

## Chapter - VI

### D I A G E N E S I S

#### GENERAL

The diagenesis is a phenomenal complex of events that transfers the loose sediments into an indurated rock. An indepth study of the diagenetic history of sedimentary rocks, especially the limestones, leads towards a proper understanding of syn-depositional as well as post-depositional environments operative during the geological past. It was Von Guembel (1868) who introduced the term 'diagenesis' in the geological literature which was then defined by Walther (1894) as "...all those physical and chemical changes which a rock undergoes after its deposition, without the introduction of rock pressure or igneous heat". However, there does not prevail any generalisation on this term amongst the scientists. Grabau (1913) designated diagenesis as

"static metamorphism", while Pettijohn (1957) used "lithification" instead. Chilingar et al. (1967), in general agreement with Krumbein (1942) and Ginsburg (1957), adopted a rather all inclusive definition of diagenesis as, "the diagenesis includes all physicochemical, biochemical and physical processes modifying sediments between deposition and lithification at low temperatures and pressures characteristic of surface and near-surface environments". Siever (1979) described the diagenesis as a function of mineralogy and chemistry of the sediments, composition of interstitial fluids, pressure temperature condition, geothermal gradient, time and nature of tectonic movement etc. and has represented schematically as per figure given below (Fig. VI.1).

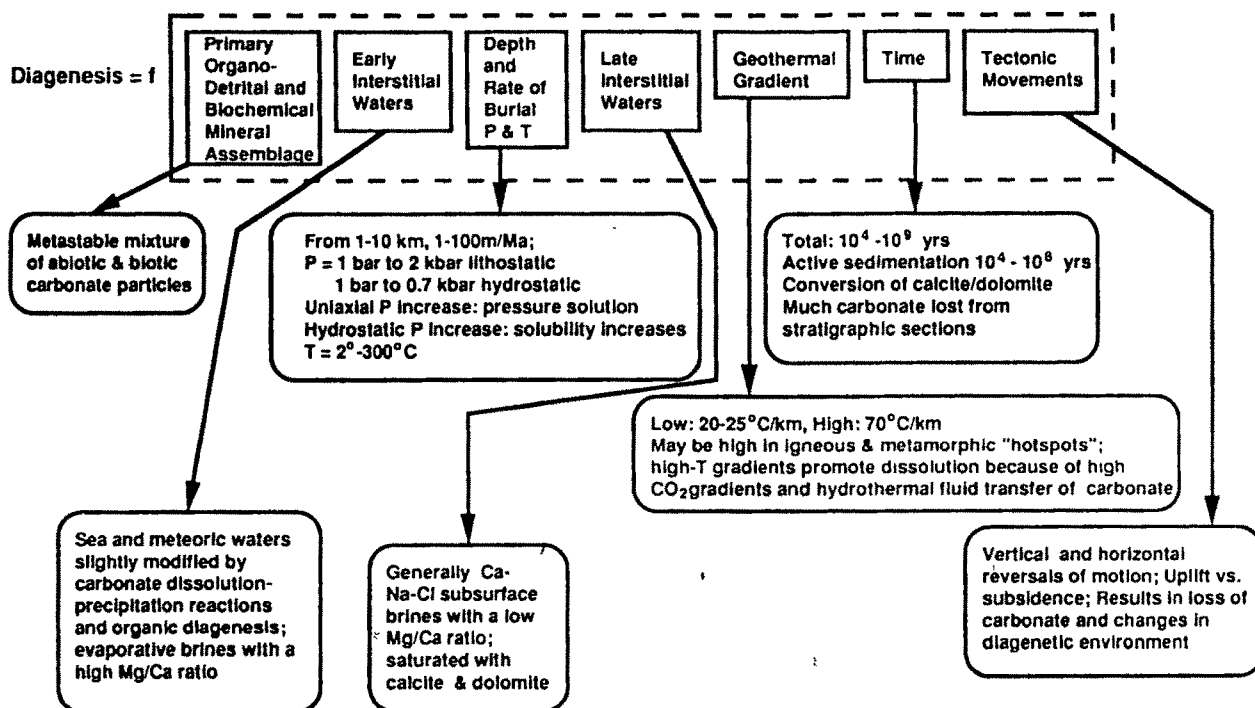
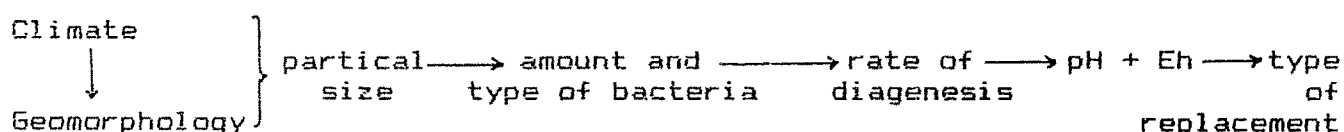


Figure VI.1 Schematic diagram of some diagenetic variables and their potential effects on the conversion of a carbonate sediment to a rock. (Adapted from Siever, 1979.)

Wolf (1963) has suggested that in the carbonate diagenesis the large scale environmental parameters like geological, geochemical, geographical, durational etc. influence the more local environments by one or another way, and these inturn influence the micro-environments. Thus, according to him there is a complete gradation and overlap of the factors that controls the consolidation of limestones which can be expressed as per below:



The organogenic carbonate sediments usually originate in shallow, warm, supersaturated tropical seas and get deposited within the subtidal to supratidal areas. In relation to this, in Saurashtra such bioclastic carbonate deposits though originated in marine environment, have been deposited in two distinct environment viz. beach and dune. It is now well accepted that the influx of freshwater into carbonate deposits, no matter beach or dune, greatly facilitates their compaction & cementation which further accomplished by dissolution and precipitation of  $\text{CaCO}_3$  and/or neomorphism. The role of freshwaters in limestone building is also evident by the following comment of Ginsburg (1957) - "...the late Pleistocene Miami oolite is thoroughly cemented by calcite at the exposed surface and below the ground-water level. But where it is still in the marine environment or above the ground-water table it is so friable that it can easily be broken down into individual ooliths". The various products have been well documented in Quaternary carbonates of Bermuda

(Friedman, 1964; Gross, 1964; Land, 1967; Land et al., 1967; Plumer et al., 1976; Budd, 1988; Budd & Land, 1990), Barbados (Matthews, 1968 & 1974; Harris & Matthews, 1968; Steinen & Matthews, 1973; Allan & Matthews, 1977), Israel (Gavish & Friedman, 1969) and Jamaica (Land & Epstein, 1970; Land, 1973).

An indepth account on the diagenesis of miliolite rocks of Kutch, that forms the counterpart of Saurashtra miliolites, was presented by Patel & Allahabadi (1988). On the basis of the occurrence of two generations of cements characterised by drusy rim cement, gravitational cement, dog-tooth cement, meniscus cement, syntaxial rim cement and pore-filling cement alongwith the vadoids & cortoids in Kutch miliolites, they (Patel & Allahabadi, op.cit.) considered their diagenesis in vadose environment under the influence of freshwater and described the lithification of these rocks into two broad stages viz. compaction and cementation. Patel (1991 b) has also given a brief account on the process of freshwater diagenesis in the inland miliolites of Kutch and Saurashtra.

In the present chapter the author has tried to evolve a comprehensive scheme of diagenesis for the Quaternary carbonate deposits of Saurashtra as a whole in light of the various laboratory studies and field observations alluded to earlier.

