Geologia Croatica	57/1	55–66	6 Figs.			ZAGREB 2004

Diagenesis of Upper Cretaceous Rudist Bivalves, Abu Roash Area, Egypt: A Petrographic Study

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Key words: Rudists, Diagenesis, Silicification, Upper Cretaceous, Egypt.

Abstract

Upper Cretaceous rudist buildup from the Abu Roash area, Egypt, is characterised by floatstone to rudstone textures. The low diversity of rudist types, the abundant fine-grained carbonate matrix, and the presence of some coral heads suggest that the investigated buildup was developed under warm, relatively quiet, somewhat protected water conditions, in a shallow shelf area or open lagoon.

The rudist shells underwent different types of diagenetic alteration (e.g. cementation, neomorphism, partial silicification, and compaction). Different types of calcite cements are recorded: (a) early marine micritic and bladed cement, (b) early meteoric isopachous and equant calcite, and (c) late meteoric vug-filling calcite of coarse crystalline texture after partial dissolution of the shells. Stabilization of the bimineralic shells took place within a meteoric phreatic milieu, where the aragonitic shell layers were dissolved or recrystallized to more stable diagenetic calcite and the calcitic layers also suffered some recrystallization.

Silicification of the shell components is the more important diagenetic event. It postdates the early meteoric diagenetic equant calcite cement and occurred before the precipitation of the late meteoric diagenetic vug-filling cement. Megaquartz and fibrous chalcedony partially replaced the shells. The silica was probably derived from different sources, pressure-solution of quartz and transformation of clay minerals during later compaction of underlying siliciclastic rocks and/or dissolution of silica-producing organisms such as silica sponge spicules and radiolaria. Silicification possibly occurred within a mixing zone environment where meteoric water, which is the carrier of silica, mixed with marine water producing a solution supersaturated with quartz and undersaturated with respect to $CaCO_3$ minerals.

1. INTRODUCTION

The Upper Cretaceous was a period when reefs and reef mounds were abundant in many parts of the world (JAMES, 1983). One of the most remarkable features of the Cretaceous carbonate platforms in tropical and subtropical environments of the Tethyan realm, was the development of facies complexes dominated by rudists, with or without associated corals (MASSE & PHILIP, 1981; ROSS & SKELTON, 1993; GILI et al., 1995b). KAUFFMAN & JOHNSON (1988) proposed that the rudists evolved to become the primary reef-builders of the Cretaceous. In the Abu Roash area, northern Egypt (Fig. 1), environmental conditions during the Turonian allowed shallow marine benthonic communities with rudists and milleporoid corals as frame builders to flourish (HAMZA, 1993). The traditional perception of rudists as reef builders has been questioned (GILI et al., 1995a), and rudist communities are interpreted as gregarious sediment-dwellers and regarded as biostromes.

Reefs are particularly susceptible to diagenetic modifications and, because of their relatively well-defined limits, are exceptionally favourable sites for the study of diagenetic processes and sequences (PURSER & SCHROEDER, 1986). Coral and algal reef diagenesis have been studied intensively, meanwhile rudist biostromes have received less attention (e.g., AL-AASM & VEIZER, 1986a, b; ENOS, 1986; M'RABET et al., 1986; WOO et al., 1993; MOSS & TUCKER, 1995; STEUBER, 1999). Rudist communities, which crop out in the Abu Roash area, have been studied by few authors. HAMZA (1993) studied the rudist–coral mounds at the El Hassana dome, Abu Roash area, from the sedimentological and palaeoecological viewpoints. DE CASTRO & SIRNA (1996) and EL-SABBAGH & EL-HEDENY (2003) have undertaken palaeontological studies. The purpose of this study is to demonstrate the different types of diagenetic alteration that affected the rudists in this buildup and to define the sequence of these diagenetic processes.

2. GEOLOGICAL SETTING AND STRATIGRAPHY

The Abu Roash area represents one of the structural highs that characterize the northern parts of Egypt. These are represented by a group of NE–SW trending, plunging syn- and anticlines, related to the Syrian arc system of folds initiated due to the Late Cretaceous tectonic movements (SAID, 1962). ABD EL SHAFY (1984) mentioned that the Abu Roash area was slightly subjected to tectonic activity in the form of interrupted pulses, during sedimentation of the Turonian rocks, thus causing their uplift. This Turonian tectonic phase is considered as an interrupted pulse of the Laramid

