

Relict ooids off northwestern India: Inferences on their genesis and late Quaternary sea level

V. Purnachandra Rao^{a,*} and John D. Milliman^b

^aNational Institute of Oceanography, Dona Paula-403 004, Goa, India

^bSchool of Marine Science, College of William & Mary, Gloucester Pt., VA 23062, USA

Abstract

Relict carbonate sands dominated by ooids and faecal pellets are common on the continental shelf, between 60 and 110 m, off northwestern India. The shiny tan/white aragonitic ooids closely resemble modern Bahamian ooids, with cortex thicknesses varying from <5 μm to 200 μm . Tangential laminae, ranging from 1 μm to 20 μm in diameter, occur as straight to contorted stacked tubules, similar in appearance to algal or microbial filaments. Bacteria associated with the decaying organic sheath of the laminae may have played an important role in subsequent aragonite precipitation. Bladed or radial aragonite microstructures are secondary features in the cortex, apparently formed during early diagenesis by mineralization of organic matter associated with the tangential laminae. Calibrated ages of the ooids range between 9.8 and >23 ka BP, and $\delta^{18}\text{O}$ values suggest that these relict ooids formed during cooler and drier post-LGM conditions and later during the re-intensified Holocene monsoon climate. An age vs. depth plot suggests that most of the ooids formed at water depths between ~10 and -40 m, thereby calling into question whether relict shelf ooids are reliable indicators of past sea level.

*Corresponding author;

Present address: Department of Civil Engineering, Vignan's University, Vadlamudi, 522 213, A.P. India; E-mail: vp Rao55@gmail.com

Key Words: relict ooids, western India, AMS ages, sea-level

Introduction

One interesting aspect about the post-glacial transgression was the wide-spread deposition of oolitic-rich sediments on many continental shelves throughout the world, including the southeastern United States (e.g., Pilkey et al., 1966; Locker et al., 1996), Yucatan (Logan, 1969), northeastern Brazil (Milliman and Barretto, 1975), the Great Barrier Reef and Gulf of Papua (Marshall and Davies, 1975; Yokoyama et al., 2006; J.D. Milliman, unpublished data), and the northern Indian Ocean and adjacent Persian Gulf (e.g., Subbarao, 1964; Loreau and Purser, 1973; Nair et al., 1979; Weidecke et al., 1999). By contrast, present-day ooid formation is restricted to saline to hyper-saline, semi-tropical and tropical shallow-water environments in the Bahamas, Persian Gulf, Red Sea and western Australia (e.g., Newell et al., 1960; Logan et al., 1969; Loreau and Purser, 1973). Depending on location, the ages of these oolitic shelf deposits range from >20 to ~9 ka BP. Modern ooids are almost always aragonitic, whereas the relict ooids can be composed of aragonite or magnesian calcite.

Although the marked difference in the distribution of modern and relict oolite has been noted (e.g., Milliman, 1974), the reason for this disparity is not presently understood. Were the climatic and/ or oceanographic conditions during and following the LGM sufficiently saline and warm for ooid formation, or did the ooids form in different environments from present-day conditions? Assuming the former, some workers have used the depth-age relationships of shelf ooids to interpret regional sea level (Subbarao, 1964; Pilkey et al., 1966; Milliman and Emery, 1968; Marshall and Davies, 1975; Milliman and Barretto, 1975; Weidicke et al., 1999). If ooids are reliable sea-level indicators, they could well help to fix the deeper part of the LGM sea-level curve, particularly given the dearth of sea-level data prior to melt-water pulse (MWP) 1A, about 14 ka BP (Fairbanks et al., 1989; Bard et al., 1990).

Using ooids as sea-level indicators, however, is complicated by the fact that ooids tend to form slowly and often around older – sometimes much older – nuclei, so that a contemporaneous oolite deposit may have a much older ^{14}C date than its time of formation. Newell et al. (1960) and Martin and Ginsburg (1966), for example, found that “modern” Bahamian oolitic sediments have bulk dates of 740-880 ^{14}C years; using stepwise dissolution, Yokohama et al. (2006) calculated that the probable age of Great Barrier Reef oolite is ~3000 ^{14}C years older than the outer 10% (in part due to likely contamination by modern boring algae) but ~6000 ^{14}C years younger than its nucleus. As a result, oolite bulk ages must be used with caution, and most likely can infer only that the actual ooid’s cortex is younger – perhaps considerably younger - than its bulk age (Kulm and Hein, 1986).

Of particular interest - and the subject of this paper - is the band of relict oolite stretching discontinuously from the Persian Gulf (Loreau and Purser, 1973), around India (Subbarao, 1964; Naidu, 1967; Nair et al., 1979), to the Ganges-Brahmaputra delta in the Bay of Bengal (von Stackelberg, 1972; Weidecke et al., 1999). Future study of the continental shelves of Yemen and Burma may widen substantially the extent of this discontinuous facies. Using available ages of sediments and sedimentary carbonate rocks from the coastal and shelf regions of western India and assuming ooids to be sea-level indicators, Hashimi et al. (1995) constructed a Holocene sea-level curve. A close look at their paper, however, shows that the authors used inferred ages for the construction of sea-level curve and, in fact, the ages of actual radiocarbon-dated ooid samples fall away from the curve. Moreover, the authors used raw radiocarbon ages of bulk sediments, instead of calibrated ages. Their curve proposed a gradual ~ 2 cm/year of sea-level rise between 10,000 and 7,000 years BP, during which glacio-eustatic sea level rose no more than ~ 35 m, nearly 20 m of which occurred during mwp 1c between 9.5 and 9.1 ka BP (e.g., Liu et al., 2004).

In this paper, we discuss the wide swath of oolitic sediments off northwestern India, which, given this margin's relatively stable tectonic character (Closs et al., 1974), may allow us to better delineate the ability of oolitic sediments to portray Holocene sea level.

