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QUATERNARY SEA-LEVEL VARIATION, SHORELINE DISPLACEMENT AND COASTAL ENVIRNMENT

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Pleistocene Climate and Sea-Levels - A Study of the Microfacies Characteristics of Carbonate Aeolianites (Miliolitic Limestone) of Gujarat Coast, India.

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ABSTRACT

Carbonate Aeolianites, a common and conspicuous facies of the Pleistocene and Holocene, provide a wealth of information on fluctuating Quaternary Climates and sea-level changes. The Indian subcontinent having a vast coastline with a varied Quaternary history, exposes along the Gujarat coast, some of the excellent outcrops of Quaternary carbonate rocks, popularly known as "Miliolitic Limestone" of Middle-Late Pleistocene Age. These carbonate deposits with varied field characteristics and textural parameters have been studied in the past to establish the fluctuations of Pleistocene climate and sea-levels. The microfacies and diagenetic character of the Pleistocene carbonate accumulations of Gujarat Coast, Western India are documented in the present paper in order to understand the palaeoclimatology and palaeoenvironmental aspects. The porous, fine-medium grained, miliolitic limestone display large-scale cross-stratification with high angle fore sets dipping chiefly to landward. The benthonic foraminifera-dominated limestone, a pelletal packstone-grainstone, is characterized by early stage cement and other diagenetic fabrics characteristic of vadose zone involving dissolution, cementation, neomorphism and micritization. Critical evaluation of the field data, compositional and diagenetic characteristics points to a Middle Pleistocene high sea (+25 m asl) which subsequently regressed to a low level (-100 m bsl) at the close of Pleistocene manifest by the reworking and sub-aerial exposure of the carbonates and subsequent action of meteoric diagenetic processes.

Key Words : Sea level, Microfacies, Carbonate, Limestone, Gujarat coast, India.

INTRODUCTION

Natural variations in sea-level are evident over a large range of time and space, from the pulse of diurnal tides to globally coherent variations in sea level occurring over many millennia. On the geologic time scale, evidence from coral reefs, oxygen isotopes and other records suggest globally coherent connections between climate and sea level. Variation in climate has causal connections with the geological, biological and hydrological processes that affect sea-level. The fluctuation of sea level in association with the transitions between cold glacial and warm interglacial periods is the most obvious mainfestation that is evident over many glacial-interglacial cycles spanning millions of years (Warrick, 1993). The Quaternary Era is distinguished by widespread sedimentological and biological evidences of climatic and sea level fluctuations. Evidence based on stable-isotope composition, textures, mineral composition and microfacies characteristics of the limestones supports the conclusions that many marine limestones of Quaternary age became rocks when their particles were subaerially exposed. Many marine limestones, whose antecedent sediments were deposited in shallow marine waters, occur in successions that are many times thicker than the inferred depth of water in which the original carbonate sediments were deposited. Such relationships require us to infer that the sea floor subsided through many hundreds of thousands of meters. By contrast, the demand that subaerial exposure was necessary for cementation required that generally subsiding sea floor be exposed periodically to fresh water. One way to reconcile these contrasting processes was to suppose that the sea floor or sea-level alternatively rose and sank (Friedman and Sanders, 1978).

Although there are many factors which determine the nature of carbonate formation, geotectonics and climate together control the sea level. Climate along with geotectonics is also important in determining water circulation, temperature, salinity, nutrient supply, turbulence, storm and tidal current stregth and wave velocity. Rises and falls in sea-level also have implications for the diagenesis of carbonates, especially in the degree of subaerial exposure and meteoric diagenesis. Therefore, the present work based on the study of the various microfacies and diagenetic characteristics of Quaternary carbonates has been utilized in order to understand the fluctuation of climate and sea-levels during the Pleistocene along the Saurashtra coast.

