VOLUMINA JURASSICA, 2013, XI: 147–162

Temporal facies and diagenetic evolution of the mixed siliciclastic-carbonate Jajiya Member (Callovian–Oxfordian), Jaisalmer Formation, West India

Ghulam Mohammad BHAT [1], Abul Hasnat Masood AHMAD [2]

Key words: temporal facies analysis, diagenesis, petrofacies, Jajiya Member, Jaisalmer Formation, West India.

Abstract. Three broad lithofacies – bioturbated packstone- to rudstone, calcareous sandstone and cross-bedded rudstone to packstone are recognized within the Jajiya Member. The facies architecture and stalking pattern suggests deposition related to TST, HST and TST events punctuated by MFZ events in sequence stratigraphic terms. The 11.4 m thick sequence represents two fining upward and three coarsening upward cycles representing bar-bank depositional settings. The framework constituents of these facies were mainly controlled by the depositional conditions through space and time and have greatly influenced their diagenetic evolution. The main diagenetic features observed within the facies include compaction, early cementation and porosity reduction, micritization and neomorphism representing early or syn-depositional and post-depositional changes. Two phases of early mechanical compaction have largely governed porosity development in these facies. However, cementation, micritization and neomorphism have also contributed significantly in this respect. Evidence suggests that marine phreatic and fresh water phreatic environments dominated the diagenetic evolution of these facies. Calcite cementation was first formed, followed by iron oxide, while silica cementation occurred probably at a late stage.

INTRODUCTION

In western India, mixed siliciclastic-carbonate successions of Mesozoic age occur in the Jaisalmer and Kachchh basins. These are pericratonic basins on the westerly dipping eastern flank of the Indus shelf. The sedimentary rocks within these basins represent rift-filled sediments and form a major part of the basin fill. The Jaisalmer Sub-basin deepens southwest of Barmer Basin (Misra *et al*., 1993). During the Permo-Triassic period, sedimentation in this basin commenced with deposition of the arenaceous Bhuana Formation (Misra *et al*., 1993) which was followed by fluvial to deltaic sedimentation (Lathi Formation) during the Middle Jurassic. This was followed by a thick sequence of stable shelf carbonates with basal sandstones (Jaisalmer Formation) during the Middle to Late Jurassic. The source of the sandstones of the Lathi and Jaisalmer formations was the hinterland in the north and northeast fromwhere the sediments were transported by the fluvial system draining the western Rajasthan shelf and deposited in a shallow marine setting in the Jaisalmer Basin. All these sedimentary successions are cyclic in nature but they are particularly well developed in the Jaisalmer Formation of Late Bajocian–Oxfordian age (Jaikrishna, 1987; Pandey and Fürsich, 1994; Pandey *et al*., 2006a, b, 2009). The Jaisalmer Formation comprises the Hamira, Joyan, Fort, Badabag, Kuldhar, and Jajiya members (Kachhara, Jodhawat, 1981; Pandey *et al*., 2012) (Table 1). The outcrops of these members occur along

[1] Department of Geology, University of Jammu, India
[2] Geology Department, Aligarh Muslim University Aligarh, India; e-mail: ahmahmad2004@yahoo.com

Table 1
Lithostratigraphy of Jurassic sediments, Jaisalmer Basin, western India (after Kachhara, Jodhawat, 1981)

Formation	Member	Age
Jaisalmer	Jajiya	Callovian to Oxfordian
	Kuldhar	
	Badabag	Bajocian to Bathonian
	Fort	
	Joyan	
	Hamira	
Lathi	Thaiat	Lower Jurassic
	Odania	

Basement rocks (Proterozoic/Cambrian/Permian–Triassic)

the raised Mari-Jaisalmer Arch in the basin. The Kuldhar and Jajiya members are predominantly composed of carbonates deposited above storm wave base in the shoreface zone to off-shore transition zone and are the only members – with the exception of the record of *Clydoniceras* by Prasad *et al.* (2007) from the Fort/Badabag Member (Pandey *et al*., 2012) – of the Jaisalmer Formation yielding ammonites, and show the maximum diversity of fauna of the entire Jaisalmer Formation (Pandey *et al*., 2010). The outcrop of the Jajiya Member is best exposed along the cliff section near Jajiya village located about 5 km southwest of Kuldhar village (26°50'28.4"N and 70°44'31.6"E), about 22 km southwest of Jaisalmer town, and at the top of the section 11 km west of Jaisalmer. The Jajiya Member is comprised of sandy limestone units, low angle cross-bedded and trough cross-bedded calcareous sandstones, and overlying sandy fossiliferous limestones. The Jaisalmer Formation has attracted the attention of sedimentologists and palaeontologists because of the easily accessible outcrops and good stratigraphic marker horizons and rich well preserved fossil assemblages. Recently Pandey *et al*. (2010) have recognised 13 parasequences within the Jajiya Member following a sequence stratigraphic approach. However, the diagenetic evolution of these sediments has not been studied in detail. Carbonates undergo significant diagenesis even at moderate burial and in many cases are recrystallized (*sensu* Bathurust, 1975). Similarly siliciclastic sediments also are subjected to early diagenesis and evolve through time. Many studies have investigated the effects of depositional environments and diagenesis on porosity (*e.g.* Murray, 1960; Powers, 1962; Robinson, 1967; Mathews, 1976; and others). Some other studies have related the effects of depositional environments to late-stage diagenesis (*e.g*. Longman, 1980; Cantrell, Walker, 1985; Evans, Ginsburg, 1987; Steinhauff *et al*., 1999; Ahmad *et al*., 2006). The Jajiya Member has not been investigated for its diagenetic history vis-à-vis its depositional environments hitherto. The aim of our study is to document and interpret the diagenetic phases of the siliciclastic and carbonate units of the Jajiya Member and establish the relations between depositional environments and diagenesis vis-à-vis temporal lithological variation.

GEOLOGICAL SETTING

Much of the geological history of the Aravalli Craton and the development of various sedimentary basins in western Rajasthan revolves around the orogenic evolution of Aravalli–Delhi Fold Belt (ADFB). Sinha Roy (1988) postulated that the 'Wilson Cycle' tectonics were operative during the Early and Middle Proterozoic which culminated in the Delhi Orogeny. Das Gupta (1975) opined that the tectonic elements of western Rajasthan have been shaped before or during the Delhi Orogeny. Reactivation of the weaker zones gave rise to the basins through uplift and subsidence along high angle normal faults within the Proterozoic basement. The oldest sedimentary basin developed on the Rajasthan shelf is the Bikaner and Nagaur basin (Misra *et al.*, 1993) which is juxtaposed to ADFB. Siliciclastics, carbonates and evaporites were deposited in this basin during neo-Proterozoic to Early Cambrian times (Kumar *et al*., 1997; Chauhan *et al*., 2004; Pandey, Tej Bahadur, 2009) and are designated as the Marwar Supergroup (Khan, 1971; Pareek, 1984). The Jaisalmer Formation is of Mesozoic age (Misra *et al*., 1993) (Fig. 1). Formation of the Mesozoic basin may be related to Pangaea's pre-rift tectonics and incipient dispersal by rifting (Early to Late Triassic, 230 Ma) of the Indian Plate (Veevers, 1989). The two basins are separated by a basement high which acted as a barrier for the fluvial system.

Geophysical investigations conducted by Oil and Natural Gas Corporation Limited (ONGC) have revealed the occurrence of four structural units within the Jaisalmer Basin, viz. the raised Mari-Jaisalmer Arch extending through the central part of the basin, the synclinal Shahgarh Sub-basin to the west and southwest, the Kishangarh Sub-basin to the north and northeast and the Maijlar Sub-basin to the south (Pandey *et al*., 2010, and references therein). The subsurface strata comprise Proterozoic to Early Cambrian and Triassic sediments, whilst the Early Jurassic to Quaternary strata are exposed along the raised Mari-Jaisalmer Arch (Das Gupta, 1975; Misra *et al*., 1996; Pandey *et al*., 2012). The sediments to the northward sloping Jaisalmer shelf were largely supplied from the northeast of ADFB (Siddiqui, 1963).

