CHAPTER - VI

DIAGENESIS

GENERAL

The term diagenesis includes all the processes involving solution, lithification and alteration of sediments after deposition, brought about by physical, chemical and biological changes. A proper understanding of the diagenetic processes is very important for the interpretation of microfacies characteristics of a rock. Especially in limestones, the diagenesis has a greater relevance because it provides valuable information on the post depositional environment.

In this chapter an attempt has been made to describe in detail the diagenetic processes by which the loose miliolitic sands have been consolidated subsequent to their deposition and transformed into the miliolite limestones. A correct appraisal of the processes of diagenesis effective in consolidating the miliolite rocks of Kutch was all the more important, because it enabled the author to fully understand the total picture of the evolution of this rock.

Except in few rare cases, carbonate diagenesis has always posed many problems. In most of the cases numerous environmental parameters influence, in one way or another the diagenetic processes of limestones. According to Chilingar et al. a or b (1967, p. 187), "The following factors influence diagenesis of carbonate sediments:

(1) Geographic factors - climate, humidity, rainfall, type of terrestrial weathering, surface water chemistry.

(2) Geotectonism - rate of erosion and accumulation, coastal morphology, emergence and subsidence, whether eugeosynclinal or miogeosynclinal.

(3) Geomorphic position - basinal versus lagoonal sediments, current velocity, particle size, sorting, flushing of sediments.

(4) Geochemical factors in a regional sense - supersaline versus marine water, volcanic fluids and gases.

(5) Rate of sediment accumulation - halmyrolysis, ion transfer, preservation of organic matter, biochemical zonation.

(6) Initial composition of the sediments - aragonite versus high- Mg and low - Mg calcite, isotope and trace element content.

(7) Grain size - content of organic matter, number of bacteria, rates of diffusion.

(8) Purity of the sediments - percentage of clay and organic matter, base exchange of clays altering interstitial fluids.

(9) Accessibility of limestone framework to surface- cavity systems permit replacements.

(10) Interstitial fluids and gases - composition, rate of flow, exchange of ions.

9 (11) Physicochemical conditions - pH, Eh, partial pressure of gases, CO_2 content.

(12) Previous diagenetic history of the sediment - previous expulsion of trace elements will determine subsequent diagenesis".

They (Chilingar et al, 1967) have further stated that "The actual processes that lead to diagenetic alteration and modifications of limestones are divisible as follows:

(1) <u>Physicochemical processes</u>: solution, corrosion, leaching, bleaching, oxidation, reduction, reprecipitation, inversion, recrystallization, cementation, decementation,

authigenic mineral genesis, overgrowth, crystal enlargement, replacements, chemical internal sedimentation, aggregation and accretion.

(2) Biochemical and organic processes: accretion and aggregation, particle - size reduction, corrosion, corrasion, mixing of sediments, boring, burrowing, gas-bubbling, breaking down and synthesizing of organic and inorganic compounds.

(3) Physical processes: compaction, desiccation, shrinkage, penecontemporaneous internal deformation and corrasion, and mechanical internal sedimentation".

Wolf (1963) has ideally summarised the carbonate diagenesis in the following gradation of the factors influencing the consolidation of limestones:

Climate
↓
Geomorphology

{ Particle size → amount and type of bacteria → rate of diagenesis → pH and Eh → type of replacement.

The role of fresh water in the diagenesis of limestones has not received considerable attention in the past, and it is only in the context of the studies on miliolite or their equivalents that the carbonate petrography has been studied from this angle. Saylės (1931), Yaalon (1967), Bathurst (1971) and Gardner (1983) have pointedly referred to fresh water diagenesis of aeolianites.

According to Bathurst (1971) "the transformation of unconsolidated sediments to limestone by exposure to fresh water has achieved the popular status of chief limestone - forming process ---- there is no doubt that vast masses of Pleistocene limestones have been cemented in this way". Thus, the role of fresh water in the lithification of Pleistocene limestones can be very well applicable to the miliolite rocks of Kutch. These Pleistocene limestones (miliolite) are similar to those of Bermuda, Barbados, S.E. India, etc., which have attracted attention of many workers, who have invoked their lithification in a fresh water environment (Schlanger, 1963; 1964; Friedman, 1964; Bathurst, 1966, 1971; Land, 1967; Land et al, 1967; Harris & Matthews, 1968; Matthews, 1968; Pingitore, 1970; Gardner, 1983).

Flügel (1982), used the term 'meteoric diagenesis' for fresh water diagenesis. According to him, the process of diagenesis can be brought about by the action of meteoric water in following environments:

i) vadose environment: zone above the level of ground water table; diagenesis under the influence of rain water (meteoric-vadose) or of splash waters on the coast (marine vadose), e.g. sub-aerial limestone crusts and caliche, cave carbonates.

ii) Phreatic environment: zone below or in the water table (meteoric -phreatic) or influenced by marine waters (marine - phreatic).

In Kutch miliolites, the vadose environment appears to have predominated, although the role played by groundwater might have been significant at times. These processes appear to have operated over a protracted period covering almost the entire Late Quaternary.

LITHIFICATION

Lithification is the primary process of diagenesis, and according to Pettijohn (1957) it is "the complex of processes that converts a newly deposited sediment into an indurated rock". The process of lithification chiefly comprises 'compaction' and 'cementation'. On the basis of thin section studies, the author has been able to identify several interesting microfacies characteristics that throw light on the diagenetic processes responsible for the lithification of carbonate particles in miliolite. The following comprises an account of the various aspects of compaction and cementation.

Compaction

Compaction is a mechanical process during which (i) packing of the individual grains (re-orientation) and (ii) reduction of pore-space within the body of the

Language to be checked

sediments is brought about by various factors, and causes a decrease in the bulk volume of the rock.

The factors affecting compaction of carbonate sands have been listed by Flügel (1982) as under:

(i) Amount of overburden,
(ii) Duration of burial stress,
(iii) Pore pressure,
(iv) Pore-water chemistry (The greater the degree of undersaturation with respect to $CaCO_3$, the less the amount of overburden needed to cause inter and intragranular pressure solution),
(v) Clay content of the carbonates,
(vi) Pre-compaction diagenesis (early cementation and dolomitization),
(vii) Grain size,
(viii) Grain architecture and
(ix) Grain mineralogy.

Coogan & Manus (1975), have ideally grouped the above factors into following three categories:

(i) <u>Inherited factors</u> include the grain size, grain shape, size-sorting, shape-sorting, grain-packing, and mineralogy,
(ii) <u>Inhibitory factors</u> include the 'preburial lithification' i.e. cementation and dolomitization. The alteration can be penecontemporaneous with

sedimentation or subaerial exposure or can take place during other diagenetic stages.

(iii) Dynamic factors include overburden pressure (amount of overburden), sub-surface temperature, duration of burial stress, pore pressure and pore fluids (Fig. VI.1).

The diagnostic criteria for the recognition of compaction in calcarenite, have been listed by Flügel (1982) as under:

(i) Breakage of grains,
(ii) Plastic bending and collapse,
(iii) Fragmentation of intact valves or single shells (e.g. ostracodes),
(iv) Collapsing and telescoping of shells,
(v) Mashing of fragile skeletal grains between compaction - resistant grains (e.g. bryozoa fragments between echinoderms),
(vi) Grain rotations (seen by rotated geopetal fabrics),
(vii) Drag fabrics (due to re-orientation and stylolization) with elongated grains showing alignment parallel or subparallel to the compaction - resistant grains,
(viii) Irregular pressure solution at grain contacts (circumidenic planar microstylolites),
(ix) Truncation of grains by adjacent grains,
(x) Interpenetration of grains.