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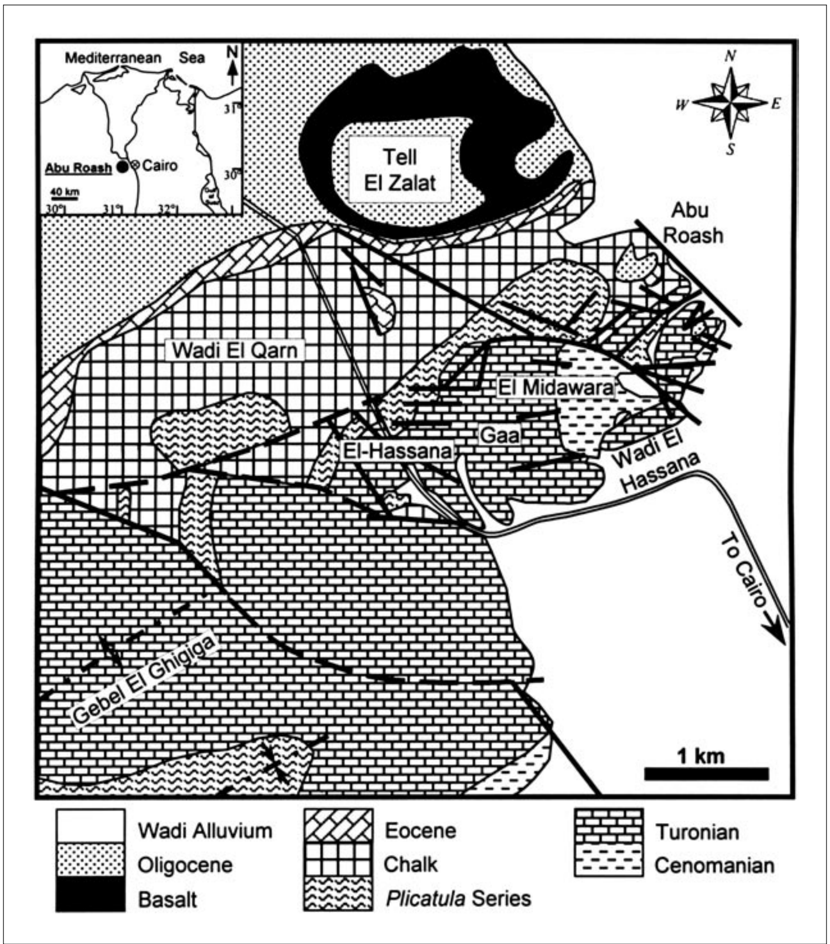

Fig 1 Simplified geological and location map of the Abu Roash area (after SAID, 1962).

movements associated with global lowering of sea level and the elevation of numerous areas which are recorded along the southern Tethyan margin, as in Syria, Palestine, Libya, Tunisia and northern Egypt (KERDANY & CHERIF, 1990; M'RABET et al., 1992; SAID, 1962). Furthermore, the Upper Cretaceous rocks at Abu Roash area were subjected, at least in localized parts, to the hydrothermal effects of Tertiary volcanicity, which resulted in differential silicification and dolomitization of some beds (ABD EL SHAFY, 1984; FARIS & SOLIMAN, 1961). MOUSTAFA (1988), however, studied the structural setting of the Abu Roash area in some detail, and recognized a series of half domes, namely El Gaa, El Hassana and El Ghigega, which were a result of the Turonian tectonic phase.

In the Abu Roash area, a complete sequence of Upper Cretaceous strata crops out (Fig. 2). The rocks are mainly composed of limestones and dolomites with shales and marly intercalations. Topographically, the elevated Upper Cretaceous rocks are surrounded by younger Tertiary rocks in lowland areas. At the El Hassana dome, the core of the domal structure is represented by Cenomanian clastics (i.e. sandstone and shales), which are overlain by 140 metres of fossiliferous and chalky limestones and marls with occasional dolomite beds of Turonian age (FARIS & SOLIMAN, 1961; GHORAB & ISMAIL, 1970). The exposed Upper Cretaceous rock sequence is divided, stratigraphically, into the following series from base to top: Sandstone Series, Rudistae Series, Limestone Series, *Actaeonella* Series, Flint Series, *Plicatula* Series and Chalk (BEADNELL, 1902; FARIS, 1948; SAID, 1962). The entire rock units beneath the Chalk are grouped into only one stratigraphic unit, which is the Abu Roash Formation of NORTON (1967). In the studied area the *Actaeonella* Series, which include the rudist biostrome, is characterized by the presence of some common Turonian index fossils including *Actaeonella* (*Trochactaeon*) *salomonis*, *Nerinea requieniana* and *Millestroma nicholsoni.*

