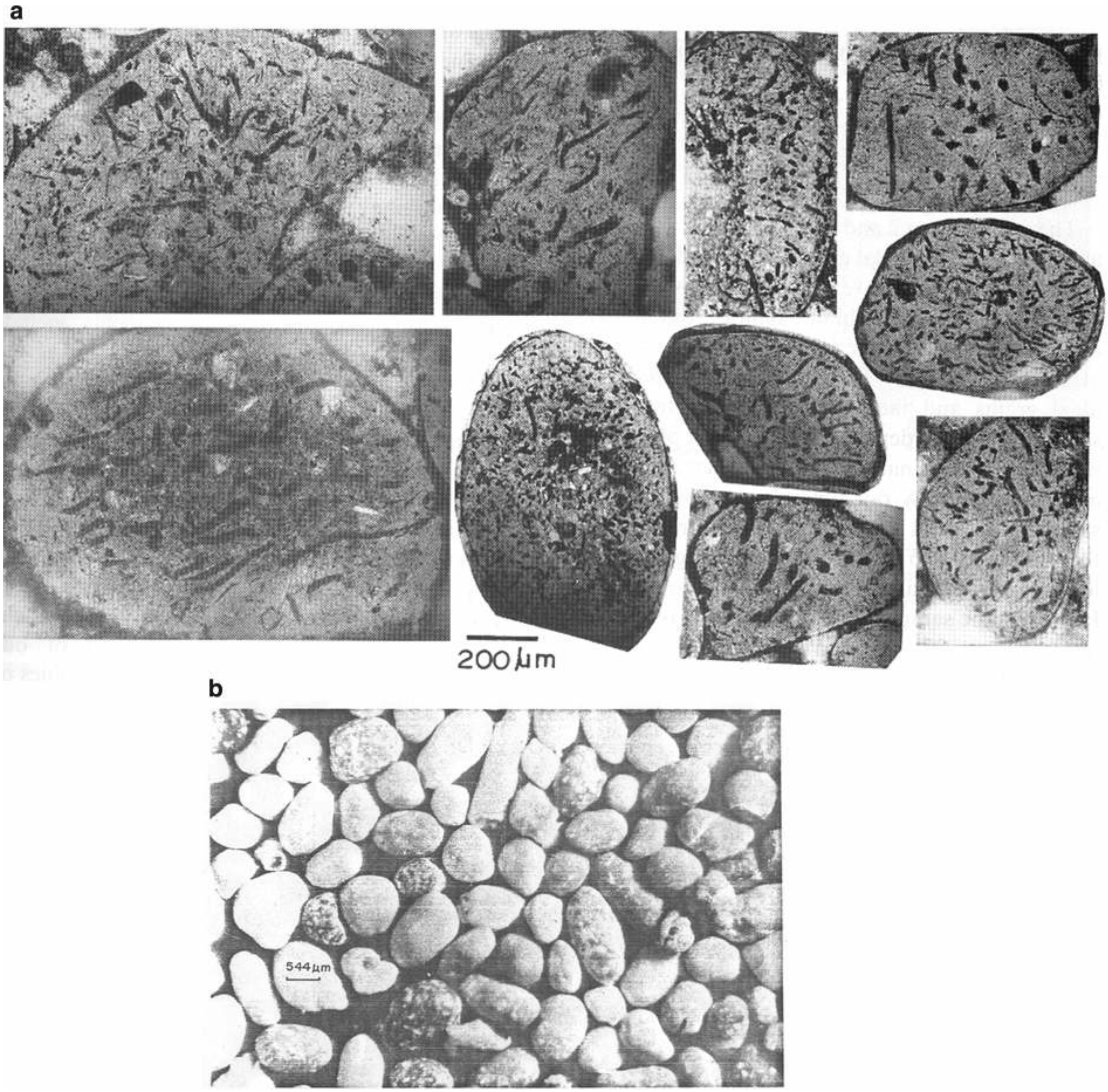

Figure 9. Sediments showing (**a**) faecal pellets and (**b**) Halimeda grains.