Examples of Quaternary carbonate deposits occurring as transverse dune ridges parallel to the shoreline are known from Bermuda, Bahamas, Yucatan, Spain, Mediterranean Coast, Trucial Coast, India, etc. (Fig.1). These rocks forming a

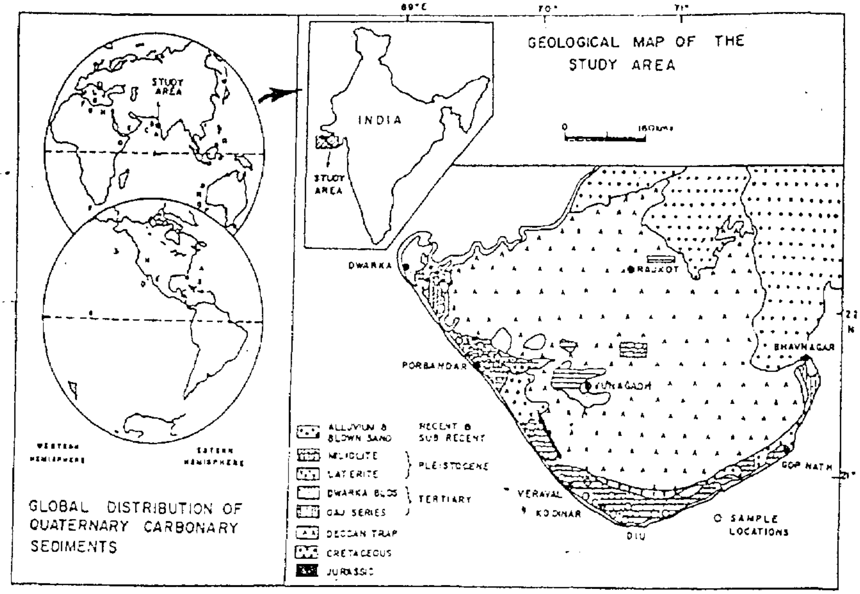

Fig.1 Location Map

conspicuous facies of Pleistocene and Holocene, are better referred to as Carbonate Aeolianites (Scholle et al. 1983). The Gujarat Coast contains some excellent outcrops of such carbonate rocks, known as "Miliolitic Limestone", belonging to Middle to Late Pleistocene Period. The varied field and textural character of these rocks provide a wealth of information on the Quaternary climate and sea-levels and attracted the attention of many earth scientists (Glennie, 1970, Verma and Mathur, 1978; Merh, 1992). In all about 200 thin sections, made out of the samples collected from all the localities along Saurashtra Coast from surface exposures and quarry sections, have been examined for their composition and diagenetic characteristics.

These rocks, exposed over an area of approx.5,300 sq.km. form a series of ridges parallel to the coast (Pl.I; Fig.1) and extend land-wards up to an elevation of about 25 m with highly variable thickness and are seen resting on shell limestone (beach rock). The porous, fine-medium grained limestone display large-scale cross-stratification with landward dipping high angle fore sets (Pl.I;Fig.2). Palaeocurrent analyses indicate a SW to NE movement of the sediment transport (Mahender, 1996). The tops of carbonates show karst erosion (minikarst-Plate-I;Photo 4&5) and development of soil or hard, dense caliche crust. ^{14}C and $^{230}Th/^{234}U$ dates (Baskaran, 1986 and Somayajulu, 1993) indicate broad age range of 30-235 kyrs. The field evidences and grain-size textural parameters suggest a fluctuating shallow marine-beach-coastal dune depositional environment. Possibly, the limestone particles have originated in a shallow marine setup during high sea level and subsequently with progressive regression of the sea are exposed to the reworking by winds and redeposited as miliolite rocks which have subsequently undergone meteoric diagenesis (Mahender, 1996).

MICROFACIES AND DIAGENETIC CHARACTERISTICS

Petrographically these rocks, described as biosparite to biopelsparites (pelletal packstone to grainstone) with a variety of allochems cemented together by sparry calcite, are comparable with the SMF-11 and SMF-18 of Wilson (1975). Allochems including the skeletal particles