2. Local geology

The continental shelf off northwestern India is characterized by a drowned carbonate platform (Fig. 1), landward of which lies a large silici-clastic depocenter – the Dahanu depression - in which pro-delta sediments have accumulated since the Eocene (Basu et al., 1980). Water depths on the carbonate platform range between 60 m and 110 m, with a general gradient of 0.2° , seaward of which the seafloor gradient increases abruptly to 3.2° (Rao and Wagle, 1997) (Fig. 1). Local shelf topography can be quite rough, characterized by valleys as deep as 20 m and pinnacles as high as 14 m (Rao et al., 1994). The shelf sediments are generally sandy and relict, containing abundant non-skeletal grains (aragonitic faecal pellets and ooids) as well as *Halimeda* plates and lesser amounts of bivalves, planktic and benthic foraminifera, and dolomitic crusts (Nair, 1971; Nair et al., 1979; Rao et al., 1994, 2003a, 2003b).

3. Material and methods

The sand (>63 μm) fractions from 71 outer-shelf sediments (Fig. 1A-B) were examined under binocular microscope, from which non-skeletal carbonates constituting $>20\%$ to 98% of the coarse fraction were chosen for detailed mineralogic and petrologic analysis. Mineralogy was carried out on a Philips powder X-ray diffractometer, using nickel-filtered $\text{Cu-K}\alpha$ radiation. The coarser grains of

each sample were impregnated in epoxy resin from which thin sections were cut. Petrographic analysis (Fig. 2) showed that ooids were abundant in 40 of the 71 samples. Scanning electron microscope (SEM) studies (Figs. 3-4) and Accelerator Mass Spectrometer (AMS) age determinations were carried out on grains from those samples containing maximum ooid concentrations. Freshly broken surfaces of the several ooids were glued on to the stubs, sputter coated with gold and then examined under JEOL 5800 LV SEM at both the Virginia Institute of Marine Science and the National Institute of Oceanography, Goa.

Spherical, shiny ooids that under reflected light showed little or no sign of obvious surficial borings were hand-picked from 14 samples taken from water depths between 62 and 105 m, and ^{14}C -dated at the National Ocean Sciences Atomic Mass Spectrometer (NOSAMS) facility at the Woods Hole Oceanographic Institution, USA. To help resolve the problem of bulk age vs. age of formation, in two samples we determined both bulk age and the age of the inner cortex/nucleus (constituting about half of the total ooid volume) (Table 1). In addition to AMS dating, 10 and 14 samples, respectively, were analyzed for $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ (Table 1, Fig. 5), thus allowing us to identify the environment of formation as well as detect possible diagenetic alteration. Measured ^{14}C ages were calibrated using CALIB rev. 4.3 (Stuiver et al., 1998). In the calibration, a local derivation ΔR 163 ± 30 was used, following Dutta et al. (2001), and calibrated ages of samples were plotted against the south Asian sea-level curve of Liu et al. (2004). We choose this curve because it merges the Barbados sea-level curve of Bard et al. (1990) with numerous data points from the Yellow and East China seas.

4. Results

4.1. Micro- and ultrastructure of the cortex

The ooids on the shelf of western India are similar to modern Bahamian ooids, being white to tan in colour with generally polished surfaces (Fig. 2A). Ooids on the landward portion tend to be tan in colour, while those on the seaward are white; all are aragonitic in composition. Ooids exhibit either a uniform cortical layer or are superficial, with several concentric laminae around a nucleus; faecal pellets or skeletal fragments usually serve as nuclei (Fig. 2B). SEM images indicate that the thickness of the cortex varies from $<5\ \mu\text{m}$ to $\sim 200\ \mu\text{m}$ (Fig. 3); mineralized filaments $\sim 1\ \mu\text{m}$ diameter are occasionally exposed. The individual laminae of the cortex range from 1 to $20\ \mu\text{m}$ in diameter (Fig. 3A-F), although sometimes individual layers cannot be differentiated. The cortex contains multiple straight (Fig. 3B-C) or contorted tubules (Fig. 3D) stacked upon one another. Larger-diameter tubules also form the outer cortex (Fig. 3E). The cortex or inner layers of the cortex

can show signs of alteration into radial or bladed aragonite; the peripheries of some nuclei have been altered into bladed aragonite (Fig. 3F).

At high magnification, the tangential laminae appear porous (Fig. 4A), and the surfaces of individual laminae are extensively mineralized and coated with minute spheres or ellipsoids or very tiny needles of aragonite (Fig. 4B). Needles joining these spheres (Fig. 4B) are aligned parallel to the laminae or perpendicular to the tangential laminae in the form of strands in the adjacent layer (Fig. 4B). The spheres/ellipsoids, 0.30 to 0.2 μm in diameter (Fig. 4C), are similar to those in ooids reported by Loreau and Purser (1973), Fabricius (1977), and Folk and Lynch (2001). Strands of bladed aragonite are noted directly above the nucleus and composed of a thin sheet of nano-grains (Fig. 4D), growing between the two tangential laminae (Fig. 4E). Radial aragonite fibers appear overprinted on the earlier formed tangential laminae and also extend towards nucleus (Fig. 4F).

4.2. ^{14}C ages of the ooids

The calibrated ages and depth of the western Indian shelf oolites range from >23 to 9.85 ka BP. Oolite from three stations have ages between >23.0 and 15.43 ka BP, those from six stations 13.57 to 12.38 ka BP, and those from five stations 11.68 to 10.54 ka BP. Whole ages of two samples were 250 and 400 years younger than their inner halves (Table 1), suggesting that oolite formation for the western India samples may have occurred at least several hundred years later than the bulk ages that we determined. When plotted against the sea-level curve for the western Pacific (Fig. 6), however, only two oolitic sediments appear to be near the derived sea-level, the remainder falling 10-40 m beneath the sea-level curve; if the age of formation was significantly younger than bulk age, these ooids would have formed in even deeper water.

4.3. Stable isotopes of the ooids

The $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values of the ooids range from 1.73‰ to 0.36‰ and 3.98‰ to 4.91‰, respectively. The $\delta^{18}\text{O}$ values are slightly heavier (0.9 to 1.73‰) for the ooids formed between 13.57 and 12.38 ka BP and lighter (0.89 to 0.36‰) for those formed between 11.68 and 10.54 ka BP (Table 1; Fig. 5).