#### DIAGENESIS IN STUDY AREA

As stated earlier, the beach rocks and miliolite limestone of the study area are well cemented indurated rocks as compared to the stabilised sand dunes which are friable and poorly cemented.

Obviously the former two have undergone a long period of diagenesis. The diagenesis of these deposits was brought about in meteoric environment and controlled by some intrinsic (mineralogy, grain size, porosity and permeability) as well as extrinsic (climate, vegetation, time etc.) factors as invoked by James & Choquette (1984).

The scrutiny of number of thin sections aided by the field study and other lab studies like XRD, TL, SEM etc. of the various Quaternary carbonate deposits of Saurashtra has enabled the author to establish the following five sequential stages of their diagenesis which are in general agreement with the diagenetic scheme proposed by Land et al. (1967) and Gavish & Friedman (1969).

- Stage I     Stabilisation of initial sediments
- Stage II    Early cementation and compaction
- Stage III   Mineralogical stabilisation
- Stage IV    Dissolution and precipitation
- Stage V     Recrystallisation

#### Stage I : Stabilisation of initial sediments

This stage incorporates the generation of carbonate sediments and their stabilisation. All the three type of Quaternary carbonate deposits of Saurashtra basically comprise various types of allochems and detritals in variable amount. The allochems include aragonitic - molluscan shell fragments, corals, Halimeda algae, ooids etc. and high magnesian calcitic -

foraminiferal tests, echinoid spines, bryozoa, coralline algae etc. These allochems are metastable in seawater probably due to its supersaturated nature and higher concentration of magnesian ions. These constituents in beach rocks were deposited within the limit of littoral to spray zone areas of the retreating Middle Pleistocene high sea as revealed by their field and laboratory studies. Subsequently the finer sediments were lifted and dumped over the Saurashtra Peninsula by glacially strengthened southwesterly onshore winds and stabilised at sheltered sites in the hilly terrain and coastal plains during the following humid phase to give rise to the miliolite limestones. Similarly the younger stabilised dunal sands related to Holocene sea were also deposited in coastal areas.

#### Stage II : Early cementation and compaction

The second stage of diagenesis commences with early cementation and compaction after the stabilisation of carbonate sediments in a particular environment, either subaerial freshwater or submarine. This early cementation begins at the grain contacts or in the voids, from the saturated interstitial fluids. In beach rocks of nearshore environment such initial cementation is characterised by fibrous and micritic cements; their mineralogy being aragonite and/or high magnesian calcite (Stoddart & Cann, 1965; Moore, 1973; Milliman, 1974; Scoffin, 1987; Morse & Mackenzie, 1990 etc.). The precipitation of such cements in beach rocks is thought to be related mostly to the inorganic processes either due to the mixing of freshwater and seawater in intertidal

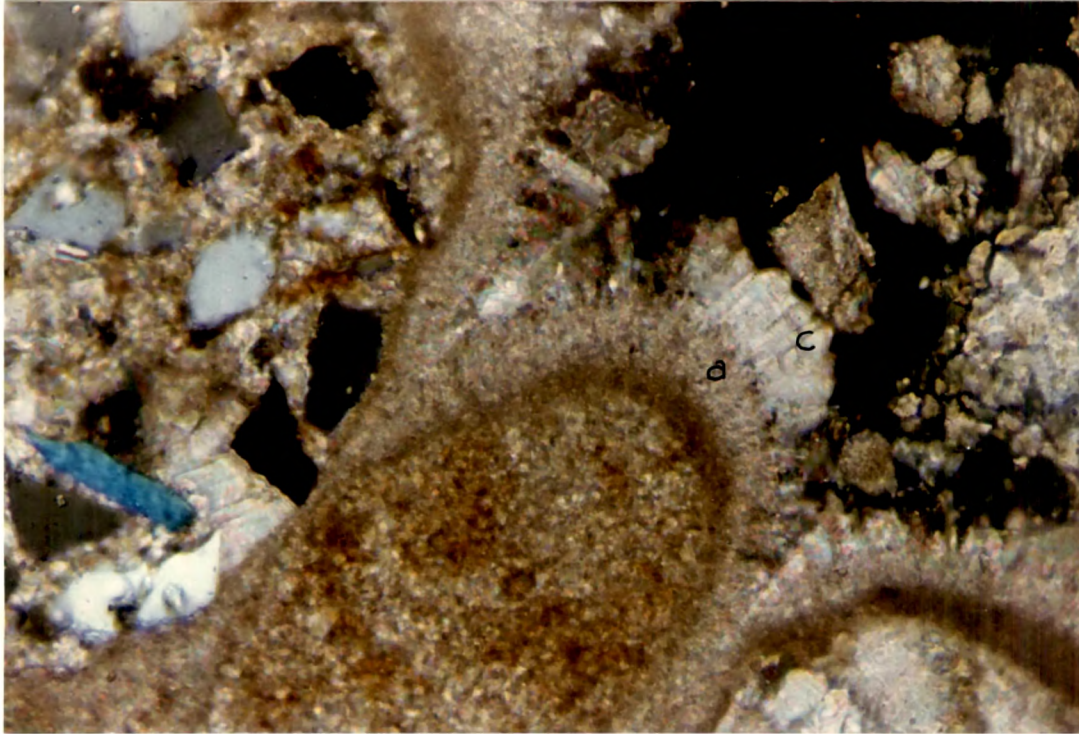
zones (Schmalz, 1971; Moore, 1973) or due to CO<sub>2</sub> degassing from the carbonate saturated nearby groundwaters (Thorstenson et al., 1972; Henor, 1978; Davies & Kinsey, 1973; Meyers, 1987). The beach rocks of Saurashtra (Dwarka, Baradia, Navadra, Porbandar, Gosa etc.) clearly show the presence of primary cement as rim of fibrous high Mg calcite and/or aragonite grown over an aragonitic micrite crust (Plate VI.1), revealing their formation in a typical littoral phreatic zone.

In miliolites the early cementation is characterised by mostly meniscus and thin drusy rim of low Mg calcite suggesting their precipitation in vadose meteoric environment (Plate VI.2). In quite a few thin sections dripstone-drapstone cement, circumgranular drusy rim cement and dog-toothspar cement are also encountered; all having low magnesian, nonferroan sparry calcite mineralogy as detected by staining solutions, which indicates shallow to deep vadose & partly phreatic freshwater conditions. During this stage even internal erosion and flowage of water might have taken place which is evident by the presence of vadose silt (Plate VI.3).

