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Late Quaternary sediments on the carbonate platform off western India: Analogues of ancient platform carbonates

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The Late Quaternary carbonate sediments and sedimentary rocks from the platform off western India were reviewed for their genesis and relationship with their ancient counter parts. Sub-marine cemented and vadose diagenetic limestones were recovered at different locations on the platform and, neomorphic limestones and caliche pisolites were recovered on the continental shelf south of the platform. Dolomites on the platform were primary and formed by microbial processes under hypersaline, sulphate-reducing conditions during the lowered sea levels. Aragonite ooids were formed from the mineralization of microbial filaments that enveloped their cortex portions. Phosphorites were found in organic-rich, aragonite muds on the continental slope adjacent to the platform and formed from the microbial mineralization of organic matter and replacement of carbonate by apatite during early diagenesis. Microbial processes thus played an important role in the formation of dolomites, ooids and phosphorites reported here and those in ancient deposits. Halimeda bioherms on the platform were grown luxuriantly from the nutrients brought by upwelling currents during the Late Pleistocene–Early Holocene sea level transgression and are similar to the Holocene–Recent deposits in the Indo-Pacific region. Lime muds were bio-detrital and formed primarily from the disintegration of Halimeda bioherms and carbonate skeletal on the platform and then exported to the slope. They resemble fine-grained limestones abundantly reported in ancient platforms. Thus, the different carbonate components on the platform are genetically related to their ancient ones and serve as Late Quaternary analogues for the ancient platform carbonates.

Keywords. Carbonate sediments; dolomites; phosphorites; lime muds; ooids; analogues.

1. Introduction

Carbonate platform is a sedimentary body which possess topographic relief and composed of autochthonous calcareous deposits (Wilson 1975). Clear water and favourable climatic and oceanographic conditions are necessary to produce carbonate sediments on the platform. However, the growth potential of the platform is controlled by the initial topography of the platform, sediment production rate, relative sea level and direction and magnitude of winds and currents (Fulthorpe and Schlanger 1989; Eberli *et al.* 2004). Academic research to study ancient and recent examples of carbonate systems has been increased dramatically in view of the discovery of important oil fields associated with ancient carbonate platforms (Kuznetsov 1997; Kusumastuti *et al.* 2002; Kendall *et al.* 2007; Burgess *et al.* 2013). The investigations on modern carbonate sediments of the platform, however, have great advantage that environmental parameters can be directly measured, allowing to link sediment parameters to environmental (oceanographic and ecological) conditions.

Therefore, modern analogue studies are helpful for understanding carbonate systems, establishing models and comparing interpretations with those in the rock record. Examples of the platforms or shallow continental shelves with modern day carbonate precipitation include the Bahamas, the Florida platform, Yucatan peninsula, the platform on which the Great Barrier Reef (GBR) is growing, the Maldives atolls, the Persian Gulf and hypersaline lagoons and bays around Australia (Halley *et al.* 1983; Gillispie 2013). These modern carbonate systems have been extensively studied for the processes and factors that influence carbonate growth and/or demise and for the reconstruction and interpretation of ancient carbonate deposits. The purpose of this paper is to review the genetic aspects of various carbonate components (limestones, dolomites, ooids, phosphorites, Halimeda bioherms and lime muds) deposited during the Late Quaternary on the platform off western India and compare with those in the modern and ancient carbonate systems and suggest that the sediments on the platform serve as analogues for the ancient platform carbonates. Further, there has been an increase in the discovery of extensive microbial activity in deposits associated with modern and ancient microbial carbonate systems (Griffin and Awramik 1989; Summons *et al.* 2013). Cyanobacteria are the driving force for the vast majority of microbialites and presumably this was the case throughout the most geological time. By studying the genesis of Late Quaternary deposits on the platform, the role played by microbes can also be verified.

2. Study area

A carbonate platform lies at depths between 60 and 90 m on the outer continental shelf off western India (figure 1). It is located off the Narmada and Tapi rivers that debouch abundant water and terrigenous sediments (Rao 1975). This platform is separated from the mainland by a huge clastic depocenter – the Dahanu depression, in which, pro-delta sediments were extensively deposited (figure 1) since the Eocene (Basu *et al.* 1980). Petroleum occurs in the deeper Miocene strata of the platform and is being exploited in the present day. The sediment filled Dahanu depression is the present-day inner shelf. The amazing aspect and uniqueness of the platform come from abundant carbonate sedimentation with only <10% terrigenous material, despite its location in the proximity of major rivers. The surficial sediments on the platform comprise various type of carbonate deposits of Late Quaternary age. Rao and Wagle (1997) reviewed the genesis of authigenic, carbonate and detrital sediments deposited on the entire continental shelf off western India. Scientific articles published after 1997 were more informative regarding the genesis of various carbonate deposits, especially on the platform. Therefore, the present review focuses only on genetic aspects of sediments on the carbonate platform and adjacent shelf and provide evidence that they serve as analogues of ancient platform carbonates.

3. Sedimentary rocks

Nair (1971), Nair *et al.* (1979) and Rao and Nair (1992) investigated and described various types of limestones (figure 1) from the carbonate platform and adjacent shelf. Coarse components such as ooid-peloids, faecal pellets, benthic foraminifers or shell fragments were present in these limestones. There is no significant change in the coarse components, but the cements that bind them showed significant variations. Cements are the diagnostic features of a particular environment and are fairly well known for each diagenetic environment, marine phreatic, fresh water vadose, fresh water phreatic conditions (Folk 1965; Bathurst 1975). Rao and Nair (1992) reported sub-tidal limestones on the western edge of the platform. Aragonite and high-magnesium calcite were carbonate minerals. Pellets and peloids were enclosed in a fine-grained, aragonite matrix. Cements were characterized by acicular and fibrous calcites and micrite of high-magnesium calcite (figure 2A) and are similar to those in sub-tidal limestones reported by MacInyre (1977) and Meyers (1978). Halimeda and faecal pellet-dominated limestones occur on the platform (Rao *et al.* 1994). Vadose diagenetic cements in the limestones are of two types (Schoeder 1973; Longman 1980). Aragonite with minor calcite were major carbonate minerals in these limestones. Solution stage vadose diagenetic cements were recognized by their porous nature and partly dissolved skeletals and pellets (figure 2B), whereas the precipitation stage vadose diagenetic cements were recognized by rim cements with rhombohedral crystals on grain surfaces, syntaxial overgrowth of calcite on skeletals (figure 2C), precipitation of calcite cements and blocky calcite crystals in the pore spaces (Rao and Nair 1992).

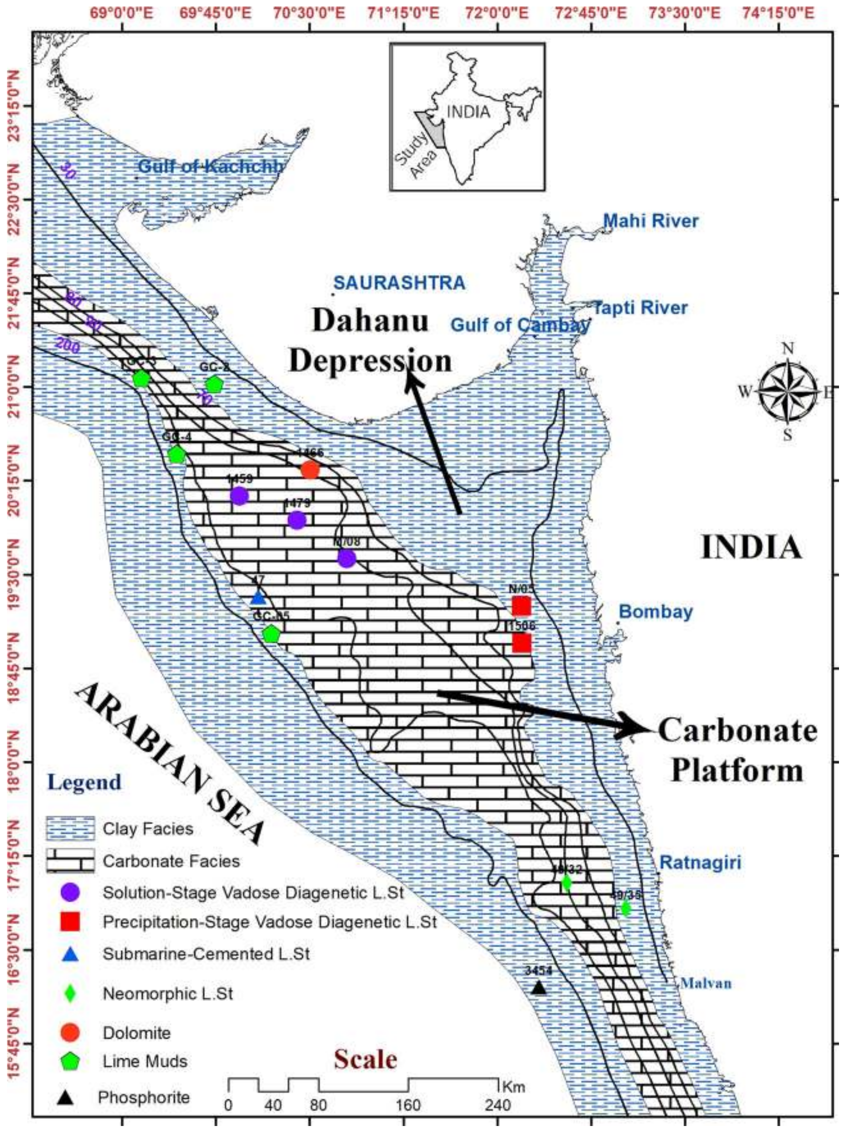

Figure 1. Location of the carbonate platform off western India. Locations of different types of limestones, such as submarine-cemented, solution stage- and precipitation stage vadose diagenetic limestones and neomorphic limestones, dolomites, gravity cores (GC–1 to GC–6) in which lime muds recovered and phosphorites are also shown.