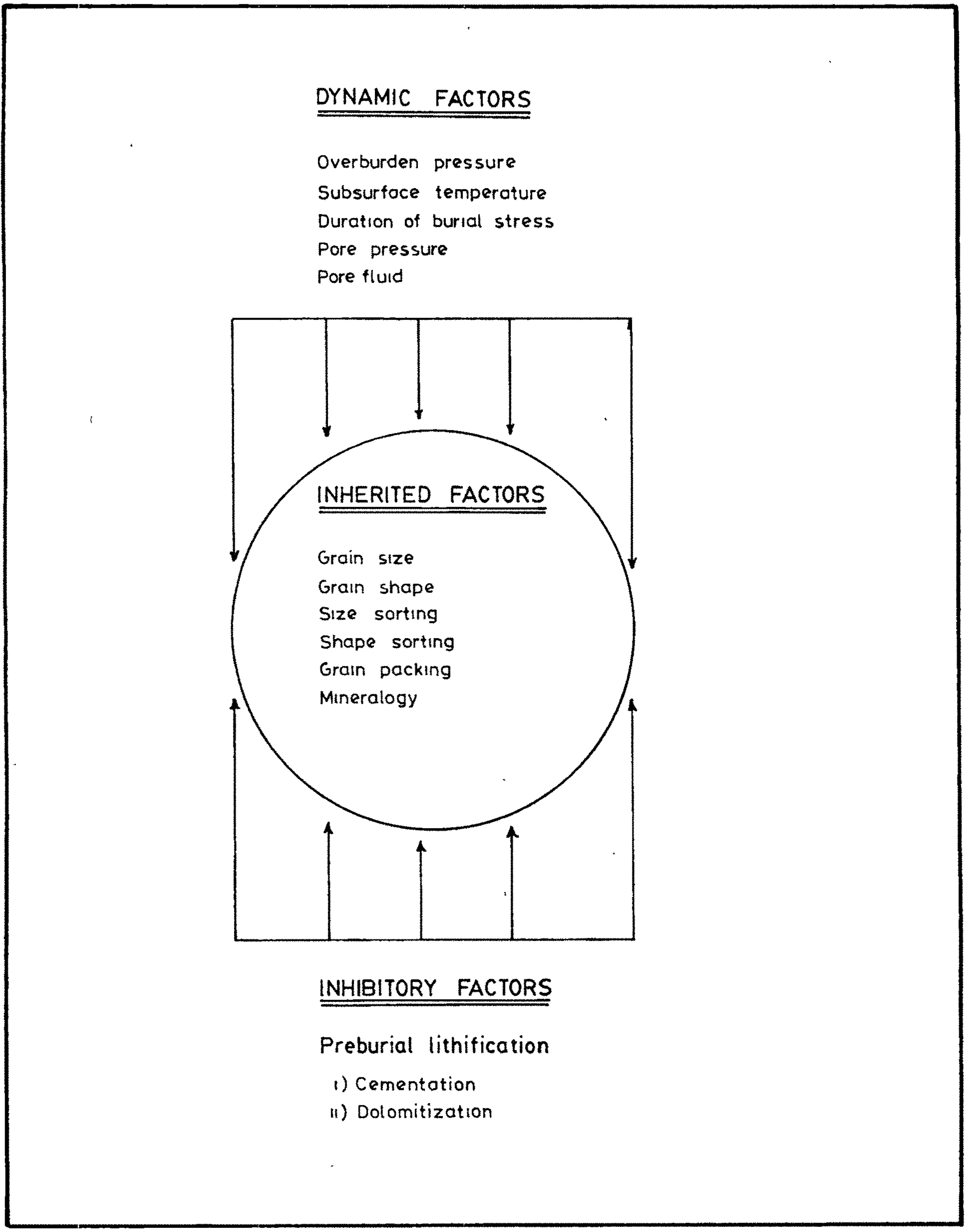


Fig.VI 1 Factors Affecting compaction of carbonate sands
(after Coogan and Manus,1975)

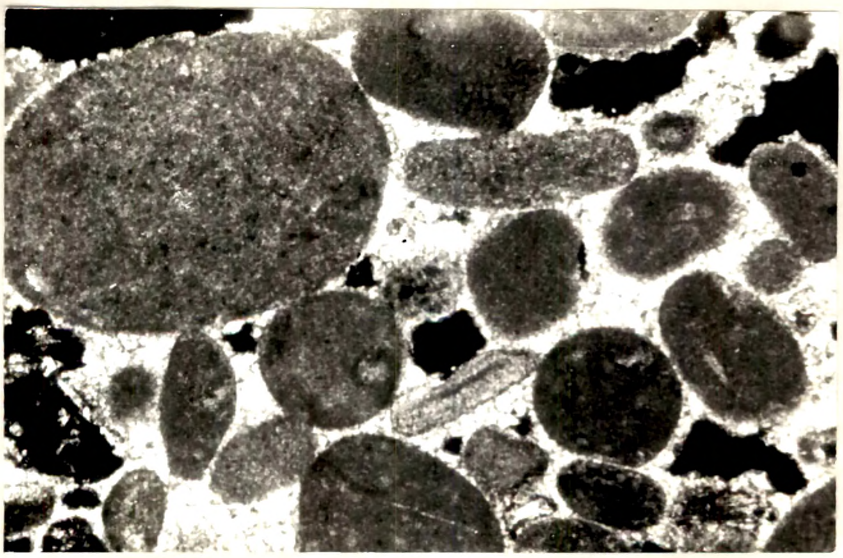
(xi) Densely packed grains (over-packing) forming a 'mash' structure with almost no intergranular space.

A majority of the miliolite occurrences of Kutch do not show significant compaction. Thin sections reveal that the grains or particles are not in contact with each other (Plate VI.1). This points to a very loose packing of grains at the time of deposition. However, the lithification of miliolite does show occasional instances of compaction, and in all such cases, most of the above criteria and evidences of compaction are well illustrated (Plate VI.2). The author on the basis of a critical petrographic study, observed following features related to the overburden pressure, grain architecture, grain mineralogy and the action of meteoric water:

(a) <u>Breakage and splitting of grains</u>: In some thin section, it is seen that during compaction the grains are fractured and then displaced along them. The first generation cement or micritic envelope is present only on the original grain surface and the fractured surfaces have been covered directly by second generation cement or vadose crystal silt (Plate VI.2a). This textural feature is identical to that observed by Bathurst (1971).

(b) <u>Plastic bending</u>: During the compaction of miliolite, some grains (mainly biogenic) show a slight bending on account of the overburden pressure (Plate VI.2b).