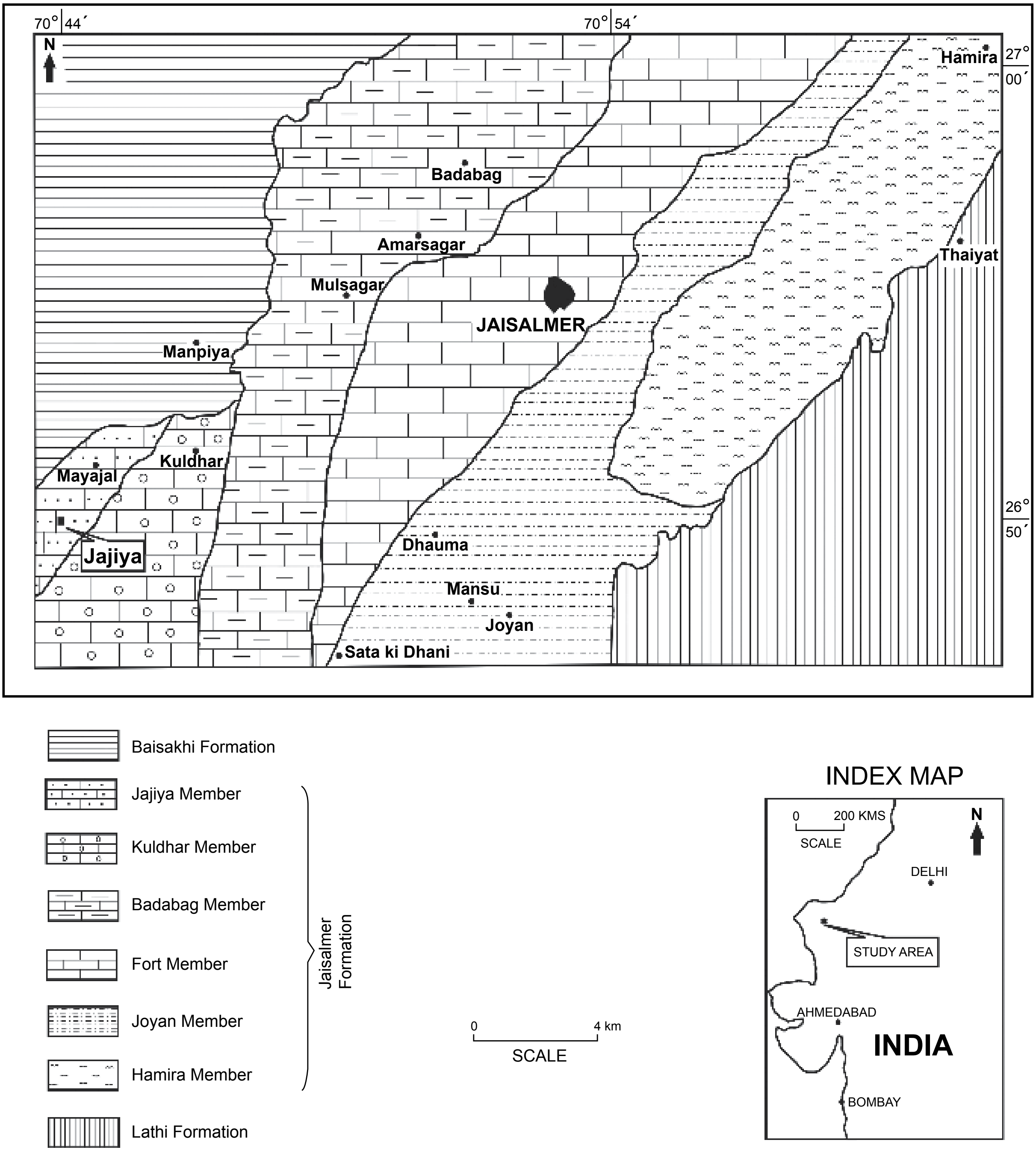

Fig. 1. Geological map of the area of investigation

METHODOLOGY

We studied the 11.4 m thick Jajiya Member in detail for lithofacies variations through space and time and sampled the siliciclastic and carbonate units at different stratigraphic levels (Fig. 2). We measured and sampled the section along Jajiya cliff near Jajiya village. Special attention was paid to the study of the facies variation, nature of sedimentary structures like cross-bedding, lamination, ripple marks, nature of bed contacts, colour variation, lateral and vertical facies changes, *etc*. Oriented standard thin sections were prepared of 21 samples for microfacies and petrofacies analysis, and the study of the types of cements and other diagenetic signatures which included compaction, porosity evolution, neomorphism and micritization (Tables 2, 3).

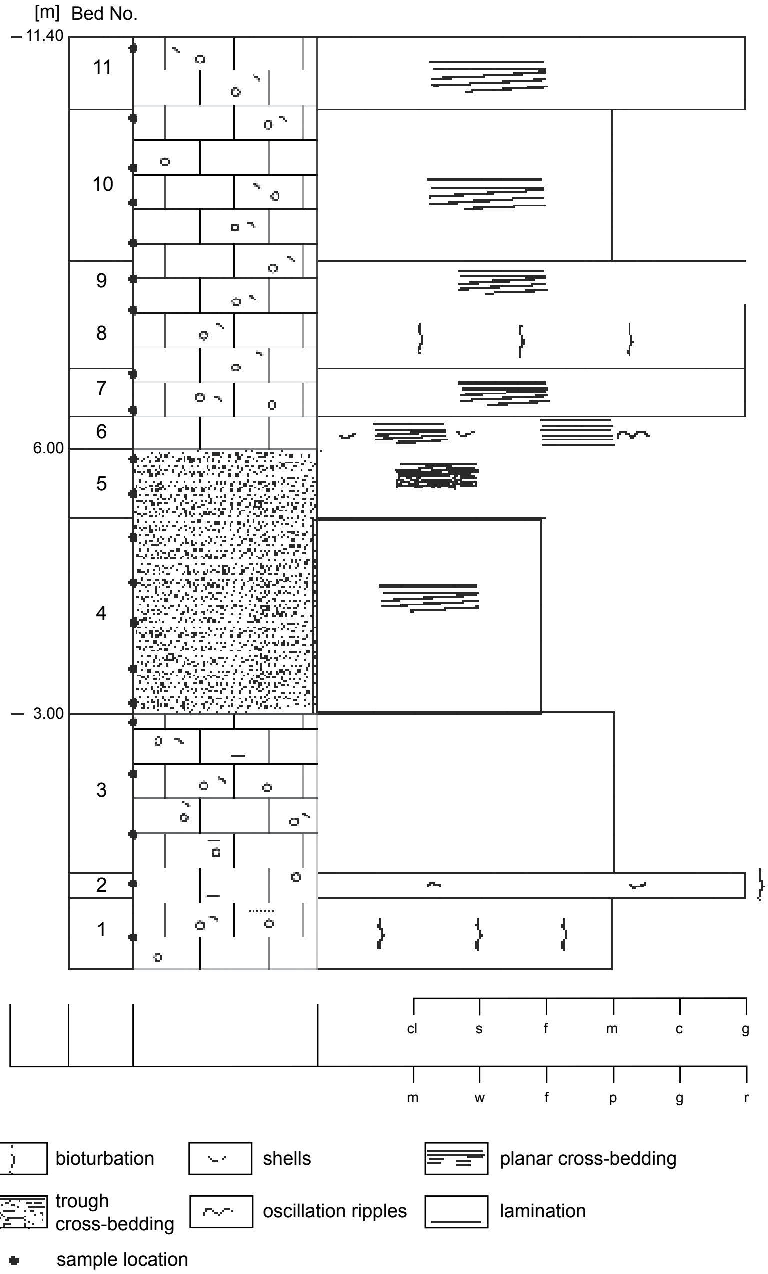

Fig. 2. Lithology of the measured section (modified after Pandey *et al.*, 2012)

m = mudstone, w = wackestone, f = floatstone, p = packstone, g = grainstone, r = rudstone, cl = clay, s = silt, f = fine sand, m = medium sand, c = coarse sand, g = gravel