Limestones recovered from the continental shelf off Ratnagiri (figure 1) appear weathered. Contrastingly, low-magnesium calcite was the only carbonate mineral in these limestones. Coarse components were benthic foraminifers and a few faecal pellets. Cements occur in the form of microspar or pseudospar and pellets embedded were recrystallized and only faint out lines of evidence of their existence can be seen in some limestones (Rao and Nair 1992). In other limestones, the cements were characterized by recrystallized molds of grains and skeletal material, relic fibrous structures in large calcite crystals and inclusions in bladed calcite (figure 2D). These types of cements were interpreted as neomorphic cements (Longman 1980; Maliva 1995) and indicate that the sediments were subjected to neomorphic diagenetic changes that took place in the presence of meteoric waters. In other words, the pre-existing marine cemented limestones were sub-aerially exposed and the cements as well as coarse components were transformed into low-magnesium calcite in fresh water phreatic conditions. These limestones were formed during the lowered sea levels in Pleistocene when the shelf was exposed to sub-aerial conditions. The exact time when the shelf exposed during the Pleistocene cannot be ascertained because, the original carbonate skeletals and cements associated with limestones were recrystallized and there is no way to get them dated. Terrestrial limestones such as caliche pisolites (Rao 1990) and dune-associated calcretes, rhizoliths and

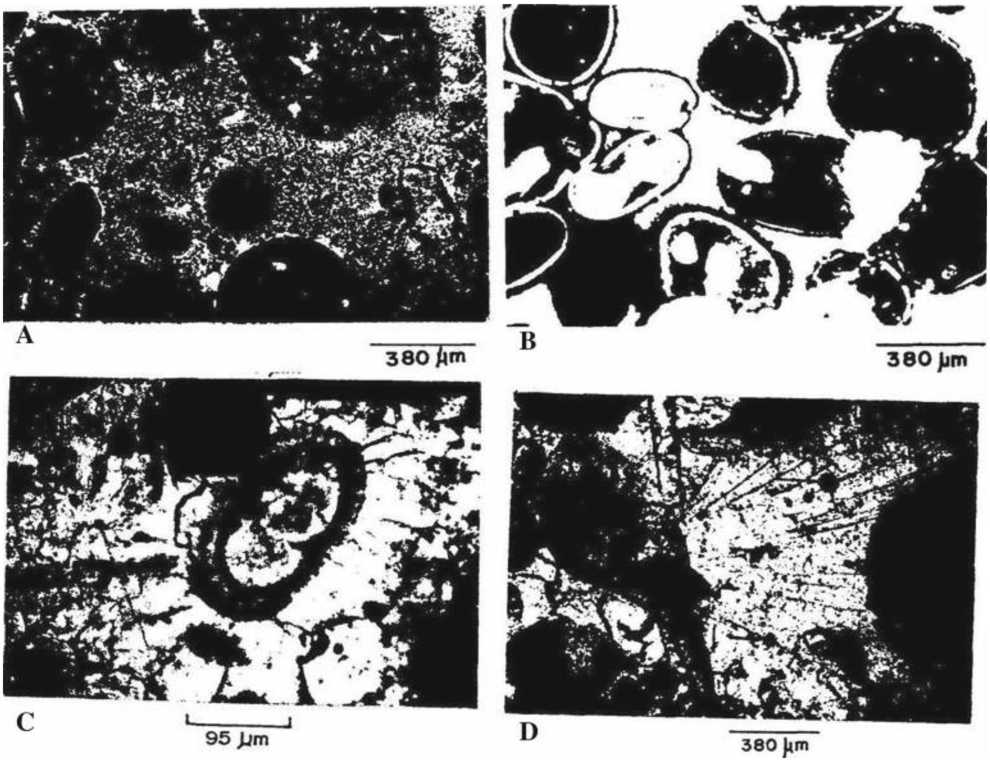

Figure 2. Photographs showing characteristic cements associated with different limestones. **(A)** sub-tidal cements, **(B)** solution stage vadose diagenetic cements, **(C)** precipitation stage vadose diagenetic cements and **(D)** neomorphic cements (figures taken from Rao and Nair 1992).

paleosols (Rao and Thamban 1997) were also reported on the continental shelf south of the platform.

Different types of limestones indicate that they were formed at different environmental conditions and times on the platform during the Late Quaternary. Sub-marine cemented and, solution stage- and precipitation stage vadose diagenetic limestones were radiocarbon dated (Rao and Nair 1992) and their occurrence on the platform implies sub-tidal and inter-tidal conditions of the platform during the Late Pleistocene–Holocene sea level transgression. Neomorphic limestones on the adjacent shelf (figure 1) indicate that the shelf was exposed to freshwater phreatic conditions during the lowered sea levels in Pleistocene. Neomorphic limestones were older than the sub-marine cemented and vadose diagenetic limestones. Absence of neomorphic limestones on the platform could be due to sample bias or were buried because of subsequent carbonate sedimentation during the Late Pleistocene–Early Holocene transgression. Sampling at close intervals on the platform is required to confirm the same. Limestones with different diagenetic cements have been reported in several platforms and continental shelves associated with low sedimentation rate (Bathurst 1975; Longman 1980; Maliva 1995).

4. Late Pleistocene dolomites

Dolomite is a common component in ancient and modern carbonate platforms. It is more stable at surface temperature and pressure than either aragonite or calcite. Modern dolomites differ from the ancient ones at least in two aspects: (a) dolomites are unequally distributed through time and occur in far greater quantity in ancient environments as compared to minor amounts in modern carbonate environments, and (b) the platform carbonates in ancient times, especially those in the Precambrian (Grotzinger and James 2000) and Cambrian (Wright 1997), have been strongly influenced by the activities of microbial systems and comprise cyanobacterial mat stromatolites (Valdiya 1972) and suggest biogeochemical processes supporting a genetic link between sulfate-reducing bacteria and dolomite precipitation. Contrastingly, modern dolomites occur in a wide variety of settings from lacustrine to sub-tidal to deep-sea environments and models proposed for their formation also