Halimeda bioherms in the form of banks and ridges with troughs and hollows, whereas Drew and Abel (1985) described them as discrete circular mounds and parallel ridges in the NGBR. Roberts *et al.* (1987a) reported the elongated ridges and valleys to hummocky mounds as a characteristic of Halimeda bioherms on the Sunda shelf, Java Sea. Hine *et al.* (1988) reported the Halimeda bioherms as mounds with lens-like geometry in the Caribbean region. The phylloidal algal mounds from the late Paleozoic in the Sacramento mountains, New Mexico (Kirkland *et al.* 1993) and Halimeda bioherms from the upper Miocene reefs of the Sorba Basin, southeastern Spain (Braga *et al.* 2015) also exhibited lenticular morphology and are considered analogues to their Holocene counterparts in the Great Barrier Reef. Bedding is also a common feature visible in seismic sections (figure 7a). The bioherms on this platform are relict. They showed well-developed mounds with lenticular morphology landward, and well-preserved surface characters of the mounds and banks seaward and therefore are *in-situ* accumulations (figures 2c and 3c).

The larger and broader mound-shaped features with a maximum height of ∼15 m on the western edge (figure 4c–e) and well-developed pinnacles on the eastern edge of the platform (figure 2a and b) suggest significant growth at seaward rather than landward of the platform. Further, both symmetrical as well as asymmetrical mounds occur on the

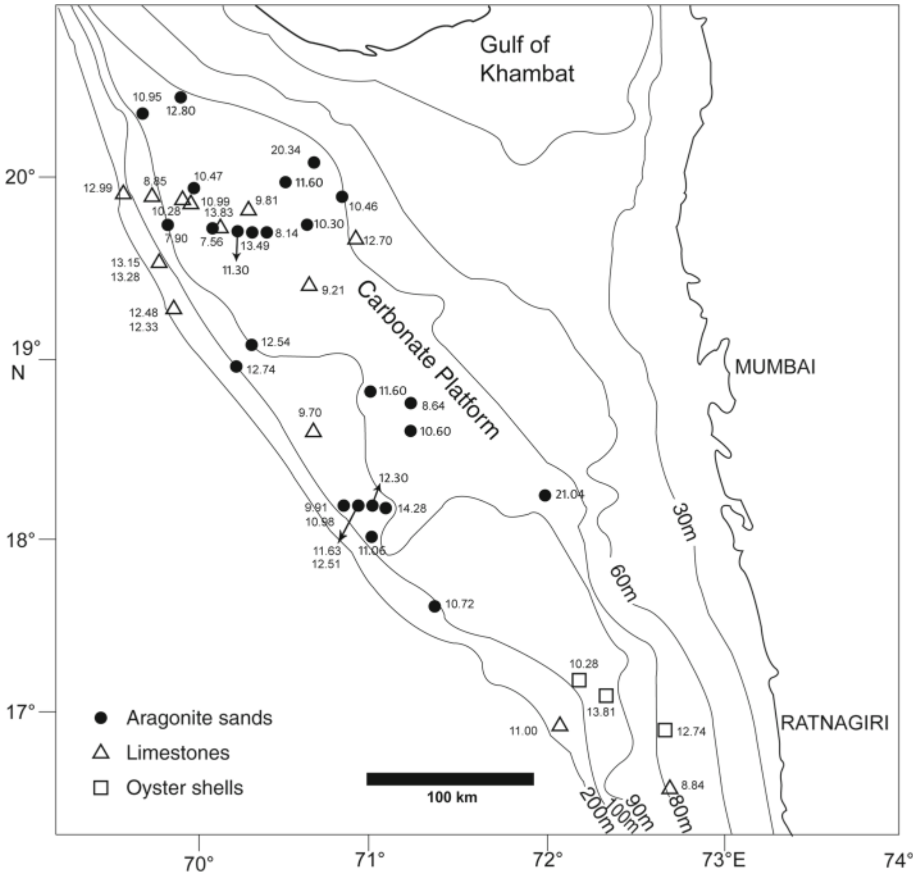

Figure 10. Calibrated radiocarbon ages (ka BP) of surficial sediments and sedimentary rocks on the carbonate platform and adjacent slope.

platform (figure 4). The asymmetry of the mounds (figure 4c) is because of strong growth, coalescence and fusing of smaller mounds on their seaward flanks. Small-scale surface ripples (figure 4c) suggest that the mounds were within the active zone of wave and current activity and reworking of surface sediment. Smoothened mound tops (figure 4a and e) are probably caused by surface erosion. In other words, the shape of the mounds and surface ripples may be interpreted to reflect high-energy settings during and after their formation. Henreit *et al.* (2011) indicated that strong bottom currents interact with the mounds in various ways from creating small sedimentary structures (ripples) to control the shape of a mound. Strong currents trigger sediment reworking and bedform formation and thus the ripples and coarse layers are indicative of reworking and/or erosion in the mound record.