The early cementation process in miliolites must have been initiated under the fluctuating or seasonally changing vadose and phreatic (dry & wet) conditions as envisaged by the occurrence of diagenetically formed coated grains (vadoids) which are concentrically laminated grains by alternate microspar/micrite and sparite lamiinae the mention of which is made in the previous chapter. These grains resemble 'vadose pisoids' of Dunham (1969 b), 'diagenetic ooids' of Siesser (1973), 'calcrete pisoids' of

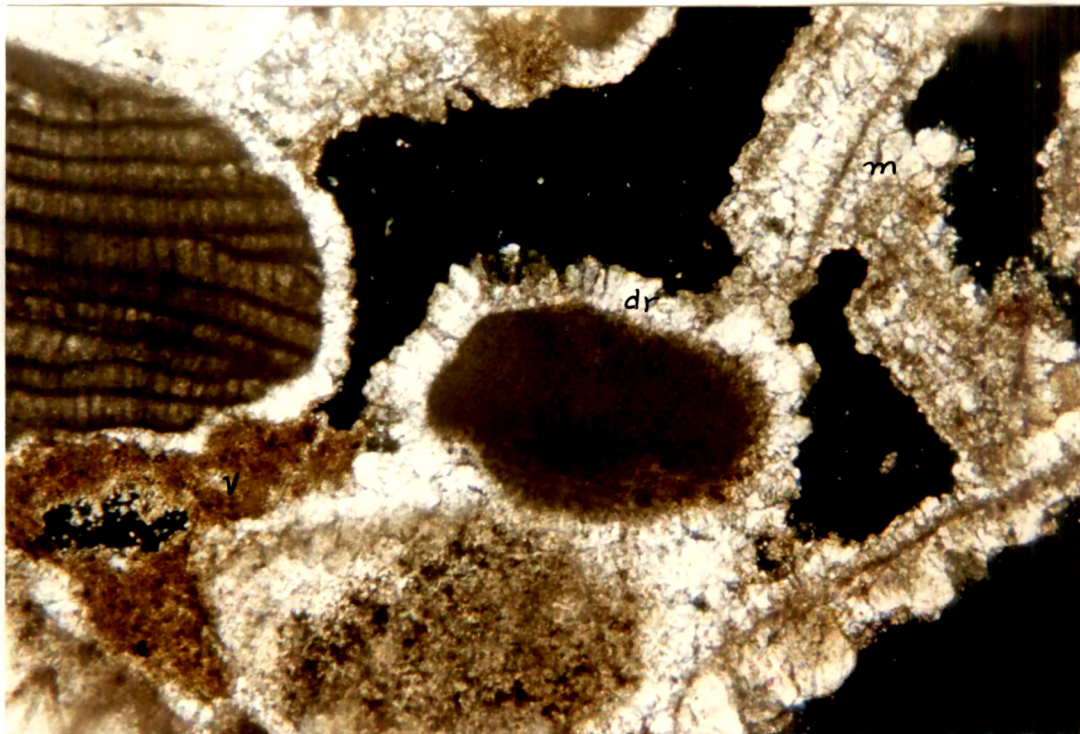


Plate VI.1



Photomicrograph of fibrous aragonite (a) and high Mg calcite (c) cements in beach rock (Crossed Nicols, 230X)

Plate VI.2



Photomicrograph showing meniscus (m) and drusy rim (dr) cements in miliolite. Note the presence of amorphous iron oxide in void (v) (Crossed Nicols, 120X)



Plate VI.3



Photomicrograph showing vadose silt (st) in miliolite (PPL, 120X)

Read (1974), Elloy & Thomas (1981) and Richter (1983), 'vadose ooids' of Harrison (1977), and 'pisoids with skeletal nuclei' of Esteban & Pray (1983). The downward or upward thickening of cortices, the transitional boundaries of these coated grains with surrounding cement and their comfortable fittings with other particles characteristically point to their insitu development (Plate VI.4). Such textural characteristics are typical of vadose freshwater diagenetic environments (Bretz & Horberg, 1949; Swineford et al., 1958; Wardlaw & Reinson, 1971; Steel, 1974; Assereto & Kendall, 1977; Hay & Reeder, 1978; Surdam & Stanley, 1979; Hay & Wiggins, 1980; Goudie, 1983; Peryt, 1983). Besides these multicortical scattered vadoids, there also occur thin alternate layers of unicortical vadoids and intragranular porosity in some of the miliolite deposits viz. Gop, Adityana, Dungarpur, Patanvav etc. (Plate VI.5). This obviously suggests a later stage of diagenesis where dissolution and precipitation of  $\text{CaCO}_3$  is involved. The process of formation of vadoids during this initial stage of diagenesis is however not fully understood. They can be formed due to the meteoric waters that flow through the similar type of carbonate sediments in upland areas enrich in  $\text{CaCO}_3$  which then gets precipitated around the nucleus to form their cortices; the coarser ones due to slow crystallisation and finer ones due to rapid crystallisation. The another mechanism involves fluctuation in groundwater table as suggested by Flugel (1982). The variation in climatic conditions is responsible in bringing about the water table fluctuations. The calcium hydrocarbonate ( $\text{CaHCO}_3$ ) dissolved in groundwater then rises to the surface by capillary action

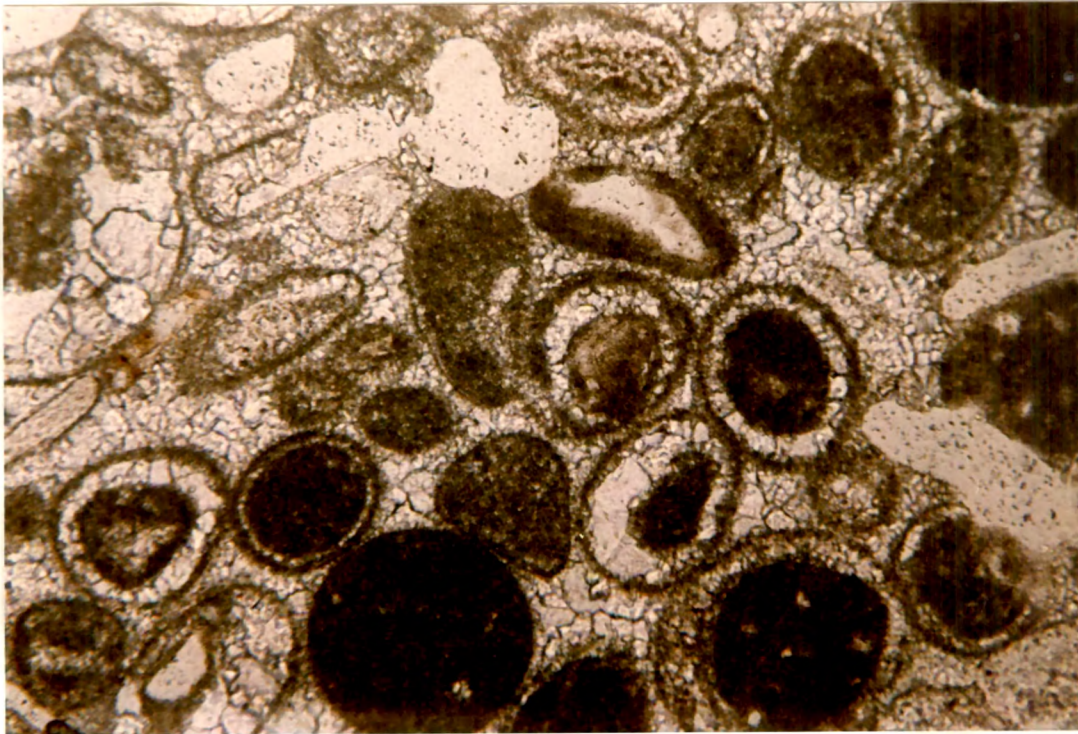


Plate VI.4



Photomicrograph showing tangential section of a multicortical vadoid in miliolite (Crossed Nicols, 120X)

Plate VI.5



Photomicrograph showing unicortical vadoids in miliolite  
(Crossed Nicols, 60X)

which upon evaporation deposits  $\text{CaCO}_3$ , thus giving rise to the alternate crystalline and cryptocrystalline coatings. The author wishes to mention that the process of formation of such vadoids must have consumed a long span of time during which the diagenesis of miliolites continued mineralogical stabilisation and diagenetic maturity as envisaged by the laboratory studies. As the process of development of coated grains (vadoids) commenced in present stage, they have been discussed at this juncture.