5. Discussion

5.1. Origin of ooids off western India

The tangential laminae in the form of straight to contorted tubules, measuring 3 to 20 μm in diameter, are ubiquitous in the cortex of ooids (Figs. 3B-F). The tubular laminae suggest two aspects of the ooids:

(a) They may represent encrusted organic filaments, their diameters ranging from microalgae to bacteria (Wray, 1977); and fungal filaments are usually $<1 \mu\text{m}$ in diameter and are branching. Therefore, it could be that algal/bacterial filaments have periodically encrusted on the available nuclei and then mineralized into distinct laminae. The reported association of algal, bacterial and fungal filaments with the cortex of the ooids (see Bathurst, 1967, 1975) and the fact that oolite can occur in association with algal mats (e.g., Shark Bay - Davies, 1970; Gulf of Aqaba - Friedman et al., 1973; Baffin Bay - Land et al., 1979) suggest that ooid structures may be the product of CaCO_3 -producing micro-algae or cyanobacteria.

(b) The tubular laminae also suggest that the mucilaginous sheathes of the laminae may have been mineralized. The bacteria associated with decaying organic matter during early diagenesis may be responsible for mineralization. The type of crystals that encrust on the laminae vary (Fig. 3E; Figs. 4B, 4C and 4F) depending on the nature of organic matter and environmental conditions associated with the filament formation. Fabricius (1977) stressed the importance of algae, fungi and organic substrate for the formation of marine ooids, and proposed that ooids are the product of biomineralization in concert with the environment. Several workers reported mineralization of organic matter through microbial processes in shallow water carbonate deposits.

Bladed / radial microstructures have been reported in modern as well as relict ooids, and variously interpreted as a result of algal precipitation, quiet-water deposition, diagenesis and hypersalinity (Davies, 1970; Friedman et al., 1973; Loreau and Purser, 1973; Kahle, 1974; Sandberg, 1975; Davies and Martin, 1976; Land et al., 1979). Loreau and Purser (1973) suggested that when aragonitic ooids initially form they contain loosely packed radially oriented crystals, upon which subsequent agitation can form tangential crystal structures. Bladed/radial microstructures in the ooids off western India tend to be minor compared to tangential microstructures, and are discontinuous and locally confined to certain zones of the cortex, indicating that the suggestion of Loreau and Purser (1973) may not apply to our ooids. Moreover, the occurrence of bladed/radial microstructures immediately adjacent to the nucleus (Fig. 3A), below the concentric tubules (Fig. 3E) or tangential laminae (Fig. 3F), and between two successive concentric laminae (Fig. 4E) and overprinting of radial fibers on the previously formed tangential laminae (Fig. 4F), imply that these microstructures are not primary but formed subsequently. The formation of radial structures in the ooids may reflect rapid, early diagenesis and mineralization of organic matter associated with microbial laminae. Evidence of dissolution of inner cortical layers - and thereby the formation of bladed aragonite (Fig. 3E) and/or acicular aragonite crystals (Fig. 3F) - also suggests that the bladed aragonite is secondary. Several workers (Kahle, 1974; Marshall and Davies, 1975; Davies et al., 1978) have noted that radial

fabrics are secondary, developing during diagenetic alteration of concentric and radial fabrics. The dense, bladed aragonite apparently grew in areas rich in organic matter (see Fig. 3A-B). The overprinting of radial fibers on some tangential laminae (Fig. 4F) suggests that the ooid microfabrics are controlled by the nature of organic substances associated with the mucilagenous sheath. Oxygen isotope ratios - 0.36 to 1.73 ‰ (Table 1) – suggest formation under normal marine conditions; hypersalinity may not have been needed for the formation of radial aragonitic structures. Since the radial microstructures form under quiet-water conditions (Loreau, 1970; Davies and Martin, 1976), it is likely that western shelf ooids may have periodically experienced quiet environments. In summary, then, the radial microstructures in the ooids off western India appear to be secondary, formed during early diagenesis of organic matter associated with microbial laminae in the cortex, under normal marine and intermittent calm-water conditions. The nano-spheres documented here (Fig. 4C-D) appear similar to ‘subspherical nanograins’ found in ooids in the Persian Gulf (Loreau and Purser, 1973), ‘nanograins’ in marine ooids (Fabricius, 1977), and ‘mineralized nano-bacteria’ in the Bahamian ooids (Folk and Lynch, 2001), which these workers suggest formed during the early diagenesis of organic matter.

Since the $\delta^{18}\text{O}$ values of modern ooids usually appear to be in equilibrium with the environment of their formation (e.g., Milliman, 1974), the ~ 1.4 ‰ decrease in $\delta^{18}\text{O}$ content between 13.5 and 10.5 ka BP (Fig. 5) may in part reflect a shift from post-glacial to early Holocene environmental conditions (L. Keigwin, 2000, personal communication). But it may also represent increased freshwater runoff to the coastal rivers in response to the increased intensity of the SW monsoon in southern Asia (Sirocko et al., 1993; von Rad et al., 1999). The relatively close agreement between $\delta^{13}\text{C}$ values of ooids of the western India (3.97-4.91‰; Table 1) and those presently formed in the Bahamas (4.77-5.2 ‰; Milliman, 1974) (from 4.37 - 4.81‰ to 4.34 - 4.02 ‰) suggests a similar mode of formation, perhaps cyanobacteria as suggested by Fabricius (1977).

5.2. Ooids off western India as Sea-level Indicators?

The fourteen ooid samples selected for dating came from the entire length and width of the carbonate platform (Fig. 1), extending 4° in latitude and about 1.5° in longitude, an area of $\sim 28,000$ km² (Rao et al., 1994). Given its uneven topography (Rao et al., 1994) and the difference in color between landward and seaward stations (tan vs. white; Table 1), it seems doubtful that the west Indian shelf ooids were transported significant distances after their formation. Handpicking ooids used for dating minimized surficial contamination from borings or mixed types of ooids. In other words, utmost care was taken to select the as pure as possible ooid samples that had not been

transported from their site of formation. The $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ contents of the ooids (Table 1) suggest little or no diagenetic effect. Moreover, the differences in age between bulk and cortex portions of the ooids seem to be only few hundred years (Table 1), suggesting relatively rapid formation of the oolitic coatings.