The studied rudist shells are collected from the well-developed organic buildup (biostrome) at the El Hassana Dome. This biostrome crops out in the form of an isolated mound and consists of rudist–coral communities in which rudists of the elevator type (radiolitids) are common. DE CASTRO & SIRNA (1996) stated that the rudist biostrome of the El Hassana Dome is made up mostly of radiolitids, referred to *Durania arnaudi*. In a more recent study, EL-SABBAGH & EL-HEDENY (2003) recorded seven radiolitid species belonging to three genera (*Durania*, *Lapeirousella* and *Sauvagesia*). The rudist shells are present in the form of isolated specimens or small clusters embedded in marly lime-

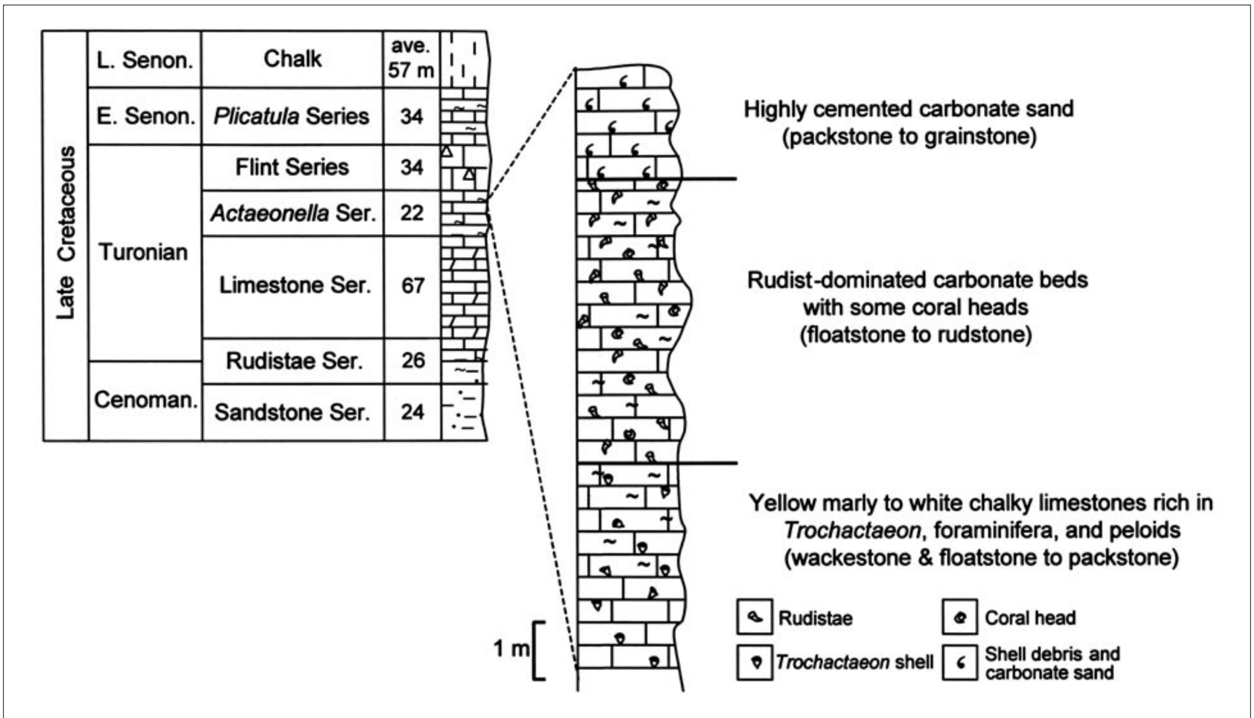

Fig 2 (a) General sequence of the Upper Cretaceous rock units in the Abu Roash area (after SAID, 1962). (b) Rock succession and related microfacies in the studied mound at the El Hassana Dome.

stone beds in an interval about 5 metres thick. The size of the whole shell reaches 20 cm. The rudist shells are associated, in some intervals, with coral heads of hemi-sphaerical growth forms that may reach 30 cm in size. The rudist–coral dominated beds occur and are exposed on the top of the *Actaeonella* Series, flanking the crest of the dome (Fig. 2). These limestone beds are underlain by pale yellow to white fine-grained compacted limestones crowded with gastropod shells (mostly *Actaeonella* (*Trochactaeon*) *salomonis*), rich in miliolid foraminifera and overlain by fossiliferous carbonates composed of sand-size particles.