Table 2

Types of cement, void space, detrital grains and porosity in the sandstones of Jajiya Member Calcareous Sandstone facies

Sample no.	Cements/matrix [%]						Total cement [%]	Detrital grain [%]	Existing optical porosity [%]	Minus cement porosity [%]
	silica	iron	carbonate		clay	matrix				
			spar	micrite						
6	0	3	15	2	0	2	22	75	3	25
7	0	10	1	11	0	3	25	74	1	26
8	0	18	7	3	0	3	31	64	5	36
9	1	2	18	5	0	2	28	70	2	30
10	0	8	9	7	0	2	26	72	2	28
11	0	2	11	6	0	3	22	74	4	26
12	1	10	6	8	0	2	27	71	2	29

Table 3

Percentage of major constituents of Carbonate facies of Jajiya Member

S/No.	Intraclast	Bioclast	Ooid	Pellets	Spar	Micrite	Terrigenous admixture
Bioturbated Packstone to Rudstone facies							
1	2	7	38	–	22	26	5
2	2	6	39	1	20	28	4
3	3	7	36	–	24	27	3
4	3	6	38	1	23	28	1
5	2	7	36	–	24	26	5
Cross-bedded Rudstone to Packstone facies							
13	2	2	42	–	33	20	1
14	2	3	43	–	25	22	5
15	3	1	46	–	20	24	6
16	3	4	42	–	22	25	4
17	2	3	44	–	19	27	5
18	3	2	45	–	20	27	3
19	1	4	43	–	18	30	4
20	2	6	42	–	16	29	5
21	2	6	50	–	12	24	6

STALKING PATTERN OF SEDIMENTARY FACIES

Bed by bed measurement and field observation of the Jajiya Member reveals rapid lithological variations through time. The individual beds are generally bounded by sharp, mostly erosional surfaces. The bed thicknesses vary from a few centimeters to a maximum of 1.0 m. The lithostratigraphic units separated by erosion surfaces represent different depositional episodes punctuated by frequent episodes of non-deposition. These depositional events are cyclic in nature and are related to the creation of accommodation space during transgressive episodes whilst the omission events are related to the pulses of regression. In the absence of any tectonic signatures in the basin during this period, these sedimentary cycles are related to forced transgressive--regressive episodes caused by climate controlled sea level changes. The Jajiya Member represents three major sedimentary facies showing alternate upward coarsening and fining trends. The basal part of the succession is marked by the presence of a prominent bounding surface – a hardground formed just below the sediment–water interface due to syn-sedimentary lithification and colonized by encrusting and boring organisms. Recently this hardground has been considered coeval to one in Kuldhar section (Late Bathonian) and Pandey *et al*. (2012) have assigned it to the Badabagh Member. The major facies observed in the measured sections are described in the order of superposition.

BIOTURBATED PACKSTONE TO RUDSTONE FACIES

This facies lies over the hardground (top of the Kuldhar Member – Pandey *et al*., 2012) exposed in the river-bed at the Damodra–Jajiya road crossing. The hardground surface is bored, erosive and exhibits well-cemented rudstone encrusted by abraded oyster shells (corresponds to the MFZ in terms of sequence stratigraphy of Pandey *et al*., 2010). The 3 m thick ooid- and bioclast-bearing packstone to rudstone facies (bed nos 1–3) is dominantly bioturbated and occasionally rippled. The bioclasts include fragments of fossils (bivalves: oysters, *Trigonia*, heterodonts, pterimorphs; brachiopods – rhynchonellids; belemnites, ammonites, crinoids, and other unidentified shell fragments). The bioclasts are abraded, bored and coated with ferruginous material and micrite coatings and are mostly associated with the packstone facies. Petrographically, the facies consist of biooosparite (Fig. 3A–C, pelbiosparite (Fig. 4A, B) and oobiosparite (Fig. 5A–C) in ascending order representing three parasequences recognized by Pandey *et al*. (2010). The bioclasts recognised in thin-sections include echinoderm plates and spines, bryozoans, solitary corals, ostracods, foraminifera, gastropods, bivalves, dasycladacean algae, brachiopod spines and other unidentified fossil fragments. An association of pelloids with the infaunal elements is also observed in the thin sections. The ooids present include true ooids, superficial- and composite varieties of oval and oblate shapes and their size ranges from 0.2 to 0.8 mm. Ooids are characterized by sub-angular and sub-rounded quartz and calcite grains and shell fragments as their nuclei. Angular to sub-rounded quartz grains of silt size and feldspar grains are

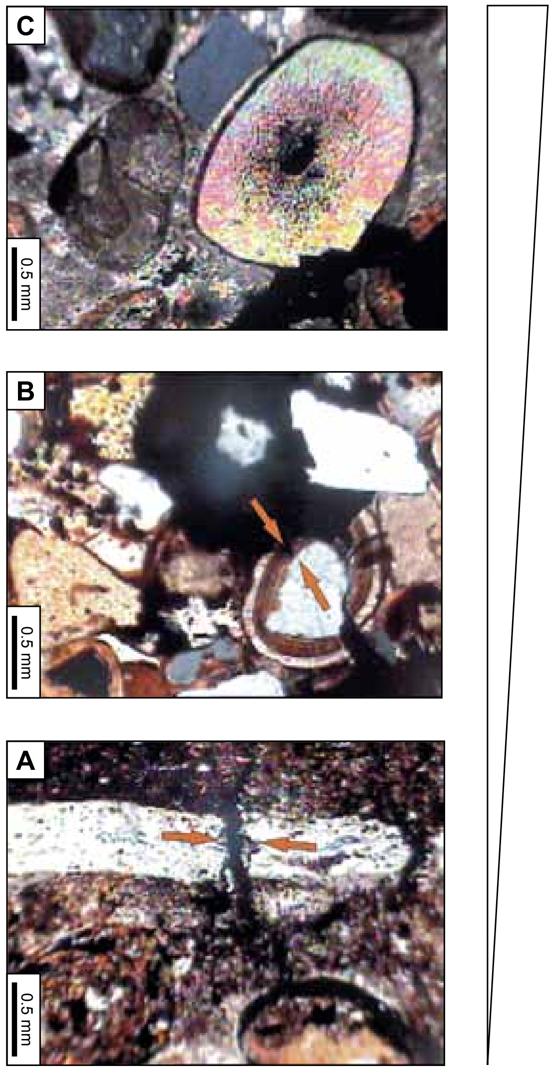

Fig. 3. Bio-oosparite facies

Irregular patches of neomorphic calcite crystals within micrite matrix (**A**). Fractures cut across the bioclasts, ooids and associated fibrous rim cement and geopetal inter-allochem calcisiltite matrix (**A–B**). Mechanically formed closely packed rock fabric and inter-allochem spaces filled with micritic matrix (**B**). First generation calcite and ferroan rim cements, drusy and blocky cements are present (**B–C**). Blocky cement occurs within intergranular pore spaces and filling up internal cavities of the bioclasts (**C**) also present within the micrite. Lumps of aggregate grains (intraclasts and bioclasts) are associated with a rudstone facies (Fig. 4A, B) within this lithological unit (bed no. 2 – corresponds to TST of Pandey *et al*., 2010). These lithoclasts have been derived from the underlying bed no. 1 (corresponds to HST of Pandey *et al*., 2010). The upper part of the facies is represented by bioturbated, poorly to well cemented, ooid- and bioclast bearing packstone with concretions in the top (bed no. 3). Pandey *et al*. (2010) have found this to be a condensed ammonite zone and interpreted this unit as a MFZ (their bed no. 5).