Fig. 6 shows the water depth vs. age plot of the ooids on a glacio-eustatic sea-level curve for the southern Asia (Liu et al., 2004). The ages of ooids from three stations (1830, 1835, SK111/10 – see Table 1) appear anomalous, their calibrated ages and water depths ranging between >23 and 15.43 ka BP and between 88 m and 72 m, respectively; that is, considerably shallower than glacial to post-glacial sea level. This implies that the nuclei of these ooids are much older; diagenetic alteration, on the other hand, would have incorporated young carbon into the ooid cortex, thus making the ooid appear younger, not older. Alternatively, neotectonic uplift might have been involved; as suggested for pristine dolomite crust (of stromatolitic origin) from 64 m depth on the platform dated at 20.29 ka BP (Rao et al., 2003b).

Six oolite samples from depths between 68 m and 98 m range in age from 13.57 to 12.26 ka BP (Table 1), just after MWP-1A, during which time eustatic sea level stood at ~70 m. As a result, most of these oolitic sediments plot as many as 30 m below the sea-level curve (Fig. 6). Five other oolite samples, collected at depths between 62 m and 105 m have ages between 11.68 and 10.60 ka BP (Table 1), that is during or just after MWP-1B, when sea level rose rapidly from 60 m to 38 m (Fig. 6). Plotted on the sea-level curve, these ooids appear to have formed at depths as great as ~43 m (Fig. 6). In other words, of the 11 ooid samples dated with ages between 13.57 and 10.5 ka BP, only two fall on or close to the Liu et al. (2004) sea-level and 9 below the curves by 10 m to ~40 m, suggesting that ooid formation off western India occurred at sub-tidal depths. Thus, while our petrographic and geochemical data indicate that the western Indian ooids are generally visually and geochemically similar to present-day Bahamian and Persian Gulf ooids, they appear to have formed at water depths as great as 40 m.

The interval from ~13.5 to 10.5 ka BP was particularly conducive for ooid formation on the northwestern Indian shelf, during which there was a period of relative stable sea level after MWP 1A, then a 400-yr period of rapid transgression during MWP 1B. Why ooid formation essentially ceased after 10.5 ka BP is not clear, but it may have been related to the re-intensification of the SW monsoon, and the resulting increased precipitation and river runoff. Hopefully future research on other shelf ooids will shed further light on this perplexing problem. In the meantime, however, we caution against oolitic sequences as evidence of intertidal formation; in fact, they may have formed at subtidal depths.

6. Conclusions

The ooids on the northwestern Indian continental shelf, which occur at depths between 60 m and 105 m, are white or tan in colour and aragonitic in composition. Cortex thickness varies from $< 5 \mu\text{m}$ to $\sim 200 \mu\text{m}$, containing both tangential laminae and radial/bladed microstructures. SEM studies show straight to contorted stacked tubules, resembling microbial or algal filaments. Accordingly, bacteria associated with decaying organic sheath may have facilitated aragonite precipitation. Bladed/radial aragonite microstructures are minor components and discontinuous in the cortical layers; they seem to be secondary, formed during early diagenesis by mineralization of organic matter associated with the tangential laminae. Calibrated ages of the ooids range from 9.8 to >23 ka BP. The age vs. depth plot indicates that most of the ooids formed in water depths at least 10 to 40 m below sea level. We therefore conclude that the ooids off western India apparently were formed by microbial processes and are unreliable indicators of prior sea-level.

Acknowledgments

VPR thanks the Director, National Institute of Oceanography, Goa, and Vice-chancellor, Vignan's University, Vadlamudi for their encouragement in this research. VPR's visit to the School of Marine Science at the College of William and Mary at Virginia was funded by ONR-IFO. Funding for JDM was furnished by several grants from the U.S. National Science Foundation.

References

- Andres, M.S., Summer, D.Y., Reid, R.P. and Swart, P.K., 2006. Isotopic fingerprints of microbial respiration in aragonite from Bahamian stromatolites. *Geology* 34, 793-796.
- Bard, E., Hamelin, B., Fairbanks, R.G., 1990. U–Th ages obtained by mass spectrometry in corals from Barbados: sea level during the past 130,000 years. *Nature* 346, 456–458.
- Bard, E., Hamelin, B., Arnold, M., Montaggioni, L., Cabioch, G., Faure, G., Rougerie, F., 1996. Deglacial sea-level record from Tahiti corals and the timing of global meltwater discharge. *Nature* 382, 241-244.
- Basu, D.N., Banerjee, A. and Tamhane, D.M., 1980. Source areas and migration trends of oil and gas in Bombay offshore Basin, India. *American Association of Petroleum Geologists Bulletin* 64, 209-220.
- Bathurst, R.G.C., 1967 Oolitic films on low energy carbonates and grains, Bimini Lagoon Bahamas. *Marine Geology* 5, 89-109.
- Bathurst, R.G.C., 1975. Carbonate sediments and their diagenesis. *Developments in Sedimentology* 12, Elsevier, Amsterdam, 658 pp.