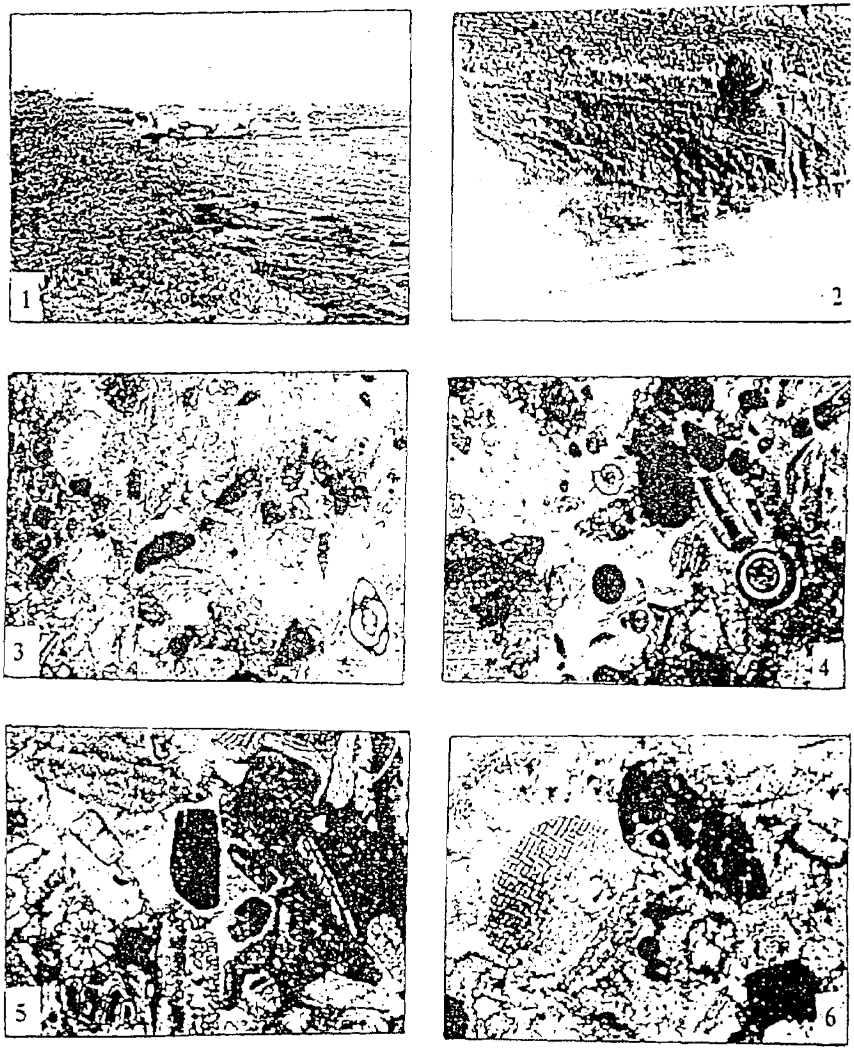

Plate-I

(Magnification of phtotmicrographs -40X, otherwise mentioned)

1. Carbhonate aeolianite ridge paralleling the southern Saurashtra Coast.
2. Photograph displaying large scale cross-bedding characteristic of Aeolianites.
3. Photomicrograph exhibiting the dominant foraminiferal assemblage varying from broken to well preserved tests.
4. Photomicrograph displying the various skeletal allochems (mollusc, brachiopod, forams etc) set in a sparry calcitic cement.
5. Photomicrograph representing the echinoid skeletal allochems. Also seen in the center, two cement generations one of which is isopachous cement with a radial fabric and the other one is a drusy mosaic of sparry calcite.
6. Photomicrograph displaying transverse section of a bryozoan bioclast and syntaxial growth of echinoid skeletal element.

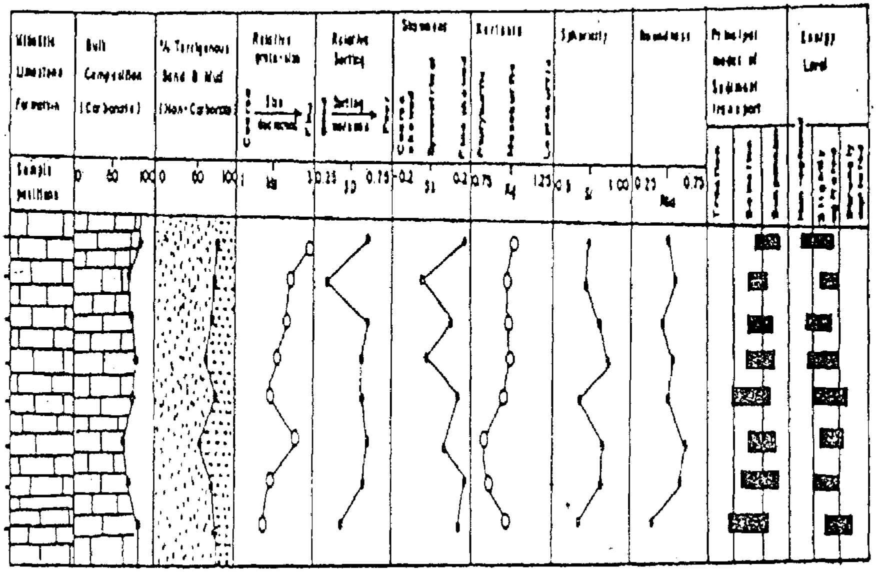

Fig.2 Vertical Relationships Between Grain Textural Attributes and the Parameters of the Depositional Environment