In this stage the mechanical processes, besides the chemical precipitation, were also active that brought about the compaction by packing of the various constituents with reduction in pore spaces, thus causing decrease in bulk volume of the rock. In general the degree of compaction depends upon the frequency ratio of fine grained to coarse grained sediments. The smaller value of this ratio suggests poor compaction while its higher value facilitates better compaction. Coogan & Manus (1975) and Flugel (1982) have recognised several factors that effect compaction in bioclastic carbonate deposits. Based on the role played by the various parameters, these factors can be broadly classified as per below :

1. Inherited factors

Grain size, shape & their sortings, Grain packing and Grain mineralogy.

2. Dynamic factors

Overburden pressure, subsurface temperature, duration of burial stress, pore pressure and pore fluids.

### 3. Inhibitory factors

Preburial lithification i.e. early cementation and dolomitization.

Depending upon its degree, the compaction can alter the texture and structure of carbonate rocks and give rise to a typical grain fabric. Considering the various modifications in their grain fabrics, the following criteria for compaction (based on Flugel, 1982) are recognised in miliolite rocks of Saurashtra.

Breakage of grains

Plastic bending and collapse of grains

Fragmentation of intact shells

Grain rotation

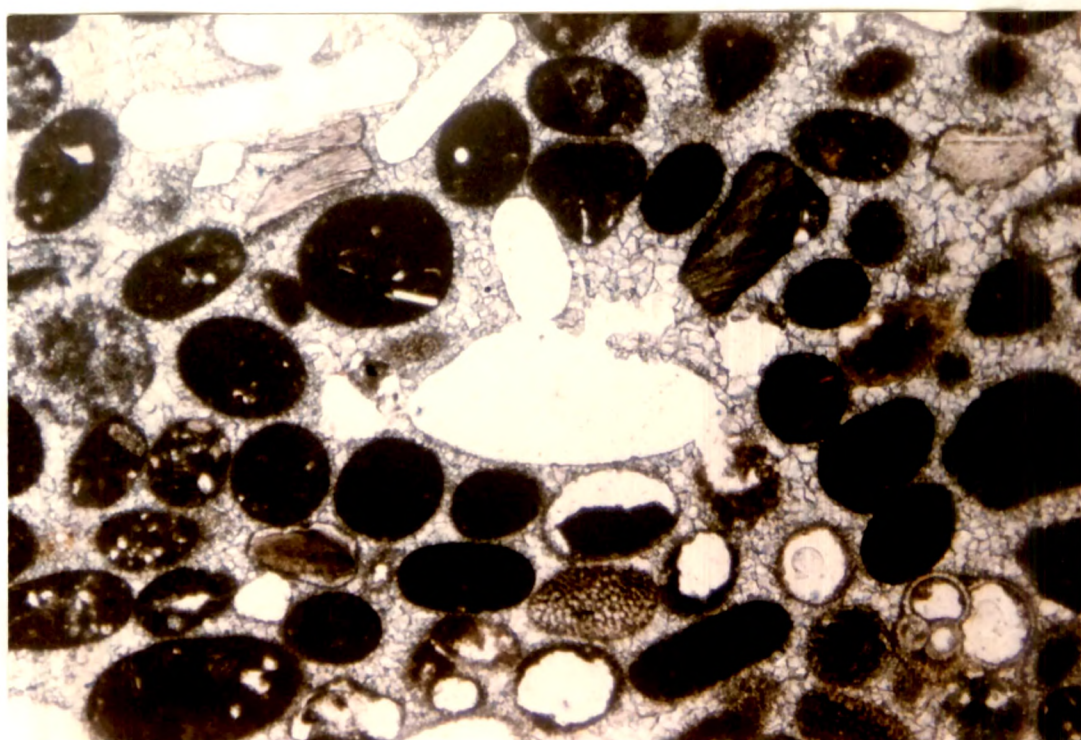
Parallel or imbricated grain arrangement

Truncation at grain contacts etc.

In general, the beach rocks as well as miliolites do not show much compaction. This is obvious in case of beach rocks as they are characteristically coarse grained and unsorted in nature. The miliolites being medium to fine grained are supposed to show better compaction but as they have remained free from much burial or overburden pressure under subaerial conditions, do not show significant compaction. Most of the thin sections of miliolites exhibit very loose packing shown by point contacts and even floating texture (Plate VI.6). However, some of the deposits, especially the sheet deposits & base of the dune deposits show tangential contact, orientation of longer grains, plastic bending



Plate VI.6



Photomicrograph showing point contacts between grains, and floating texture in miliolite (PPL, 60X)

& breakage in molluscan shell fragments and grain rotation, suggesting the effect of compaction in these rocks (Plate VI.7,8,9).

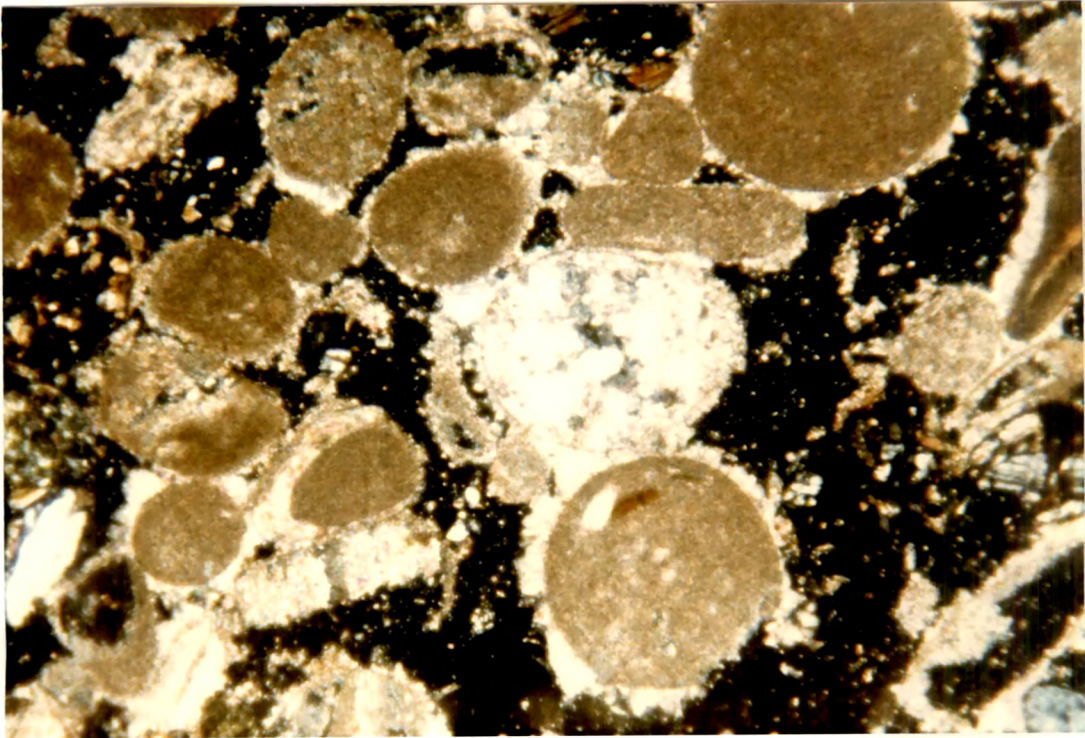
The stabilised sand dunes though reached upto this stage of diagenesis, the intensity of compaction and early cementation is not that much remarkable so as to leave any impression on these deposits.