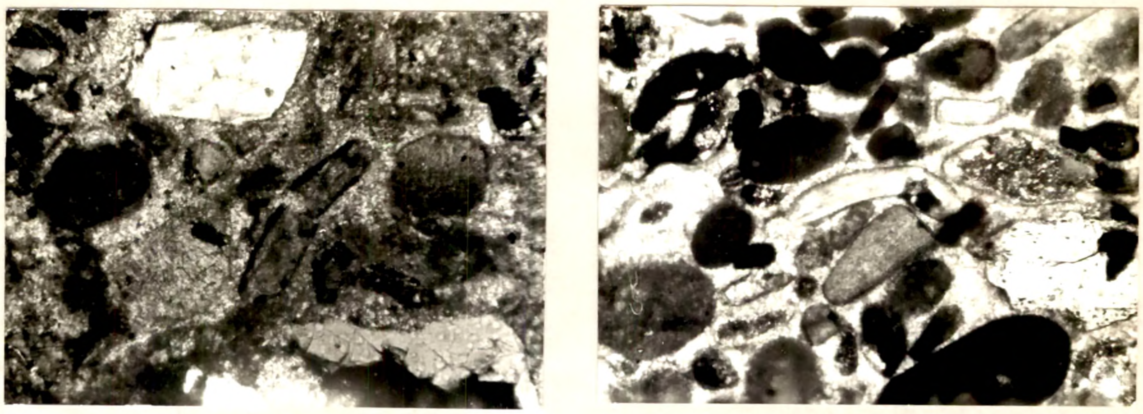
Plate VI. 1



Photomicrograph showing loose packing of miliolite constituents
(X 90, PPL)

Plate VI. 2

Photomicrograph showing some of the diagnostic features of compaction in Kutch miliolites

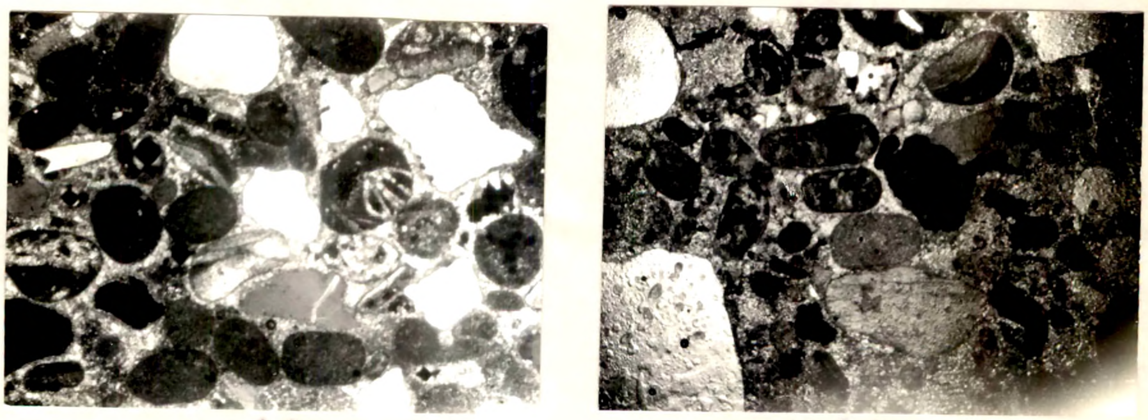


(a)

Breakage of grains
(X 70, PPL)

(b)

Elastic banding of bioclasts
(X 70, PPL)

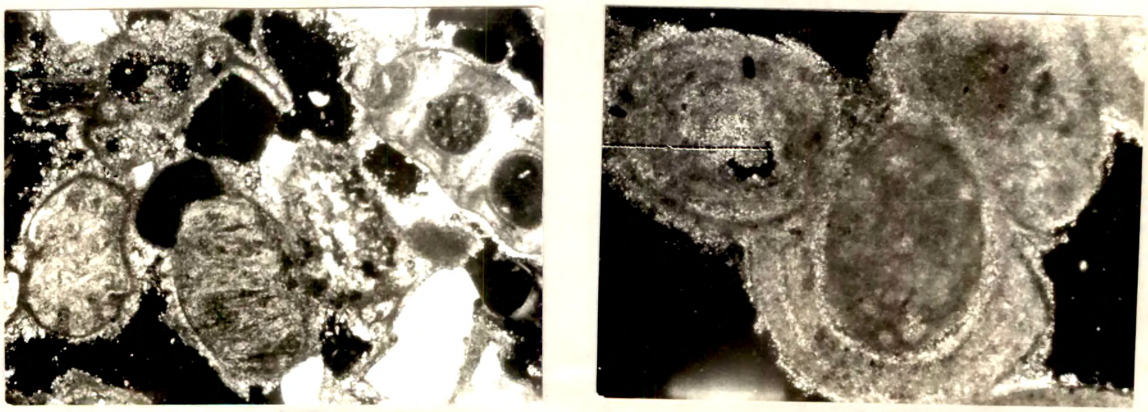


(c)

Grain rotation
(X 40, PPL)

(d)

Tangential contact
(X 40, PPL)



(e)

Interpenetration of grains
(X 140, PPL)

(f)

Truncated contact
(X 140, PPL)

(c) Grain rotation: Compaction has caused some grains to get re-oriented and align themselves parallel to the compaction-resistant grains, perpendicular to the direction of overburden pressure (Plate VI.2c).

(d) Tangential contact: Some elongated grains show an alignment parallel/sub-parallel to the compaction-resistant grains without interpenetration (Plate VI.2d). This type of compaction is also called as 'point contact' (Taylor, 1950).

(e) Interpenetration of grains: Due to compaction, the grain under pressure has penetrated into the compaction-resistant grain (Plate VI.2e). This phenomenon is however not common in miliolite rocks.

(f) Truncated contact: The growth of a vadoid is interfered by another grain adjacent to it; as a result the mutual yielding of grain takes place (Plate VI.2f).

Cementation

Cementation comprises the process by which the individual carbonate particles are held together by a secondarily developed material, commonly associated with the processes of solution, corrosion, leaching and replacement. Several generations of cement may develop until all the pore spaces have been completely filled up.

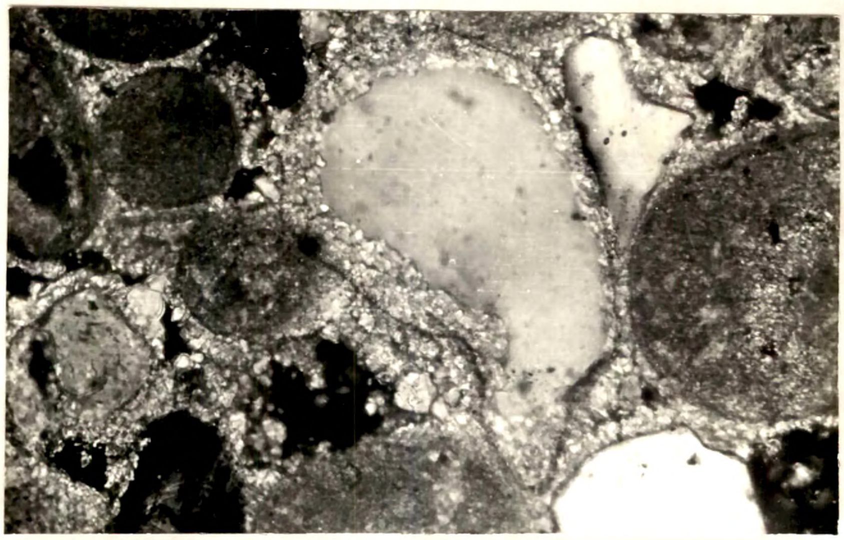
In the miliolite rock, the compaction and cementation has been found to have taken place in a vadose environment under the influence of fresh water, and the account that follows would make this fact very clear, establishing a fresh water diagenesis of Kutch miliolites.

