

A re-evaluation of palaeoclimatic conditions during the Pleistocene and Holocene from the western continental shelf of India - Evidences from the petrology of the limestones

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Abstract – The western shelf of India is characterised by the presence of Recent clayey sediments on the inner shelf and relict carbonate sediments and a variety of limestones on the outer shelf. The limestones of the outer continental shelf between 60 and 150 m water depth were studied for their petrology and to evaluate the palaeoclimatic conditions during Quaternary. The limestones, dated $11,150 \pm 130$ years B.P. and occurring at 150 m water depth consist of alternate layers of fine-grained carbonate mud followed by grain supported mud which exhibits peloidal texture. Recrystallised fibrous aragonite skeletal grains are also present. These were formed at subtidal depths by submarine cementation. The limestones of the Fifty Fathom Flat, dated $8,960 \pm 200$ years B.P., exhibit solution stage of the vadose diagenetic conditions; while the limestones of the inner shelf show precipitation stage in vadose conditions. It appears that the sea level rose very rapidly during the Holocene. Arid climate associated with low rainfall prevailed during the Holocene and weak SW monsoon conditions continued much later than 8,960 years B.P. Increased rainfall is indicated after the arid climate about 8,000 years B.P. by 30 to 50 m thick mud accumulation in the inner continental shelf.

The limestones characteristic of abundant microspar and pseudospar are found at water depths 65 and 95 m, respectively on the continental shelf off Ratnagiri. They also consist of marine fauna. These are neomorphic limestones which evidence the Pleistocene high sea levels on the shelf. Caliche pisolites recovered at 60 m depth off Goa indicate continental conditions associated with arid climate and low rainfall during Late Pleistocene. The occurrence of neomorphic limestones and caliche pisolites on the shelf implies varied climatic conditions within the Pleistocene.

INTRODUCTION

The continental shelf sediments of the west coast of India can be divided into two distinct sediment facies: modern clayey sediments on the inner shelf and relict carbonate dominated sediments with a variety of limestones on the outer shelf. Earlier studies on the unconsolidated carbonate sediments of the outer continental shelf indicate that these are the erosional products of reefs accumulated during the Holocene transgression. Relatively few papers describe the nature of limestones outcropping the outershelf (NAIR, 1971; 1974 and NAIR *et al.*, 1979; NAIR and HASHIMI, 1980 and 1981) and very little attention has been paid on the diagenetic textures and fabrics of the limestones (RAO *et al.*, 1990; RAO, 1990). Cements are the diagnostic features of a particular environment and are fairly well known for each major diagenetic environment : marine phreatic, fresh water vadose and fresh water phreatic environments. It has been noted that subaerially exposed Pleistocene sediments exhibit stable mineralogy while the younger sediments consist of unstable mineralogical constituents (BATHURST, 1975). As the shelf was exposed to subaerial conditions during the Pleistocene lowered sea levels, it is believed that the limestones of the outer shelf reveal the sequence of diagenetic changes that the carbonate sediments have undergone. Therefore, the present study is to demonstrate the diagenetic textures of the limestones in order to understand the environmental conditions of their formation during Quaternary.

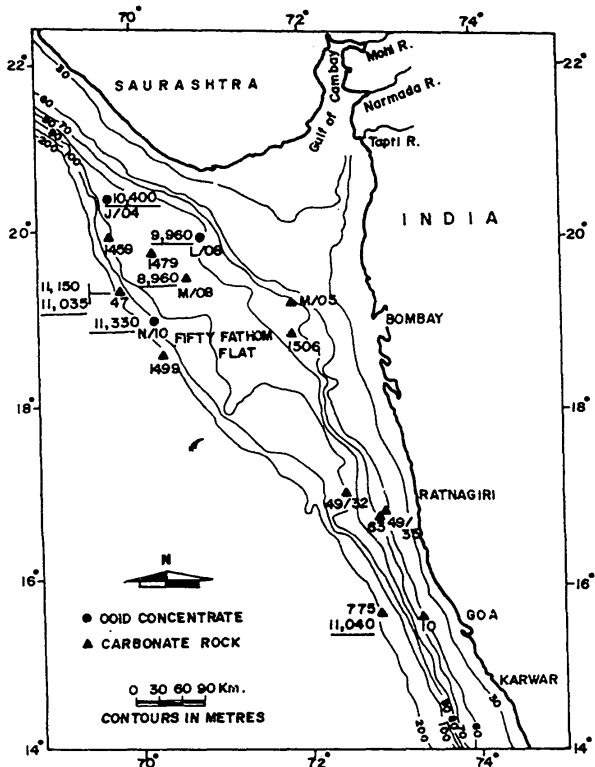
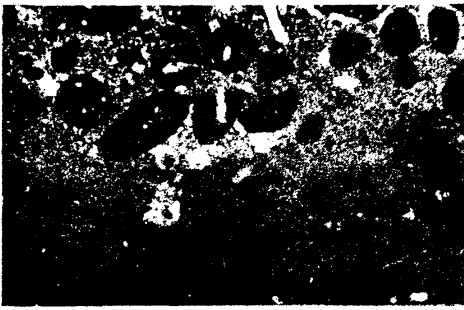


Fig. 1. Sample location map. Samples used in this study are 47, 1459, 1479, M/08, N/05, 1506, 775, 49/32, 49/35, 63, 10.

Submarine cemented limestones

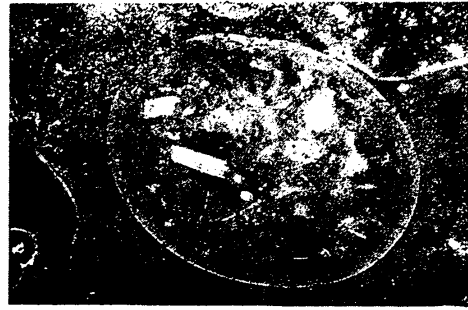
Station 47

These limestones are recovered from 150 m water depth. They are yellowish grey in colour, moderately compact with numerous cavities on their surfaces. Aragonite is the most abundant mineral followed by high-magnesium calcite in these limestones. In thin section, the rock consists of alternate layers of yellowish brown to light grey fine-grained matrix followed by matrix with well rounded to ellipsoidal grains similar to oolites but lack concentric structures (Fig. 2a). These grains range in size from 300 to 1000 μm in diameter, dense and difficult to identify their internal structure. Nevertheless, few of the grains identified are cemented composite grains (Fig. 2b) and algal fragments (Fig. 2c). Skeletal fragments recrystallised to fibrous aragonite are also present (Fig. 2d). Silt size grains are found in the fine-grained matrix (Fig. 2e). In the grain supported fabric, the interstices of the grains are also filled by similar type of matrix material. However, this matrix material preferentially exhibits peloidal texture near grain boundaries. The peloids are ovoid to spherical grains 20 to 80 μm diameter and are apparently formed by repeated nucleation and cementation of micrite size magnesium calcite (Figs. 2f - 2g). Several workers (GINSBURG et al., 1971; JAMES et al., 1976; MACINTYRE, 1977 and 1984; LIGHTY, 1985; REID, 1987; AISSAOUI, 1988; SUN and WRIGHT, 1989) reported peloids as simple in situ precipitates and several others