- Closs, H., Hari Narain and Garde, S.C., 1974. Continental Margins of India, In: C.A. Burk and C.L. Drake (Eds.), *The Geology of Continental Margins*, Springer – Verlag, New York, pp. 629-639.
- Davies, G.R., 1970. Carbonate bank sedimentation. Eastern Shark Bay western Australia In: *Carbonate sedimentation and environments, Shark Bay Western Australia*. American Association of Petroleum Geologists Memoir 13, 85-168.
- Davies, P.J. and Martin K., 1976. Radial aragonite ooids, Lizard Island Great Barrier Reef, Queensland Australia. *Geology* 4, 120-122.
- Davies, P.J., Bubela, B. and Ferguson, J., 1978. The formation of ooids. *Sedimentology* 25, 703-730.
- Duguid, S.M.A., Kyser, T.K., James, N.P. and Rankey, E.C., 2010. Microbes and ooids. *Journal of Sedimentary Research* 80, 236-251.
- Dutta, K., Bhushan, R., and Somayajulu, B.L.K., 2001. ΔR correction values for the northern Indian Ocean. *Radiocarbon* 43, 483-488.
- Fairbanks, R.G., 1989. A 17,000 year glacio-eustatic sea-level record: influence of glacial melting rates on Younger Dryas event and deep ocean circulation. *Nature* 342, 637-642.
- Fabricius, F.H., 1977. Origin of marine ooids and grapestones. *Contributions to Sedimentology* 7, Schweizerbart'sche Verlagsbuchhandlung, Stuttgart, Germany 113 pp.
- Folk, R.L., and Lynch, F.L., 2001. Organic matter, putative nanobacteria and the formation of ooids and hardgrounds. *Sedimentology* 48, 215-229.
- Friedman, G.M., Amiel, A.J., Braun, M. and Miller, D.S., 1973. Generation of carbonate particles and laminites in algal mats. Examples from sea-marginal hypersaline pool, Gulf of Aqaba, Red Sea. *American Association of Petroleum Geologists Bulletin* 57, 541-557.
- Hashimi, N.H., Nigam, R., Nair, R.R., Rajagopalan, G., 1995. Holocene sea level fluctuations on western Indian margin: an update. *Journal of Geological Society of India* 46, 157-162.
- Kahle, C.F., 1974. Ooids from Great Salt Lake, Utah, as an analogue for the genesis and diagenesis of ooids in marine limestones. *Journal of Sedimentary Petrology* 44, 30-39.
- Kump, L.R., and Hine, A.C., 1986. Ooids as a sea-level indicator In: O. Van de Plassche (Ed.), *Sea-level Research: A Manual for the Collection and Evaluation of Data*. Geo books, Norwich, pp. 175-195.
- Land, L.S., Behrens, E.W., Frishman, S.A., 1979. The ooids of Baffin Bay, Texas. *Journal of Sedimentary Petrology* 49, 1269-1278.
- Liu, J.P., Milliman, J.D., Gao, S., Cheng, P., 2004. Holocene development of the Yellow River's subaqueous delta, North Yellow Sea. *Marine Geology* 209, 45-67.
- Locker, S.D., Hine, A.C., Tedesco, L.P., Shinn, E.A., 1996. Magnitude and timing of episodic sea-level rise during the last deglaciation. *Geology* 24, 827–830.

- Logan, B.W., 1969. Coral reefs and banks, Yucatan shelf, Mexico. American Association of Petroleum Geologists Memoir 13, 1-37.
- Logan, B.W., Harding, J.L., Ahr, W.M., William, J.D., Snead, R.G., 1969. Carbonate sediments and reefs, Yucatan shelf, Mexico. American Association of Petroleum Geologists Memoir 11, 1-198.
- Loreau, J.-P., 1970. Ultrastructure de la phase carbonate des oolithes actuelles. Comptes Rendus de l'Académie des Sciences 271, 816-819.
- Loreau, J.-P., Purser, B.H., 1973. Distribution and ultrastructure of Holocene ooids in the Persian Gulf. In: B.H. Purser (Ed.), The Persian Gulf, Springer-Verlag, New York, pp. 279-328,.
- Lowenstam, H.A. and Epstein, S., 1957. On the origin of sedimentary aragonite needles of the Great Bahama Bank. Journal of Geology 65, 364-375.
- Marshall, L.F., Davies, P.J., 1975. High-magnesium calcite ooids from the Great Barrier Reef. Journal of Sedimentary Petrology 45, 285-291.
- Martin, E.G. and Ginsburg, R.N., 1966. Radiocarbon ages of oolitic sands on Great Bahama Bank. In: International Conference Radiocarbon and Tritium Dating. 6th Proceedings of United States Atomic Energy Committee Report CONF-650652, pp. 705-719.
- Milliman, J.D., 1974. Marine Carbonates. Springer-Verlag, Heidelberg. 375 p.
- Milliman, J.D. and Barretto, H.T., 1975. Relict magnesium calcite ooids and subsidence of the Amazon shelf. Sedimentology 22, 137-145.
- Milliman, J.D., Emery, K.O., 1968. Sea-levels during the last 35,000 years. Science 162, 1121-1123.
- Naidu, A.S., 1967. Radiocarbon date of an oolitic sand collected from the shelf off the east coast of India. Bulletin of National Institute of Science, India 38, 467-471.
- Nair, R.R., 1971. Beach rock and associated carbonate sediments on the Fifty Fathom Flat, a submarine terrace on the outer continental shelf off Bombay. Proceedings of the Indian Academy of Sciences 73B, 148-154.
- Nair, R.R., Hashimi, N.H., Gupta, M.V.S., 1979. Holocene limestones of part of the western continental shelf of India. Journal of Geological Society of India 20, 17-23.
- Newell, N.D., Purdy, E.G., Imbrie, J., 1960. Bahamian oolitic sand. Journal of Geology 68, 481-497.
- Pilkey, O.H., Schnitker, D., Pevear, D.R., 1966. Oolites on the Georgia continental shelf edge. Journal of Sedimentary Petrology 36, 462-467.
- Rao, V.P., Veerayya, M., Nair, R.R., Dupeuble, P.A. and Lamboy, M., 1994. Late Quaternary *Halimeda* bioherms and aragonitic faecal pellet-dominated sediments on the carbonate platform of the western continental shelf of India. Marine Geology 121, 293-315.
- Rao, V.P., Rajagopalan, G., Vora, K.H. and Almeida, F., 2003a. Late Quaternary sea-level and environmental changes from relic carbonate deposits of the western margin of India. Proceedings of Indian Academy of Sciences (Earth and Planetary Sciences) 112, 1-25.