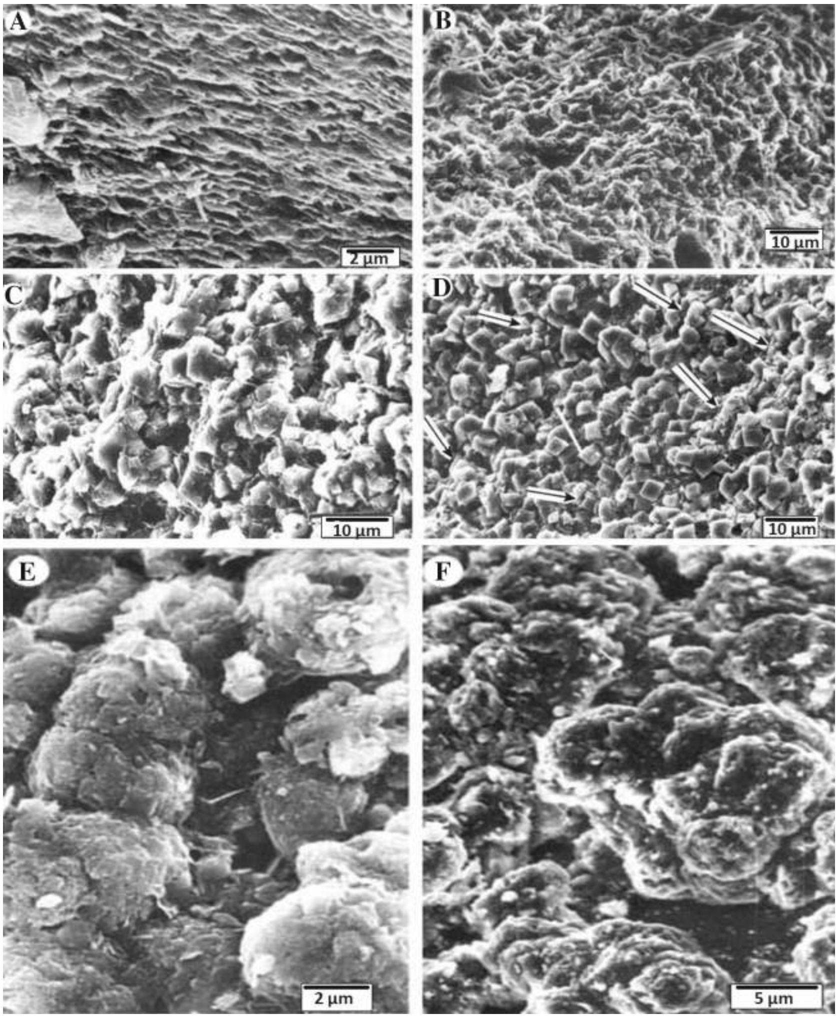

Figure 3. SEM photographs of dolomites. **(A–B)** sub-micron sized, stacked tubular laminae and contorted tubules interspersed with bioclastic detritus, **(C)** dolomite crystals adhered to the filaments **(D)** microfabric consisting of dolomite crystals with faint outlines of microlaminae (arrows), **(E)** hollow ovoid-type globular bodies arranged in straight chains and **(F)** dolomitized colonies of bacteria in the form of rosettes (figures taken from Rao *et al.* 2003a).

vary (Patterson and Kinsman 1982; Machel and Mountjoy 1986; Hardie 1987; Mitchel and Land 1987; Rosen and Coshell 1992; Rao *et al.* 2003a and references therein). It is often hypothesized chemical mediation for the formation of recent dolomites from shallow settings. Further, many theories have been advanced for dolomite formation in different environments but no one of them has been universally accepted. The problem of the origin of dolomite and explanation for its unequal distribution through time – known as 'dolomite problem' (Van Tuyl 1916; Arvidson and Mackenzie 1999) are still debated. Therefore, it is questionable whether the modern dolomites are analogues for their ancient ones. Recent investigations based on laboratory and field studies, however, proposed microbial mediation for dolomite formation (Vasconcelos *et al.* 1995; Warthmann *et al.* 2000; Wright 2000).

Dolomites from the carbonate platform off western India occur as dark grey crusts. Both thin sections and SEM studies of the crusts indicate the presence of well-preserved, stacked dolomitized tubular laminae interspersed with bioclastic detritus (figure 3A), contorted dolomite tubules (figure 3B), dolomite crystals adhered onto microlaminae (figure 3C and D) and hollow, 1–3 µm sized ovoid-type globular bodies arranged in straight chains (figure 3E) and forming rosettes (figure 3F). These have been interpreted as polygenic assemblage of mat-forming microorganisms of probable cyanobacterial affinity (Rao *et al.* 2003a). The microstructures reported in our dolomites are similar to dolomite stromatolites, wherein dolomite precipitation is a metabolic product of mat-forming microorganisms, largely cyanobacteria. Dolomite encrustations on tubules (figure 3C) and overgrowth of dolomite on cell-like structures suggest that dolomite formation continued on the sheath during early diagenesis. Microcrystalline dolomite fabric with few relics of microorganisms (figure 3D) are interpreted to record progressive and continued mineralization of organic sheath. These studies indicate that dolomite is a bio-mineral and biogeochemical processes are involved in its formation (Rao *et al.* 2003a).

High-magnesium calcite (HMC), dolomite, pyrrhotite and marcasite were present in the order of abundance in these crusts. The intimate association of sulfide minerals with microbial laminae suggests that dolomitization of microbial laminae occurred in anoxic, sulphate-reducing environments. High δ^{18}O of dolomite (4.1‰) in our dolomites (Rao *et al.* 2003a), similar to the present-day dolomites in tropical, hypersaline lagoons of Lagoa, Brazil (Vasconcelos and McKenzie 1997), suggests hypersaline conditions for dolomite precipitation. Positive δ^{13}C values of HMC (2.5‰) and dolomite (0.9‰) than in the carbonates precipitated during organic diagenesis suggest that carbonates pool during dolomitization may have derived from both organic matter and dissolution of carbonate detritus. Dolomitized microbial mats (figure 3A and B) and cell-like microstructures (figure 3E and F) suggest that dolomitization is a rapid early diagenetic process, wherein microbes played a major role in their formation (Rao *et al.* 2003a). Modern dolomites in the hypersaline lagoons, Lagoa, Vermelha, Brazil (Vasconcelos *et al.* 1995; Vasconcelos and McKenzie 1997), and lacustrine environments from the Coorag region, Australia (Von der Borch and Lock 1979; Wright 2000) and laboratory studies using sulphate-reducing bacteria from lagoonal sediments (Warthmannn *et al.* 2000) demonstrated possible involvement of benthic microbial communities in the precipitation of dolomite.

Dolomites from the platform are of Late Pleistocene age and represent a rare example of primary precipitation of dolomite by biogeochemical processes. These dolomites are in contrast with the more commonly reported processes – secondary replacement and dolomitization of limestones or chemical precipitation. Dolomites from the carbonate platform (Rao *et al.* 2003a), many ancient dolomites (Valdiya 1972; Grotzinger and James 2000) and newly reported recent dolomites (Vasconcelos *et al.* 1995; Warthmannn *et al.* 2000; Wright 2000) suggest that the micro-organisms and microbial processes played important roles in their formation and thus the dolomites of Late Pleistocene age reported here serve as analogues for the ancient ones.

5. Halimeda bioherms

Bioherm is an organic reef of mound-like form built by a variety of marine invertebrates, including corals, echinoderms, mollusks, green algae and others. Halimeda is a genus of green macroalga from the phylum Chlorophyta. Halimeda bioherms are large reef-like or mound-like geological structures formed by the growth of Halimeda. Halimeda species is capable of producing extensive biohermal calcareous sediment accumulations and commonly found in tropical oceans around the world (Multer 1988) and are considered as carbonate producing factories (Pomar and Hallock 2008). Aragonite is the predominant mineral in these deposits.

The calcareous sediment produced by Halimeda is known to occur only from the Cretaceous onward (Hillis-Colinvaux 1980; Hillis 1997). Except a few recently reported ancient bioherms, the Paleozoic phylloidal algal mounds in the Sacramento mountains (Kirkland *et al.* 1993) and Miocene mounds of Sorba Basin, SW Spain (Braga and Martin 1993; Braga *et al.* 2015), Halimeda bioherms do not have rich fossil record. The mound-building activity of Halimeda was, however, well recognized since 1978 in several deposits formed during the Late Pleistocene–Holocene sea level transgression and Holocene in the Indo-Pacific region (Orme *et al.* 1978; Roberts *et al.* 1987; Hine *et al.* 1988; Liddell *et al.* 1988; Marshall and Davies 1988; Searle and Flood 1988; Rao *et al.* 1994; Heyward *et al.* 1997; Xu *et al.* 2015). The limited fossil record of Halimeda mounds and several Holocene occurrences hint at specific climatic and environmental conditions responsible for their favored growth and preservation. Rao *et al.* (1994, 2018) investigated carbonate sand buildups on the carbonate platform and identified Halimeda bioherms formed during the Late Pleistocene–Holocene transgression and specified the environmental conditions responsible for their growth and demise.

Detailed bathymetric studies on the platform revealed linear and laterally coalesced pinnacles in the form of mounds, well-developed large

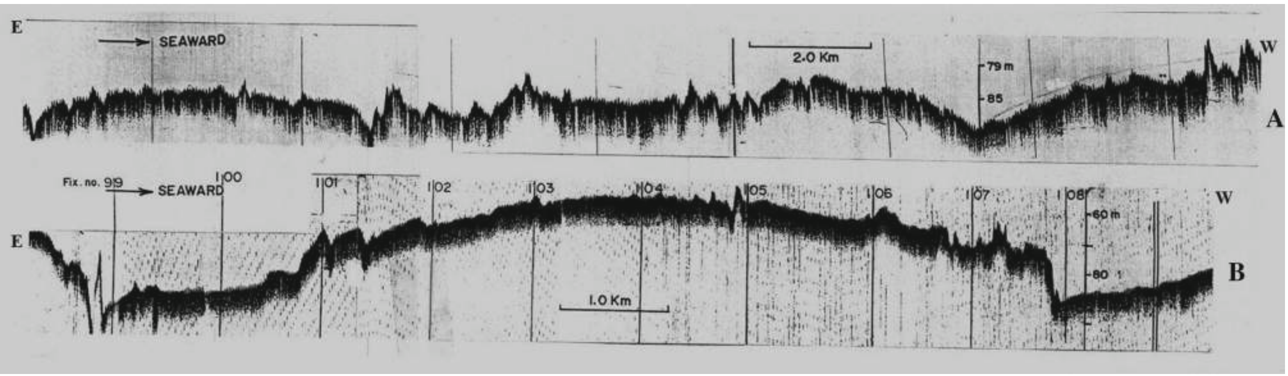

Figure 4. Bathymetry of the carbonate platform showing **(A)** coalesced ridges in the form of small mounds and **(B)** elongated broad mounds, characteristic of Halimeda bioherms (figures taken from Rao *et al.* 2018).