The constituents are seen bound and cemented together by medium to coarse calcitic (sparite) cement, which has also filled the primary (interstitial) and secondary vugs and openings in the rock. In some cases, the calcium carbonate cement has replaced quartz grains and given rise to corrosion rims (Plate VI.3). Baskaran & Somayajulu (1986), have shown that the constituents of miliolite deposits of Saurashtra are predominantly calcitic and aragonitic, and quartz occurs as minor component. According to them, "it is possible that aragonite in the surface samples can get recrystallised into calcite in association with meteoric water, whereas the deeper samples are protected". Flügel (1982), stated that in meteoric environment low - Mg calcite > aragonite > high - Mg calcite. Patel (1982) has also chemically analysed some of the miliolite rocks from different localities of Kutch Mainland, and has shown that these rocks contain negligible amount of magnesia (Table VI.1).

Source of $CaCO_3$ Cement

The source of the sparite cement in miliolite is mostly endogenic, i.e. the $CaCO_3$ has been derived from within the rock formation itself, on account of the dissolution of aragonite and high-Mg calcite constituents and precipitation

Plate VI. 3



Photomicrograph showing corrosion rim around quartz (X 180, PPL)

Table VI.1

Chemical analysis of some of the Kutch miliolites

Locality	Category	Major oxides (% by weight)						
		Loss on ignition	SiO_2	Fe_2O_3	Al_2O_3	FeO	CaO	MgO
SW of	A_1	29.88	26.98	1.29	2.63	0.24	33.95	1.87
Habo and	A_1	26.20	33.00	3.19	1.81	0.24	33.65	1.51
S of	A_2	29.70	29.50	1.99	1.01	0.24	34.35	2.53
Baladia	A_2	25.72	35.00	3.19	0.81	0.44	33.65	1.01
Jhura	B_2	18.80	51.50	2.79	1.21	0.64	23.83	1.01
	B_1	20.80	46.80	3.19	1.81	0.40	25.96	1.51
Sumrasar	B_2	29.00	27.80	2.79	0.71	0.44	37.15	2.02
	A_1	29.15	23.65	3.39	4.01	0.20	36.68	2.26
	B_1	13.30	63.00	4.39	1.61	0.80	15.42	1.01
Nakhatrana-Kotada	A_1	34.07	16.80	1.99	2.01	0.12	42.76	1.51
	A_1	30.00	26.12	0.82	2.61	0.20	38.42	1.32
Roha	A_1	29.16	29.30	2.79	1.71	0.28	35.05	1.51
	B_2	34.60	16.40	1.99	2.51	0.08	42.06	1.51
Bhuj-	B_1	33.80	18.35	1.40	1.72	0.28	39.66	1.27
Mandvi	B_1	32.70	21.00	2.60	1.90	0.16	40.67	0.50
Road	B_1	29.14	27.26	2.40	4.10	0.48	35.01	1.01
	B_1	27.90	32.70	2.79	0.21	0.36	33.65	1.01
	B_1	25.50	37.50	3.19	0.31	0.88	31.55	1.51
	B_1	13.80	59.82	1.56	4.04	0.12	17.11	1.49
NW of Sanatorium	B_4	23.50	41.70	2.40	0.60	0.44	30.43	1.01

as low-Mg calcite mainly by meteoric waters. Only in some exceptional cases, $CaCO_3$ might have been brought to the site of precipitation from an outside source.

According to Chillingar et al. (1967), the precipitation of $CaCO_3$ cement is mainly controlled by physicochemical, bacterial decompositional and algal processes.

Harris & Matthews (1968) observed that sparry calcite cement is derived locally by the reprecipitation of dissolved aragonite of the allochems. These workers also measured the ratio of Sr^{2+}/Ca^{2+} in the water and estimated that efficiency of reprecipitation of dissolved aragonite was more than 90%.

Regarding the source of cement Gardner (1983), who has worked on the aeolianites of S.E. Indian (which appears to be quite similar to miliolites) has stated that "small amounts of calcium may be supplied internally by the breakdown of calcic felspar, but by far, the largest potential contribution is from dissolution of aragonite allochems".

Yaalon (1967), on the basis of his studies on the aeolianites of the coastal plain of Israel, suggested that cementation of these rocks has taken place above the water table as a result of wetting by rain water. He further stated that only about 8% $CaCO_3$ was required to initiate the process of cementation.

The present author too has found that a major part of the cement in the miliolite rocks of Kutch is mostly endogenic and is derived from precipitation of dissolved aragnoite allochems by the action of fresh water above the water table. The evaporation of vadose water, increases the suction pressure (capillary rise) and causes upward movement of saturated solution from the lower level and gives rise to precipitation of $CaCO_3$. A small amount of $CaCO_3$ cement could have come from external sources, like migrating groundwater, weathering of calcic felspar, aerosoles, nearby miliolite or older Jurassic limestones (Fig. VI.2).

Mechanism of Fresh Water Cementation

The original unconsolidated miliolitic sands consisted of (a) organic particles with aragonitic skeleton (the molluscs, corals and Halimeda algae), and (b) organic particles with high magnesian calcite skeleton (most of the foraminifers, coralline algae and echinoderms).

These organic particles would have varying degree of susceptibility to calcitisation and cryptocrystallisation which varies from each other. Schlanger (1964) and Bathurst (1971) have arranged the various skeletal minerals in order of decreasing susceptibility to calcitisation as under:

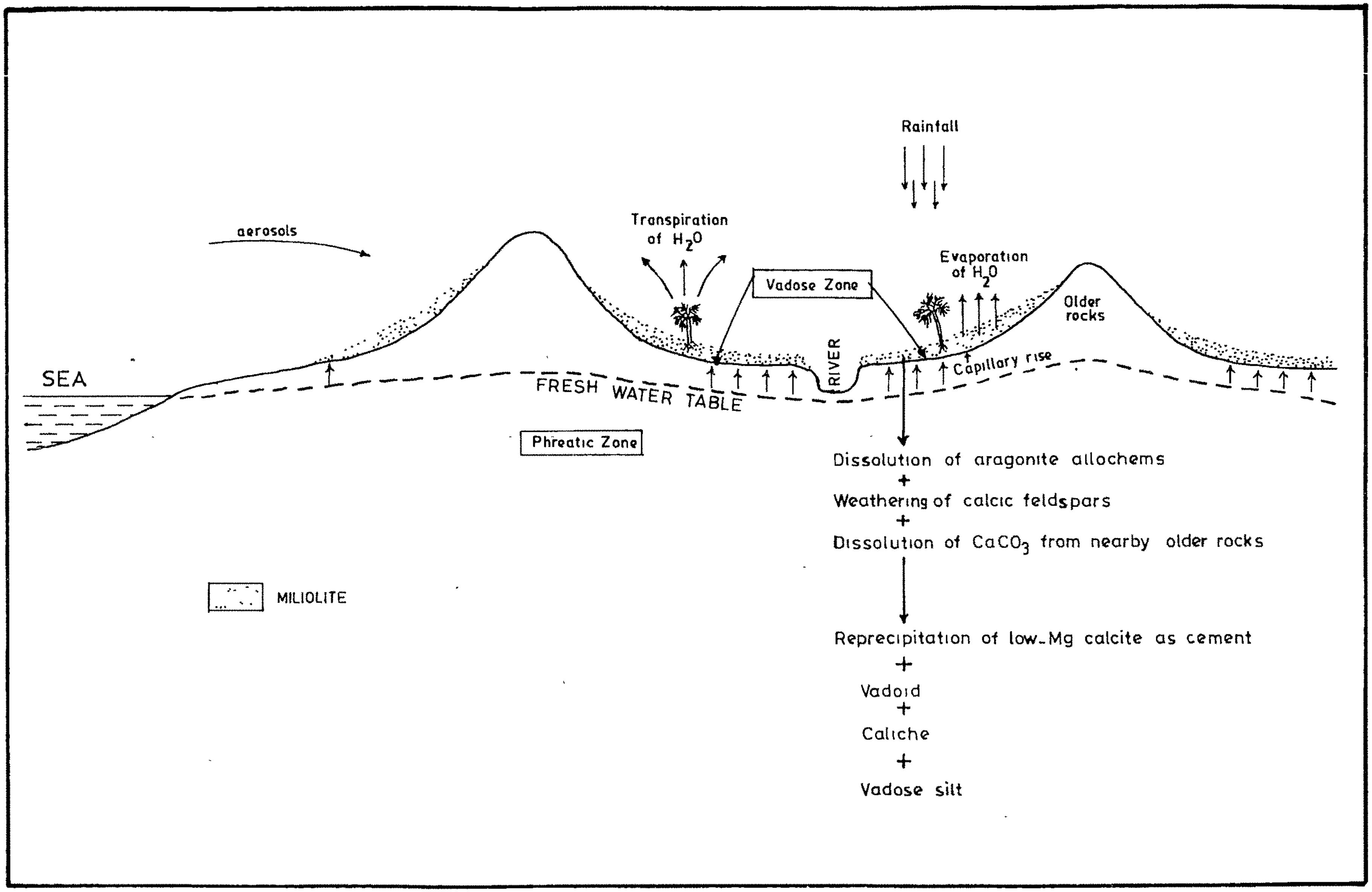


Fig.VI.2 Schematic diagram showing the source of calcium carbonate cement in Kutch miliolites.

Coral	(Aragonite)	↓ decreasing susceptibility to calcitisation.
Halimeda	(Aragonite)	
Molluscs	(Aragonite)	
Pelagic foraminifers	(Mg-calcite)	
Larger foraminifers	(Mg-calcite)	
Echinoids	(Mg-calcite)	
Coralline algae	(Mg-calcite)	

It can thus be deduced that the low magnesian calcite which is derived from the calcitisation of echinoid (Mg-calcite) could be younger than that derived from corals on account of the differences in their susceptibility to calcitisation.

The author has postulated a model for his miliolites in which the original unconsolidated miliolitic sands were aerially exposed and almost all the original aragonitic skeletal fragments present in the sand were partly or fully dissolved; the remaining particles were cemented by precipitation of calcite from percolating fresh water. Such a process has been widely accepted by geologist wherein the aragonite bearing sediments are converted into limestone by exposing them to fresh water.

Fresh water derived from the rainfall is slightly acidic and undersaturated with respect to calcium carbonate. When it strikes the surface of the unconsolidated carbonate sands, on account of gravity forces, it percolates downward through the pore system of the sediments. In due course, it becomes highly concentrated with $CaCO_3$, since aragonite shell particles are unstable and dissolve rapidly in fresh water to form calcium bicarbonate. This chemical change has been explained by Friedman & Sanders (1978) as:

$$CaCO_3 + \underset{\text{(liquid)}}{H_2O} + \underset{\substack{\text{(aqueous)} \\ \downarrow\uparrow \\ CO_2 \\ \text{(gas)}}}{CO_2} \rightleftharpoons Ca^{2+} + 2HCO_3^-$$

With increasing dissolution of aragonite, the solution becomes saturated, the pH climbs to about 8, where upon the dissolution stops.

According to Weyl (1958) and Glover (1964), the above phenomenon constitutes a very important process that produces good amount of dissolution for the precipitation of low-Mg calcite. This process of dissolution of calcium carbonate mineral is increased and accelerated due to

(i) the delivery of new H_2O from rainfall,
(ii) addition of CO_2 and organic acids by bacterial decay and
(iii) cooling on account of changes in weather (Dunham, 1969b).

Dunham (1969b), has also suggested that "the gas phase provided pathways by which CO_2 and gaseous H_2O moved from one part of the system to another, or back out to the atmosphere". The CO_2 produced by bacteria increases hydrogen ions and pH, and adds HCO_3^-. The precipitation of $CaCO_3$ takes place when it is exposed to environment of higher pH and higher CO_3^{2-} content (Cloud, 1960). Hence the percolating rain water in miliolites becomes supersaturated with $CaCO_3$ in three ways by:

(i) evapotranspiration of pore water, especially near the surface of the carbonate sands (Gardner, 1983),

(ii) a decrease in partial CO_2 pressure due to degassing to the atmosphere, and

(iii) dissolution of aragonite shells and then percipitates slowly as low-Mg blocky calcite cement in open spaces between and within particles causing the blockage of many original openings.

According to Gardner (1983), "aeolianites in the early stages of sub-aerial diagenesis will exhibit higher Sr^{2+} content than their more degraded counterparts from which the unstable aragonite has been removed".

"The stable isotope values of carbon within dune sands becomes increasingly negative during cementation by $CaCO_3$ in a sub-aerial environment. The progressive change in $\delta^{13}C$ values during aeolianite diagenesis reflects the alteration of marine carbonate grains and the precipitation of calcite cement in a zone of fresh water, containing both soil carbonate and marine carbonate (Gross, 1964; Keith & Weber, 1964; Magaritz et al, 1979)".

The conversion of these loose carbonate sands (miliolitic sands) into consolidated rock (limestone) would therefore include following three main diagenetic processes during which the calcitization of metastable minerals to low-Mg calcite took place:

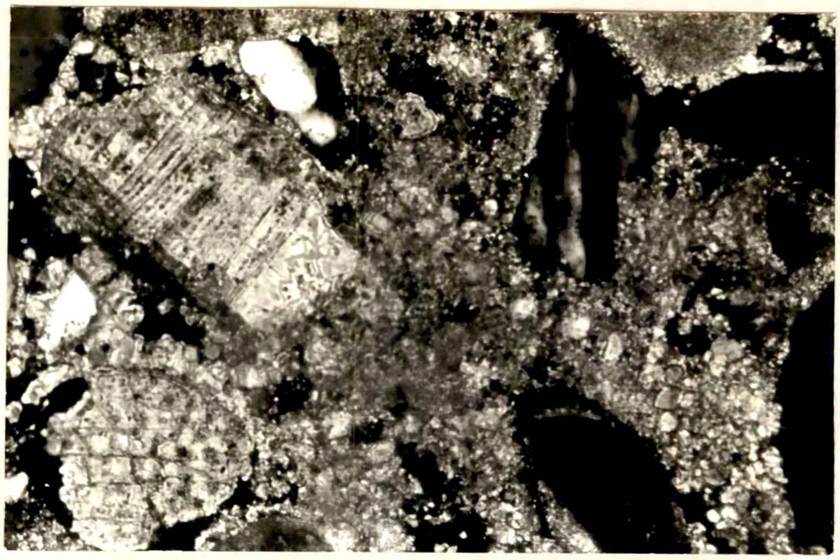
(a) Conversion of high magnesian calcite to low magnesian calcite, during which the original texture of the shell was preserved with a thin micritic envelope (Purdy, 1968). Bathurst (1971) has termed this process as 'incongruent dissolution', where the pore water solution gets saturated with calcite (Plate VI,4).