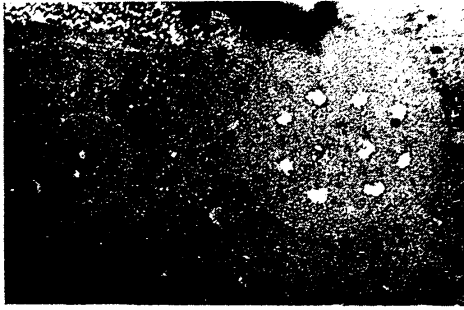
a

750 μm



b

380 μm



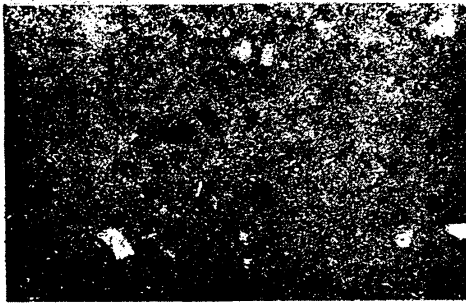
c

380 μm



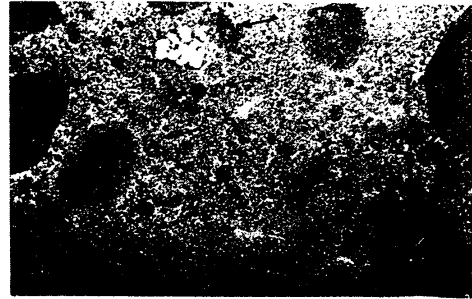
d

750 μm



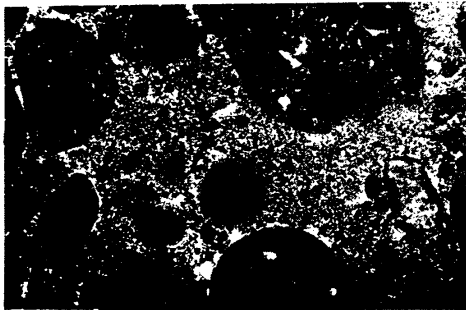
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380 μm



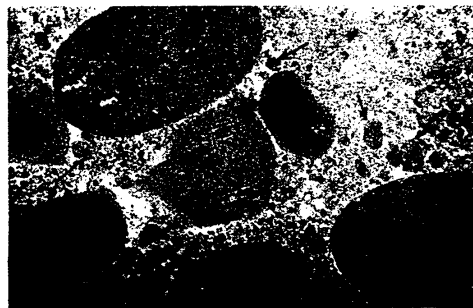
f

380 μm



g

380 μm



h

380 μm

Fig. 2. Photomicrographs (sample 47) showing (a) fine-grained high-magnesium calcite matrix overlain by grain supported matrix, (b) pseudo-oolite apparently formed by cementation of skeletal material and fine-grained aragonite, (c) well rounded skeletal fragment in fine-grained matrix, (d) recrystallised fibrous aragonite skeleton, (e) fine-grained matrix and (f-h) matrix showing peloidal texture (arrows show the location of peloids).

(LAND and GOREAU, 1970; LAND and MOORE, 1980; MARSHALL and DAVIES, 1981; MARSHALL, 1983; CHAFETZ, 1986) suggested biogenic influences including bacteria in the precipitation of initial peloids in shallow submarine cemented limestones. Pumping of sea water through the pores of the sediments is required to produce peloids. Therefore wave and tidal action are considered to be important factors in the formation of peloids and in turn submarine cement formation in shallow water conditions.

The radiocarbon date of the limestones is about $11,150 \pm 130$ years B.P. (NAIR *et al.*, 1979). It may be that shelf edge reefs are kept pace with the rise of sea level during Late Pleistocene and as a consequence were subjected to a high energy environment. This results in the production of fine-grained algal material. Oolite size grains could have been brought on top of the fine-grained sediments in relatively high energy conditions. Yellowish brown to grey colouration of the fine-grained sediments probably indicates oxidising conditions at the time of cementation. JAMES *et al.* (1976) reported submarine cementation in subtidal oxidising conditions. They also reported the pore size effect in the degree of submarine cementation; if the pore size of the sediments is smaller a small volume of cement is required for cementation and even slight oscillating conditions would be adequate to get cemented. MACINTYRE (1984) reported the characteristic features such as the occurrence of both acicular and fibrous calcite, micrite cement of high- magnesium calcite and recrystallisation of aragonite skeletal fragments for diagnosing the cements of submarine origin. As the limestones under study are fine-grained and satisfy all the conditions of MACINTYRE (1984), it is suggested that the limestones formed by submarine lithification in association with moderate energy conditions.

Additional evidence in favour of intertidal to subtidal conditions at water depths between 120 and 150 m during $11,040 \pm 400$ years B.P. has been obtained from the occurrence of algal nodules recovered at these depths on the continental margin off Vengurla. Algal nodules are not good bathymetric indicators because of their wide range of occurrence (ADEY and MACINTYRE, 1973). However, the algal nodules at these depths (dated $11,040 \pm 400$ years) show the alternate layers of coralline algae and thick laminations. The individual filaments of the laminae are formed by wrapping and trapping of sediment particles by adhesion of grains to the sticky filament. This mechanism of mat formation is a well known algal activity which occurs exclusively at intertidal depths (MONTY, 1976). These furthermore are phosphatised algal nodules and a complete discussion on these algal nodules has been given elsewhere (RAO *et al.*, 1990).