lens-shaped mounds (figure 4A and B), ridges and banks (Nair 1975; Vora and Almeida 1990; Rao *et al.* 2018). These features were 2–6 m high landward and up to a height of 20 m seaward to the platform. Seismic data indicate that these mounds were transparent with no rigid internal structure and can be defined as Halimeda bioherms. Sediments everywhere on the platform were predominantly aragonite sands (Nair and Pylee 1968; Nair and Hashimi 1981; Rao and Wagle 1997). Thin sections of the sands exhibit their internal structures that indicate most of the sands were Halimeda grains (figure 5A), followed by faecal pellets (figure 5B) and a few ooids and peloids (Rao *et al.* 1994). On the basis of bathymetry and sediments, Rao *et al.* (1994, 2018) interpreted that the Halimeda bioherms on the platform produced abundant carbonate sands and mud and, the mud was subsequently fixed by Crustaceans as faecal pellets and peloids. The age of the carbonate sands mostly ranges between 11 and 7.5 ka BP and is presumed as the growth period of Halimeda bioherms. Rao *et al.* (2018) suggested that the nutrients brought by upwelling currents are responsible for their luxuriant growth. The growth of bioherms stopped after 7.5 ka BP on the platform and subsequently became drowned, like many other drowned carbonate platforms common in the geological record. In tropical regions sea level changes are expected to be less dramatic and an order of magnitude slower than the average carbonate production rate (Eberli 1991). Similarly, little subsidence occurs on passive margins. Therefore, these factors are obviously not sufficient to drown the healthy platforms. It is suggested that a combination rather than a single factor is necessary to terminate platform growth (Eberli 1991). Environmentally stressed conditions would be easier to drown the platforms. It is possible that a change in climatic conditions may have resulted in excess availability of nutrients (Hallock and Schlager 1986) that produces blooms of heterotrophic organisms, which in turn reduce the growth of reefs and carbonate secreting benthos. It is therefore suggested that the shift in upwelling centers and sea level changes after 7.5 ka BP may have led to their demise (Rao *et al.* 2018). These authors also estimated the mass calcium carbonate content on the platform as 1.8 Gt, comparable with that on the Great Barrier Reef during the Holocene. Halimeda bioherms are few in the

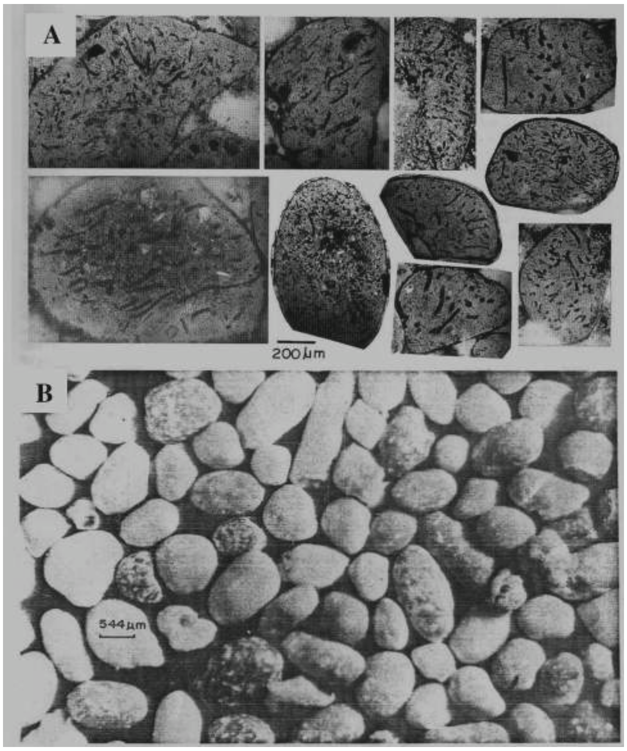

Figure 5. **(A)** Halimeda grains and **(B)** faecal pellets (figures taken from Rao *et al.* 1994).

ancient geological history. However, the bioherms reported here resemble the Late Pleistocene and Holocene bioherms in the Indo-Pacific region and thus serve as Late Quaternary analogues. Detailed investigations are required to quantitatively evaluate the mass calcium carbonate content on the platform with additional data on shallow seismic studies and long sediment cores.

6. Lime muds

Fine grained carbonate sediments or sedimentary rocks are reported from Precambrian to Recent in many carbonate platforms or continental shelves around the world. Ancient carbonate deposits with abundant lime muds are source of significant petroleum reserves in the Arabian Gulf (Kendall *et al.* 2007). Lime muds with high organic matter content have been reported in Recent sediments from the Bahamas and Arabian Gulf. Source rock analyses of carbonate mud demonstrate that the muds trap abundant organic matter, which might have generated large volumes of its oil. Carbonate mud sediments therefore are future source beds for the hydrocarbons (Kendall *et al.* 2007).

Isolated platforms in shallow water environments are dynamic systems and produce enough sediments to build vertically to sea level and prograde laterally over its slopes (Gischler and Zingeler 2002). Moreover, the sediments deposited are strongly influenced by energy conditions of the overlying water, caused by waves, currents and storms. A large portion of fine-grained carbonate sediments (lime muds) generated on the platform are often exported to the adjacent lagoons or slope (James *et al.* 2005), and coarse sediments are usually retained on the platform. The origin of fine grained sediments/sedimentary rocks is unclear in many ancient carbonate deposits and important to understand their source for constructing depositional model. Aragonite-dominated lime muds are formed inorganically in the Persian Gulf and the Bahamas even in the present day.

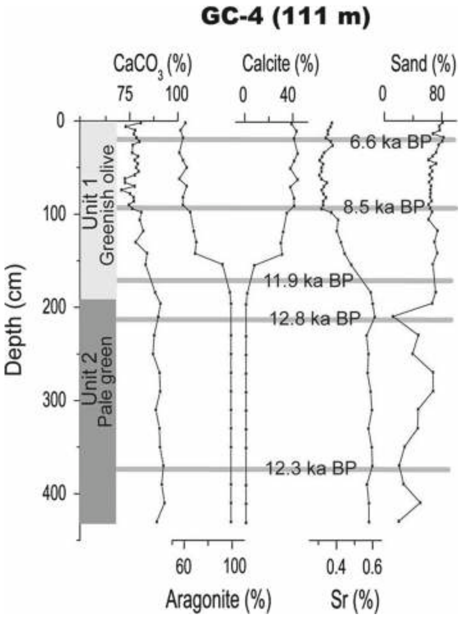

Figure 6. Geochemical characteristics of sediments in gravity core (GC–4), showing lime muds in the lower portion of the core (figure taken from Rao *et al.* 2012).

Two basic concepts are debated abundantly in the literature regarding the origin of lime muds (Wells and Illing 1964; Stockman *et al.* 1967; Neumann and Land 1975; Kendall *et al.* 2007; Rao *et al.* 2012 and references therein): (a) lime muds are primarily the result of post-disintegration of several species of calcifying green algae and biological and mechanical breakdown of other calcareous skeletal, (b) aragonite muds are inorganically precipitated directly from the water column (whitings) in shallow environment. Investigations revealed whitings (dense lime suspensions) are abundant both in the Arabian Gulf and the Bahama banks. Radioisotopes, especially short-lived isotopes of the whitings support instantaneous character of white precipitation in the water column (Robbins and Blackwelder 1992; Kendall *et al.* 2007). Some whitings in the Bahamas may be the result of microbial carbonate precipitation (Yates and Robbins 1999) or physical agitation by storms or suspended from the bottom because of physical phenomena (Shinn *et al.* 1989).