Some of the organisms (in particular green algae) are used for bathymetric estimates for mound depositional environment. The sediments everywhere on the platform are sandy and comprise the crustacean faecal pellets and Halimeda (figure 9a and b), and shells and shell fragments dominated by pelecypods. The higher proportions of shells and shell fragments landward (figure 8b) indicate the suspended sediment feeders such as pelecypods grew more on the eastern portion of the platform may be because they are feeding on little suspended terrigenous sediment reaching from the east of the platform. Higher proportions of non-skeletal grains on the west of the platform (figure 8a) indicate the luxuriant biohermal growth and high carbonate sedimentation occurred at the seaward of the platform. Detailed investigations by Rao *et al.* (1994) indicated that the Halimeda plates were disintegrated into sand and mud fractions but the mud was fixed up by crustaceans in the form of faecal pellets and thus abundant aragonite faecal pellets on the platform. It is likely that some mud was transported onto the continental slope because of high-energy conditions, prevalent during the lowered sea levels and post-glacial rise. Rao *et al.* (2012) reported the lime mud-dominated sediments in sediment cores recovered from the continental slope and suggested that they are detrital and transported from the platform.

4.2 *Factors responsible for Halimeda growth*

The spatial distribution and morphology of the bioherms and associated sediments have implications for understanding the sources of nutrients for the biohermal growth. The Halimeda bioherms on the Kalukalukuang Bank (Roberts *et al.* 1987a, b; Roberts and Phipps 1988) and the Great Barrier Reef (Orme and Salama 1988) were developed in reef protected settings and their abundant growth was facilitated by upwelled, nutrient-rich oceanic waters intruded onto the outer shelf through narrow passages of Ribbon reefs. In contrast, the bioherms investigated here were developed in open marine settings, with no coral reef growth seaward. Moreover, the well-developed bioherms with abundant carbonate sands comprising <10% terrigenous material suggest two important revelations: (a) The limited terrigenous sediment deposition onto the platform despite the huge sediment input expected from the Narmada and Tapi rivers during the early Holocene lowered sea levels implies that the sediments from these rivers have not reached the platform, may be because the platform was isolated from the western shelf until the early Holocene. Terrigenous sediments may have filled the inner shelf, which was a huge clastic depocentre – the Dahanu depression in which extensive prodelta silts and muds were deposited since the Eocene (Basu *et al.* 1980). Alternatively, the terrigenous sediments may have diverted southwards under the influence of southwest monsoon current. If the terrigenous material discharged by the Narmada and Tapi rivers (∼60 million m^3 of water and suspended sediment annually – Rao 1975) reached the platform during the early Holocene, it must have experienced turbid conditions that hindered and adversely affected the photosynthesis and flourishing of Halimeda bioherms. Littler *et al.* (1988) proposed the nutrient- and light-limited photosynthesis in Halimeda. In other words, little terrigenous sediment supply indeed favoured the Halimeda growth on the platform. (b) The luxuriant growth of bioherms, more on the western edge of the platform between 11,000 and 7500 yr BP (surface ages of sediments – see figure 10), implies the supply of clear, nutrient-rich upwelled water from the offshore favoured their growth. Several investigators reported the intensified southwest monsoon winds and their associated upwelling between 13 and 6 ka BP (Prell 1984; Sirocko *et al.* 1993) on the west coast of India, more specifically between 11 and 10 ka BP (Kessarkar *et al.* 2013) and/or after 9–8 ka BP (Thamban *et al.* 2001, 2007). Intense upwelling brings excess nutrients to the surface and excess nutrients are detrimental to the carbonate sedimentation (Hallock and Schlager 1986; Hallock *et al.* 1988). Recent study indicated that the monsoon-induced upwelling is much more intense and active on the southwestern margin of India between 7° and 14°N (Muni Krishna 2008) than on the carbonate platform, located between 17° and 21°N. It appears that the carbonate platform experienced moderate upwelling during the early Holocene and responsible for the luxuriant growth of Halimeda bioherms. The asymmetry of the mounds (figure 4c) may be due to higher growth seaward and suggests that the upwelled water from offshore facilitated significant growth. Hopley (1994) suggested high-nutrient levels and clear water favoured Halimeda growth on the Great Barrier Reef. Why reef growth stopped after 7.5 ka BP on the platform is unknown. Wolanski *et al.* (1988) suggested that 40–45 m deep water is necessary for the development of modern bioherms. Sea level rise after 7.5 ka BP is not much as sea level reached its present position around 7 ka BP. Therefore, it is likely that the bioherms were affected by combination of factors, such as rising sea level or shift in upwelling centres after the early Holocene caused environmental stress and drown the platform after 7.5 ka BP.