Implications

It is evident from these studies that intertidal to subtidal conditions existed between 120 and 150 m water depth at about $11,040 \pm 400$ years B.P. This position of the shelf does not correspond to the global sea level position (FAIRBANKS, 1989) for the above period implying that local tectonic disturbances of the western margin played a major role in determining the sea level positions. MERH (1987) reported Holocene high sea level position of about + 8 - 10 m from the present sea level and also the withdrawal of high seas during early Holocene on the Saurashtra coast. AGRAWAL *et al.* (1973) suggested that the sea level started rising at about 15,000 years B.P. It may be that the lowered sea level at 18,000 years B.P. on the western continental margin coincides with the global lowered sea level at -130 to -160 m reported by MOORE (1982).

Vadose diagenetic limestones

(a) Limestones collected from Fifty Fathom Flat

Stations 1459, 1479, and M/08

The rocks are recovered from 95 to 85 m water depth and resemble oolitic limestones. X-ray diffraction study shows that they are composed of aragonite and calcite. Peak

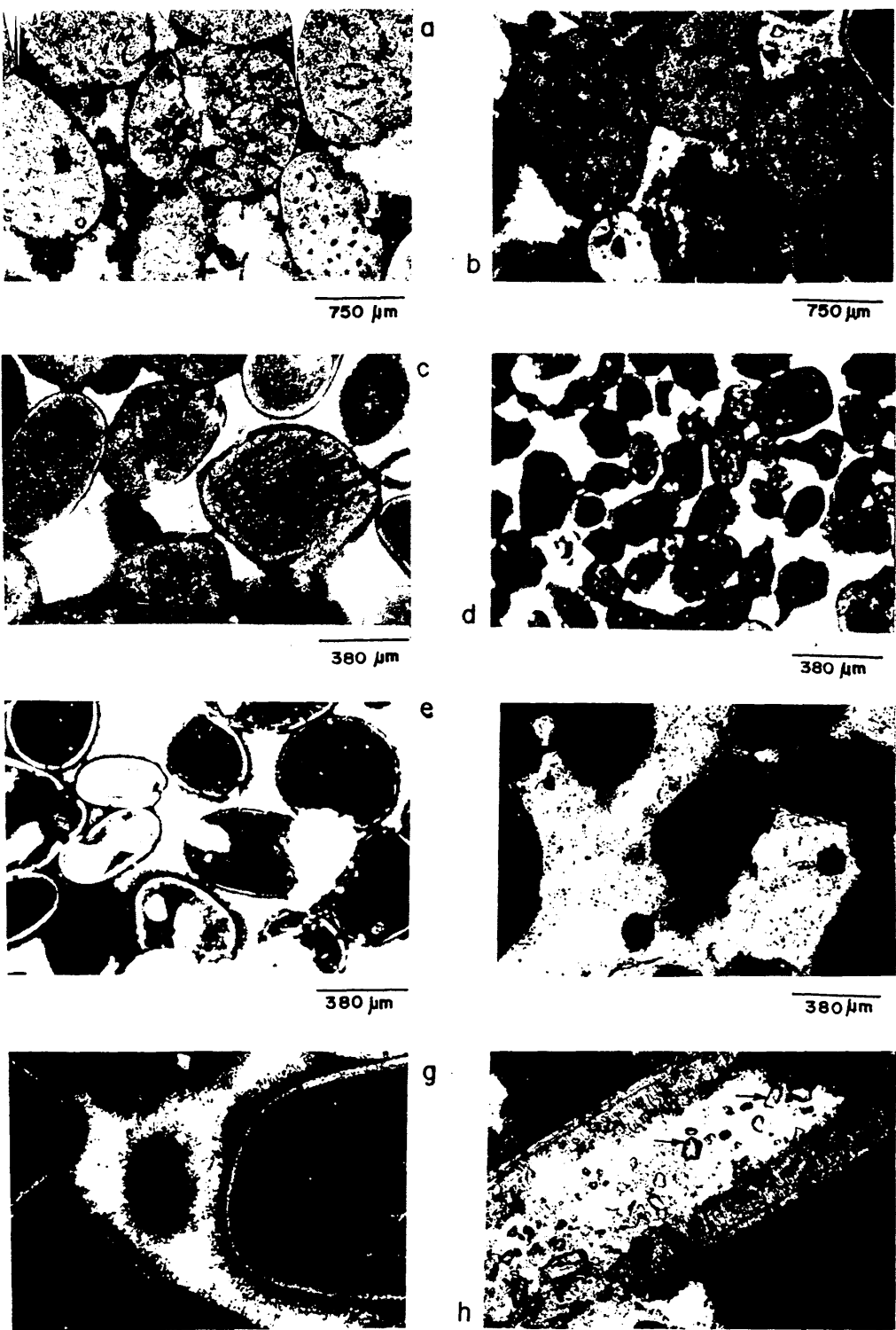


Fig. 3. Photomicrographs of samples from Fifty Fathom Flat, (a - c) well rounded oolite size grains formed by fragmentation and abrasion of coralline algal material and cementation of fine-grained matrix, (d) grains with abundant pore space, (e - f) etching of skeletal grains and empty pore spaces in the cavities formed due to dissolution, (g) relic needle fibre aragonite adhered to the grains and (h) dissolution of aragonite skeleton replaced by precipitation of rhombohedral calcite (arrows) in the cavities.

height ratios of aragonite to calcite vary from 7.0 to 4.4 and the weight percent of aragonite in these samples is more than 95 %. The radiocarbon date of the limestones (M/08) is $8,960 \pm 200$ years B.P. (NAIR, *et al.*, 1979).

Well rounded to ellipsoidal grains similar in size to oolites (described below) are the major components of the limestones. The grains range from 1000 to 1500 μm in diameter and contain neither nucleus nor concentric structures. The larger diameter grains are associated with deeper stations (1459) and exhibit clear internal structure; many grains are well rounded algal fragments (Fig. 3a and 3b); some are formed by aggregation of minute aragonite crystals and skeletal material similar to those illustrated in Fig. 2b; some grains show pits and grooves on their surfaces suggesting a probable microbial role in their formation (Fig. 3c). Therefore, it is suggested that these are the accretionary products of bioclastic/skeletal material resulting due to the fragmentation of algal colonies. Similar type of grains have been reported as pseudo-oolites by ILLINGS (1954) from Bahama banks. The rock samples recovered from relatively shallow depths of the flat (1479 and M/08) consist of smaller diameter grains, dense and no internal structure can be recognised. Grains of very small diameter contain superficial coating but they are very rare.