(b) The aragonite allochem's dissolution is partial or complete, resulting in the total loss of texture of allochem. The void spaces or cavities created by this process, reflect the original allochem outline with micritic coating envelope forming a mould of the allochem referred to as 'moldic porosity' by Friedman & Sanders (1978). Bathurst (1971) termed this as 'congruent dissolution' (Plate VI.5).

(c) Precipitation or calcitisation of low-Mg calcite derived from the dissolution of aragonite and high-Mg calcite allochems to occur as cement between particles or as mould filling cement within intraparticles spaces.

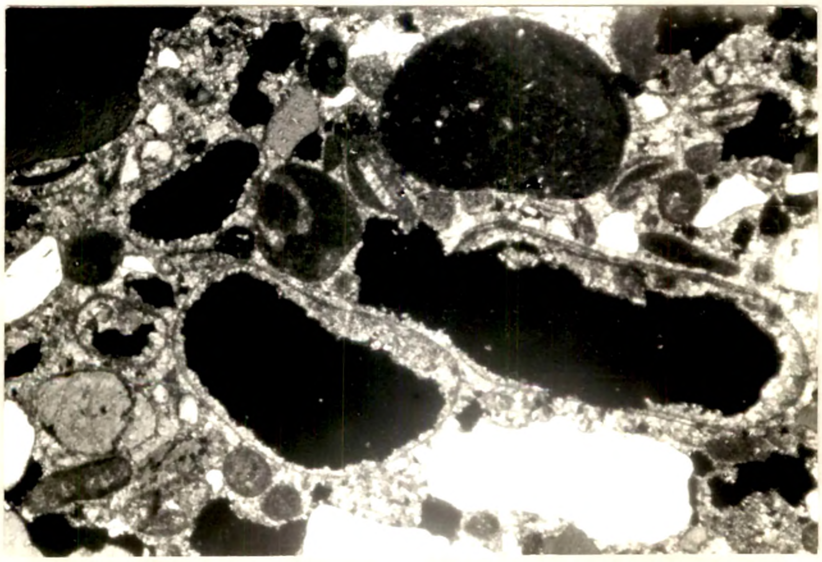
The above scheme has been accepted by Friedman, 1964, 1975; Schlanger, 1964; Purdy, 1968; Gavish & Friedman, 1969; Land, 1967; Bathurst, 1971; Wilson, 1975; Ward, 1975; Friedman & Sanders, 1978; Flugel, 1982 and Gardner 1983;

Plate VI. 4



Photomicrograph showing partial dissolution of bioclast with preservation of original texture (? incongruent dissolution)
(X 180, PPL)

Plate VI. 5



Photomicrograph showing complete dissolution of bioclast (congruent dissolution)
(X 50, PPL)

who have worked in different parts of the world on similar rocks.

In the light of above, it has been concluded that the precipitation and growth of cement in miliolite limestones of study area have been controlled by the various factors, summarised as under:

(i) Climate,
(ii) mineralogy of allochems,
(iii) availability of fresh water,
(iv) rate of supersaturation of solution (fresh water),
(v) nearby geological formations,
(vi) mode of distribution of miliolitic sands.

Depending upon the above factors, the miliolite rocks show varying degree of cementation e.g. the sheet miliolites are more consolidated and less friable than obstacle deposits which are loosely consolidated and more friable in nature. This is because the sheet miliolites being more ore less horizontal or sub-horizontal remained in contact with meteoric water (rain/river water) for a longer time than those of the obstacle deposits. The stagnation of rain water as well as fluvial action would give rise to conditions conducive for letter cementation. Thus the rate of dissolution of allochem and precipitation of low-Mg calcite would be more in the case of sheet miliolite than the obstacle deposits.

Cementation phases

As already stated, the Kutch miliolites show atleast two generations of cement. Many workers (Bathurst, 1958, 1971; Oldershaw & Scoffin, 1967; Milliman, 1974; Flügel, 1982; Gardner, 1983) have examined this phenomenon in limestones from different parts of the world and have observed their significance. In chapter V, the author has, following the nomenclature used by Flügel (1982), designated the two generation of cements as cement 'A' and cement 'B' (Ref. Plate V.5 & 6). According to Bathrust (1958) these cements are the precipitated low-Mg calcite, resulted from the dissolution of aragonite in fresh water, sub-aerial environment under low overburden.

In Kutch miliolites, the two generations of cement, viz., 'A' and 'B' reflect two phases of precipitation, and are separated by an intervening period of compaction and fracture, as it is observed that many shell fragments have been broken during the compaction after deposition. The first generation cement is observed to occur on the pre-fracture surface of the shell and the fractured surfaces are seen directly covered by the second generation blocky cement 'B' or vadose crystal silt. Thus, thin sections ideally establish that the cement 'A' is the early diagenetic cement as its absence is marked on the fractured surface of the shells, and the cement 'B' belong to a late diagenetic event.

The 7 types of cements (Ref.Plate V.5 & 6) have been grouped generationwise and, their micromorphology and diagenetic details/significance have been discussed in the following text.

1) Drusy rim cement

The drusy rim crystals are smaller than those of the pore filling cement, and usually form the early diagenetic cement 'A'. The diagnostic feature of this cement is that it contains the rings of fibrous and bladed calcite crystals occurring as rims around the grain, or lining the walls of the primary openings or secondary cavities produced by the dissolution of allochems. The larger axes of these cement crystals are usually perpendicular to the boundaries of the pore walls or particle surfaces.

Most of the particles present in miliolites are seen to have been coated by double films of calcite, made up of the inner thin micritic laminae and the outer fibrous drusy rim cement.

This first generation rim cement has been preserved beneath the later overgrowth of second generation pore filling cement. The sharp boundary between these cements is the strong evidence of their formation at different times with a time interval.

2) Gravitational cement

Features shown by this cement is typical of fresh water diagenesis in vadose environment. The occurrence of this cement is characterised by small-sized calcite crystals, occurring as incomplete rims of cement 'A' and exhibit a characteristic downward thickening, somewhat akin to a small scale stalactites into the interstices from beneath or lower boundaries of grains.

The growth of this type of cement is on account of precipitation of the supersaturated droplets of water at the lower surface of the particles in vadose environment (Jacka, 1974; Badiozamani et al, 1977). This structure is ideally seen in many thin sections of miliolites cut perpendicular to the bedding plane where the lower surface of many grains show effect of gravitational cementation identical to the phenomenon illustrated by Muller (1971); Badiozamani et al, (1977). Many workers (Purser, 1969; Bernoulli & Wagner, 1971; Bechstädt, 1975) have named this type of cement as 'dripstone cement'.

3) Dog-tooth cement

This occurs as cement 'A' and comprises small calcitic blocky crystals that line the cavities and also coat the surface of miliolite particles. The crystals are commonly fashion, as a result the precipitated calcite as cement also occurs in a meniscus fashion in between grains.