### Stage III : Mineralogical stabilisation

The metastable carbonate constituents i.e. high magnesian calcite and aragonite when exposed to the subaerial freshwater conditions, tend to achieve mineralogical stabilisation by releasing  $Mg^{2+}$  from magnesian calcite and  $sr^{2+}$  from aragonite. The stained thin section studies of beach rocks and miliolites supplemented by XRD studies of all the three types of deposits, suggest almost absence of high Mg calcite in miliolites and then in beach rocks as compared to the stabilised sand dunes where considerable amount of high Mg calcite (~ 15% Mg) and aragonite is noticed. Amongst the beach rocks and miliolites, the former possesses relatively higher wt% of Mg (6-9%) in calcite. This suggests the diagenetic immaturity of stabilised sand dunes with regards to that in beach rocks and miliolites. The beach rocks, being deposited in nearshore environment originally had higher amount of high Mg calcite and aragonite which on account of their long exposure to the meteoric environment have reached upto the present level with loss of Mg%. The loss of  $Mg^{2+}$  during this

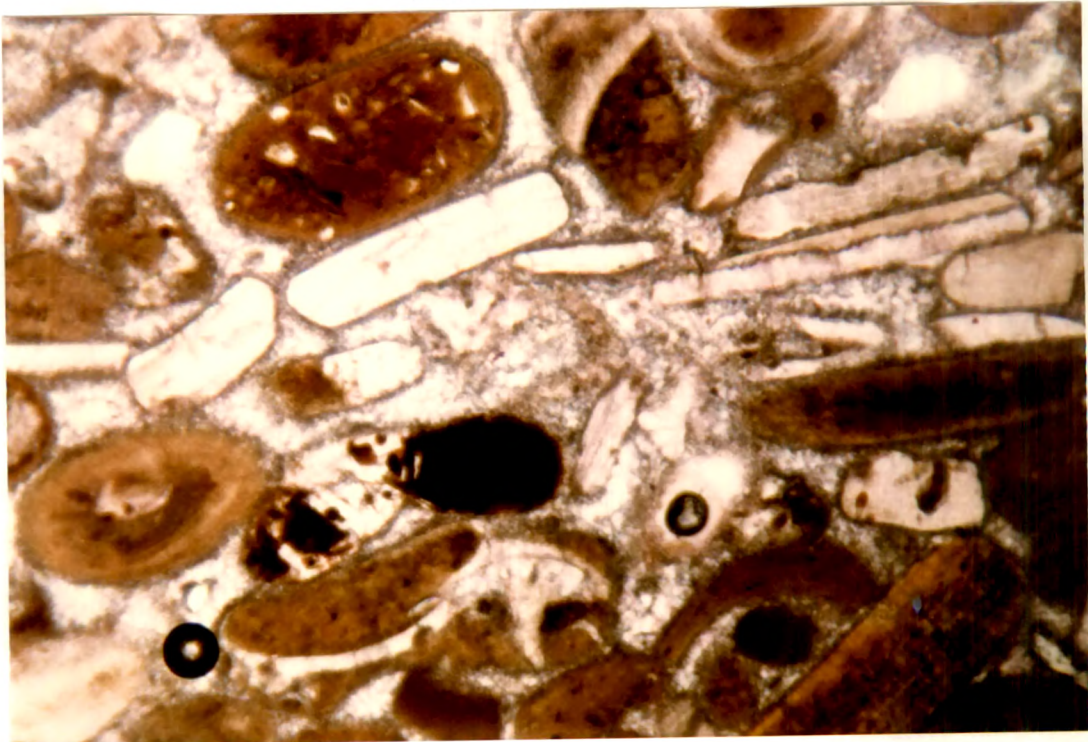


Plate VI.7



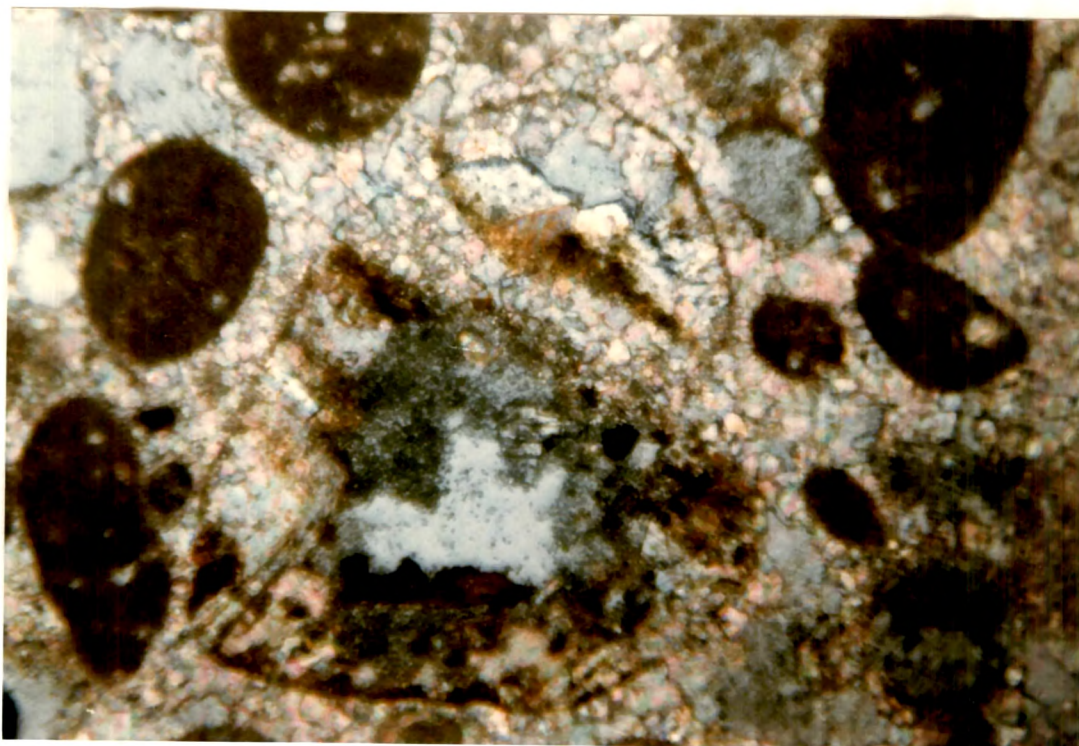
Photomicrograph showing tangential contact between bioclasts in miliolite (Crossed Nicols, 60X)

Plate VI.8



Photomicrograph showing orientation of molluscan shell fragments in miliolite (Crossed Nicols, 60X)

Plate VI.9



Photomicrograph (with mica plate) showing breakage of molluscan shell fragment in miliolite (Crossed Nicols, 230)



stage do not make visible change in once high Mg calcite constituents and hence it is very difficult to delineate the boundary between this stage III and the previous one. Such loss of magnesian ions from the high magnesian calcite of coralline algae without noticeable fabric change has been also reported by Friedman (1964), Gross (1964), Purday (1968), Gavish & Friedman (1969) etc.