These limestones show unique fabric characterised by abundant intergranular pore spaces (Fig. 3d). Empty pore spaces are more in shallower station (1479). Solution features such as etching of grain boundaries (Fig. 3e) and empty pore spaces resulted due to dissolution of aragonite cements (Fig. 3f) and partly dissolved relic aragonite needles adhered to grain boundaries (Fig. 3g) are the characteristic features of the limestones. Precipitation of rhombohedral calcite occurs as a replaced material on partly dissolved skeletal components (Fig. 3h).

(b) Samples collected from the continental shelf off Bombay

Stations 1506 and N/05

The rocks are from 70 m water depth and the stations are located at the outer edge of the inner continental shelf and near to the landward edge of the Fifty Fathom Flat. The rocks from these stations are similar to pelletal limestones (Fig 4a). Aragonite, low-magnesium calcite and quartz are present in order of abundance. The ratio of aragonite to calcite ranges from 0.2 to 0.3 indicating that the weight per cent of aragonite varies from 50- 60%. The rocks consist of pellet size (60 - 120 μm) grains of aragonitic composition and low-magnesium calcite cement (Fig. 4b). Rhombohedral crystals occur as rim cements on grain surfaces (Fig. 4c). Calcite cementation occurs in some places (Fig 4d). Syntaxial overgrowth of calcite is common on skeletal components (Fig. 4e). In contrast to the samples of the Fifty Fathom Flat, these samples show less number of incompletely filled pore spaces. Wherever incomplete infillings occur the cement outlines are concave towards the interior of the pores (Fig.4f) similar to the meniscus cements described by DUNHAM (1971). Rounding of pore space, precipitation of calcite crystals limited to grain boundaries and blocky calcite crystals in the pore spaces (Fig. 4f) are common.

Interpretation

It is clear that the grains in these limestones are not true oolites but are pseudo-oolites formed due to the cementation of aragonite material and/or skeletons (Fig. 3a-3c). CAROZZI (1975) reported the genetic relationship between oolites, superficial oolites and pseudo-oolites and emphasised that the intensity of local agitation and clasticity of grains play a major role in their formation. He suggested that if the intensity of local agitation is stronger than the clasticity of grains the product of environment would be oolites. On the other hand, if the intensity of local agitation is equal to or

smaller than the size of the smallest particles then pseudo-oolites occur. As the pseudo-oolites are dense and smaller at shallower depths it is suggested that moderate agitated water conditions existed at the time of their formation.

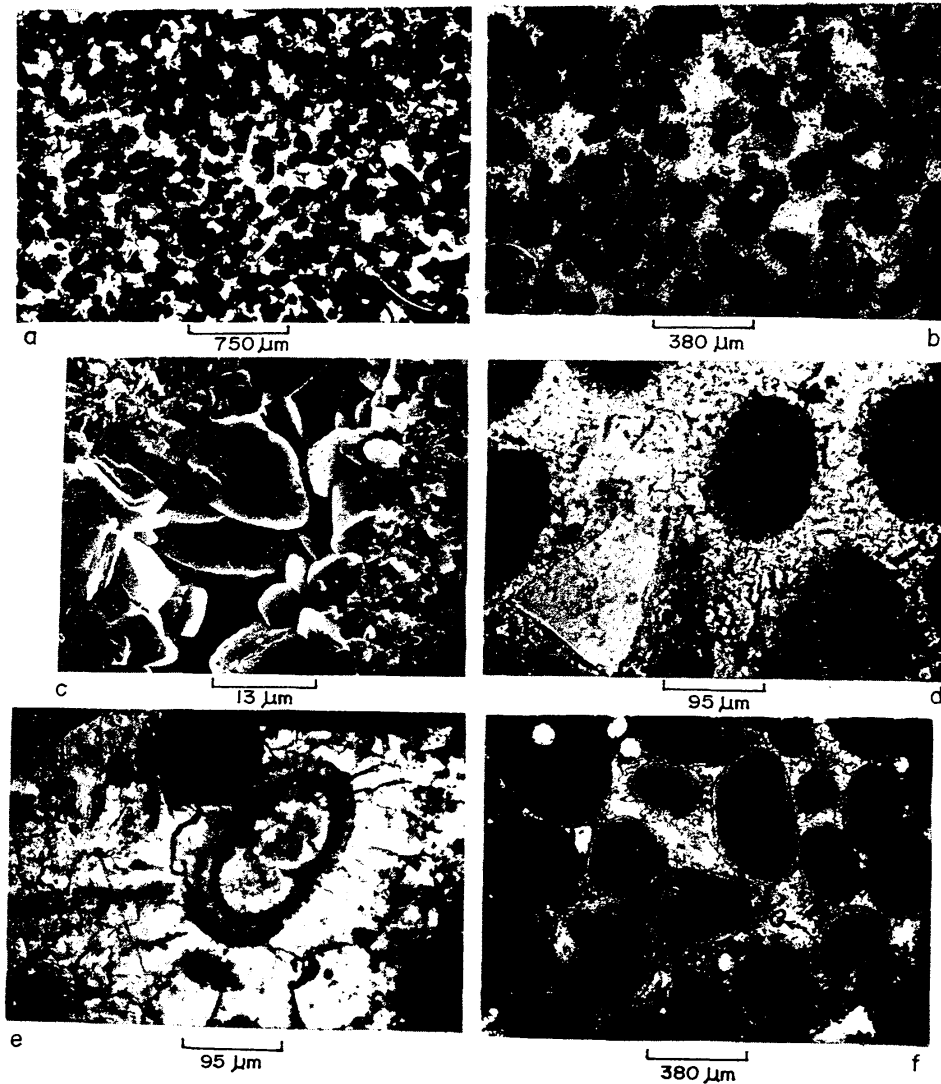


Fig. 4. Photomicrographs of the limestone samples from the shelf off Bombay, (a and b) pelletal material with partly precipitated calcite in the pore spaces, (c) rhombohedral crystal near grain contacts (SEM photo), (d) fine-grained calcite filled pore spaces, (e) syntaxial calcite on skeletal components and (f) rounded pore spaces (arrows) and blocky calcites (arrows) in the cavities.