4.3 *Mass $CaCO_3$ content*

Halimeda is the single most and dominant contributor of carbonate sediments on the platform and it is possible to estimate the mass calcium carbonate production. The Holocene bioherms in the Indo-Pacific region seem to be growing off the prominent reflector that corresponds to the late Pleistocene surface (Roberts *et al.* 1987a, b; Orme and Salama 1988). The prominent reflector is indistinct with the limited seismic data available on the platform (figure 7). Moreover, the thickness of the Halimeda bioherms is hard to assess because they form a series of sinuous ridges, troughs, banks and mounds (figures 2–6) and are transparent internally (figure 7). Bathymetric records, however, show that the height of the bioherms ranges between 2 and 20 m and the majority of bioherms are 10–15-m height. The average height is ∼7 m and therefore considered as the average thickness (T) of the bioherms for the estimation of mass calcium carbonate production. Despite the area (A) occupied by the platform between 80 and 90-m depth contours is 28,336 km^2 (Rao *et al.* 1994), the bathymetric data are available only for 20,000 km^2 area and this area was considered for the estimation of mass $CaCO_3$. Since the sediments on the platform were largely derived from Halimeda, the density (D) of sediments is considered as 2.9 g/cm^3, following Kinsey and Hopley (1991). The sediments are carbonate sands and their porosity (P) is considered as 50%. The calcium carbonate content of the sediments (C) is 90% because the sediments comprise <10% terrigenous minerals.

The mass calcium carbonate (M) production on the platform can be estimated by the equation (Rees *et al.* 2007)

$$M = A \times T \times D \times P \times C,$$

where A is the area of the platform; T is the thickness of the bioherms; D is the density; P is the porosity and C is the carbonate content of the sediments. Since the calibrated radiocarbon ages of carbonate sediments of the platform mostly ranges between 11 and 7.5 ka BP, we presumed that the growth of Halimeda bioherms was high during this period. It is a reasonable assumption because the sediments older than 11 ka BP (figure 10) are found from the floor of the platform, rather than from the biohermal structures.

Using the above equation, it is estimated that the platform contains 1.827 Gt of mass carbonate produced in 3500 yr, i.e., between 11,000 and 7500 yr BP. It has been reported that the global Halimeda bioherms contain 180 Gt of mass carbonate, and Halimeda bioherms in the NGBR contain 3.9 Gt of mass carbonate accumulated during the entire Holocene (Rees *et al.* 2007). In other words, the mass carbonate produced in 3500 yr on the carbonate platform is very significant, because we have considered only part of the area on the platform and the average thickness as 7 m, despite bioherms up to 20 m were found on the platform (figures 2–4). If the complete area of the platform is surveyed with ORE sub-bottom profiler, the mass $CaCO_3$ content must be much higher and close to that of the Great Barrier Reef. The platform thus contributed significantly to the global carbonate system during the early Holocene. Since marine carbonate production releases CO_2 and rises atmospheric CO_2 levels, the CO_2 content released to the atmosphere must have been high during the growth period of Halimeda bioherms, i.e., during the early Holocene. This is because of isolated platform conditions and moderate upwelling during the early Holocene. For the exact quantification of mass $CaCO_3$ content, good seismic records and long sediment cores are to be obtained from the platform. A systematic study of the platform is essential in the present scenario of global rise in carbon dioxide content and modelling climatic conditions. Organisations such as the CSIR-National Institute of Oceanography and Ministry of Earth Sciences, India may realise the importance of Halimeda bioherms and come forward to take up this challenging programme.

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