#### Stage IV : Dissolution and Precipitation

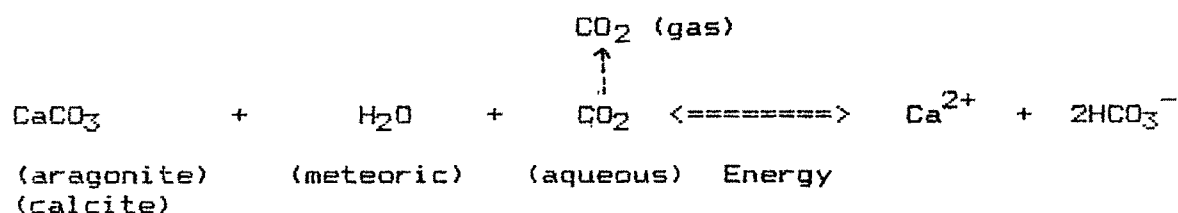
This stage of diagenesis pertains to the carbonate rocks exposed to the meteoric freshwater environment. In this stage, the aragonitic sediments get dissolved to give rise to the intragranular (secondary) porosity in the rock. On an average, the absolute porosity remains reasonably constant as the development of this is balanced by the occlusion of primary porosity (Land et al., 1967). Where the aragonite grain is coated with a thin layer of sparite or micrite cement, this layer persists after the dissolution of aragonite and forms a mould which is consequently being filled with crystalline sparry calcite cement. In near surface conditions, the dissolution process in limestones can also produce red soils (*tera rossa*) and ultimately karst topography.

The early process responsible for the dissolution of aragonite is often associated with the increase in  $\text{PCO}_2$  that results from the oxidation of organic matter. The organic acids produced by the break down of organic matters may contribute substantially to carbonate mineral dissolution. Number of

factors like degree & duration of the sediment exposure to the freshwater, porosity & permeability of the system, movement of freshwaters (input/output) and their chemistry, temperature conditions etc. control the dissolution and consequently the precipitation of aragonitic to calcite in solutions of various composition at a temperature higher than 50°C, have been experimentally studied by several workers (Brown et al., 1962; Fyfe & Bischoff 1965; Metzger & Bernard, 1968; Bischoff, 1969; Jackson & Bischoff, 1971 etc.). The major findings of these investigations are;

- \* The rate of reaction is dependent on the nucleation and growth rate of calcite, and not the dissolution rate of aragonite, though the absolute rate depends upon the aragonitic material used.
- \* The aragonite to calcite transition rate is temperature dependant, especially above 50°C, with an activation energy in dilute solutions of 240 KJ/mole, although in natural system it is not so. This suggests a different mechanism in natural system.
- \* The transformation of aragonite to calcite can be catalyzed in solutions containing electrolytes which are not inhibitors of calcite precipitation.
- \*  $Mg^{2+}$  is a strong inhibitor and exerts a major control on the reaction.  $SO_4^{2-}$  and some organic compounds can also inhibit the transformation of aragonite to calcite.

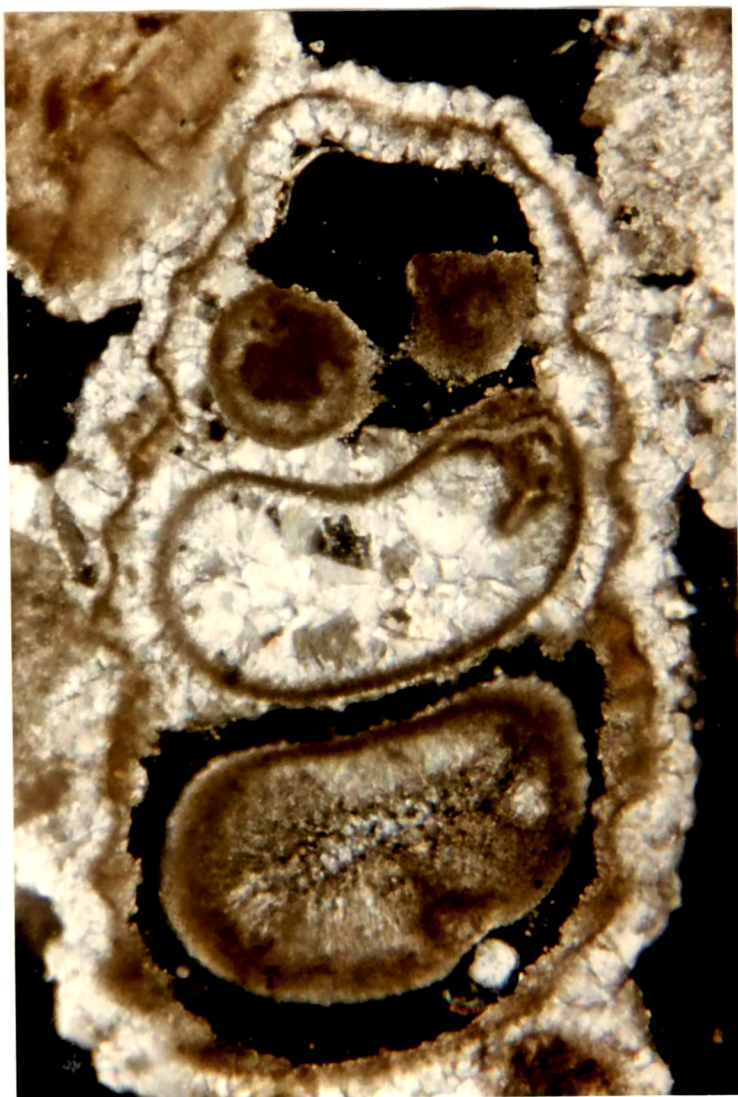
The chemical process involved in dissolution & precipitation of  $\text{CaCO}_3$  can be expressed as following equation after Friedman & Sander (1978).



The process begins in the right side when the pH is less than 7 (i.e. acidic) and the dissolution of aragonite takes place. When the solution becomes saturated, the pH climbs to about 8 and precipitation of calcite starts while dissolution of  $\text{CaCO}_3$  is accelerated by delivery of new water from rainfall, addition of  $\text{CO}_2$  and organic acids by bacterial decay (Dunham 1969).

The precipitation of low magnesian, non-ferroan calcite cement in miliolite rocks of Saurashtra is due to the percolating meteoric waters which have become saturated with  $\text{CaCO}_3$  by three ways viz. evapotranspiration of pore waters, decrease in partial  $\text{CO}_2$  pressure due to degassing and dissolution of aragonitic constituents. The dissolution of aragonite in miliolites is evident by the frequent occurrence of secondary porosity in the form of moulds preserved by thin micritic boundaries (Plate VI.10). The occurrence of intercalations of red kankary palaeosol layes and solution channels & vugs that too lined with red sediments (Plate IV.51) as encountered at various miliolite localities viz. Mangrol, Veraval, Naip, Juna Rajpura, Gopnath etc., suggest the dissolution of majority of metastable carbonate