The packstone to rudstone facies is interpreted as wave- and storm-generated on a shallow marine shelf. Allochems of sand and silt size were emplaced and deposited under oscillatory currents related to storm activity and its waning phases. The presence of ooids suggests high energy within the frontal area with currents rising up the lower ramp. An association of intraclasts indicates active intraformational reworking and redistribution of the bottom sediments. The currents, tides and occasional storm waves redistributed the bioclasts (brachiopod, echinoderm, foraminifera, pelecypods, corals and bryozoans) both seaward and lagoonward from the bioclastic bar. The presence of pelloids and an active infaunal association suggests deposition in areas of low

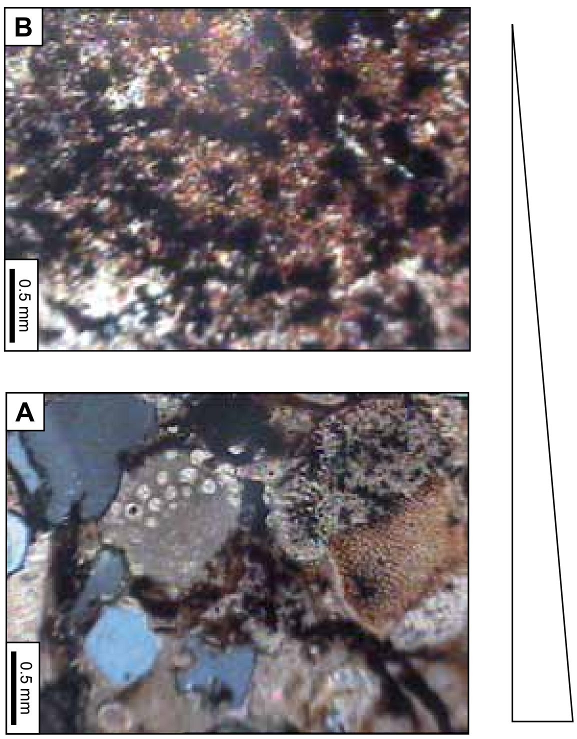

Fig. 4. Pelbiosparite facies

Inter-allochem spaces are filled with micritic matrix in which bioclasts are truncated against each other and form a condensed to fitted fabric (**A**). Lumps of aggregate grains (intraclasts and bioclasts) along with early diagenetic secondary euhedral to subhedral quartz crystals occur within intergranular pore spaces (**A**). Irregular patches of neomorphic calcite crystals occur within micrite matrix (**B**). The non-selective dissolution of grains of microcrystalline lime-mud has created micro-vugs with a patchy distribution (**B**)

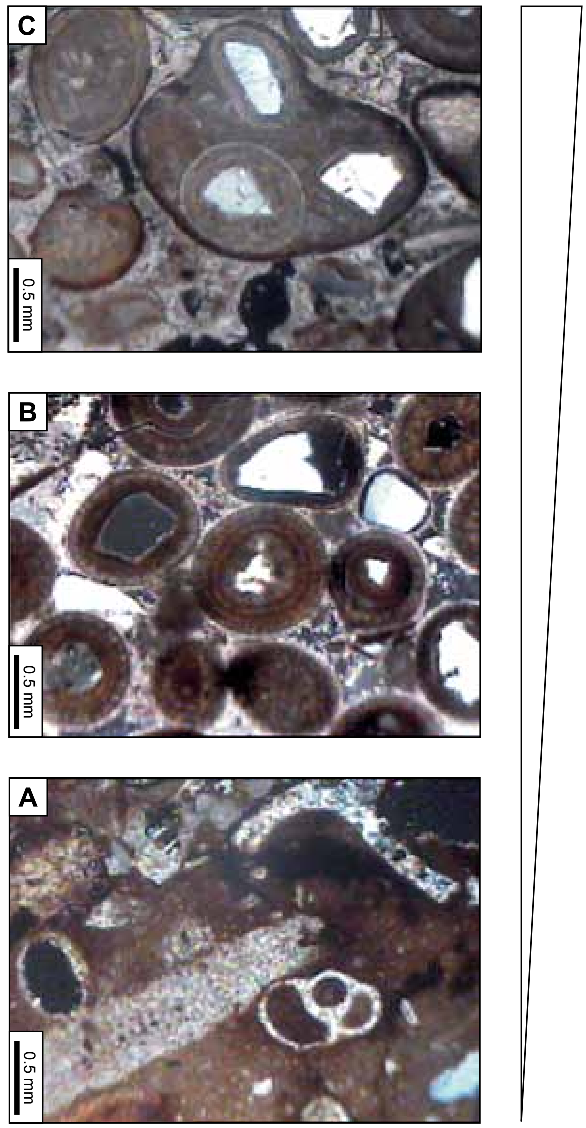

Fig. 5. Oobiosparite facies

Plastic deformation of bioclasts resulting in their bending but without inducing any physical breakage (**A**). Mechanically formed closely packed ooid fabric (**B**). Equant crystals make a zigzag transition into fibrous growth on the ooids (with euhedral and subhedral quartz as their nuclei) on one side and into the micrite on the other side within the void space (**B**). Inter-ooid spaces are filled with sparry calcite and micritic matrix representing first generation calcite and ferroan rim cements, drusy and blocky cements (**B–C**) energy with restricted circulation (*e.g*. lagoons). Aggregates of intraclasts within the oolitic limestones may be linked to an erosion phase as these are associated with the intraformational erosion surfaces and lithologically these are similar to the underlying beds. Some intraclasts have an irregular shape and appear to be an aggregate of smaller grains. Laporate (1978) suggested erosional intraclasts as intertidal and aggregate intraclasts as shallow subtidal in origin. In the present case, erosional intraclasts are common in the middle part of the facies (bed no. 2) deposited in the upper shoreface region by storm activity. Pandey *et al*. (2010) have observed mixing of the ammonites in bed nos 1 and 2 (their bed nos 3 and 4) and suggested condensed deposition of sediments due to sediment starving in the basin at the maximum flooding zone. Abrasion, boring and encrustations also indicate a long residence-period of shells before final burial.

CALCAREOUS SANDSTONE FACIES

The 3 m thick coarsening upward calcareous sandstone facies (Fig. 6A–D) is low-angle cross-bedded in the lower part and trough cross-bedded in the upper part. These lithological units are separated by uneven, sharp contacts between them (bed nos 4 and 5) and are rippled. The quartz grains are fine- to medium grained, sub-angular to subrounded and are embedded in fine carbonate matrix including small fossil fragments consisting of bryozoans, ostracods, echinoderm spines, and other unidentified bioclasts. In the lower part of the facies biotite and feldspars are also present. The sandstone beds are 30 cm to 1 m thick, fine grained, reddish brown, soft, poorly-to well-cemented, poorly sorted and occasionally nodular and sometimes bioturbated. These sandstones are thick- and thinly bedded. The sand grains are poorly to moderately sorted.