The lime muds occurring in sediment cores (GC–1 to GC–5; figure 1) recovered at depths between 56 and 121 m on the continental shelf off the Gulf of Kachchh and carbonate platform off western India were investigated for their origin. The muds were confined to the lower portions of gravity cores, while their upper portions were terrigenous sediments suggesting relict nature of lime muds (figure 6). The total carbonate and aragonite contents of the lime mud-dominated sediments on the shelf cores were lower (60–75% and up to 80%) than those on the platform slope (90–95% and >95%, respectively; figure 6), suggesting that the lime muds on the shelf were contaminated with higher proportions of terrigenous material. The lime mud comprises of broken fragments of shallow water carbonate skeletals and bioclasts on the shelf and ovoid to spherical microparticulates of aragonite on

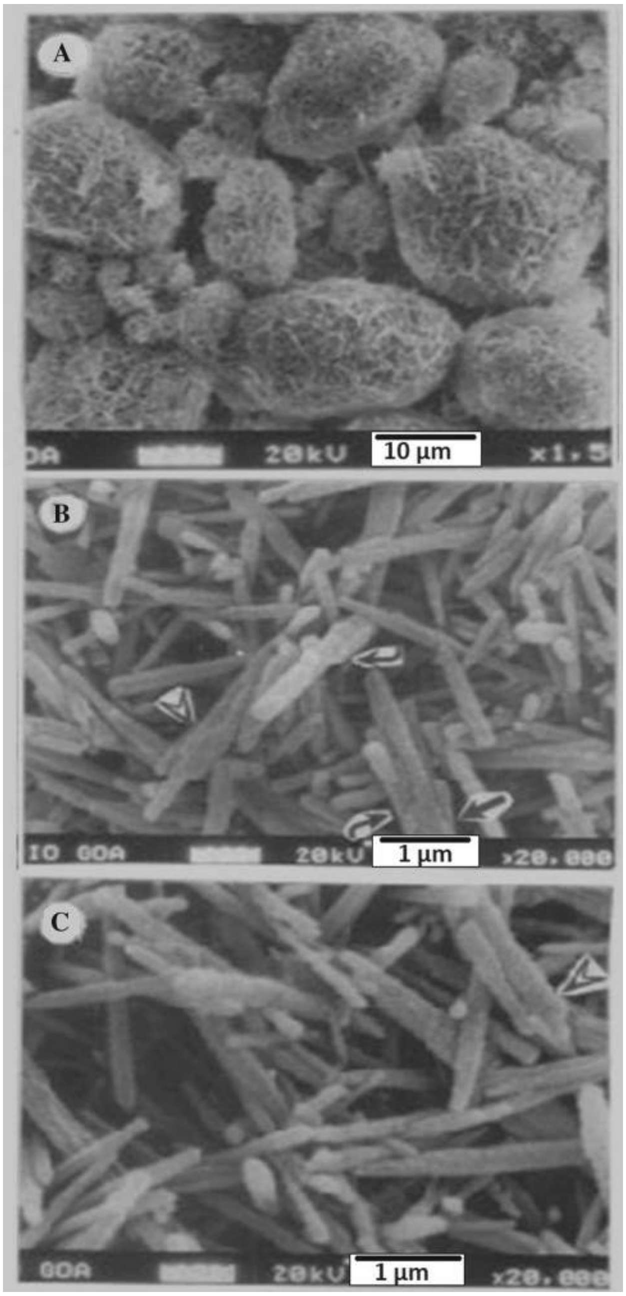

Figure 7. SEM photographs of lime muds showing **(A)** cemented micrites and **(B–C)** acicular aragonite needles apparently disintegrated from Halimeda plates (figures taken from Rao *et al.* 2012).

the platform (figure 7A), suggesting that the shelf muds are detrital-derived and platform muds are diagenetically formed in lime muds.

On the basis of the Sr content of lime muds one would know the sources of Sr in lime muds. The lime muds from the Bahamas (0.72–1.06%), Abu Dhabi (0.94%) and inorganically formed aragonite needles (>0.85–1.0%) exhibit high Sr values and were formed by inorganic processes (Dix 2001). Similarly, the corals and Codiacean algae have higher Sr content (0.63–0.86%) and are referred to as high Sr skeletals (Dix *et al.* 2005). As the Sr content of lime muds from the platform slope ranged from 0.58 to 0.77% lime muds might have been derived from the disaggregation of high Sr skeletals, rather than inorganically formed from the water column (Rao *et al.* 2012). This argument is supported by the Sr/Ca ratios of lime muds (0.022 to 0.024) that are close to that of Halimeda (0.024). The occurrence of heavily broken prismatic aragonite needles, jointed needles, rods emanating from the envelope of mineralized aragonite (see arrows in figure 7B and C) suggests that they were disintegrated from the soft tissues of algae. The stable isotope values were within the range for sedimentary aragonite needles. Rao *et al.* (1994, 2018) reported abundant Halimeda bioherms formed during the Early Holocene. The platform sediments showed the presence of well-rounded Halimeda grains whose size is much smaller than that of Halimeda plates, indicating that the plates were disintegrated and the muds thus produced were exported to shelf break during high-energy conditions. In other words, the lime muds were biodetrital and disintegrated from Halimeda and then transported to the slope of the platform.

7. Ooids

Ooids are small (<2 mm), spheroidal and concentrically laminated sedimentary grains, usually composed of calcium carbonate but sometimes composed of iron and phosphate-based minerals. They are typically limited to tropical coastal settings. Numerous investigations revealed ooids or oolitic strata or oolitic-peloidal sediments are common throughout the geological history from Precambrian onward (Simone 1980) and mostly formed in shallow sea level conditions and active water circulation on carbonate platforms and bank tops (Kindler and Hearty 1996). Ooids display wide range of grains as nucleus and consist of tangential and radial fibrous microstructures in the cortex.

Two aspects of the ooids, (a) microstructure and mineralogy and (b) origin are discussed widely in the literature to understand whether the Late Quaternary and modern ooids (see references in table 1) are analogues for their ancient counter parts. Similar to dolomites and lime muds, ooids occur abundantly in ancient carbonate deposits and in lesser quantities in Late Quaternary and

Table 1. *Characteristics of the Late Quaternary and modern ooids in different regions of the World Ocean.*

Area of occurrence	Depth (m)	Age	Mineralogy	Microstructures	References
The Amazon Shelf	80–150	Late Pleistocene	High-magnesium calcite (HMC)	Radial	1
The Bengal Shelf	120–130	Late Pleistocene	HMC	Radial	2
The Great Barrier Reef	80–150	Early Holocene	HMC	Radial	3
The Georgia Shelf	35–150	Late Pleistocene	Aragonite	Tangential	4
The Eastern margin of India	80–150	Late Pleistocene–Early Holocene	Aragonite		5
The Western margin of India	60–110	Late Pleistocene–Early Holocene	Aragonite	Tangential and radial	6, 7, 8
The Baffin Bay, Texas		Holocene	HMC	Radial	9
The Gulf of Aqaba	<5	Holocene	Aragonite	Radial	10
The Shark Bay		Holocene	Aragonite	Radial	11
The Great Salt Lake		Modern	Aragonite	Radial	12
The Laguna Madre	<5	Modern	Aragonite + HMC	Tangential and radial	13, 14
The Bahamas		Modern	Aragonite	Tangential	15, 16, 17, 18
The Persian Gulf		Modern	Aragonite	Tangential	19

1. Milliman and Barretto (1975), 2. Wiedicke *et al.* (1999), 3. Marshall and Davies (1975) 4. Pilkey *et al.* (1966) 5. Subbarao (1964), 6. Von Stackelberg (1972), 7. Nair *et al.* (1979), 8. Rao and Milliman (2017), 9. Land *et al.* (1979), 10. Friedman *et al.* (1973), 11. Davies (1970), 12 Sandberg (1975), 13. Rusnak (1960), 14. Freeman (1962), 15. Illing (1954), 16. Newell *et al.* (1960), 17. Milliman (1967), 18. Folk and Lynch (2001), 19. Loreau and Purser (1973).

modern deposits. Differences occur in mineralogy of the ooids, which are always calcitic in ancient limestones and, both aragonitic and calcitic in modern and Holocene ooids (table 1). Mineralogy and microstructure of the ooids are strongly influenced by sea water chemistry, Mg/Ca ratio, atmospheric CO_2 partial pressure and carbonate saturation state. Similarly, microstructures in the cortex portions of the ooids are different. For example, the ancient ooids exhibit only radial fibrous microstructures, whereas the Recent/Holocene ooids exhibit co-existence of radial and tangential microstructures (Simone 1980). Bladed/radial microstructures in ooids from different localities and environments were interpreted as a result of algal precipitation, quiet water deposition, diagenesis and hyper-salinity (Logan *et al.* 1969; Friedman *et al.* 1973; Davies and Martin 1976; Fabricius 1977). One needs to realize that modern marine settings are not always the best analogues for ancient carbonates. Since the Recent/Holocene ooids are least altered diagenetically, their detailed microstructure would be helpful to distinguish whether microstructures are primary or secondary and possible factors that controlled their formation.