(forminifera mollusca, brachiopoda, bryozoa, echinoderm, algae and corals) and non skeletal particles (pellets, oolites, aggregate grains, intraclasts and detrital materials) are in medium to fine sand range and generally moderate to well rounded. The skeletal allochems vary from <10% to 50% and comprise well presevee tests of forams and broken fragments of diverse fauna and display varying degree of abrasion and rounding. The allochem composition has a striking similarity with present day unconsolidated beach and coastal dune sands and can be comparable to foramol association characteristic of temperate carbonates. The detailed nature of occurrence and character of individual allochems is given in Table .1. The vertical variation of textural parameters of the allochemical constituents (Fig.2) and selected chemical elements (Fig.3) clearly suggest a fluctuating condition of the sea with varying energy conditions. The orthochemical constituents of these rocks include various pore filling and neomorphic spares consisting of fibrous/drusy calcite, coarse sparite and micrite seen in the form of isopachous rims, syntaxial over growth, meniscus and dripstone varieties etc. In composition, the carbonate fraction of these rocks consists mainly of calcite and aragonite.

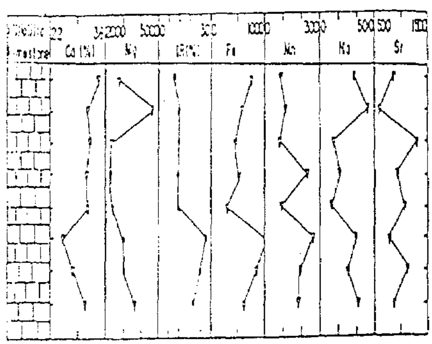

Fig.3 Vertical Variation of Selected Chemical Elements of Miliolic Limestone Diu

Diagenetically, these rocks are characterized by early stage cements (meniscus or grain-contact cement gravitationa or pendulous cements) and the diagenetic fabric characteristic of vadose zone involving processes of dissolution, cementation, neomorphism, micritization and compaction. The various diagenetic features observed in these rocks include (i) a thin layer of

Table-1 Microfacies characteristics and environmental interpretations

Limestone	Nature of Preservation	Environmental Interpretations Constituents
Foraminifers	Represent dominant benthonic and a few planktonic forms belonging to Rotalid, Miliolid, Textularidae and Globigerinidae families, are commonly well preserved as multi chambered although the chambers are detached in some and interior of chambers is filled with sparite/micrite. (Pl.1: Fig.3).	Abundant benthonic forams, their abraded nature is indicative of high energy shallow water environment.
Molluscs	Pelecypod and gastropods are seen as broken fragments with their characteristic lamellar, foliating shell wall structures The original aragonitic wall structure in some samples is neomorphosed to calcite spar. (Pl.1; Fig 4)	The fragmented and abraded bioclasts indicate high energy conditions
Brachioped	The skeletal elements are normally well preserved because of their low-Mg calcite shell mineralogy. (Pl. 1; Fig 4)	Presence of rotten bioclasts to micrite rimmed grains is also indicative of shallow water depths
Echinoderms	Represented by random slices through plates and spines, have been identified as single crystals of calcite The plates though exceedingly organisms porous, are often well preserved due to their stable Low Mg calcite mineralogy. Syntaxial growth on the tropics the plates is a common feature (Pl. 1 Fig 5)	Significant amount of reef building (corals) and non-skeletal particles are indicative shelf association characteristic of sub-
Bryozos	Are represented by polymorphic tubes of various width and with their arrangement in the axial surface of the zoaria. Except for filling of pores the bryozoans have not suffered any obvious diagenetic alteration suggests considerable reworking. (Pl 1, fig 6)	The near spherical, highly rounded and abraded nature of bioclasts
Pellets	Ranging in size from 30 to 200 microns have a uniform diameter with a length to width ratio of 2:1 and vary from 10% to 40%. These are usually spherical-elliptical, well-rounded, often with thin dark rim which helps to define outer boundaries of pellets in micritic matrix (Pl 2, fig 1)	In general the allochem composition is comparable to foramol association characteristic of temperate climates.
Aggregate	Scattered aggregate grains resembling to grapestone lumps sometimes coated with micritic envelops are noticed consisting of agglutinated pellets, bioclasts and a detrital materials The cementing material within the agglutinated particles is similar to that of whole rock	The petrographic composition of the carbonates clearly suggest a shallow marine-beach-coastal dune depositional environment.
Ooids	Multi layered as well as superficial ooids are present in having relatively large nucleius which is usually a micritic pellet, quartz grain or bioclast Some samples show sparsely distributed oolites with well preserved concentric and radial structures The individual laminae of the ooids range from 3 to 15mm in thickness and the cortex of some ooids is partially/wholly lost due to diagenesis (Pl 2, Fig 1)	The limestone particles originated in shallow marine waters during high sea-levels are exposed to reworking by winds during subsequent regression and have been redeposited as miliolite rocks
Cortoids	Some grains with relatively thin micrite coatings preserving in some case the internal structures are identified as cortoids, originated probably, due to decomposition of indigenous organic matter and simultaneous replacement by micrite and clay-sized carbonate particles (Pl 2, fig 2)	
Non-carbonate particles	The detrital terrigenous materials such as abundant quartz and a few grains of feldspar, pyroxene, and rock fragments of basalt and quartzite constitute the non-carbonate sand silt fraction	