The age of the pseudo-oolitic limestones has been taken into account in the foregoing discussion. This age (8,960 years) is younger than the radiocarbon dates (range from 9,600 to 10,400 years B.P.) of the uncemented oolites in the vicinity (Fig. 1). It is reasonable because the oolite-size grains in the sediments are similar to pseudo-oolites which have been described and interpreted above. Therefore the age of the uncemented pseudo-

oolites represents the age when the skeleton/ aragonite muds were formed. Whereas in pseudo-oolitic limestones, aragonite cements were formed in early diagenetic submarine conditions initially and subsequently were exposed to vadose conditions (discussed below). Therefore the ages are obviously younger as found. However, it is not known why all oolite-size sediments are not cemented in the vicinity of the oolitic limestones. It may be they have been transported from elsewhere or they have been reworked from the algal colonies.

The cements described from both the limestones of the Fifty Fathom Flat and from the seaward edge of the inner continental shelf represent the resultant products of vadose diagenetic environment. In vadose conditions meteoric water plays a major role.

The meteoric (rain) water are undersaturated with respect to calcium carbonate. When this water percolates into the carbonate sediments dissolution occurs of metastable calcites such as high-magnesium calcite and aragonite. This process thus involves the gross removal of material in solution along their path and continue down the formation till the solutions attain saturation with calcite. Solution of aragonite gives a porous fabric to the rock and this has been observed in the limestones at Stns 1459, 1479 and M/08 (Figs.3d - 3h) and thus the samples of the Fifty Fathom Flat represent a solution stage of the vadose zone. Once the solutions reach saturation with respect to calcite, precipitation of calcite starts in the voids created by dissolution and in pore spaces. Precipitation starts at grain contacts and extends into the interior of the pore. Rim cement precipitation of calcite in some pore spaces and syntaxial calcites (Figs. 4a - 4e) in the limestones near to the inner shelf indicates this stage. As interstices in vadose zone are filled with air, precipitation of calcite attain curved nature which has been described as meniscus cements by DUNHAM (1971). Rounding of pore spaces and blocky calcite attached to pore spaces (Fig. 4f) are also related to the precipitation stage of vadose diagenetic environment (SCHOERDER, 1973). Therefore, the cements in the limestones of the inner shelf represent a stage of precipitation in vadose conditions.

Implications

1. The intensity of dissolution of aragonite and concurrent precipitation of calcite depends on the rainfall and climate (LONGMAN, 1980). As the pseudo-oolitic limestones from the Fifty Fathom Flat exhibit only solution stage of the vadose diagenetic conditions, it is inferred that low rainfall and arid climate prevailed at that time.

2. On the other hand, Narmada and Tapti rivers are located at the proximity of the inner continental shelf limestones and these show precipitation stage in vadose conditions. Much of the rain water is transported to the sea in the form of river discharge and therefore these limestones were influenced by both meteoric water and fresh water discharge from the rivers. Even then, these limestones exhibit unfilled pores (Figs. 4b and 4f), indicating that (a) these rivers actually contributed less discharge during that time and (b) the Narmada and Tapti river discharge did not reach the outer continental shelf during the Holocene and which is evidenced by a porous fabric of the limestones of the Fifty Fathom Flat. HASHIMI and NAIR (1976) reported less than 5% acid insoluble residue in the unconsolidated outer shelf sediments of the Flat further confirming the above observation. Coarser calcite crystals indicate slow precipitation in phreatic conditions while finer crystals indicate faster crystallisation (BUCKLEY, 1951). As the limestones are cemented by fine-grained calcite (Fig. 4b, c and d) it confirms the prevalence of arid climatic conditions at the time of their formation; arid climate results in rapid evaporation which favour smaller crystal precipitation in pore spaces.

3. Aragonite constitutes 95% of the rock and therefore the ^{14}C age of the rock is not influenced by fresh water cementation. Aragonite is found to be the initial cementing

material as evidenced by the relic aragonite needles (Fig. 3g). The age of the limestones of the Fifty Fathom Flat (8960 ± 200 yrs) therefore represents the age when rocks were initially cemented with aragonite in early diagenetic conditions in the marine environment. However, during lithification stage these limestones were exposed to vadose conditions which imparted a porous fabric to the rock. It indicates (a) that there are sea level fluctuations within the Holocene which can be attributed to eustatic changes and/or due to tectonic disturbances on the outer shelf. (b) It is reported that SW monsoon is weak during the Late Pleistocene and intensified at about 9000 years B.P. (LUTHER *et al.*, 1990; PRELL *et al.*, 1990). If the SW monsoon is active and intensified at 9,000 years B.P., the pores of the limestones would be filled with meteoric water and calcite cementation could have taken place in these pores, however it is not the case. It implies that arid climate associated with low rainfall continued much later than the age of the rocks (8,960 years B.P.) and thus the prevalence of intensive SW monsoon conditions must be much younger than 8,960 years.