The cross-bedded sandstone facies with uneven and erosional surfaces in the middle and a sharp base above the ooid bearing packstone facies suggests regression, possibly

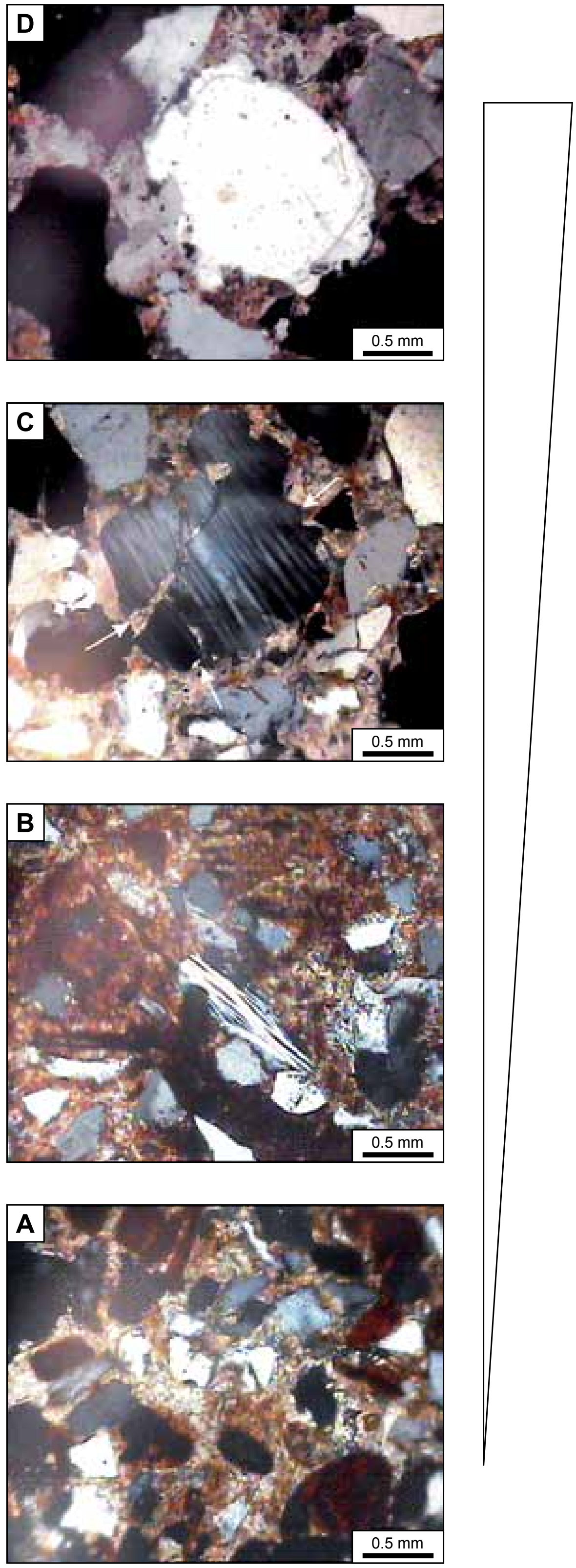

Fig. 6. Detrital silt, chert and muscovite and clay materials in the form of matrix (**A**). Floating grains in fine grained matrix with occasional point contacts (**A–C**) with occasional long contacts (**D**). Good sorting and early cementation (**A–B**). Muscovite and biotite occur as tiny to large elongated flakes with frayed ends (**B**). Strained and fractured detrital minerals grains floating in carbonate cements (**C**). Detrital grains occur as protrusions, embayments and notches (**C**). Corroded quartz grains and an indistinct boundary between quartz grains and calcite cement (**C–D**). Authigenic quartz overgrowth on detrital quartz grains that also partially filled the intergranular pore space (**D**)

forced by sudden sea level fall or due to a sudden increase in the terrestrial sediment influx (*e.g.* Pandey *et al*., 2010). The upper part of the calcareous sandstone facies is trough cross-bedded and associated with rippled beds. This is related to strong wave action. These are generally coarsening upward in nature. This type of facies mixing indicates its deposition in a lower shoreface transition zone of an intertidal mixed flat environment. The interbedded fine sand units reflect a transition from a wave agitated shoreface – foreshore below wave base-depositional setting. Pandey *et al*. (2010) have termed the facies as progradational HST or deposited during forced regression (FSST).

CROSS-BEDDED RUDSTONE TO PACKSTONE FACIES

This facies association is represented by 5.4 m thick low-angle cross-bedded and trough cross-bedded limestone units marked by oscillation ripples and bioturbated beds (bed nos 6–11). These limestones are yellowish brown, thickly- and thinly bedded, hard and compact, and low-angle cross-bedded. The cross-bedding azimuthal data show polymodal distribution pattern (Siddiqui, 1963). The main mode is directed towards the SE followed by NE and NW. Most of the cross-beds are in co-sets. The bounding surfaces of cross-beds are undulating. Some tabular cross-stratified units formed by subordinate currents are superimposed on the trough cross-beds. The upper and lower boundaries of the beds are sharp. This facies is dominated by bioclasts, oolites, sparry calcite and sometimes by micrite, particularly towards its top. Internally these beds consist of several thin beds. Overall the facies sequence is fining-upward in nature. The allochems are mainly composed of bioclasts, ooids and minor amount of pellets, intraclasts, lumps and ferruginous admixture which are poor to moderately sorted. This litho-unit contains bioclastic grainstone, bioclastic-lithoclastic grainstone, oolitic grainstone and bioclastic packstone--wackestone facies (Fig. 7A–E). The ooids present are

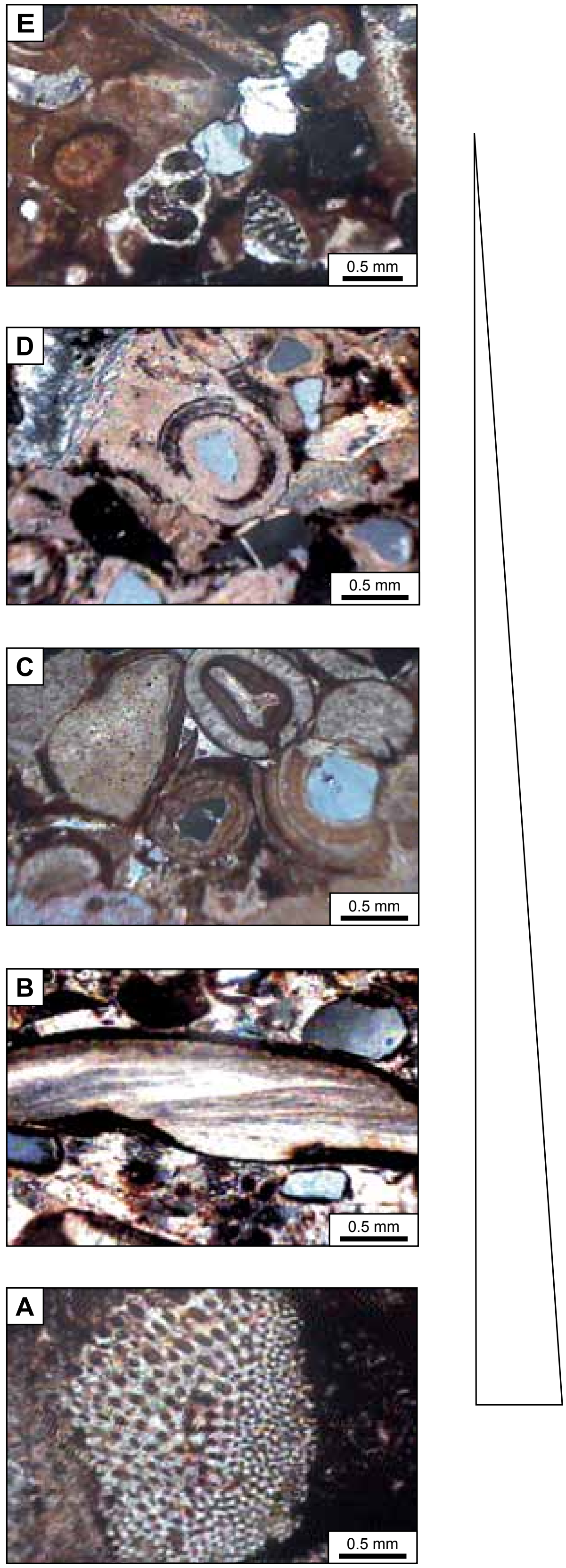

Fig. 7. Altered bioclasts (bryozoans) display a fabric-selective mosaic in which the individual crystals in the original bioclasts do not extend beyond the original boundaries into the void filling cement (**A**) in which the micritic groundmass has compensated compression leaving the allochems undeformed. Irregular patches of neomorphic calcite crystals within micrite matrix and a bioclast enveloped by micrite (**B**). Mechanically formed closely packed ooid fabric with quartz grains and bioclasts as nuclei of ooids (**C**). Inter-allochem spaces are partially filled with micritic matrix and sparite (**C**). Ooids and bioclasts are truncated against each other and form a condensed to fitted fabric (**C–D**). Blocky cement which generally occurs in intergranular pore spaces and also occurs as intragranular cement filling up internal cavities of the bioclasts (**E**)