tightly packed needle-like calcite crystals that grew normal to the grain-surface and projecting outward into the intergranular pore space (Pl.1; Fig.5), forms a rind approximately 100mm thick, (ii) in some samples this coat is followed by blocky/drusy cement which in turn is separated by vadose silt, (iii) Syntaxial growth of calcite on early formed grains documented for single crystals of echinoderm (Pl.2; Figs. 3 and 4) fragments formed due to the development of large optically continuous crystals, (iv) large scale development of caverns and pot holes in the miliolitic limestone related to the dissolution process (Pl.2; Fig.6), (v) neomorphic processes (calcification, micritization) represented by diagenetic structures composed of calcite prisms arranged in spherical, elliptical, bodies (Pl.2; Fig.5) which can be compared with Microcodium as described by Ward (1975) and Calvet et al. (1975). These according to Klappa (1978), are spherical structures with radiating calcite prisms produced by the calcitization of microhizal associations and commonly seen in aeolianites and calcretes and (vi) occasional instances of compaction evidenced by breakage/telescoping of some grains, tangential / truncated contacts, and overpacking (Pl.2; Fig.6).

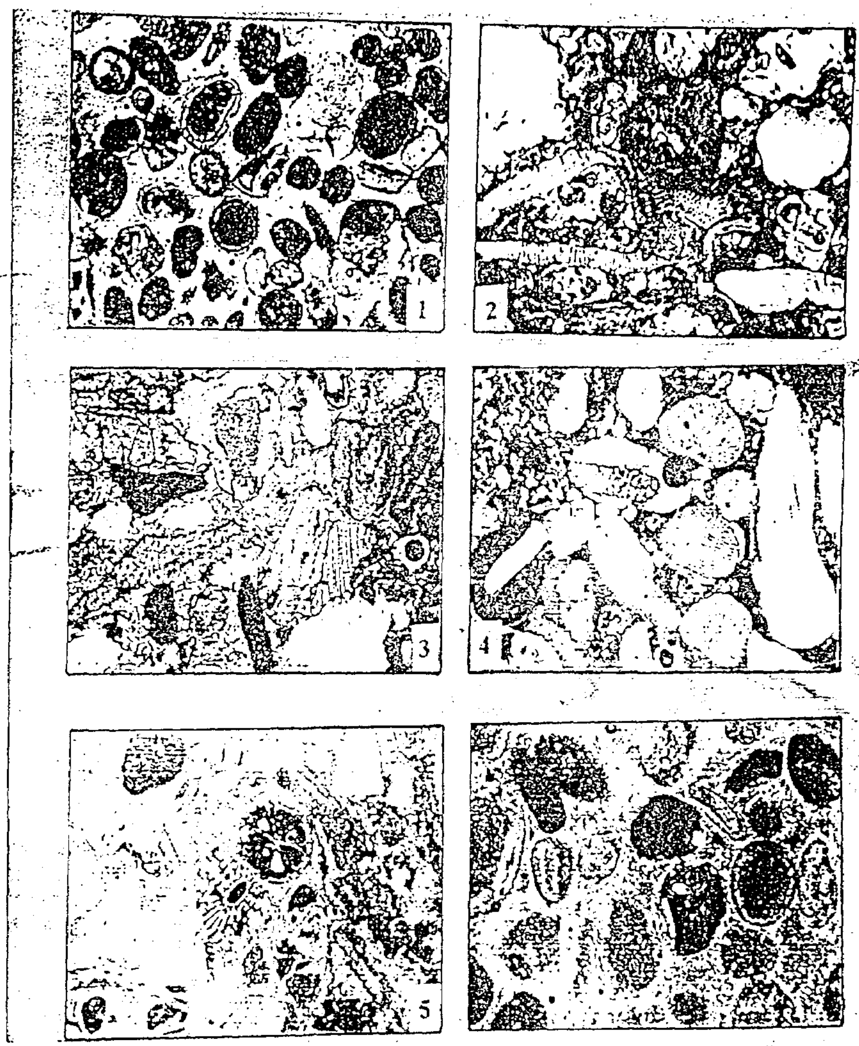

Plate-2

(Magnification of phtotmicrographs 40X; otherwise mentioned)

1. Photomicrographs displaying the non-skeletal framework elements (*pellets, oolites etc.*) of *carbonate aeolianites*. Micritization of oolites, bioclast to pellet transformation is also observable.
2. Aggregate grains also with some non-carbonate terrigenous particles of cherty quartz present in the limestone.
3. Photomicrograph presenting the significance of micrite envelop in preserving a sparite filled molluscan fragment during diagenesis and syntaxial rim cementation of echinoid skeletal elements.
4. Photomicrograph displaying gravity (and/or meniscus) cements.
5. Sparite cements and possible root void (microcodium) filled with radiating prisms are observable in the section.
6. *The effects of compaction (telescoping of oolites, close packing) and selective dissolution ooids exhibited by the* carbonate aeolianites.

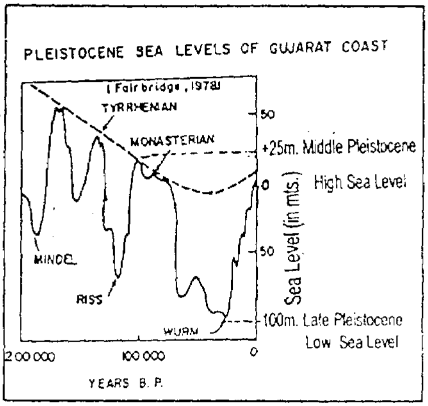