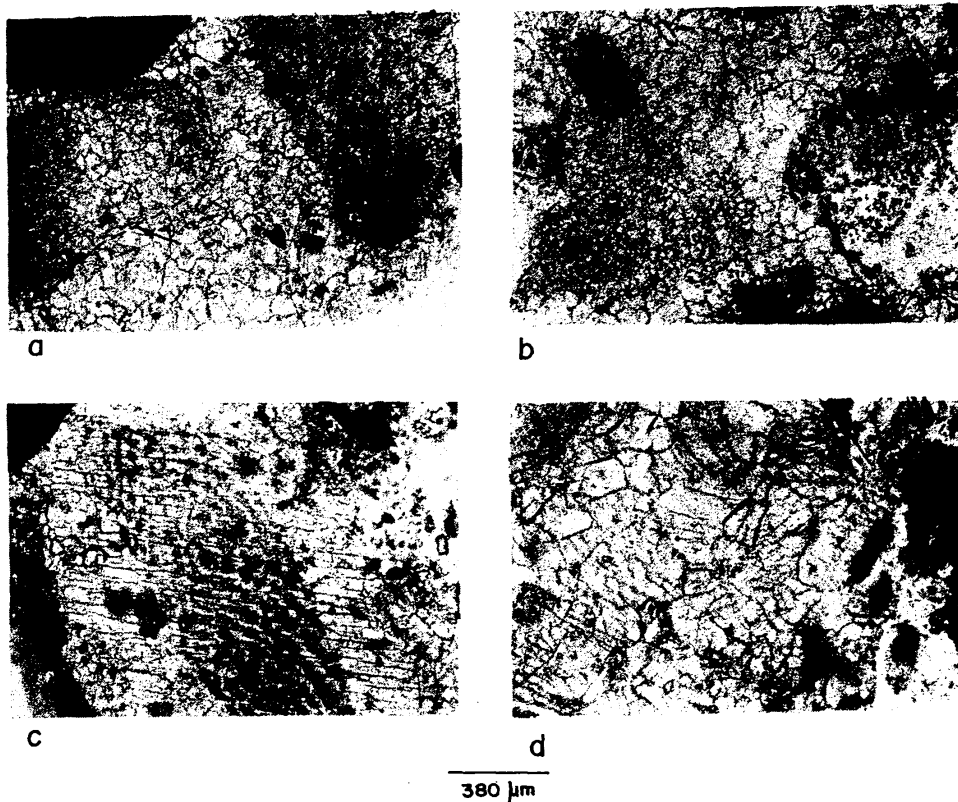


Fig. 5. Photomicrographs of sample (49/35) off Ratnagiri, (a) recrystallised microspar in the pellets [faint outlines (marked with pen) of the grains can be seen], (b) patches of graded microspar, (c) syntaxial calcite transecting the skeletal material and (d) inclusion bound sparry calcite.

4. The limestones studied are located in different parts of the Fifty Fathom Flat and their recovery depths vary from 82 to 95 m. From point 3 it is assumed that the limestones were submerged much later than 8,960 years B.P. Sea level reached the present level at about 5,000 to 6,000 years B.P. (MOORE, 1981; KALE and RAJAGURU, 1985; MERH, 1987). Applying these facts to the rate of sea level rise, it appears that the sea level rose at approximately 25 m /1000 years between 8,960 and 5,000 years B.P. In this estimation we have not taken into account the sea level stand stills during

the Holocene. This inference also assumes that pseudo-oolitic limestones would not be transported easily like uncemented oolite size grains.

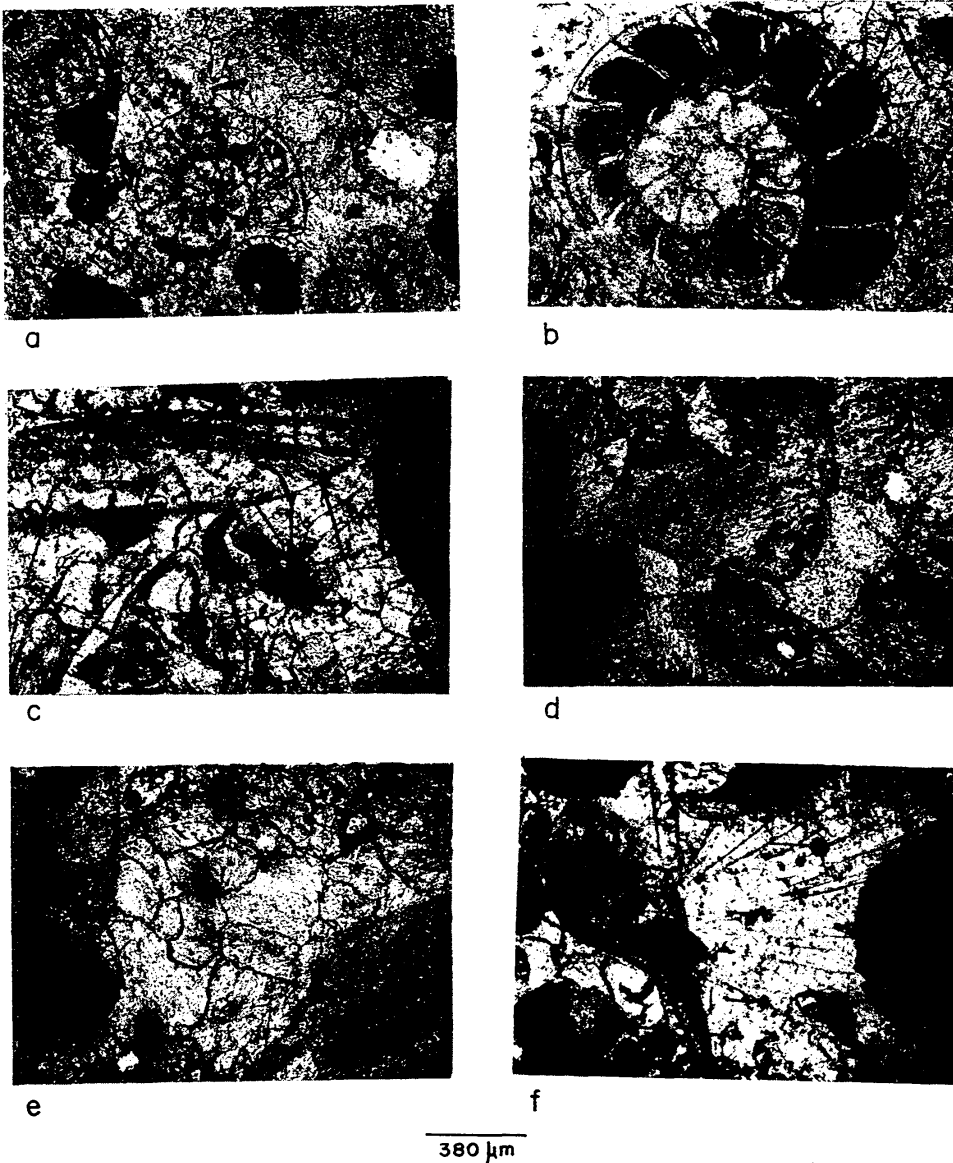


Fig. 6. Photomicrographs (sample 49/32 off Ratnagiri), (a-b) Pseudorotalid foraminifera, (c) completely recrystallised molds (arrows) of skeletons, (d - e) pseudospar calcite with curved intercrystalline boundaries and relic fibres preserved in them and (f) fine bladed calcite with inclusions (arrows) encrusted on skeletons.