Plate VI.10



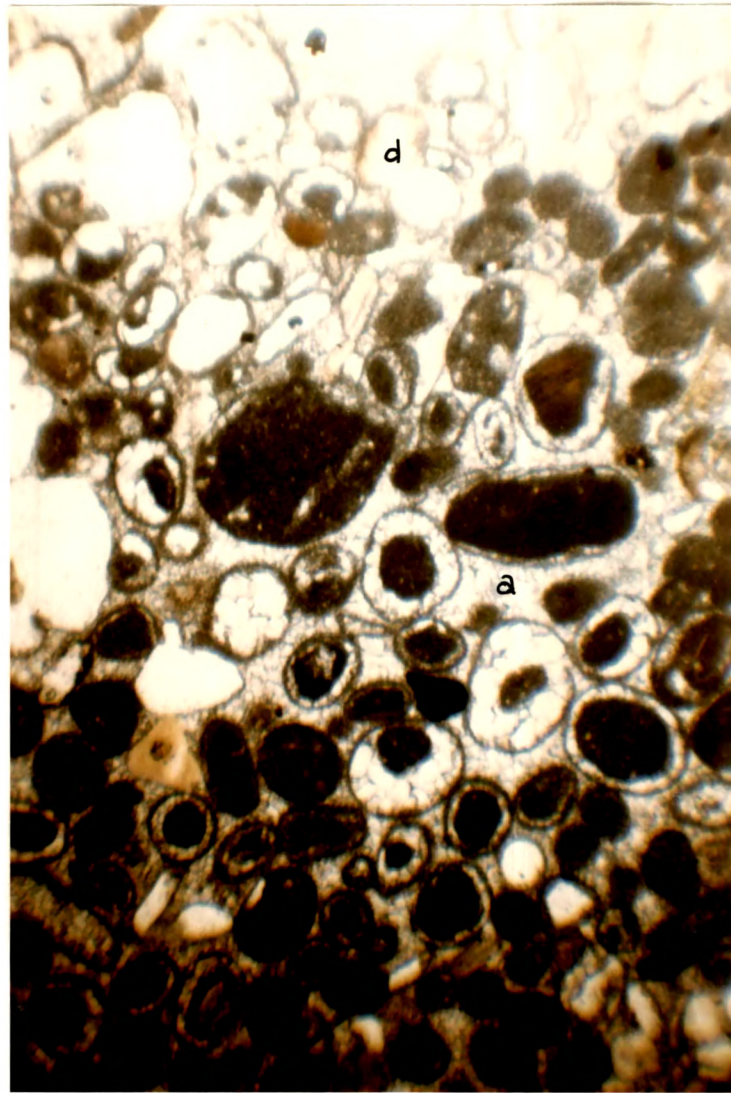
Photomicrograph showing dissolution of aragonitic gasteropod shell and initial precipitation of sparry calcite cement  
(Crossed Nicols, 120X)

minerals during small scale intervening wet climatic phases in a prolonged, dry-arid Quaternary palaeoclimate, that gave rise to these aeolianites.

On the other hand, the beach rocks, especially from the deeper portions, show considerable preservation of aragonite constituents as well as cement. The XRD studies further show the presence of aragonite not only in beach rocks but also in some inland obstacle deposits of miliolites suggesting their diagenetic immaturity as compared to those of south Saurashtra coast between Porbandar-Veraval-Diu-Mahuva & Gopnath which show reddening and high degree of cementation. These clearly reveal that the cementation in the miliolites is greatly dependant on the dissolution of aragonitic constituents. The survival of aragonite in the beach rocks of Dwarka-Baradia-Harshad - Porbandar areas could be due to their longer exposure to the phreatic saline water conditions that contain  $Mg^{2+}$ ,  $SO_4^{2-}$  and some organic compounds which inhibit the dissolution of aragonite (Jackson & Bischoff, 1971). However, it is not possible to detect the temperature control in the rocks of the study area over this process as suggested by Bischoff (1969). The precipitation of calcite cement in the miliolites remained a contemporary event to the dissolution of aragonite. This is ideally seen in the thin sections of miliolites and also their X-Radiographs where alternate thin layers of intragranular porosity and isopachous granular sparry calcite cements occluding the porosity are encountered, which as per Bathurst (1971) are respectively termed as 'donor' and 'accepter' layers (Plate VI.11 & 12).



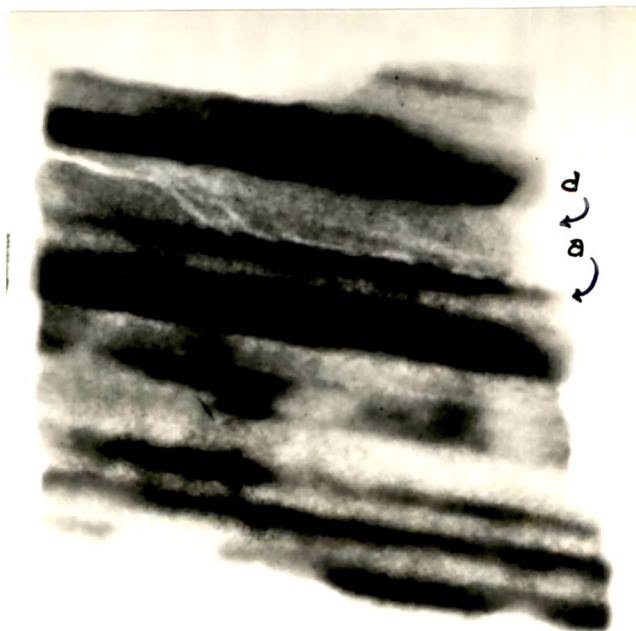
Plate VI.11



Photomicrograph showing alternate 'donor' (d) and 'accepter' (a) layers in miliolite (PPL, 60X)

Plate VI.12

X-Radiographs of miliolite slabs showing alternate 'donor' (d) and 'acceptor' (a) layers (contact prints)



The various ultra-structures exhibited by these low magnesian, non-ferroan sparry calcite cements in miliolites were interpreted to infer the possible diagenetic conditions. As stated earlier, the fibrous & micritic aragonite cement in beach rocks suggest their precipitation in deep vadose, active littoral condition in early stage of diagenesis while the void filling, equant nonferroan sparite were formed in quite late stage when the beach rocks were exposed to the meteoric environment. The early cementation in miliolites is characterised by meniscus & occasionally drusy rim cement, both from the solution derived by dissolution of aragonitic constituents. The meniscus cements suggest a shallow vadose condition whereas the gravitational i.e. dripstone & drapstone cements represent deeper vadose condition (Muller, 1971). The isopachous (circumgranular) rim cement indicates condition of precipitation at or below the water table while the blocky void filling cements are characteristic of phreatic condition where constant availability of solution is obvious. The syntaxial rim cement can be developed in any of the condition. The mineralogy of all these cements in miliolites, being low magnesian sparry calcite as revealed by XRD and stained thin section studies clearly suggests meteoric freshwater environment substantiating the subaerial depositional condition for miliolites. The nonferroan nature of calcite cement in miliolites as well as beach rocks further suggest that these rocks have not experienced the reducing diagenetic environment (Morse & Mackenzie, 1990; Scholle et al., 1991).

The low magnesian nature of the cement precipitating in meteoric environment is due to the low salinity, low Mg/Ca ratios, low  $\text{SO}_4^{2-}$  concentration,  $\text{PO}_4^{3-}$  content and generally less concentration of dissolved organic carbon (Morse & Mackenzie, 1990). The nature of the distribution of cements in rock is also controlled by the kinetics of nucleation (Wollast, 1971; Waltar, 1986; Busenberg & Plummer 1986; etc). As the supersaturation of meteoric waters with respect to calcite in  $\text{CaCO}_3$  solution requires several thousand times the product of  $\text{Ca}^{2+}$  &  $\text{CO}_3^{2-}$  at equilibrium and temperature changes of some tens of degrees centigrades, that too insufficient for homogeneous nucleation of calcite crystals in such solutions, and hence the heterogeneous nucleation of calcite cement is common in meteoric environment only (Wollast, 1971). As suggested by him, the rate of calcite cement growth in meteoric environment is even influenced by degree of supersaturation and temperature. Thus, the heterogeneous cementation, as encountered in majority of miliolites, represents normal natural conditions for their formation under meteoric freshwater environment. The stabilised sand dunes that lack in above microstructures, obviously are far behind from this stage of diagenesis.

#### Stage V : Recrystallisation

This is the final stage of limestone diagenesis where all other metastable carbonate minerals like aragonite & high Mg calcite are almost removed and the culmination to low Mg calcite is achieved with considerable loss in porosity. Only a few

exposures of miliolites and beach rocks of the study area have reached upto this stage.