5) Syntaxial rim cement

This refers to the overgrowth and development of a single crystal (cement) over an original free surface of pre-existing crystal (allochem) in such a fashion that it shares the same crystallographic axes with the allochem. In other words, the overgrowth calcite cement is in lattice continuity with that of the allochem substrate, with free surface acting as nucleus. Bathurst (1958) called this type of overgrowth as 'rim cementation' which results from the precipitation of low-Mg calcite as an overgrowth cement on a polycrystalline substrate surface. Such syntaxial overgrowth of low-Mg calcite cement forming a rim on the surface of abraded echinoderm spines is observed in the miliolites. The development of a 'syntaxial rim cement' is typically indicative of fresh water subsurface or subaerial cementation (Pettijohn, 1949; Bathurst, 1958, 1971; Lucia, 1962; Orme & Brown, 1963; Evamy & Shearman, 1965, 1969; Schneider, 1977; Neugebauer & Ruhrmann, 1978; Burgess, 1979; Gardner, 1983).

Interestingly, the author has observed that the syntaxial overgrowth on echinoderm spines is of second generation, as some echinoderm spines show an intervening rim of first generation (fibrous) cement developed over a micritic envelope, which in turn, shows the overgrowth of second generation syntaxial cement. There is no optical continuity between the allochem and cement 'A', whereas the allochem and the syntaxial rim cement (B) remain in optical continuity.

6) Pore filling cement

Pore filling cement comprises the principal type of cement and is represented by crystals larger and clearer than the fibrous cement. This cement occludes the inter (primary) and intra (secondary) granular pore spaces, and is made up of blocky or granular sparite. It is a product of late diagenesis, and forming the second generation cement 'B'. The crystals of this type of cement commonly lack in parallel orientation and tend to fill the pores randomly rather than rimming them. The crystal size generally increases towards the centre of the pore from the pofe walls. The sparite cement is observed to unite the constituents and also filling the empty chambers of some of the tests like Milioliidae, Rotaliidae, gasteropods, etc. At places, the secondary spaces, produced due to dissolution have been filled with this cement and in such bases it is very difficult to detect the exact boundary of the allochem. The author has recorded occurrence of completely dissolved allochems that have been replaced by this cement, where its original shape is recognised by a faint micritic rim which forms the mould or ghost of the allochem (Ref.Plate VI.5). The fresh water environment precipitation of this cement is indicated by its coarseness pointing to a slow rate of precipitation uninfluenced by organic reactions and free from interference with Mg^{++} or other ions (Folk, 1974).

The voids and interstices in some miliolite rocks have been filled with sediments composed of well sorted '<u>vadose</u> <u>silt</u>', which are characterised by the following features:

1) It has been deposited in the primary (interstices) and secondary (solution) vugs.
2) Below the crystal silt, is fibrous or drusy calcite cement and above it is blocky calcite cement.
3) This cement usually post-dates the precipitation of fibrous or drusy cement and pre-dates the precipitation of blocky calcite cement.
4) It shows a scarcity of clay size particles, sand-size particles and recognisable skeletal debris.

In many thin sections of miliolite the grains show successive rims of fibrous cement followed by vadose crystal silt and in turn, by the blocky cement (Ref.Plate V.6 d). This phenomenon indicates that the silt postdates the fibrous cement. According to Dunham (1969a) "Mineralogically the sediment is calcite; texturally it is silt" and it confirms the diagenesis in sub-aerial environment. In all probability, this crystal silt cement is of secondary origin and has been accumulated at some spots within the miliolite by percolation of surface water into the sediment system.

VADOIDS

Origin and significance

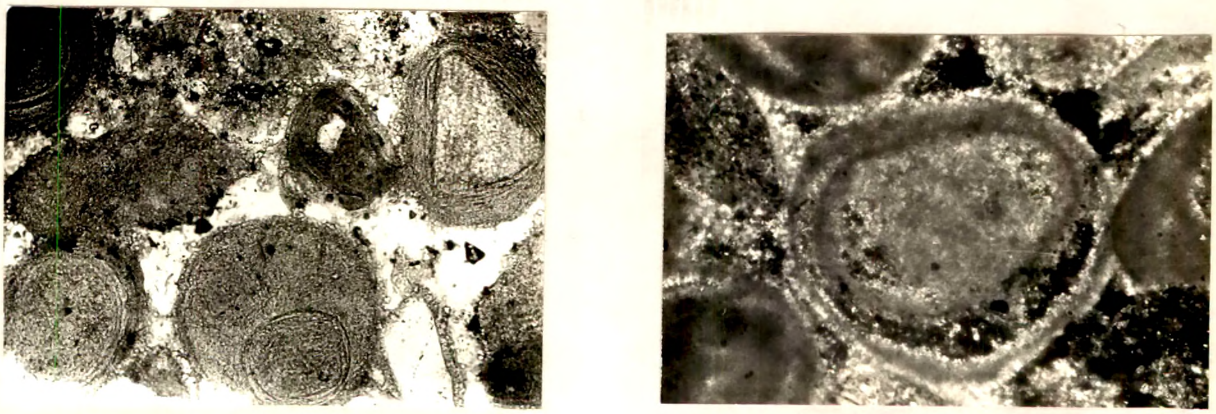
The occurrence of vadoids in the Kutch miliolite, has provided a conclusive evidence in support of their fresh water diagenesis. The present author has already alluded to these coated grains while describing the petrographic characters of the rock. These grains reveal quite a lot towards a proper understanding of the diagenesis of Kutch miliolites and an indepth study of these vadose environment products has enabled the author to an understanding of the genetic processes.

The miliolite limestones of Kutch are characterised by the presence of coated grains enveloped by alternate light (microspar) and dark (micrite) concentric lamellae with nucleii of skeletal material like foraminifera, mollusc fragments, echinoderm spines, algae and peloids (Ref.Plate V.3) These grains attain a maximum size upto 0.8 mm and resemble 'vadose pisoids' of Dunham (1969 b), 'diagenetic ooids' of Siesser (1973), 'calcrete pisoids' of Read (1974); Elloy & Thomas (1981), and Richter (1983), 'vadose ooids' of Harrison (1977), and 'pisoids with skeletal nuclei' of Esteban & Pray (1983). Recently, Peryt (1983) has given the name 'vadoids' to the coated grains originated in vadose environment, which are often of microid size, and according to this author to it belong grains that have been variously termed, e.g. cave pearls, fluvial pisoids, caliche pisoids and vadose pisoids. He has also reinterpreted many pisoids (and microids) which were earlier interpreted as 'oncoids' and termed them as 'vadoids'.