mainly true circular ooides with at least three concentric rings. These ooides normally show a tangential microstructure. A few superficial ooids are also present. The micrite which dominates up-section in the facies sequence is ferruginous and has recrystallized to Fe-spar within some horizons. Superficial ooids are abundant but true and composite ooides are also present. The bioclasts are predominantly fragmented, but whole fossils occasionally also occur. They include calcispheres, foraminifera, colonial corals, brachiopods, bivalves (oysters, heterodonts, pteriomorphs), gastropods and echinoderms. The ghosts of bioclasts show the original wall microstructure suggesting their derivation by micritization. Pandey *et al*. (2010) have interpreted this facies as a TST sequence.

Large scale tabular cross-bedding indicates high energy, combined-flow conditions in a storm-influenced lower shoreface environment (Duke *et al*., 1991). The sediments formed by high energy currents during transgression are characterized by irregular to sharp contacts, clusters of ooids and bioclasts and large scale cross-beds and ripples above fair weather wave base. This facies-development forms in oolitic bar to bank systems (Ahmad *et al*., 2006). Oolites form a considerable component of bioclastic bar systems with corresponding maxima of their frequency and clasticity in the high energy frontal area with currents rising up the lower ramp. The currents and tides and occasional storm waves redistribute bioclasts (foraminifera, bryozoans, brachiopods, echinoderms, and others) both seaward and lagoonward from the bioclastic bar. The concentration of ooids and brachiopods in the oolitic bar-to-bank system indicates their distribution under high energy conditions, which were partially dispersed seaward by currents and tides. Moderate sorting with a low standard deviation and the well-rounded nature of the allochem population also indicates high energy shallow marine settings for these carbonates. However, an association of radial ooids indicates either agitated marine conditions or may be related to diagenesis (Kumar and Tiwari, 1978; Ahmad *et al*., 2006).

DIAGENESIS OF LIMESTONE

We observed environment-depositional-specific sequential diagenetic signatures in the carbonate samples investigated in this study. The main diagenetic features observed include compaction, early cementation and porosity reduction, micritization and neomorphism (Table 3). These facies specific diagenetic features represent early or syn-depositional and post-depositional changes that took place in different diagenetic environments.

COMPACTION

Within the different parasequences, two phases of compaction are observed. The pronounced evidences of these compaction phases include mechanical rearrangement, deformation and breakage of the allochems. Mechanical rearrangement has generally resulted in the formation of a closely packed rock fabric (Fig. 3B, 5B, 7C). Within the coarsening upward parasequences (CUPS), plastic deformation of bioclasts and ooids, resulting in their bending but without inducing any physical breakage, represents the first phase of early mechanical deformation (Fig. 5A). In certain cases, during this phase maximum compaction is compensated within the micritic groundmass, leaving the allochems undeformed, as observed in the fining upward parasequences (FUPS) of this study (Fig. 7A). The second phase of early compaction is represented by partial dissolution in both the CUPS and FUPS at the contacts of ooids and bioclasts, and initial spalling of ooid cortices. Inter-allochem spaces are filled with micritic matrix (Fig. 3B, 4A, 5B, C, 7C). Elsewhere, these early compaction phases have been related to a marine phreatic environment (Ahmad *et al*., 2006 and the references therein).

In some of the cases in CUPS, fractures cut across the bioclasts, ooids and associated fibrous rim cement and geopetal inter-allochem calcisiltite matrix (Fig. 3A, B, 4B). These early fractures are filled with Fe-calcite which shows optical continuity with cavity-filling Fe-cement. However, there appears no dissolution along these fractures, but broken parts of the allochems show little relative displacement suggesting a post-cement phase of compaction. In case of FUPS, the ooids and bioclasts are truncated against each other and form a condensed to fitted fabric (Fig. 4A, 7D). Similar diagenetic features observed elsewhere (Ahmad *et al*., 2006 and references therein) from the microfacies of the landward margin of the oolitic-bar-bank system, have been interpreted as representing an early fracture phase in the undersaturated freshwater phreatic environment.

CEMENTATION

Four distinct types of cement are recognised in the carbonates of the Jajiya Member. These include ferroan and calcite rim cements, fibrous, bladed and blocky cements. Generally, early marine cements form during deposition or shortly thereafter at the sediment-water interface (*e.g*. Steinhauff, 1989, 1993). Blocky and fibrous cements form drusy overgrowths of uniform thickness around the rim of the allochems and also occur as bundles of calcite crystals embedded in micrite. Three types of these first generation cements, calcite and ferroan rim cements, drusy and blocky cements, are present in the CUPS of this study (Fig. 3B, C, 5B, C). On the other hand only ferroan and calcite rim cement and silica cement are present in the FUPS (Fig. 7B–E). These are the characteristic first generation cements in many carbonates of the marine phreatic environment (*e.g.* James, Choquette, 1984; Singh, 1987) and have been reported from the Kuldhar and Keera Dome carbonates of western India (Ahmad *et al*., 2006). The second generation equant crystal habit cement grows in optical continuity with fibrous cement. The crystals are polygonal and equigranular and occur as patchy intergranular and void-fill cement (*cf.* Whittle *et al*., 1993). These equant crystals make a zigzag transition into fibrous crystals on the one side and into micrite on the other side within the void space (Fig. 5B). The distribution and fabric of the equant habit cement is characteristic of the meteoric vadose environment, whilst the fibrous calcite cement most probably represents replacement of primary fibrous aragonite cement (*e.g.* Bathurst, 1975), as the length/breadth ratio of the fibrous crystals is around 7:1 as reported by Bathurst (1959) for fibrous aragonite cement. This is also evidenced by the formation of modern day marine cements as isopachous crusts of acicular crystals of aragonite or Mg-calcite (*e.g.* Longman, 1980; James, Choquette, 1983) and all Recent submarine and beach rock cements are of a bladed to fibrous nature (Bricker, 1971).

The third type of carbonate cement is blocky cement which generally occurs in intergranular pore spaces and sometimes also occurs as intragranular cement filling up internal cavities of the bioclasts (Fig. 3C, 5C, 7E). Blocky cements generally occupy central portions of the pore spaces and are precipitated in meteoric water environments where low Mg^{2+} content facilitates precipitation of blocky calcite. Blocky cements have been interpreted as fresh water diagenetic and are analogous to meteoric cements in many Holocene ooid sequences. Ferroan rim cement is more common in both the CUPS and FUPS of this study. The ferroan coating around the allochems (bioclasts, ooids) has obliterated syntaxial and fibrous cement growth on them. The probable source of Fe-cement is the presence of a hardground within the sequence.