Fig.4 Fluctuating Pleistocene Sea Levels Along Gujarat Coast, Superimposed on the Sea Level Curve of Fairbridge, 1961

IMPLICATION OF CLIMATE AND SEA LEVEL FLUCTUATIONS

The quaternary Period is characterised by climatic variations, mostly related to the alternating world-wide glacial and interglacial stage which ultimately are responsible for eustatic sea-level changes. The various sea-level curves generated for specific areas are found to be useful in reconstructing global scenarios. Fluctuating Quaternary climate and sea level signatures are well recorded and are revealed by various field and laboratory features. Merh (1987, 1992) provides an exhaustive review of the sea-level changes along Indian Coastline. The fluctuating condition of climate and sea-levels along Saurashtra Coast is clearly evident from Fig.2. The interpretations derived out of the present study are in agreement with those of other works.

The predominant accurrence of smectite group of minerals in the clay fraction of alluvial deposits and the presence of pedogenic carbonates within the fluvial deposits suggest a semi-arid climate, with a mean annual rainfall of little less than 700 mm (Lele, 1975). The micromorphological characters such as haematitic coatings on weakly weathered hornblende and plegioclase grains and dissolution features of these rocks attributed to a semi-arid climate of Middle Pleistocene Period. Petrographic composition of miliolitic limestone is similar to temperate carbonates with sea water temperature fluctuating between 0°-15°C (corresponding to Middle Pleistocene High' Sea). The textural characteristics, mineralogy, and diagenetic observations (early diagenetic vadose cements, cement geometry, microcodium, dissolution features etc.) suggest an arid to semi-arid climatic conditions corresponding to the regressive phases of the High sea. The petrographic and mineralogic observations suggest fluctuating climatic conditions from temperate (at the time of their initial formation of particles) to semi-arid conditions of a sub-aerial environment during which the particles have been reworked by wind and rain water to give rise the present setup. Reworking of the these sediments is supported further by the surface textures of quartz and forminiferal tests (Pl-2, Figs.5 and 6).