3. PETROGRAPHY AND FACIES ANALYSIS

The rudist-dominated mound is, petrographically, composed of floatstones to rudstones where whole rudists and fragments of their shells are, in addition to rounded dark pellets and some sand-sized bioclasts, embedded in a carbonate matrix. The matrix is of fine-grained texture and more or less marly in composition. The recorded bioclasts include bivalves (rudists are more common), corals, rare echinoderms and bryozoa, in addition to a few benthic foraminifera. A little micro-crystalline calcareous cement is observed in parts, where the amount of micritic matrix decreases, and it cemented the fine bioclasts. The fine-grained matrix is, in parts, neomorphically crystallized to a coarser crystalline texture.

The studied Turonian rudist shells are mainly those of radiolitids. In general, the radiolitid rudist shells are composed of three layers (SKELTON, 1974; ROSS & SKELTON, 1993), an outer well preserved thick layer composed of fibrous prisms of low-Mg calcite and two inner thin aragonitic layers (AL-AASM & VEIZER, 1986a). The inner metastable aragonitic layers are either altered to more stable diagenetic low-Mg calcite or are completely dissolved. Petrographic studies of the investigated radiolitid rudists reveal that only the outer calcitic layer is preserved, while the inner aragonitic layers were dissolved.

The outer calcitic layer is composed of a thick outer cellular layer called the "cellular–prismatic layer" by DESCHASEAUX et al. (1969), and a thin brown inner prismatic layer. The outer cellular layer is characterized by an original hollow structure of honeycomb-like cells (WOO et al., 1993; STEUBER, 1999), and shows a reticulate pattern in thin section. The calcite prisms of the outer layer are cut by dull inclusions, probably representing organic matter remnants, arranged in lines similar to the pattern of growth laminae in modern unaltered bivalve shells (BATHURST, 1975; WOO et al., 1993; STEUBER, 1999). The cells are now filled with diagenetic coarse crystalline calcite cement (intraskeletal void-filling spar) and authigenic coarse quartz crystals. In contrast, the body cavities of the shells are either filled with a fine-grained marly carbonate matrix or are partially lined by coarse crystal-line calcite cement.

In general, rudists were abundant in low-latitude, warm, shallow carbonate-dominated seas (ROSS & SKELTON, 1993). HAMZA (1993) suggested that the frequent fine carbonate sediment accumulation, the low content of terrigenous materials, and the enormously thick rudist shells in the rudist–coral buildup in the Abu Roash area, Egypt, indicate development under a warm, arid climate, in an outer shelf area. The low diversity of the studied rudists (very rare species of elevator rudists of broad-conical morphotype are dominant), and their association with some miliolid foraminifera may indicate shallow, relatively quiet water, of somewhat protected areas in the inner shelf or lagoonal settings (cf. SKELTON et al., 1997; STEUBER, 2000). However, the occasional association of rudists with some coral heads suggest that depositional environment varied from a shallow inner shelf area to slightly deeper and more open water settings where the corals are more developed (cf. HAMZA, 1993; ROSS & SKELTON, 1993; SKELTON et al., 1997).

Alternatively, the rock succession at the studied rudist-dominated mound includes, in addition to the rudist carbonate facies, different fossiliferous fine-grained carbonate facies with nerineids, acteonelids and miliolids, which suggest that sedimentation took place in an open lagoon (cf. SANDERS & PONS, 1999). Petrographic investigations of the rock succession indicate that the rock microfacies varied vertically (Fig. 2). The rudist dominated beds are underlain by white to yellow fine-grained limestones, represented by biopeloidal wackestones and floatstones to packstones rich in *Actaeonella (Trochactaeon) salomonis*, peloidal grains, miliolid foraminifera, fine echinoid shell fragments and micritized bioclasts. These microfacies show obvious affinities with a shallow marine, semi-restricted setting of low energy, in the inner to middle shelf environments (ENOS, 1983). In contrast, the rudist-dominated beds are overlain by coarse-grained limestones of sand-sized grains of different fossils, bioclasts, peloids and intraclasts, and are represented by packstone to grainstone microfacies. The variations from wackestone and floatstone at the base of the succession to packstone and grainstone near the top parts and with the upward decreasing of the amount of the fine-grained matrix indicate a shallowing upward trend in the depositional environment.

4. DIAGENESIS

The rudist bivalves underwent different types of diagenetic alteration under both marine and meteoric-diagenetic environments. Diagenesis of the studied rudists involved variable types of calcite cements, partial silicification of the rudist shells, and neomorphic alteration of the original metastable carbonate components.

4.1. Carbonate cementation

Different calcite cement types are observed within the rudist shells (Fig. 3a–d). The cements occlude primary and secondary pore spaces of the shells and each one exhibits its own peculiar texture, origin and timing of formation.