The silica cement is present in the FUPS within the intergranular pore space. The source of silica cement appears to be the dissolution of quartz grains present with the facies and nuclei of the ooids. The dissolution of the silica nuclei is evidently due to mechanical compaction of ooids. The early marine cements reported in this study represent high energy environments (active marine phreatic zone of Tucker and Wright, 1990) and are mainly confined to the outer ramp and bioclastic bar-bank system. In this environment, early marine cementation is favoured at the sediment-water interface.

MICRITIZATION

Micritization of bioclasts is common in the Jajiya Member carbonates. However, in some cases other allochems are also micritized leaving behind micritic lumps. Generally, micritization occurs where endolithic colonies (cyanobacteria) thrive in shallow marine low energy environments. These cyanobacteria initially bore around the margins of the allochems and the bores are filled with micrite forming a micritic rim around the allochems. In some ooids the alternate brownish and light coloured microcrystalline aragonite layers are dissolved (Fig. 8). This type of micritization is attributed to borings by endolithic cyanobacteria which are infilled by aragonite (*e.g.* Harris *et al*., 1979). Micritized grains also form due to syndepositional recrystallization of skeletal carbonate to the equant micritic fabric (Reid *et al*., 1992; MacIntyre, Reid, 1995, 1998). Evidence of little sediment transport, the presence of ubiquitous microbes and little cementation suggest micritization by endolithic algae in the present case. This type of micritization is prevalent within the restricted lagoon environments containing the stagnant marine phreatic zone environment (*e.g.* Tucker, Wright, 1990).

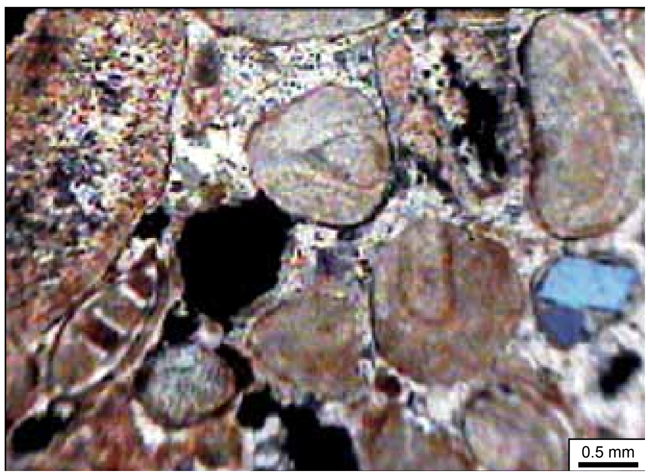

Fig. 8. Alternate brownish and light coloured microcrystalline aragonite layers represent micritized and dissolved portions of the bioclasts and ooids. This type of micritization is attributed to borings by endolithic cyanobacteria which are infilled by aragonite

NEOMORPHISM

Evidence in the present study of intercrystal dissolution-precipitation characteristic of a meteoric environment reflects fabric selective neomorphism. In this type of neomorphism the altered bioclasts display a fabric-selective mosaic in which the individual crystals in the original bioclasts do not extend beyond the original boundaries into the void-filling cement (Fig. 7A). Bryozoans have retained their skeletal microstructure but have lost Mg^{2+} to intercrystal dissolution-precipitation. Evidence of aggrading neomorphism is reflected in the form of irregular patches of neomorphic calcite crystals found within the micrite matrix (Fig. 3A, 4B, 7B). The non-selective dissolution of microcrystalline grains, in well-lithified lime-mud, has created vugs with a patchy distribution (Fig. 4B) which reflects neomorphism within the meteoric vadose zone (*e.g*. Sherman *et al*., 1999). Also, pelloids have been replaced internally by coarse calcite grains with a less ordered crystal mosaic representing aggrading neomorphism (*e.g*. Bathurst, 1975). In most of these cases much of the internal structure has remained intact even after replacement by neomorphic calcite crystals.

Also, evidence suggests early diagenetic silicification resulting in the growth of secondary euhedral to subhedral quartz crystals within ooid cores and in the intergranular pore spaces (Fig. 4A, B, 5B, C). This neomorphism is attributed to the mixing freshwater phreatic environment which is analogous to the dorag-type dolomitization (*e.g*. Carozzi, 1989).

PETROFACIES AND DIAGENESIS OF SANDSTONE PETROFACIES

The calcareous sandstones studied are mainly composed of three varieties of quartz followed by feldspar, mica, rock fragments and heavy minerals. Most of the quartz grains are monocrystalline along with some polycrystalline grains. The varieties recorded are common quartz and recrystallized and stretched metamorphic quartz. Both muscovite and biotite occur as tiny to large elongated flakes with frayed ends (Fig. 6B). Biotites are green and yellow coloured. Mica grains usually show the effect of compaction. Rock fragments are commonly composed of siltstones, phyllites and schists. Heavy opaque minerals include zircon, tourmaline, epidote, rutile and garnet.

DIAGENESIS

The main diagenetic features observed within the calcareous sandstone facies include mechanical compaction and porosity reduction, authigenic overgrowth of silica, and carbonate matrix and cementation. The evidence suggests early diagenetic changes which commence with the onset of the sedimentation of this facies. We examined in detail the diagenetic features in the sediments under the investigation and attempted to relate them to a series of events controlled primarily by the depositional environment of this facies through time.

COMPACTION AND POROSITY

The framework constituents of the Jajiya Member calcareous sandstones exhibit mainly floating grains in fine grained matrix with occasional point contacts (Fig. 6A–C). In the upper part of the facies long contacts are also observed. However, floating grains are dominant, followed by point and occasional long contacts (Fig. 6D) suggestive of limited pressure solution activity in these sandstones. The contact index values for these sandstones are very low (average of 0.9%). However, minor dissolution of feldspar is observed in a few cases. The high percentage of floating grains and point contacts with low contact index values are mainly in those sandstones with the pervasive development of calcite and Fe-oxide cements, which were probably precipitated at a very early stage. The early stage of cementation restricted large scale mechanical and chemical compaction, which normally take place after deposition and is concomitant with burial under the overlying sediments. Less mechanical compaction and high content of intergranular calcite cement may be related to high grain strength, good sorting and early cementation (Fig. 6A, B). This evidence indicates compaction due either to shallow burial or early Ca- and Fe-cementation or both. The nature of the point contacts and the contact index are useful for understanding the aggregate packing of the rocks. In our case, the rock fabric is mostly represented by floating detrital minerals in carbonate matrix and cements followed by point contacts. Framework grains constitute about 26–32% of the rock. The primary pore-filling matrix appears to have influenced mechanical compaction and early cementation as is evident by the presence of strained and fractured detrital mineral grains floating in carbonate cements (Fig. 6C).

The evidence suggests that the replacement of early calcite cement by silica may have resulted in the retention of the original intergranular porosity. This is evident by the authigenic quartz overgrowths on detrital quartz grains that also partially fills the intergranular pore space (Fig. 6D). The overgrowth around the quartz grains occurs locally as cryptocrystalline quartz seams instead of a homotaxial overgrowth. The possible source of this silica is dissolution of feldspar and micas along with minor amounts contributed by restricted pressure solution.

The original porosity of sandstones generally varies from 30–50% which can be reduced by 10–17% by mechanical compaction (Pryor, 1973; Beard, Weyl, 1973) and early calcite cementation. The intergranular cement (minus cement porosity) in the present case is about 29% (Ahmad *et al*., in press) which is attributed to less mechanical compaction during early diagenesis. Syndepositional calcite cementation, high grain strength and good sorting appear to have inhibited mechanical compaction.

CEMENTATION AND MATRIX

Two types of cements are identified in Jajiya Member calcareous sandstones (Table 2). The calcite cement is present in three different forms: first as thin coatings around detrital grain boundaries; second as isolated patches and the third as pervasive pore fillings. In some thin sections corroded quartz grains exhibit calcite cement infillings. This evidence suggests the presence of a syndepositional calcite cement. The early precipitation of carbonate cement takes place a few centimetres below the sediment-water interface (Bjørlykke, 1983). This type of cementation occurs by exchange of interstitial marine pore water either by meteoric water or by pore water expelled from underlying sediments. The cement has corroded the detrital grains extensively. In some instances, the clastic grains have lost their grain morphology and are present now in the form of protrusions, embayments and notches (Fig. 6C).