The present author has followed the terminology of Peryt (1983) for the concentrically laminated coated grains observed in the Kutch miliolites. The vadoid grains observed by the author typically show nuceli of skeletal particles and peloids of different size, shape and nature, coated by an envelope of alternate dark and light laminae (Plate VI.6). The size of the nucleus varies from one vadoid to another, and there exist a direct relationship between the nucelus size and that of the vadoids. No relationship is observed between the nucleus size and the envelope thickness. On the

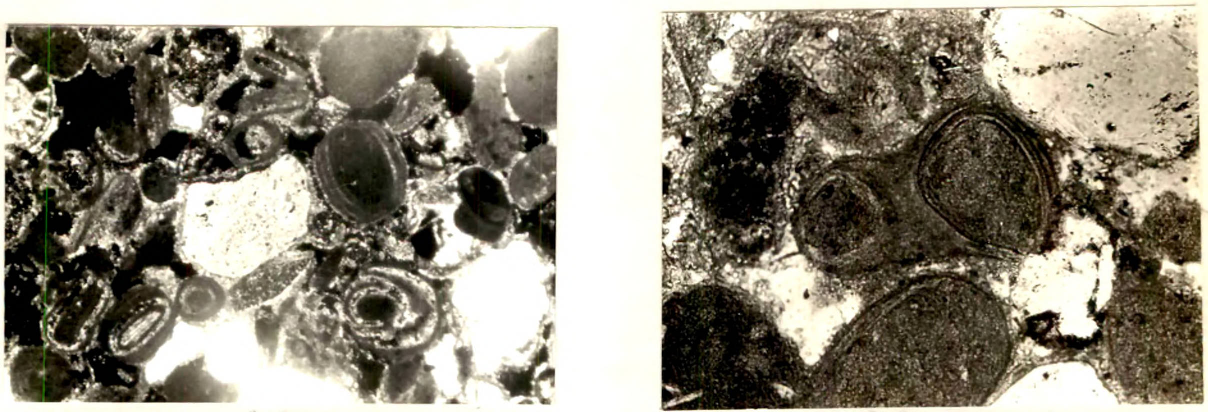
Plate VI. 6

Photomicrograph showing characteristic features of vadoids in Kutch miliolites



(a)
Vadoid with triangular nucleus
(X 140, PPL)

(b)
Downward thickening of vadoid
(X 140, PPL)



(c)
Vadoid with nucleii of various shapes
(X 40, PPL)

(d)
Two nucleii with common envelope in vadoid
(X 140, PPL)

(e)
Two elongated nucleii showing a common coating
(X 140, PPL)

other hand, the shape of these vadoids depend on the shapes of the nucleus; e.g. in the case of the vadoids with elongated or triangular shaped nuclei the development of laminae is thicker along the longer sides and thinner or sometimes absent at the shorter side or edges (Plate VI.6a).

The envelopes sometimes show either upward of downward preferential growth and thickening or both (Plate VI.6b,c). This textural characteristic is typical of a fresh water diagenesis and has been described by many other earlier workers (Bretz & Horberg, 1949; Swineford et al, 1958; Dunham, 1969 b; Wardlaw & Reinson, 1971; Steel, 1974; Read, 1974; Assereto & Kendall, 1977; Hay & Reeder, 1978; Surdam & Stanley, 1979; Hay & Wiggins, 1980; Esteban & Pray 1983; Goudie, 1983; Peryt, 1983). The downward thickening of such grains envelope is similar to the downward growth of 'calcrete' described by Goudie (1983) and according to him "This is because in a vadose environment, in which most calcretes form, a gravitational type of cement would develop after the bulk of the mobile water had drained out of the pores, with a thicker water film occurring at the lower surface of the grains in the direction of the gravity vector".

The presence of (i) thicker laminae on the upward or downward side in some vadoid grains and (ii) comfortable fitting of them among other particles, characteristically points to their 'in situ' growth. Coating of two nucleii by a common envelope is also another very interesting and important phenomenon that point to the 'insitu' growth of these grains (Plate VI.6d,e).

The development and formation of vadoid grains appears to have been controlled by many factors, the important ones being as under:

(i) presence of nucleus (fossils and peloids),
(ii) presence of fresh water,
(iii) mineralogy of rock constituents,
(iv) geological setting of the host rocks and
(v) climate, etc.

It is significant that in Kutch, the occurrences of vadoid grains are mostly restricted to sheet miliolites at the base of obstacle deposits, river banks and also to the thin (30-40 cm) layers of calcrete (caliche), that rest over such sheet deposits, where percolation and capillary rise of fresh water has been more as compared to those of obstacle deposits (Fig.VI.3).

Though the precise mechanism of the origin of calcrete layers over sheet miliolites is not fully understood, it is mostlikely that they originated by following two quite distinct processes:

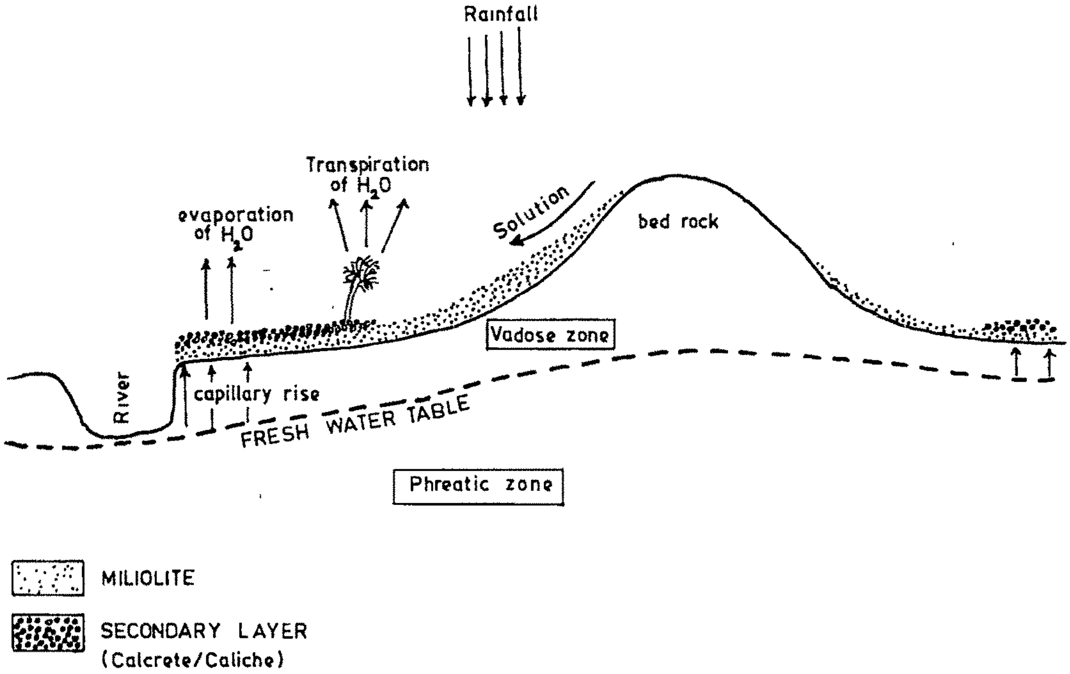


Fig.VI 3 Schematic diagram showing zone of formation of 'vadoid' in Kutch miliolites.

(i) on account of the action of rain water where the calcium carbonate would get dissolved from the upslope of the terrain (dune deposits) and washed to the lower parts where it would accumulate as secondary layers (calcrete or cliche) over underlying sheet miliolites and

(ii) by a mechanism similar to that invoked by Flügel (1982). According to him caliche or calcrete is formed when the "Calcium hydrogen carbonate dissolved in pore water rises to the surface by capillary action and upon evaporation deposits cryptocrystalline calcareous crusts on or in the surface. The occurrence of these terrestrial calcareous crusts is restricted primarily to arid or semiarid regions, where the annual relative humidity is about 200-600 mm and evaporation exceeds the annual rainfall".

The Kutch region having semiarid climate with annual rainfall less than 400 mm is an ideal region for the formation of such calcrete crusts. The vadoid grains present in miliolite of Kutch have originated on account of the precipitation of calcium carbonate from the super-saturated fresh water around a nucleus, where the evaporation is more than the annual rainfall. The presence of alternate dark and light laminae around the nuclei is on account of the alternating dry and humid periods in semi arid climates. Siesser (1973), has also invoked the similar phenomena to explain the origin of his 'diagenetic ooids'.