Neomorphic limestones

Samples from the continental shelf of Ratnagiri

Stations 49/32 and 49/35

These limestones occur as 3.0 cm thick slabs and appear weathered. Low magnesium calcite is the only carbonate mineral followed by minor amounts of quartz. Thin sections show that these are packstones. The foraminifera belongs to *Rotalidae* family, *Rotalinae*

sub-family, *Pseudorotalia* genus is the most abundant component in both the limestones. Differences exist in the nature of grains and associated microspar.

Samples from the station 49/35 are characterised by micrite and fine crystalline microspar, apparently formed at the expense of the earlier precipitated micrite. Some of the pellets embedded in the microspar have been recrystallised to microspar so that only faint outlines of evidence of their existence can be seen (Fig. 5a). The crystal size of the microspar in recrystallised pellets and in the adjacent matrix are identical. Patches of microspar with uniform grain size grade into the other patch of microspar of higher grain size (Fig. 5b). This type of microspar has been considered by BATHURST (1975) as products of grain growth and by FOLK (1965) as products of neomorphic recrystallisation. Syntaxial calcite transected the fabrics of skeletal particles (Fig. 5c). Sparry calcite has a fractured appearance (Fig. 5d). Foraminiferal skeletons also exhibit fracturing; sometimes only disconnected relics of the test remains. BATHURST (1975) described these features as diagnostic criteria for neomorphic spar. CHAFETZ (1972) reported the above characters to represent the resultant diagenetic products of surface weathering.

In the sample 49/32, the morphology of foraminiferal skeletons, although altered to low-magnesium calcite, is maintained (Fig. 6a and 6b). Partially replaced to completely recrystallised molds of grains and skeletal material are present (Fig. 6c). Large cloudy calcite crystals with curved intercrystalline boundaries (Fig. 6d and 6e) and radial arrangement of fine bladed calcites encrusting on grain surfaces (Fig. 6f) are common. Relic fibrous structures preserved in large calcite crystals (Fig. 6d and 6e) and inclusions in the fine bladed calcites (Fig. 6f) provide evidences that these are not pore filling cements and are formed by inversion of aragonite to calcite. These are similar to pseudospar calcites reported by FOLK (1965) and CONIGLIO (1989) which were formed by neomorphism.

The limestones (Stn. 49/35) showing neomorphic fabrics of microspar are located near to the coast and at shallow depths (65 m). Pseudospar associated limestones (stn. 49/32) are far from the coast and occur at slightly greater depth of 95 m. The differences in the neomorphic fabrics may be related to delayed lithification in the limestones farther from the coast. FOLK (1965) and BATHURST (1975) pointed out that longer the lithification is delayed, the more time there is for neomorphism to proceed further which produces pseudospar. BRAND and VEIZER (1980) suggested that the sequences of changes from micrite to microspar and to pseudospar reflect the increasing maturity of the sediment.

The term neomorphism encompasses two insitu processes : polymorphic transformation and recrystallisation (FOLK, 1965). Aragonite to calcite transformation has taken place by preserving the original wall structure of the skeletons (Fig. 6c). According to BATHURST (1975), this is a wet polymorphic transformation process which proceeds with the aid of solution films. Several workers (FRIEDMAN, 1964; MATTHEWS, 1967; LAND, 1967; GAVISH and FRIEDMAN, 1969; STEINEN and MATTHEWS, 1973; STEINEN, 1974; CHILINGAR *et al.*, 1979; LAND *et al.*, 1980) studied the carbonate diagenesis in ancient and recent rocks and carbonate sediments which interacted with meteoric water and suggested that kinetics of water transport through the sediment controls the efficiency of aragonite to calcite transformation. The alteration of aragonite to calcite is more rapid in fresh water phreatic conditions.

Implications

Modern and Holocene limestones are composed mostly of unstable minerals aragonite and high-magnesium calcite (MATTHEWS, 1968). As the neomorphic limestones studied here comprise of only low- magnesium calcite, their formation during the Holocene

and Recent has been ruled out. The neomorphic limestones further consist of marine fauna (*Pseudorotalids*). It could be that the sediments that were neomorphosed might have formed on the shelf during one of the Late Pleistocene high stands of sea level. MOORE (1981) showed six well established interglacial high sea level positions (with high points between -40 and +7 m) and five low sea level positions (upto -70 m) during Late Pleistocene (Between 28,000 years and 135,000 years B.P.) relative to the present sea level.

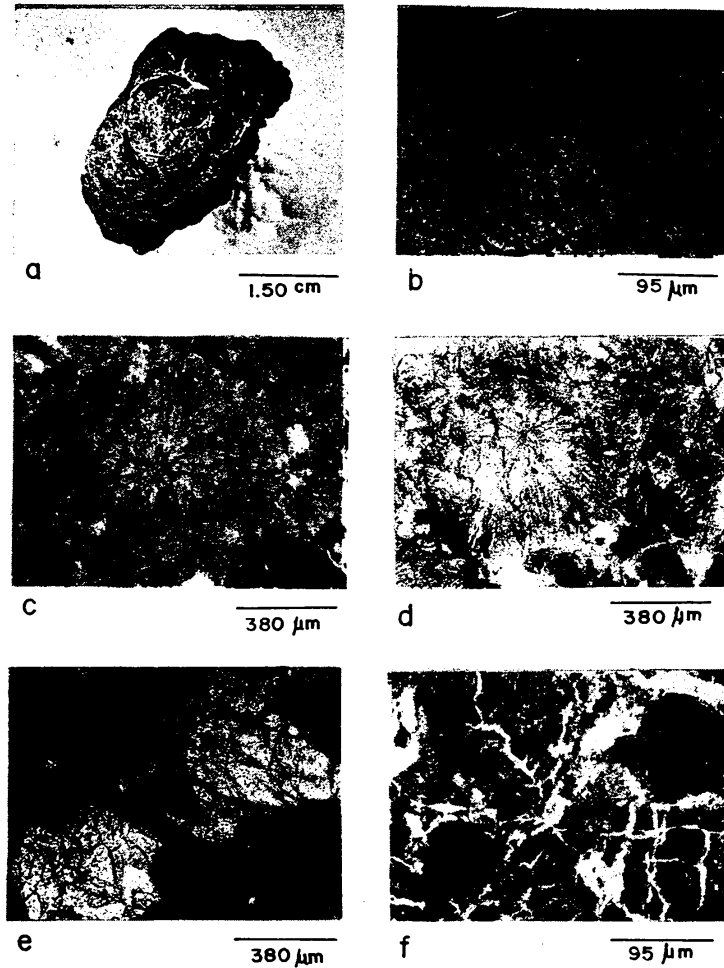


Fig. 7. Sample no 10 off Goa, (a) polished section of pisolite showing macro- and micro fractures and one side thickening of pisolite, (b-f) photomicrographs: (b) *Microcodium*, (c) neomorphosed *Microcodium*, arrows show the positions of inclusions which are former crystal terminations (d) fibrous calcite cement, (e) acicular calcite (arrows) filling the dissolution cavities and (f) dendritic calcite cement.