Ooids have been reported in Late Pleistocene–Holocene and modern sediments on the continental shelves and platforms in the world ocean (table 1), including Indian margins (Subbarao 1964; Naidu 1967; Nair 1971; Von Stackelberg 1972; Wiedicke *et al.* 1999; Rao and Milliman 2017). Numerous models discussed the origin of ooids, especially, whether they are exclusively chemical precipitates (Milliman 1974; Davies *et al.* 1978) or formed by organo-mineralization (Trichet and Desfarge 1975; Reitner *et al.* 1997; Davies *et al.* 1978) or whether microbes involved in their formation (Folk and Lynch 2001; Duguid *et al.* 2010). There is still no consensus as to the formation of ooids, despite biogenic origin of ooids has been progressed in recent years (Gillispie 2013; Summons *et al.* 2013; Rao and Milliman 2017). Abiotic or inorganic models involve precipitation in suspension in supersaturated, agitated water. These models, however, fail to account for the high organic matter content in the ooids. Biotic models involve ooids colonized by a defined microbial community and microbes possibly mediated calcification of cortical layers. Ooids are intimately associated with stromatolites in ancient carbonates. Recent studies, however, demonstrate

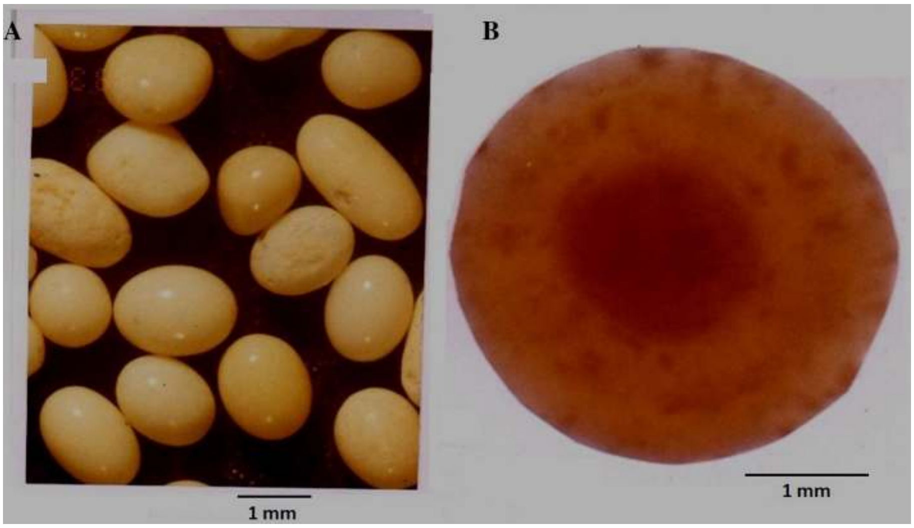

Figure 8. **(A)** Ooids and **(B)** section of ooid showing thick coating at cortex portions.

that at a few locations, such as the Hamelin pool, a hypersaline basin in western Australia and Pleistocene Bahamas ooids are intimately associated with stromatolites (Summons *et al.* 2013) favouring biotic origin of ooids and in varied environmental settings. Recent works tend to recognize close analogues between the ancient and Recent ooids.

The Late Quaternary ooids from the carbonate platform off western India (figure 8) were investigated for their mineralogy, microstructure and origin (Rao and Milliman 2017). These ooids came from 14 stations, representing the entire platform. Ooids were tan coloured at landward (figure 8A) and white seaward of the platform. Aragonite was the only carbonate mineral in ooids at all stations. They found that the thickness of the cortex varied from <5 to 200 μm (figure 8B). Using scanning electron microscopy, they showed that the concentric/tangential microstructures were ubiquitous in the cortex which, in turn, were made up of individual layers that range from 1 to 20 μm (figure 9). The tangential laminae further displayed multiple straight or contorted tubules stacked upon one another (figure 9A and B) resembling encrusted organic filaments with their diameter ranging from microalgae to bacteria (figure 9A and E). The individual laminae elsewhere in the cortex (figure 9E) are extensively mineralized and coated with nanospheres or ellipsoids (figure 9F), which have been described as nanobacteria by Folk and Lynch (2001). Rao and Milliman (2017) suggested that the algal/bacterial filaments were periodically encrusted on available nucleus and then mineralized into discrete laminae. The algal/bacterial filaments usually have mucillagenous sheath organic matter of variable thickness. They emphasized that the microorganisms associated with decaying organic sheath during early diagenesis were responsible for mineralization of the individual laminae. Rao and Milliman (2017) suggested microbial origin for the cortex portions of ooids, rather than chemical precipitation.

Rao and Milliman (2017) also reported bladed/radial microstructures as discontinuous structures in the cortex of the ooids or below microbial filaments (figure 9C and D) and suggested that these microstructures are not primary but formed subsequently. They showed radial fibers on tangential laminae and argued that these are secondary and microfabrics are controlled by the nature of organic substances associated with the sheaths. In summary, the ooids were biogenic in origin and microorganisms associated with decaying organic matter in the encrusted/bacterial filaments during early diagenesis were responsible for mineralization of individual laminae in the cortex. Diagenetic alteration probably resulted in radial microstructures and stable calcite in ancient ooids and therefore different from the Holocene and modern ooids.

Recent investigations on modern ooids in the Shark Bay, Australia (a hypersaline basin) indicate the presence of high organic matter, which in turn are composed of straight chain, saturated fatty acids and long-chain fatty ketones (Gillispie 2013). The δ^{13}C values of ooid cortex fall between -12 and $-30‰$ finger print of

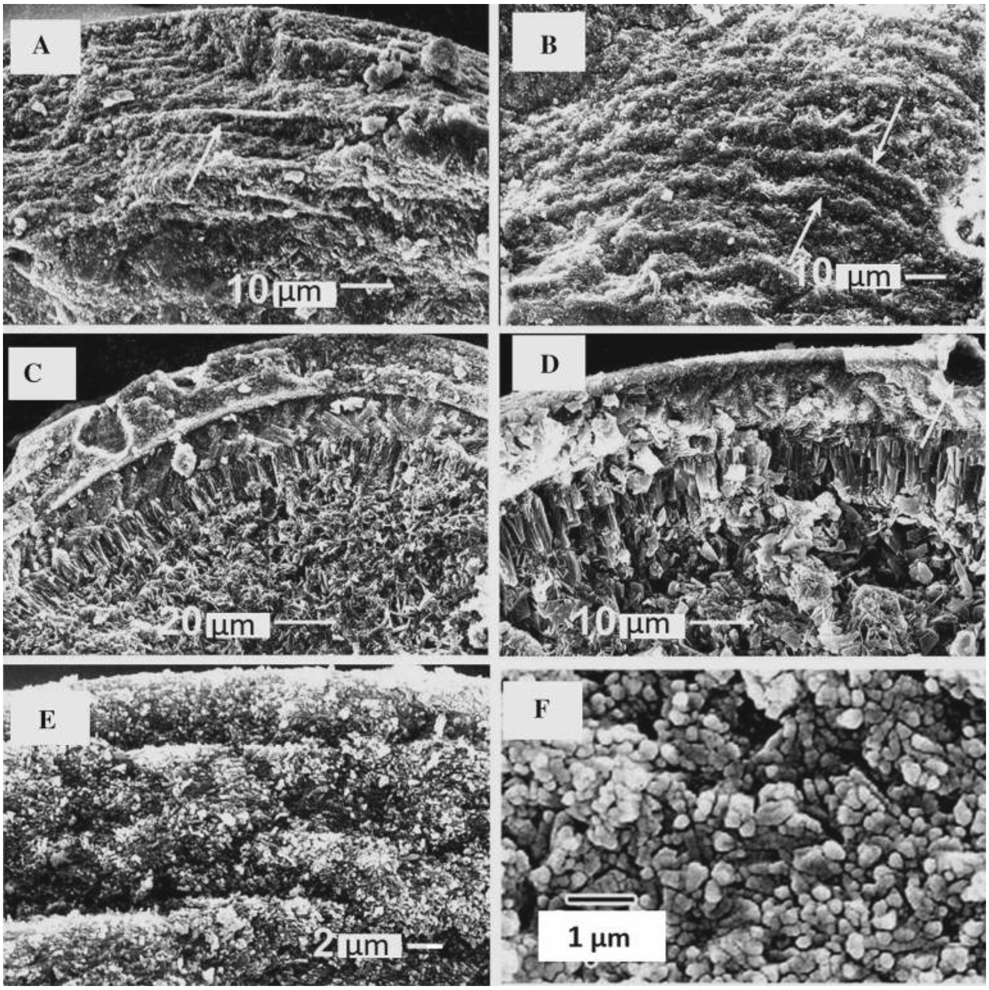

Figure 9. SEM photographs at cortex portions of the ooids showing **(A–B)** sub-micron size mineralized microbial laminae and contorted laminae stacked one upon another, **(C–D)** larger diameter mineralized laminae indicating that the laminae belong to algae. **(E)** Closer view of the microlaminae indicating its hollow nature and **(F)** sub-micron size particles described as nanobacteria on the surface of the laminae (figures taken from Rao and Milliman 2017).

the complex microbial community that lives close proximity to the growing ooids. The results suggest that the consortium of microbes alter the microenvironment of growing ooids in such a way that stimulates carbonate precipitation and protect ooids from dissolution. Summons *et al.* (2013) reported a large fraction of lipids abound to carbonate matrix and lipids were being incorporated continuously during ooid growth. They reported elemental sulfur, which forms exclusively by microbial processes in the extracts indicating an origin from sulfate-reducing bacteria. The ooids of Jurassic age also revealed the preservation of hydrocarbons as well as appreciable amounts of fatty acids indicating that the ooids preserve organic bio-signatures. Further, the comparison of biomarkers from ooids from different environmental conditions and preservation state will provide insight into syngenetic molecular signals of environmental conditions and biological activity in ancient oolites (Mariotti *et al.* 2015; O'Reilly *et al.* 2017).