- Rao, V.P., Kessarkar, P.M., Krumbein, W.E., Krajewski, K.P. and Schneider, R.J., 2003b. Microbial dolomite crusts from the carbonate platform off western India. *Sedimentology* 50, 819-830.
- Rao, V.P. and Wagle, 1997. Geomorphology and surficial geology of the western continental shelf and slope of western India. *Current Science* 73, 330-349.
- Sirocko, F., Sarnthein, M., Erlenkeuser, H., Lange, H., Arnold, M., and Duplessy, J.C., 1993. Century scale events in monsoonal climate over the past 24,000 years. *Nature* 364, 322-324.
- Stuiver, M., Reimer, P.J., Bard, E., Beck, J.W., Burr, G.S., Hughen, K.A., Kromer, B., McCormac, F.G., van der Plicht, J. Spurkm, M., 1998. INTCAL 98 radiocarbon age calibration, 24,000 – 0 cal BP. *Radiocarbon* 40, 1041-1083.
- Subbarao, M., 1964. Some aspects of continental shelf sediments off the east coast of India. *Marine Geology* 1, 59-87.
- von Stackelberg, U., 1972. Faziesverteilung in sedimentendes Indich – Pakistanischen Kontinental-Randes (Arabisches Meer) Meteor Forschungsgebn, Reihe C9, 1-73.
- von Rad, U., Schulz, H., Riech, V., den Dulk, M., Berner, U., Sirocko, F., 1999. Multiple monsoon-controlled breakdown of oxygen-minimum conditions during the past 30,000 years documented in laminated sediments off Pakistan. *Palaeogeography Palaeoclimatology Palaeoecology* 152, 129-161.
- Wiedicke, M., Kudras, H.R., Hubscher, Ch., 1999. Oolitic beach barriers of the last glacial sea-level low stand at the outer Bengal shelf. *Marine Geology* 157, 7-18.
- Wray, J. L., 1977. Calcareous algae. *Developments in Palaeontology and Stratigraphy*, 4, Elsevier, Amsterdam. 185 pp.
- Yokoyama, Y., Purcell, A., Marshall, J. F., Lambeck, K., 2006. Sea-level during the early deglaciation period in the Great Barrier Reef, Australia. *Global and Planetary Change* 53, 147–153.

Figure captions

Fig. 1. Sample locations of oolitic sediments on northwestern Indian continental shelf. Sample data are given in Table 1.

Fig. 2. Ooid surfaces (a) and microstructure as shown in thin section (b).

Fig. 3. SEM photographs of the cortex portions of ooids showing (a) massive cortex, (b) tangential laminae in the outer cortex and bladed aragonite below, (c-d) straight to contorted tubular laminae (arrows point the hollow nature of the tubules), (e) tubular laminae that form the outer cortex (arrow points to hollow tubule) and bladed aragonite in the inner cortex, (f) altered carbonate at the nucleus periphery.

Fig. 4. (a) High magnification SEM photographs showing (a) thick cortical layer with porous microstructure, (b) needles composed of nano-spheres that are parallel to the tangential laminae in one layer and perpendicular to laminae in the adjacent layer, (c) nano-spheres on the tangential laminae, (d) bladed aragonite below the tangential laminae- see Fig. 3b, that are composed of nano-spheres, (e) aragonite needles between tangential laminae, and (f) fibrous needles overprinting on tangential laminae.

Fig. 5. $\delta^{18}\text{O}$ vs. $\delta^{13}\text{C}$ in NW Indian ooids (in red) vs. the well-documented present-day Bahamian ooids (in blue; $R^2 = 0.92$). Bahamian data from Lowenstam and Epstein (1957), Andres et al. (2006) and Duguld et al. (2010).

Fig. 6. Plot of the age and depth of NW Indian ooids relative to the western Pacific (Liu et al., 2004) glacio-eustatic sea-level curve.

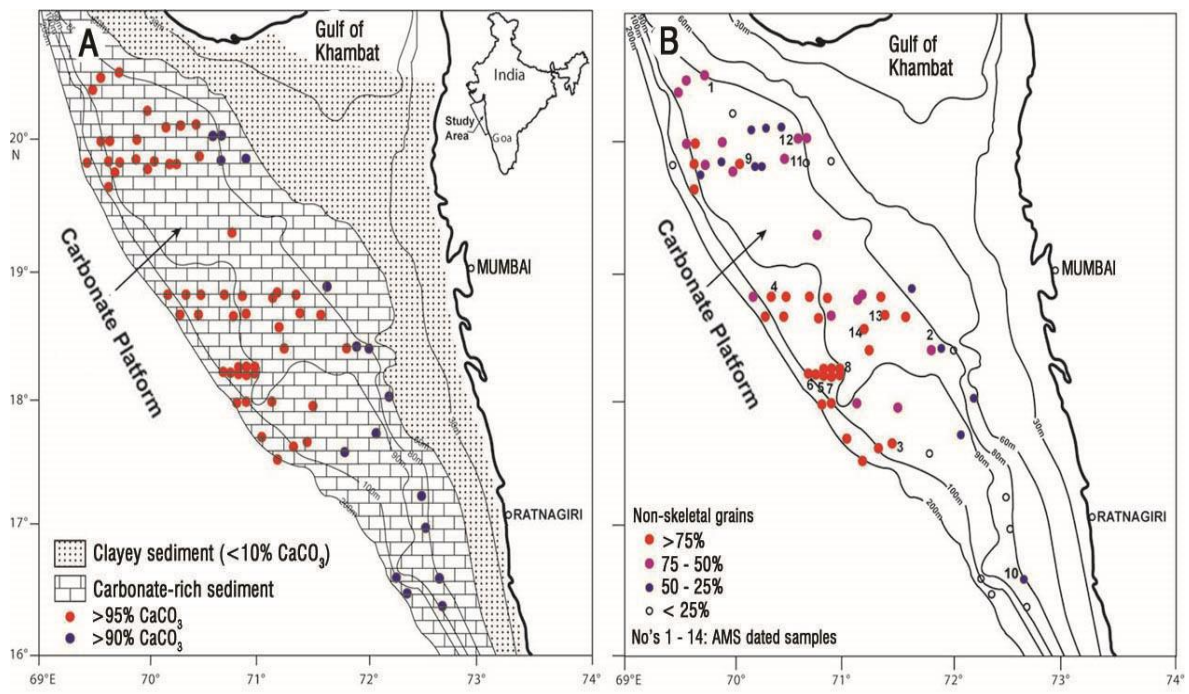
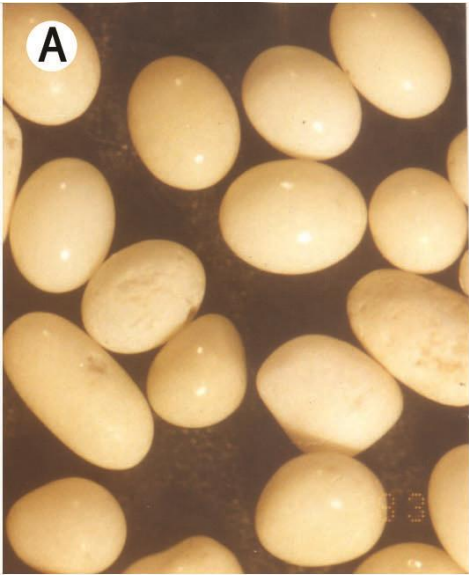
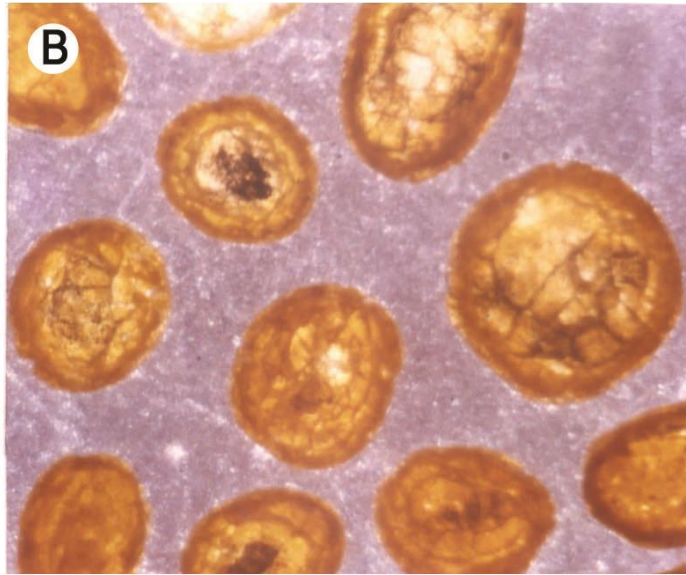