The occurrence of the Miliolitic rocks at various heights prompted many workers to invoke a succession of high strandlines during the Quaternary. Verma and Mathur (1978) recongnized five levels and correlated them with the world-wide eustatic high sea-levels of Faribridge (1971). Merh (1977) came to the conclusion that the high sea responsible for the deposition of the miliolitic limestones had never risen to these heights. In the absence of isotopic data it was assumed that this high strandline dated back to Early Pleistocene was represented a regression to a depth of -20 m during Late Upper Pleistocene. Patel (1991) provides evidences of a +20 m to +25 m high strandline corresponding to Miliolite formation.

The marine nature of the carbonates as evidenced from field and laboratory study and the occurrence of beach rock at the base of limestone up to 25m altitude suggest their formation during the Middle Pleistocene transgression when the sea-level was +25m asl (Fig.4). The submerged miliolites and 'sandy' ridges and the gradient configuration of the Present outer continental shelf clearly indicate that subsequent regression of the sea exposing major part of the limestones for sub-aerial processes. The various diagenetic features and fresh water cementation of the miliolitic limestone clarly suggest their sub aerial exposure after the formation of the constituent particules in shallow marine environment. The depth up to which these rocks occur below the present sea-level can be related to low strand line during which these rocks are subaerially exposed. The various evidences in favour of fluctuating condition of Pleistocene sea are listed in Table 2. Based on the observations made in the present work and the other evidences (Table 2) a low strand line of -100 m bsl at the close of Pleistocene can be suggested. Therefore the petrographic study of these confirms the Middle Pleistocene +25 m high strandline and a Late Pleistocene -100 m low strandline. These two levels are comparable with the published strandline curves (Fairbridge, 1960, 1961, Shepard and Curry, 1967) related to Middle Pleistocene transgression and Late Pleistocene regression corresponding to interglacial and glacial periods respectively.

phases of Middle Pleistocene high Sea. The progressive regression of Middle Pleistocene high sea synchronized with glacial stage marked by semi-arid dry climate exposed enormous amount of beach and littoral sands to reworking by SW-NE onshore winds and rain waters resulting the deposition of the carbonate sediments. Subsequent humid phase and fresh water diagenetic processes in a vadose environment resulted in consolidation and cementation of the miliolitic limestone. Present study supports the Middle Pleistocene High sea-level (+25 m asl) which progressively fell down to -100 m bsl by the Close of Pleistocene.

Table-2 Envidences of fluctuating condition of Pleistocene sea along *Saurashtra Coast*

	Evidences in favour High Strandline		Evidences in favour Low Strandline
1.	Location of alluvial plains at around 20-30m all along the south Saurashtra coast resulted probably due to combined fluvial and coastal marine processes (Patel, 1991).	1.	Submerged terraces on the western continental shelf of India at depths of -92, -84, -71,-65, -55 and -31 metres prominent of these is fifty fathom flat (-90m terrace) (Nair, 1975, Wagle et al 1994)
2	Fan shaped drainage pattern of river channels and alluvial deposits at around 25-30m contours and straight courses until they meet the present sea.	2.	Relict carbonate sand zone consisting of coated grains, ooids, benthic foraminifera of shallow water origin and large foraminifera encrusted with intertidal barnacles at the depth of 60-90m (Hashmi & Nair, 1976; Chauhan & Almeida, 1993).
3.	Relict alluvial patches and terraces etc	3	Presence of beach rock at 91m depth and oolitic limestones at 95m depth showing vadose diagenetic textures indicates the subaerial condition of present-day outer continental shelf during Pleistocene glaciation (Rao et al. 1990).
4.	Occurrence of Beach rock at 25m. elevation	4	Partially buried algal reefs on outer shelf to the south of the study area (Vora & Almeida, 1990).
		5.	Presence of caliche pisolites (of Late Pleistocene) on the western continental shelf of India (Rao, 1990) characterizing semi-arid climatic conditions with moderate rainfall.

CONCLUSIONS

The fluctuating Quaternary climate and sea levels are well reflected in the variation of textural and compositional attributes of the Miliolitic Limestone. The skeletal composition, excellent preservation of pellets and some of the fossils, and the presence of broken as well as intact tests of the forminifera with varying degree of abrasion leading to micritization and peloid formation clearly suggest the influence of coastal eolian, beach to shallow marine transportation and depositional processes. The rocks represent reworked ancient biogenic beach sands generated during regressive

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