Cellular cavity-filling calcite

The original intraskeletal pores within the thick cellular–prismatic outer layers of the studied rudist shells are filled with more than one cement phase: (a) micritic calcite cement lined the wall of some cells precipitated during an early marine diagenetic stage. The micritic crystals may be recrystallized to microspar during subsequent diagenetic stages. (b) thin clear isopachous calcite crystals fringe at one side of some skeletal cell walls (Fig. 3a, b). This isopachous calcite represents an early meteoric diagenetic cement and its bladed isopachous rim geometry indicates a freshwater phreatic origin (cf. LONGMAN, 1980). (c) equant calcite cement with crystals of clear subhedral, coarse crystalline texture completely filled the cells (Fig. 3a, b). This coarse equant calcite cement also occludes the intraskeletal pores of the coral heads. The fabrics of this calcite cement suggest that it formed from phreatic-meteoric water after subaerial exposure of the Turonian rocks. In later stages, this calcite cement is partially replaced by authigenic silica.

Irregular vug-filling calcite

Few small vugs, after partial dissolution of the shells by freshwater, were later filled by coarse crystalline meteoric calcite cement (Fig. 3c). These irregular pores cut the skeletal cells, which are filled by both the equant calcite cement of the early meteoric-diagenetic phase and by the silica pore-filling. This indicates that formation of this cement postdates both precipitation of the early meteoric equant cement and the silicification of the shells.

Body cavity-filling calcite

The large body cavities of the rudist shells are almost filled by fine-grained carbonate sediments with fine shell fragments, benthonic foraminifera and peloidal grains. In some cases, the position of the shells allowed the lining and partial infilling of the internal cavities by coarse crystalline calcite. These calcite crystals have two fabrics: (a) columnar calcite (Fig. 3d) of inclusion-rich, very coarse, elongate crystals where their long axes are normal to the inner prismatic shell layer, and (b) equant calcite of coarse crystalline texture.

4.2. Silicification

One of the most important diagenetic features observed in the studied rudist shells is the partial silicification of some shells. This also affected the skeleton of the coral heads. The silicification process affects the structural layers of the whole shells and also some fine rudist shell debris embedded in the matrix, while the fine-grained matrix exhibits no replacement by silica. The selective silicification of the rudist shells may be attributed to