Fig. 1



1 mm



1 mm

Fig. 2

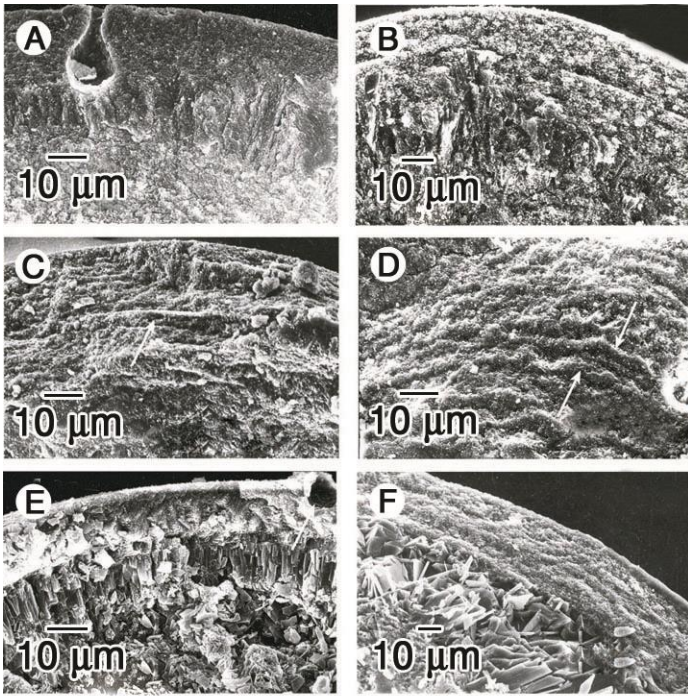


Fig. 3

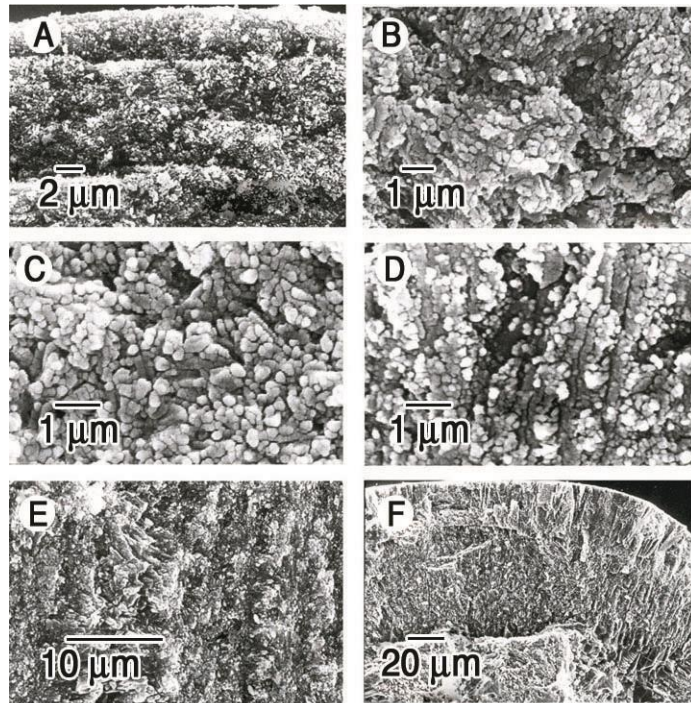


Fig. 4

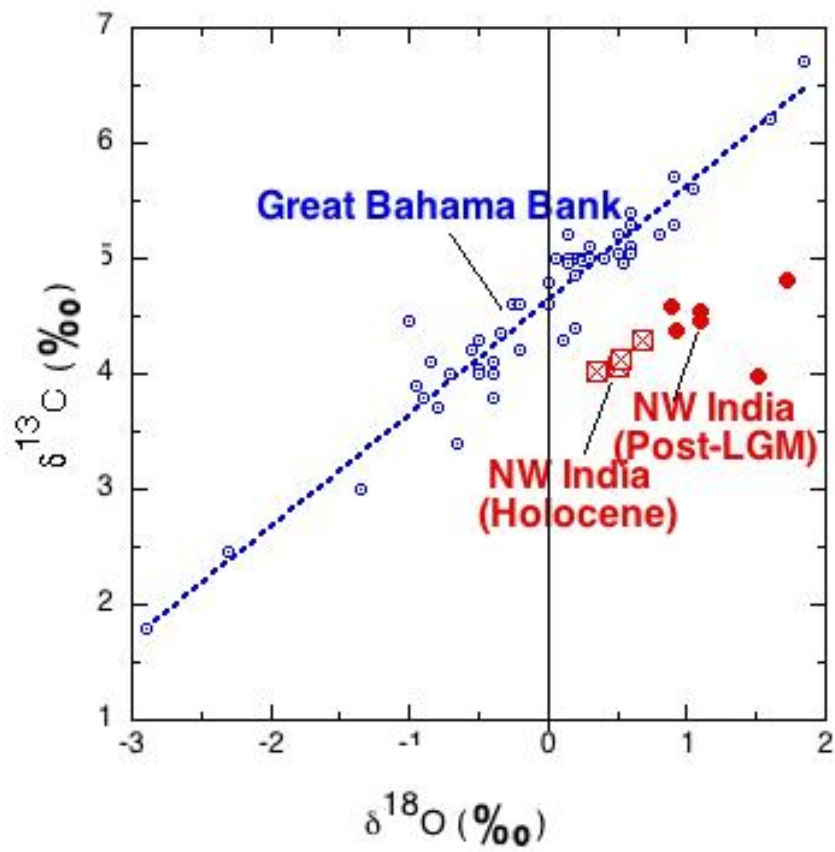


Fig. 5

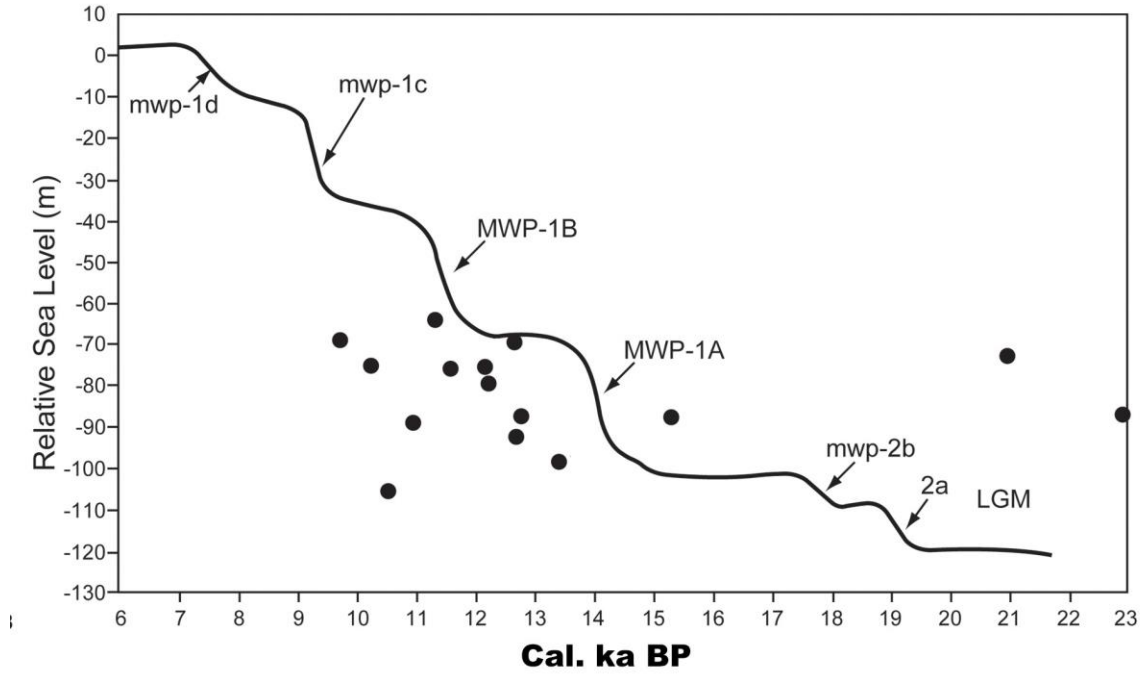


Fig 6

Table 1: AMS ¹⁴C ages of western Indian ooids

Sr. No.	Sample No and colour of ooids	Lat. (°N))	Long. (°E)	Depth (m)	NOSAMS Reference Number	Measured age	Reservoir corrected age	Calibrated age range (2σ)	Average Calibrated age	δ ¹⁸ O ‰	δ ¹³ C ‰
1	2270 – tan	20.50	69.70	68	OS-44383	11,350±40	10,950	12,606 – 12,979	12,792	-	4.39
2	1835 – tan	18.42	71.83	72	OS-44382	18,350±65	17,950	20,374 – 21,714	21,044	-	4.91
3	1830 – tan	17.64	71.44	86	OS-44381	13,550±40	13,150	14,943 – 15,917	15,430	-	4.61
4	1491 – white	18.85	70.32	89	OS-44380	11,450±50	11,050	12,630 – 13,013	12,821	-	4.55
5	SK111/07 - white	18.29	70.79	77	OS-18537	11,100±45	10,700	11,950 – 12,819	12,384	1.09	4.59