The XRD, SEM and thin section studies of beach rocks and miliolites,, the preservation of aragonite and the remnant of Mg ions in calcite together with the various morphology of sparry calcite cement with higher frequency of enfacial triple junctions in majority of these deposits suggest that they have crossed the stage of dissolution and precipitation (stage IV) to reach upto this final stage of diagenesis. However, the beach rocks of Harshad, Kukaswada, Sil, Arena, Kadwar etc. and the surface exposures of miliolites from South Saurashtra coastal areas show the development of thin (50-60 cm) dury crust due to their recrystallisation under the influence of mobile freshwaters. The miliolites pertaining to this stage of recrystallisation are characterised by a 'clink' sound while hammered and even bounces the hammer stroke in the field. In thin sections they show insitu calcitisation of allochems resulting into the loss of their internal structures and even cement morphology as reported by Budd (1984) from Bahamian Pleistocene limestones. Only a few miliolite exposures of Okhamadhi, Kukaswada, Bhanvad, Sil, Veraval, Nawa Bandar & Jafrabad etc. area seem to have reached upto this stage of diagenesis which show almost occludation of primary as well as secondary porosity and equant, granular low magnesian sparry calcite crystals. At places the initial cement morphology is still preserved by the presence of thin amorphous iron oxide layers (Plate VI.13).



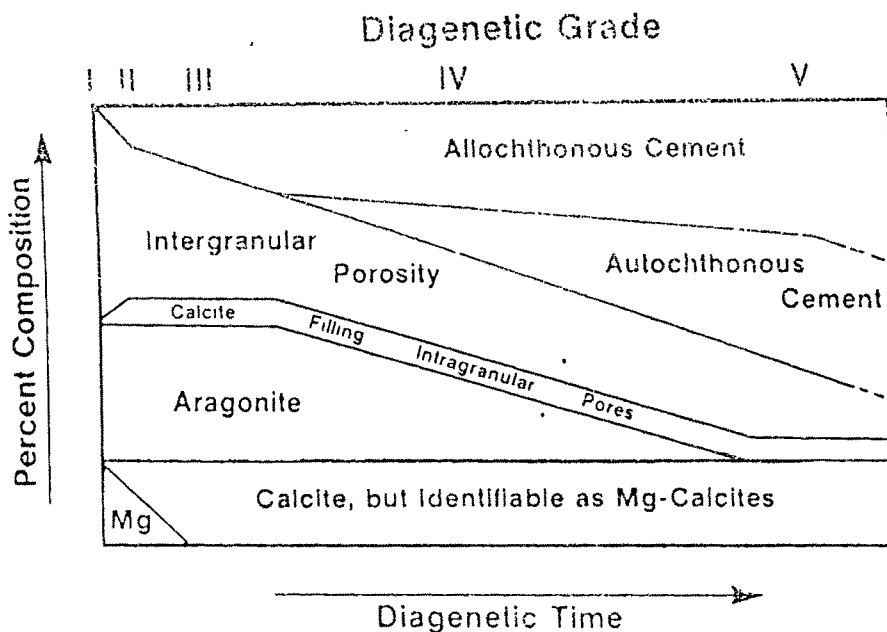
Plate VI.13



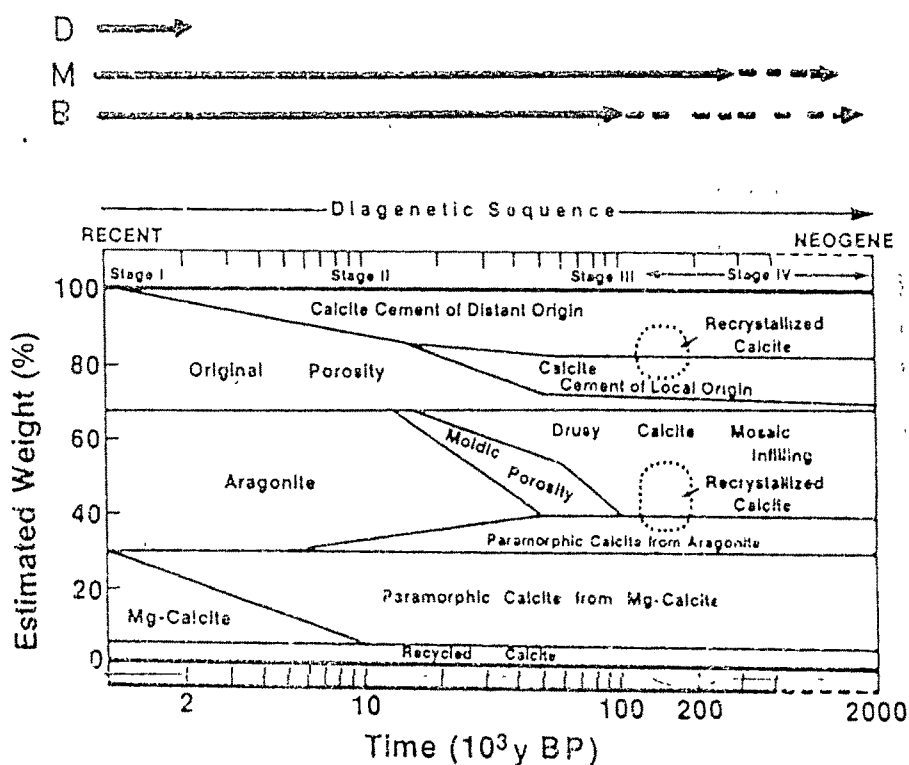
Photomicrograph showing preservation of initial cement morphology in recrystallised miliolite (Crossed Nicols, 120X)

The diagenetic sequence of textural, mineralogical and geochemical changes in carbonate sediments of the Mediterranean coast of Israel was explained by Gavish & Friedman (1969). Figure VI.2 thus shows position of the sequential stages of diagenesis of the various Quaternary carbonate deposits of Saurashtra which is in agreement with the carbonate rocks of Bermuda (Land et al., 1967) and Israel (Gavish & Friedman, 1969). Accordingly the Beach rocks and miliolites have reached upto stage of mineralogical stabilisation (stage III) and dissolution & precipitation (stage IV) while the Dunal Sand have reached upto first stage only. The diagenetic history of the Quaternary carbonate deposits of Saurashtra thus can be schematically shown in following table (Table VI.1).





( a )



( b )

FIG. VI.1 DIAGENETIC SCHEME (→) FOR  
BEACH ROCKS ( B ), MILIOLITES ( M ) AND  
STABILISED SAND DUNE ( D )

( after ( a ) Land et al ( 1967 ) and ( b ) Gavish & Friedman 1969 )

Table VI.1 : Schematic history of diagenesis of the Quaternary carbonate deposits of Saurashtra

Stage	Description	Type of deposit	Environment
I	Stabilisation of sediments with little grain packing	BR	Littoral
		M	Topographic depression
		SD	Coastal
II	Precipitation of early cement and modifications in grain fabrics	BR	Deep vadose and/or phreatic
		M	Shallow vadose meteoric
		SD	" "
III	Loss of $Mg^{+2}$ from high magnesia calcite and mineralogical stabilisation	BR	Subaerial freshwater
		M	" "
		SD	" "
IV	Dissolution of Aragonite and precipitation of low Mg calcite cement, development of secondary porosity & occlusion of primary porosity	BR	Long duration, vadose meteoric
		M	" "
		SD	---
V	Recrystallisation	BR, M	Phreatic meteoric