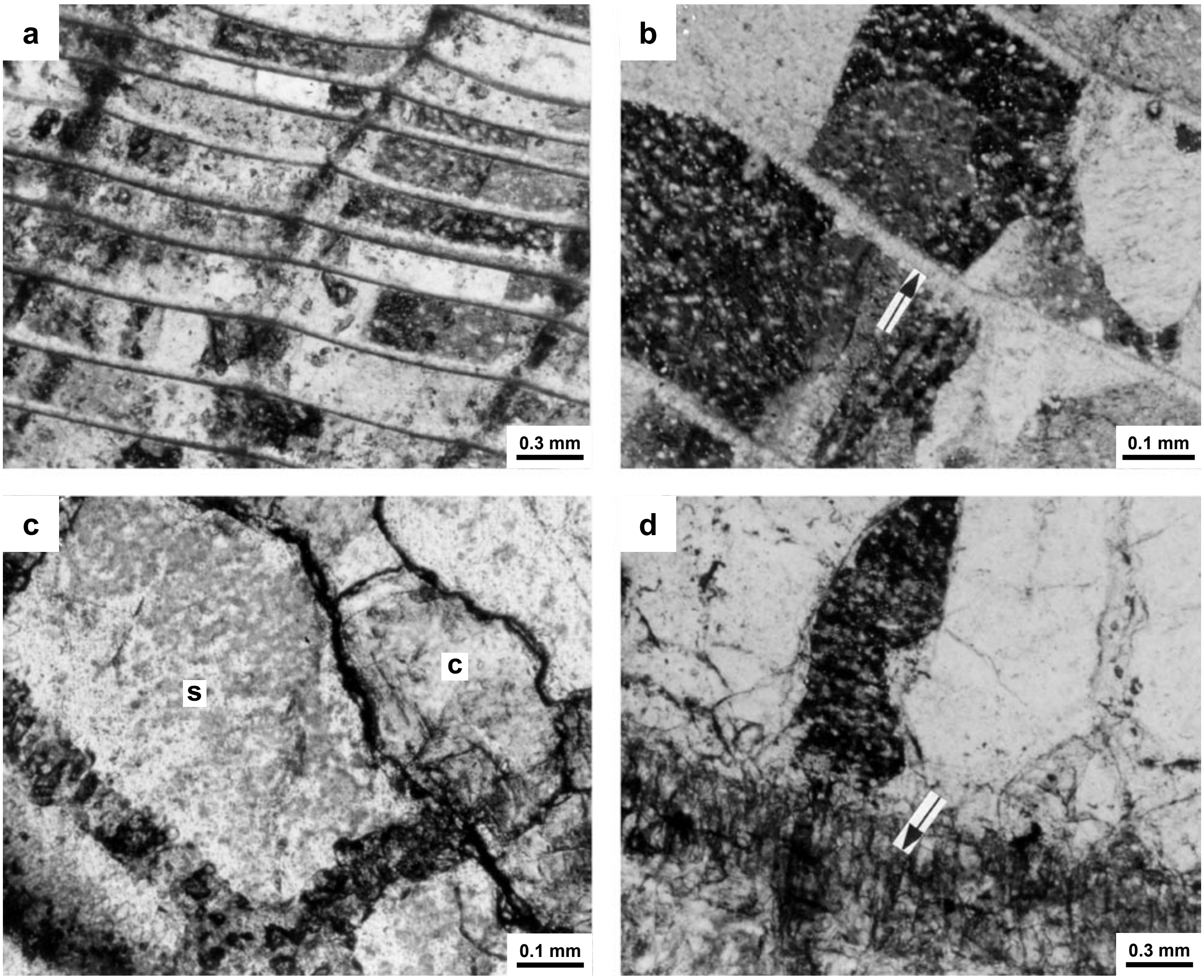

Fig. 3 (a) Photomicrograph showing the microstructure of the outer cellular–prismatic layer of a radiolitid shell. The intraskeletal pores are filled with two phases of calcite cements. Crossed nicols. (b) Enlargement of (a). Note the two phases of cements, isopachous rim (arrow) and coarse equant calcite. Crossed nicols. (c) Irregular vug is filled with coarse crystalline calcite (c). Note that the void cut the cells, which are filled with authigenic silica cement – s. Plane light. (d) Columnar calcite crystals line the internal body cavity of the shell. Note that the elongated crystals are normal to the prismatic layer (arrow). Crossed nicols.

organic matter acting in some way as a catalyst, which may increase carbonate solubility (HESSE, 1987). JACKA (1974) suggested that organic decomposition products create a special microenvironment conducive to silica-replacement. The reported authigenic silica is found either as pore-filling in the cellular shell structure or as partial replacement of the shells (Fig. 4a–f). It is precipitated in the form of equigranular megaquartz and fibrous quartz as spherulitic chalcedony.

Quartz cavity-filling

The silica is precipitated as crystals of megaquartz, infilling intraskeletal pores of the cellular–prismatic outer layer of some shells (Fig. 4a). The quartz is of clear, equant, coarse to medium crystalline fabric. Some of the crystals possess wavy extension and others are cracked. The contact of the quartz crystals with the boundary of the cell is sharp and these boundaries are not dissolved or replaced by the silica and the original shell microstructure is preserved. This indicates that the quartz crystals were precipitated as cavity-filling cement after stabilization of the wall boundaries. The presence of relics of diagenetic equant calcite cements inside the quartz crystals suggest that silicification occured after calcite cementation of cells in the shell where quartz replaced the former equant calcite cements during or after their dissolution.

Spherulitic chalcedony

In this form, crystals of chalcedony partially replaced the structural layers of the rudist shells and the coral skeleton (Fig. 4b–e). The crystals are of finely fibrous fabric with wavy extension and form small spherulitic shapes. The replacement of the rudist shells by chalcedony is mostly destructive to the shell fabric. The thin inner prismatic layers were highly subjected to silicification and partial replaced by chalcedony and their microstructure was obscured (Fig. 5c). Also, the cells of the outer cellular–prismatic layers that were filled with equant calcite crystals, are partially replaced by chalcedony and the boundaries of these cells are mostly obliterated. Relics of the original calcitic components are found between the chalcedony crystals.