6	SK111/05 - white	18.24	70.76	88	OS-18907	10,250±45	9,850	10,933 – 11,201	11,067	0.89	4.34
7	SK111/08 - white	18.23	70.81	91	OS-34400	11,150±50	10,700	11,949 – 12,822	12,385	0.92	4.37
8	SK111/10 - white	18.24	70.88	88	OS-34403	21,900±70	21,500	>23,000		1.09	4.46
9	SK111/21-tan	19.73	70.22	98	OS-18906	12,250±50	11,850	13,307 – 13,842	13,574	1.51	3.97
10	55 - tan	16.68	72.49	75	OS-34399	11,000±60	10,600	11,873 – 12,660	12,266	1.73	4.81
11	1480 – tan	19.82	70.54	76	OS-34401	9,950±45	9,550	10,283 – 10,813	10,548	0.69	4.30
12	1465 – tan	19.99	70.87	62	OS-34402	10,600±45	10,200	11,086 – 11,732	11,409	0.50	4.07
13	110E 215 - tan, bulk	18.68	71.40	105	OS-20864	10,100±55	9,700	10,340 – 10,861	10,600	0.36	4.12
	cortex			(105)		9,700±0.06	9,300		10,033		4.10
14	111E 213 – tan, bulk	18.60	71.20	75	OS-20865	10,750±70	10,350	11,243 – 12,123	11,683	0.53	4.02
	cortex			(75)		10,500±60	10,100	11,074 – 11,676	11,375		4.24