The neomorphic limestones have resulted due to subaerial weathering processes of preexisting carbonate sediments. GAVISH and FRIEDMAN (1969) reported sequence of diagenetic changes in the sediments exposed to subaerial conditions and divided the diagenetic changes into different stages and set the time period for each stage to complete. According to them, the growth of neomorphic spar occurs after the sediment mineralogy was converted into low-magnesium calcite and is present in limestones with an age ranging between 130,000 and 170,000 years B.P. At about 135,000 years B.P., the sea level was 2 m above the present position (MOORE, 1981). Therefore, it is assumed that the sediments formed at this time or earlier than this period. During

subsequent regressive stages the sediments were exposed to subaerial conditions and then onwards mineralogical stabilisation and neomorphism has taken place. Therefore, these are indicators of high sea level stands during the Pleistocene on the shelf.

The ecological conditions of *Pseudorotalia* are similar to *Ammonia*. They prefer both sandy and muddy substrates. The maximum population of *Ammonia* occur at about 30 m where precipitation exceeds evaporation and nearshore salinities are lower than normal (WALTON and SLOAN, 1990). The abundance of *Pseudorotalids* in the neomorphic limestones implies that higher rainfall conditions prevailed when the carbonate sediments were formed.

Continental limestones

Samples from the continental shelf south of Ratnagiri and Goa

Stations 63 and 10

These are the pisolitic limestones recovered from 60 m water depth. Low-magnesium calcite and quartz are the major minerals in the pisolites. Polished sections show thickening of pisolites in one side with intermittent macro- and microfractures (Fig. 7a). Microfractures are filled with sparry calcite. Micrite showing clotted and pelloidal texture is the dominant component in the pisolites. Ovoid to subspherical grains consisting of petal-like calcite prisms about 100 µm long aggregate around the nucleus and occur as rosetts (Fig. 7b). These grains resemble *Microcodium* which has been described as a resultant structure formed by fungi in association with cortical cells of a plant root (KLAPPA, 1978). Grains similar to spherulites displaying radial fibrous calcite apparently formed by neomorphism of *Microcodium* (Fig. 7c) and, root voids occluded by spar calcite are present. Fibrous calcites (Fig. 7d), acicular calcite (Fig. 7e), flower spar and dendritic calcites (Fig. 7f) occur as cements.

Microcodium grains have been extensively reported in calcium carbonate-rich soils and calcretes ranging from Eocene to the present day and are indicators of subaerial exposure conditions (KLAPPA, 1978). The occurrence of fractures, fibrous calcites (Fig. 7d) and acicular, flowerspar and dendritic calcite cements (Fig. 7e and 7f) in the pisolites were discussed at length (RAO, 1990) and the suggestion made that these resulted due to intense drying conditions at the time of their formation.

Implications

The pisolitic limestones described above are similar to caliche pisolites and are indicators of terrestrial conditions. Neomorphic growth is geologically long time required process and has been observed in caliche pisolites. It is therefore suggested that the caliche pisolites formed during the Late Pleistocene in association with moderate rainfall and arid climate.

A model of carbonate sedimentation on the western shelf of India

During the Pleistocene high sea levels, carbonate sedimentation has taken place on the continental shelf. In subsequent regressive stages, these carbonate sediments were transformed into neomorphic limestones through subaerial diagenesis. For the reasons discussed above, it is believed that the sediments in neomorphosed limestones occurring off Ratnagiri were formed in association with higher rainfall conditions at about 135,000 years B.P or earlier. In contrast, the caliche limestones collected at 60 m water depth off Goa indicate arid climate with less rainfall. The period of caliche formation is also Late Pleistocene. As caliche pisolites are not completely neomorphosed, it is believed that the caliche pisolites are younger than neomorphic limestones. The presence of caliche pisolites and neomorphic limestones on the shelf implies their

formation at different times and a varied climate and rainfall existed within Late Pleistocene probably consistent with sea level changes.

As far as the Holocene sea level is concerned, intertidal to subtidal conditions existed between 120 and 150 m water depth at about $11,040 \pm 400$ years B.P. The Fifty Fathom Flat was a shallow submerged reef during Holocene. This flat was exposed to vadose conditions after 8,960 years B.P., perhaps due to sea level fluctuations and/or due to tectonic disturbances on the outer shelf. Thus the reefs were subjected to erosion and produced fragmented skeletal components and aragonite muds. During emerging conditions the low/moderate energy conditions prevailed which were not conducive for the formation of true oolites. Pseudo-oolites were therefore formed on this flat. From vadose diagenetic textures of the pseudo-oolitic limestones, it is inferred that arid climate associated with low rainfall continued much later than 8,960 years B.P. suggesting that the intensity of the SW monsoon could be much younger than 8,960 years B.P. The submergence of the shelf has taken place due to Holocene transgression. Corals started growing with continued rise of sea level and advanced shoreward. Some time in the Middle/Late Holocene the environmental conditions switched over to humid tropical climate associated with SW monsoon. This change may have taken place at about 8000 years B.P. (admittedly tentative). This suggestion is made because relict coralline limestones dated about 8000 years B.P. were reported by VORA and ALMEIDA (1990) on the central west coast of India. With climatic change, heavy monsoonal rains are expected which bring large terrigenous flux to the sea. This abundant flux together with rapid rise of sea level (above optimum depth conditions for coral growth) were the probable factors responsible for the relict nature of coralline limestones on the shelf. Sea level reached its present position between 5,000 and 6,000 years B.P. Seasonal flux discharged to the sea started accumulating as modern clays on the inner shelf.

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