Carbonate cements occur in the form of sparry calcite and microcrystalline calcite. The boundaries of detrital grains are marked by etching and corrosion by the adjoining calcite cement. The original framework of the sandstones is modified as a result of replacement of detrital grains by calcite cement (Fig. 6C). The replacement of quartz by calcite implies that the pore waters were undersaturated with respect to quartz and supersaturated with respect to calcite in an environment of high pH and high temperature (retrograde solubility). The calcite cementation occurred slowly covering a large time span, which is evidenced by corroded quartz grains and an indistinct boundary between quartz grains and calcite cement (Fig. 6C, D). Precipitation of microcrystalline calcite cement also took place at a shallow depth above the water table by the process of concretion as is evidenced by the open framework entrapped calcite cement. This suggests that the depositional setting may have been intermittently exposed, allowing the onset of the pedogenic process that induced calcite cement precipitation. Later, during burial, micrite was replaced by sparry calcite in a meteoric water regime along the interface zone of accretion and saturation.

Quartz overgrowth is scarce in Jajiya Member calcareous sandstones. Only occasionally the sandstones show local developments of large overgrowths (Fig. 6D). The absence of a silica cement can be attributed to limited compaction of the sandstone, thereby causing very little pressure solution, which was the most important indigenous source of silica. Probably the depth of burial and the geothermal gradient were not high enough to reach the 'silica window' (*e.g*. McBride, 1989). The possible cause of the observed quartz overgrowths in these sandstones may be the intraformational release of silica during replacement, and the corrosion of feldspar and micas by calcite. A silty to clayey matrix is present in the studied sandstones. Detrital silt, chert, muscovite and clay materials are present in the form of matrix (Fig. 6A). Most of the matrix material is syndepositional hence the pore-filling. The matrix, therefore, influences diagenetic processes by supplying chemical entities and bulk properties, such as porosity and permeability by pore occlusion.

CONCLUSIONS

The Jajiya Member overlies the well-cemented rudstone with a hardground upper surface which corresponds to TST representing sediment-starved conditions. The basal thin bed, a richly fossiliferous, well-cemented, ooid-bearing, ferruginous facies corresponds to the MFZ (representing a condensed zone rich in fossil content and deposited in sediment starved conditions) of the overlying HST showing increasing energy upwards (bed no. 1 of the bioturbated packstone to rudstone facies). The overlying bioturbated, well-cemented, ooid-bearing ferruginous packstone corresponds to a TST (bed no. 2) which is followed by the bioturbated, poorly cemented, ooid- and bioclast-bearing rudstone facies corresponding to the MFZ of the upward following HST (bed no. 3).

The evidence suggests that the calcareous sandstone facies, characterised by low-angle cross-bedded to trough cross-bedded, well-cemented, poorly sorted, fine to medium-grained sandstones with sharp upper and lower surfaces, represents a progradational HST (bed nos 4 and 5) and was deposited within foreshore to shoreface environments during a forced regression (FSST), possibly induced by climate change.

The cross-bedded rudstone to packstone facies was deposited during the second TST event (bed nos 6–11) punctuated by five flooding surfaces. This facies represents an overall coarsening upward cycle. The whole sequence of the Jajiya Member represents two fining upward and three coarsening upward cycles. The mineralogical, allochemical and orthochemical compositions were mainly controlled by the depositional conditions through time and have greatly influenced the diagenetic evolution of these sediments.

The main diagenetic features observed within the carbonate dominated facies include compaction, early cementation and porosity reduction, micritization and neomorphism representing early or syn-depositional and post-depositional changes. Within the parasequences of this study, two phases of compaction are observed. Within the coarsening upward parasequences (CUPS) during the early phase of mechanical compaction, plastic deformation of allochems resulted in their bending but without inducing any physical breakage; however, within the fining upward parasequences (FUPS) these have remained undeformed. During the second phase of early compaction partial dissolution in both the CUPS and FUPS has occurred at the contacts of the allochems. These early compaction phases have been related to a marine phreatic environment. In some of the cases, in CUPS, fractures cut across the allochems, and the associated fibrous rim cement and geopetal inter-allochem calcisiltite matrix represent a post-cement phase of compaction. In case of FUPS, the allochems are truncated against each other and form a condensed-to-fitted fabric. These features are interpreted as representing an early fracture phase in the undersaturated freshwater phreatic environment.

Four distinct types of cement are recognized including ferroan and calcite rim cements, fibrous, bladed and blocky cements. Three types of the first generation cements, calcite and ferroan rim cements, drusy and blocky cements, are present in the CUPS of this study. However, in case of FUPS only ferroan and calcite rim cements and silica cement are present. These first generation cements are characteristic of the marine phreatic environment. The second generation equant crystal habit cement, growing in optical continuity with fibrous cement, is characteristic of a meteoric vadose environment, whilst the fibrous calcite cement most probably represents replacement of primary fibrous aragonite cement. The third type of carbonate cement (blocky cement) generally occupies central portions of the pore spaces and is precipitated in meteoric water environments where low Mg^{2+} content facilitates precipitation of blocky calcite. The ferroan rim cement is more common in both the CUPS and FUPS of this study. The ferroan coating around the allochems has obliterated syntaxial and fibrous cement growth on them. The probable source of Fe-cement is the presence of the hardground within the sequence.

The silica cement is present in the FUPS within the intergranular pore space. The source of silica cement may be the dissolution of quartz grains present within the facies and in nuclei of the ooids. The early marine cements reported in this study represent high energy environments (active marine phreatic zone) and are mainly confined to the outer ramp and the bioclastic bar-bank system.

Micritization of bioclasts is common, but other allochems are also micritized. Evidence of little sediment transport, the presence of ubiquitous microbes and of little cementation suggest micritization by endolithic cyanobacteria prevalent within the restricted lagoon environments with the stagnant marine phreatic zone environment.

Intercrystal dissolution-precipitation characteristic of a meteoric environment reflects fabric-selective neomorphism. Irregular patches of neomorphic calcite crystals found within micrite, and peloids replaced internally by a crystal mosaic of disordered coarse calcite grains are related to aggrading neomorphism. Non-selective dissolution of microcrystalline grains has created vugs with a patchy distribution which reflects neomorphism within the meteoric vadose zone. Early diagenetic silicification, resulting in the growth of secondary euhedral to subhedral quartz crystals within ooid cores and in the intergranular pore spaces, is attributed to the mixing freshwater phreatic environment.

The high percentage of floating grains and point contacts in the calcareous sandstone facies with a low contact index value (0.9%) are mainly in sandstones with pervasive precipitation of very early calcite and Fe-oxide cements. The primary pore-filling matrix has also influenced mechanical compaction and early cementation, as is evident by the presence of strained and fractured detrital minerals grains floating in carbonate cements.

Replacement of early calcite cement by silica has resulted in retention of the original intergranular porosity. The intergranular cement (minus cement porosity) is about 29% which is attributed to less mechanical compaction during early diagenesis.

Corroded quartz grains exhibit a calcite cement infilling suggestive of the presence of a syndepositional calcite cement. The original framework of the sandstones is modified as a result of replacement of detrital grains by calcite cement.

The observed quartz overgrowth in these sandstones may be due to the intraformational release of silica during replacement and corrosion of feldspar and micas by calcite.

Acknowledgements. We gratefully acknowledge the help received from the Chairman, Department of Geology, Aligarh Muslim University, Aligarh for providing the laboratory facilities and other logistics in the Department for completion of this work.

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