4.2.1. Sources of silica

Silica in the Turonian rocks of the studied area includes the silicification products of the rudists and the thin bands of chert interbedded with the carbonate sediments. In general, the sources of silica are unequivocal. The biogenic source of silica is considered as the common one by many workers (e.g. JACKA, 1974; KNAUTH, 1979; LAWRENCE, 1994; GIMENEZ-MONTSANT et al., 1999), where the silica can be derived from dissolution of silica-producing organisms such as siliceous sponge spicules, radiolaria and diatoms. Also, the silica can be derived from a silica-rich solution generated by pressure-solution of sand and silt quartz grains or feldspar (HESSE, 1987; HOUSEKNECHT, 1988), by the transformation of montmorillonite to illite or mica (KEENE & KASTNER, 1974; LAWRENCE, 1994), or from rapid cooling and a change in the pH of silica-supersaturated hot geothermal water (JONES et al., 1997). KEHEILA & EL-AYYAT (1992) considered volcanic ash and tuffs to be a source of silica for chert nodules in the Drunka Fm. along the Nile River valley. FARIS & SOLIMAN (1961) and ABD EL SHAFY (1984) recorded some metasomatic alteration in parts of the Upper Cretaceous and Eocene rocks in the Abu Roash area. They suggested that these rocks were subjected, at least in some parts, to silicification and to iron and manganese mineralization by the Tertiary ascending hydrothermal solutions. From the geological setting of the studied El Hassana dome area, the Turonian beds were affected by Late Cretaceous tectonic movements causing the folding of these beds, including the interbedded chert bands. Also, no volcanogenic materials and other effects of hydrothermal solution are observed. It can be suggested that the formation of these chert bands and also the silicification of some Turonian rocks preceded the tectonic movements. Therefore, the volcanic origin of silica required for silicification of the rudist shells and also formation of the interbedded chert bands can not be suggested.

It can be considered that the silica required for silicification of the rudist shells may be derived from more than one source as: biogenic silica from the host and surrounding Late Cretaceous carbonate rocks, and/or pressure-solution of quartz and feldspar and the transformation of clay minerals during the compaction of the underlying Cenomanian and pre-Cretaceous sandstone and mudstone rocks. This silica was redistributed and migrated from the host or surrounding rocks to the site of diagenesis, and then replaced the shells.

4.2.2. Mechanism of silicification

Textural relationships of silica-replacement within the rudist shells indicates that silicification postdates the deposition of the rocks and occurred after the precipitation of the early diagenetic meteoric calcite cement in the intraskeletal cavities of the cellular shell microstructure (Fig. 4e). Textural evidence shows that the authigenic quartz (megaquartz and chalcedony) were formed by volume-by-volume replacement of the original carbonate minerals of the shells or calcite cavity filling, where carbonate dissolution rarely occurred immediately adjacent to the silicified parts. This indicates that calcite dissolution is linked to silica precipitation during the silicification process and they may have occurred simultaneously. Silica can not be precipitated within a normal marine environment, but it precipitates in certain environments that controlled the prevailing physico–chemical conditions. It began to precipitate with the reduction of the pH of the waters or by the mixing of marine and meteoric waters (KNAUTH, 1979; MALIVA & SIEVER, 1988). According to MALIVA & SIEVER (1988), silicification requires a sufficient degree of local supersaturation with respect to authigenic silica and suitable conditions for nucleation of the initial crystals.

The chertification of the Lower Eocene Drunka Formation (MC BRIDE et al., 1999) and Thebes limestones (ABD EL-HAMEED et al., 1997) in some areas in Egypt, was attributed to dominantly meteoric fluids, possibly a time when meteoric water was flushing marine pore water. THIRY & RIBET (1999) proposed that silicification of limestones is considered as a groundwater process and occurs within the groundwater or in the vicinity of the water table or even above the water table after the uplift of the rocks. They suggested that the silica introduced by high flow rates of groundwater through the interstices, where the calcite–silica replacement takes place through diffusion along very thin intergranular water films. KNAUTH (1979) proposed that silica can replace carbonate in the mixing zone when silica-rich meteoric water mixes with marine water producing waters highly supersaturated with respect to quartz and undersaturated with respect to calcite and aragonite.

One of the characteristic features associated with the silicification process is the presence of a few disseminated euhedral dolomite rhombs inside some rudist shells and coral heads and also in the fine-grained matrix (Fig. 4f). These dolomite rhombs exist as individual crystals and mostly have dissolved cores with dark rims. Dolomite inclusions in the siliceous rocks are recorded and described elsewhere by many authors. KASTNER et al. (1977) attributed the origin of dolomite rhombs in chert to the release of magnesium during the transformation of opal-CT to quartz. JACKA (1974) attributed the formation of microdolomite in silicified carbonate rocks to the silicification process where, to some degree, exsolution of dolomite and replacement of high-Mg calcite by chalcedony occurred concurrently. According to the model of silicification in a mixing-zone environment proposed by KNAUTH