8. Phosphorites

Phosphorites, similar to carbonate deposits, occur abundantly in ancient sedimentary deposits, but a few phosphorite occurrences are reported in the modern day. Numerous stromatolitic phosphorites have been reported during Precambrian–Cambrian (Cook and Shergold 1986), Mesozoic (Follmi 1996) and Eocene (Soudry and Panczer 1994) times and phosphate stromatolites in Quaternary (Rao *et al.* 2000a). Extensive reworking and/or benthic microbial communities might have played a major role in their formation. Modern phosphorite deposits

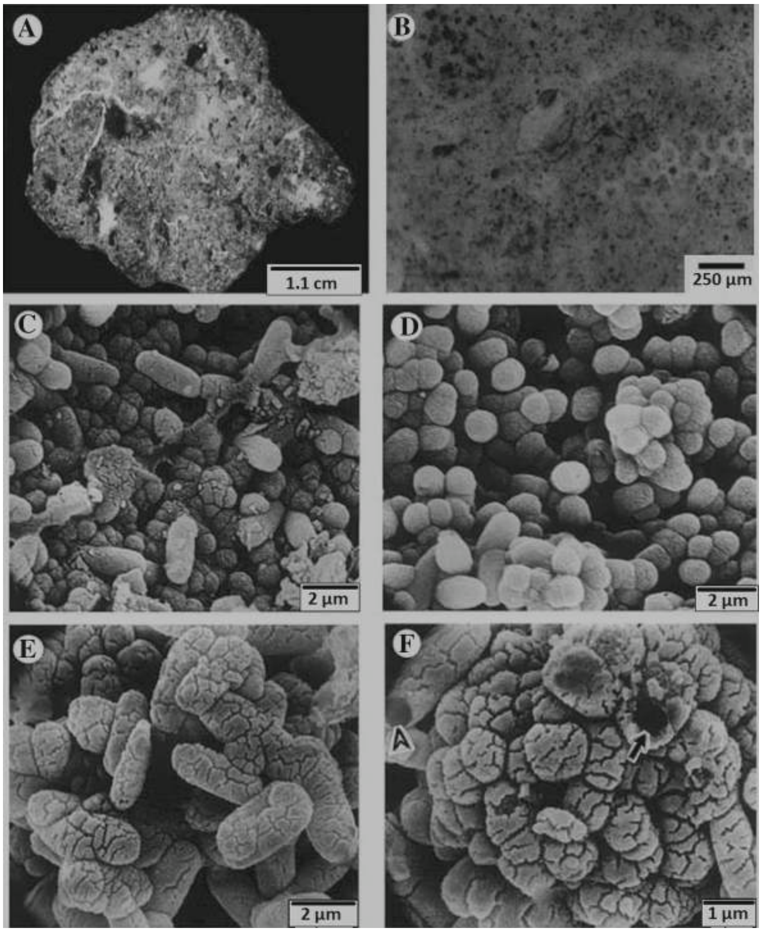

Figure 10. Phosphorites **(A)** phosphorite nodule, **(B)** thin section of phosphorite showing that the carbonate mud and skeletal are being replaced by phosphate, **(C–D)** phosphate microparticles in the form of rod and ovoid type particles resembling phosphatized bacteria and **(E–F)** colonies of mineralized bacteria. Microparticles are hollow and sheath organic matter associated with bacteria acted as substrate for phosphate mineralization (figures taken from Rao *et al.* 2000b).

are smaller in size and occur as scattered nodules and pellets at the sediment-water interface (within the top few centimetres of sediments) and at or near to the boundary of the oxygen-minimum zone (Burnett 1977; Baturin 1982; Glenn *et al.* 1994). Most of the modern phosphorites occur on western margins associated with upwelling (Kazakov 1937; Burnett and Riggs 1990) but a few occur in the eastern margins of the continents (O'Brien *et al.* 1981). The sources of phosphorus for modern phosphorites have been presumed to be sedimented plankton organic matter, fish debris, and the iron redox cycle phosphate pump (Jarvis *et al.* 1994; Follmi 1996). Microbial mediation in phosphorite formation was suggested even for modern phosphorites (O'Brien *et al.* 1981; Rao and Nair 1988; Lamboy 1990).

Phosphorites, phosphatised limestones and phosphate–glaucony grains of Late Pleistocene–Holocene age have been reported on the western margin of India (Baturin 1982; Nair 1985; Rao and Nair 1988; Rao *et al.* 1990, 1993, 2000b; Rao and Lamboy 1995, 1996) and also on its eastern margin (Rao *et al.* 2000a). However, high-grade phosphorites as phosphorite nodules (figure 10A) and grains occur within the upper few centimetres of lime muds on the continental slope, adjacent to the carbonate platform (figure 1; Rao *et al.* 2000b). They occur at a depth of 232 m and within the present-day oxygen minimum zone. Carbonates, fluorapatite and calcite were major minerals in these phosphorites. The phosphorite consists of light-brown microcrystalline apatite containing a few skeletal fragments and planktonic foraminifera. Thin sections showed evidence of dissolution of skeletal calcite or mud and filling of the resulting cavities by phosphate (figure 10B). Phosphatization seems to have occurred through replacement of abundant micrite. Scanning electron microscope (SEM) studies further showed microbial filaments and rod-shaped apatite particles of about 2–3 μm in length, which are constricted at one end and appeared hollow and, ovoid-shaped apatite particles of about 1–2 μm in diameter (figure 10C and E). The ovoid particles join together into club-shaped particles or globose forms or rosettes (figure 10F). Similar apatite particles and particle aggregates have been described as fossilized phosphate bacteria and colonies of microbial cells by several workers, both in older and present day phosphorites and phosphatised limestones and phosphate-glaucony grains (O'Brien *et al.* 1981; Mullins and Rasch 1985; Southgate 1986; Rao and Nair 1988; Soudry and Lewy 1988; Lamboy 1990; Breheret 1991; Krajewski *et al.* 1994; Rao and Lamboy 1995). Rao *et al.* (2000b) discussed the genesis of apatite in high-grade phosphorites and suggested replacement of carbonate by apatite and the direct precipitation of carbonate fluorapatite by microbial mediation. It is further suggested that microbes are instrumental in determining environmental conditions (pH and Eh) favourable for the dissolution of calcite and precipitation of phosphate, and microbes act as substrates for phosphate mineralization as sheath phosphate. Rao *et al.* (2000b) suggested that phosphatization was subsequent to the demise of carbonates on the platform and lime muds, oxygen minimum conditions and upwelling favoured the formation of phosphorites on the continental slope and both replacement of carbonate by phosphate and microbial processes played major role in their formation. Recent phosphorites from Peru and Cretaceous phosphorites from France formed by the similar processes and thus our phosphorites serve as analogues to them.

9. Evidences of neotectonic activity during Late Pleistocene and Holocene

Several workers proposed Late Pleistocene and Holocene sea level changes and neotectonic activity along the western margin of India, including the carbonate platform (Nair 1971; Nair *et al.* 1979; Rao and Nair 1992; Hashimi *et al.* 1995; Rao and Veerayya 1996; Rao *et al.* 1996, 2003b, c; Rao and Milliman 2017). The Holocene sea level curve proposed by Hashimi *et al.* (1995) is only an imaginary curve and cannot be used as a reference sea level curve for the western margin of India, as the points making the curve are '*inferred ages*' and, actual radiocarbon dated samples fall away from the curve. Several other points have also been raised and cautioned users to realize serious short comings in making the curve and stop using it (Rao *et al.* 1996, 2000b; Rao and Veerayya 1996; Rao and Milliman 2017). We highlight 3 points to show evidences of Late Quaternary neotectonic activity on and around platform: (1) dolomites occur at 64 m depth on the platform (figure 1) and detailed investigations indicate direct precipitation of dolomite in the form of dolomite stromatolites in hypersaline and anoxic conditions in lagoons. The age of dolomite measured by accelerated mass spectrometer (AMS) method was 17,750±80 yr and corresponds to the last glacial maximum (LGM; 18,000 yr BP). The age and depth (64 m) at which dolomites occur on the platform do not correspond to the age and sea level position (– 120 m) at LGM. This implies neotectonic activity and subsidence of the platform during or after dolomite formation (Rao *et al.* 2003a). However, we agree that more data are required to substantiate this point.

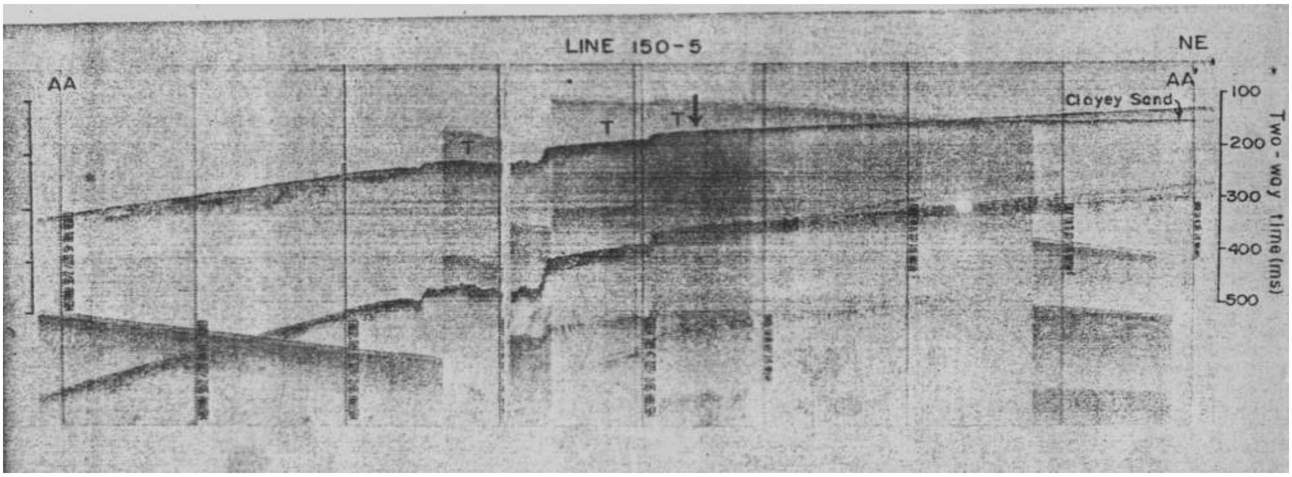

Figure 11. Bathymetry at the edge of the platform showing submarine terraces (*T*) at deeper depth. Terraces at 130, 145 and 170 m are shown in the figure (taken from Rao and Veerayya 1996).

(2) Submarine terraces are important geomorphic features on the continental margins and may record former sea levels still stands. Nair (1975) and Rao and Veerayya (1996) reported submarine terraces on the seaward slope of the platform at depths of 35 and 170 m and relict reef structures at 370–392 m deep (figure 11). The terraces at depths between 120 and 35 m on the platform were suggested to record sea level still stands that occurred during the course of glacio-eustatic sea level rise (Nair *et al.* 1979). The terraces deeper than 120 m and up to 170 m on the platform slope (figure 11) are difficult to interpret because the maximum sea level low was − 120 m during LGM. The deeper depth terraces probably suggest neotectonic activity and subsidence after LGM. This inference is also supported by the oolitic limestones collected on the terrace at 130 m depth (Rao and Veerayya 1996). The petrology of the limestones indicates that these limestones were formed at inter-tidal depths and the calibrated ^{14}C age of the limestones was 11,900 yr BP; this implies that the 130 m depth terrace was at intertidal depths at ~12,000 yr BP (Rao and Veerayya 1996). The eustatic sea level, however, was at − 90 m at 12,000 yr BP. This disparity of depth by ~40 m indicates subsidence of the platform, sometime after 12 ka BP. (3) Our detailed study of ooids on the carbonate platform indicated biogenic origin. In other words, ooids may not have necessarily formed at or near to sea level. The calibrated ^{14}C AMS ages of ooids (Rao and Milliman 2017) and oolitic limestones (Nair *et al.* 1979) and their depth of occurrence on the platform were plotted on the sea level curve (figure 12) of Bard *et al.* (1990). Only ooids at two stations were plotted on the curve but those at other stations plot away or much away from the curve implying ooids on the platform were formed not at sea level but at deeper water depths. Therefore, ooids are not indicators of sea level. Similarly, the age and depth of aragonite sands (Rao *et al.* 2003b) plot parallel to the age-axis and that the minimum age of the sand was 7.5 ka BP. It implies that the carbonate growth on the platform ceased after 7.5 ka BP. This could be due to the environmental stress caused by excess nutrient availability and the platform drowned subsequently after 7.5 ka BP.

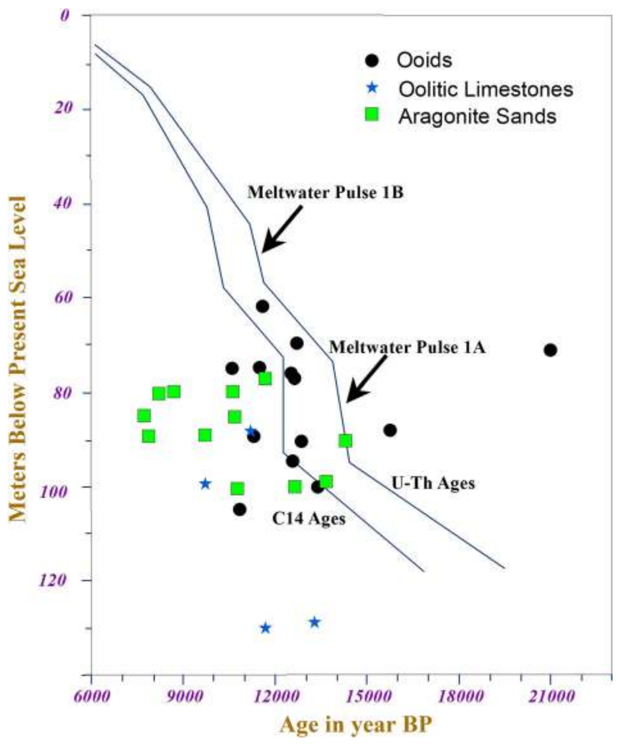

Figure 12. Plot of calibrated ages of ooids on the platform *vs.* depth on the Barbados sea level curve (Bard *et al.* 1990). Data taken from Rao and Veerayya (1996), Rao *et al.* (2003b), Rao and Milliman (2017) .

10. Conclusions

The carbonate platform located on the outer continental shelf of northwestern India comprises various carbonate components (limestones, dolomites, ooids, phosphorites, Halimeda bioherms and lime muds) formed during the Late Quaternary. The genetic aspects of these deposits were reviewed in relation to their ancient deposits. Submarine cemented and vadose diagenetic limestones on the platform and, neomorphic and terrestrial limestones on the continental shelf south of the platform indicate that the neomorphic limestones were probably buried on the platform because of subsequent carbonate sedimentation. Dolomites on the platform are primary deposits, resemble dolomite stromatolites, wherein dolomite is precipitated by the metabolic activity of microorganisms, rather than dolomitization of carbonates or chemical precipitation. Microbial mediation is abundantly reported in the dolomites from ancient deposits. The ooids reported here demonstrate that they were formed by mineralization of microbial laminae enveloped by their cortical layers. Radial microstructures were formed by diagenesis. Variations in mineralogy and microstructures between the ancient ooids and modern ones could be due to diagenetic transformations in older ooids. Phosphorite formation was subsequent to the carbonate sedimentation and formed by microbial mineralization of organic matter and replacement of carbonate by apatite. Evidence of mineralized microbes and microbial activity in the dolomites, ooids and phosphorites of Late Quaternary age suggests that these deposits are genetically related to their ancient counter parts and thus serve as Quaternary analogues for the ancient deposits. We could not answer why were dolomites, ooids and phosphorites occur abundantly in ancient deposits but a few occurrences in modern days. Evidences are ever increasing in favour of microbial role in mineral formation, both in ancient and modern carbonate systems (Griffin and Awramik 1989) and, microbial involvement becomes an acceptable mechanism for sedimentary mineral formation in different environments. Awramik *et al.* (1976) reported changes in fossil morphotypes of microbiota through Precambrian to modern times and modern microbial mats composed of communities of cyanophytes, eucaryotic algae, fungal structures and photosynthetic bacteria. Gillispie (2013) reported complex microbial communities and consortium of microbes in the present-day microbial systems. We therefore suggest changes in morphotypes of microbial communities and microenvironments through time are responsible for variations in their abundance. In recent years, biomarkers are being used to identify organic bio-signatures in ancient deposits. Further research on biomarker studies will answer the role of microbes and microbial environments more clearly in mineral formation.

Halimeda bioherms do not have rich fossil record in the Earth's ancient history but the bioherms reported here were similar to those formed in the Late Pleistocene–Holocene transgression in the Indo-Pacific region. Lime muds resemble fine-grained limestones in ancient times. Lime muds were bio-detrital and formed from the disintegration of bioherms and skeletal components. Evidences of Late Quaternary neotectonic activity on the platform were presented. More data are required to better understand sea level changes and neotectonics activity on the platform.

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