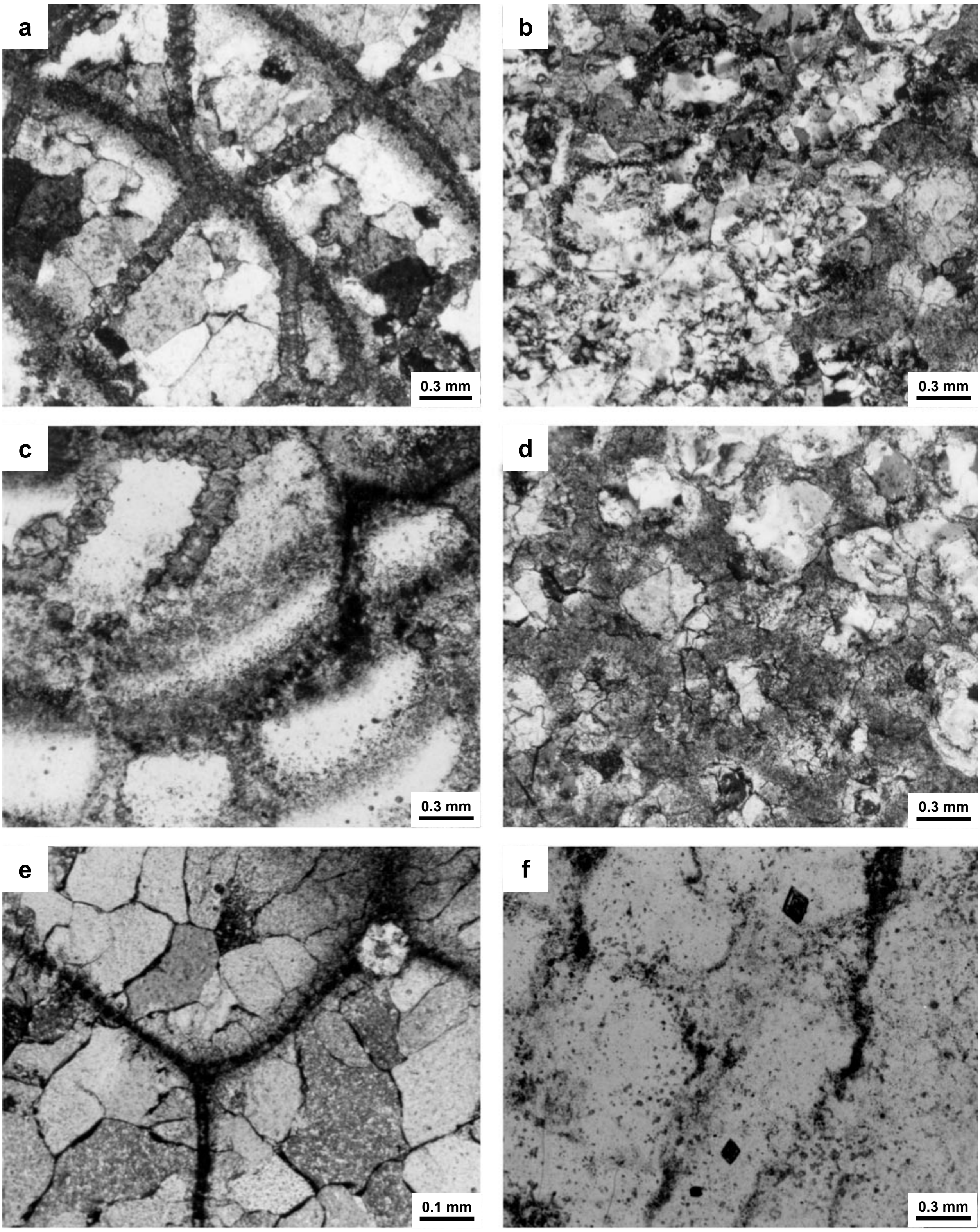

Fig. 4 Photomicrographs showing partial silicification of the rudist shells. (a) Equant megaquartz crystals fill the pores of the cellular–prismatic layer after their replacement by equant calcite cement. Note the preservation of the original microstructure of the cell walls. Crossed nicols. (b) High silicification of the cellular–prismatic layer and the replacement of calcitic components by chalcedony. Crossed nicols. (c) Similar as (b) – The original cellular microstructure has begun to be destroyed by the presence of remnant organic materials. Plane light. (d) Partial silicification of the skeleton of a coral head. Note the destruction of the original microstructure after its replacement by chalcedony. Relics of equant calcite cement are still present. Crossed nicols. (e) Start of silicification of the shells after the filling of the intraskeletal pores of the cellular–prismatic layer by coarse equant calcite cement. Crossed nicols. (f) A few dolomite rhombs associated with the silicified shell after its replacement by chalcedony. Plane light.

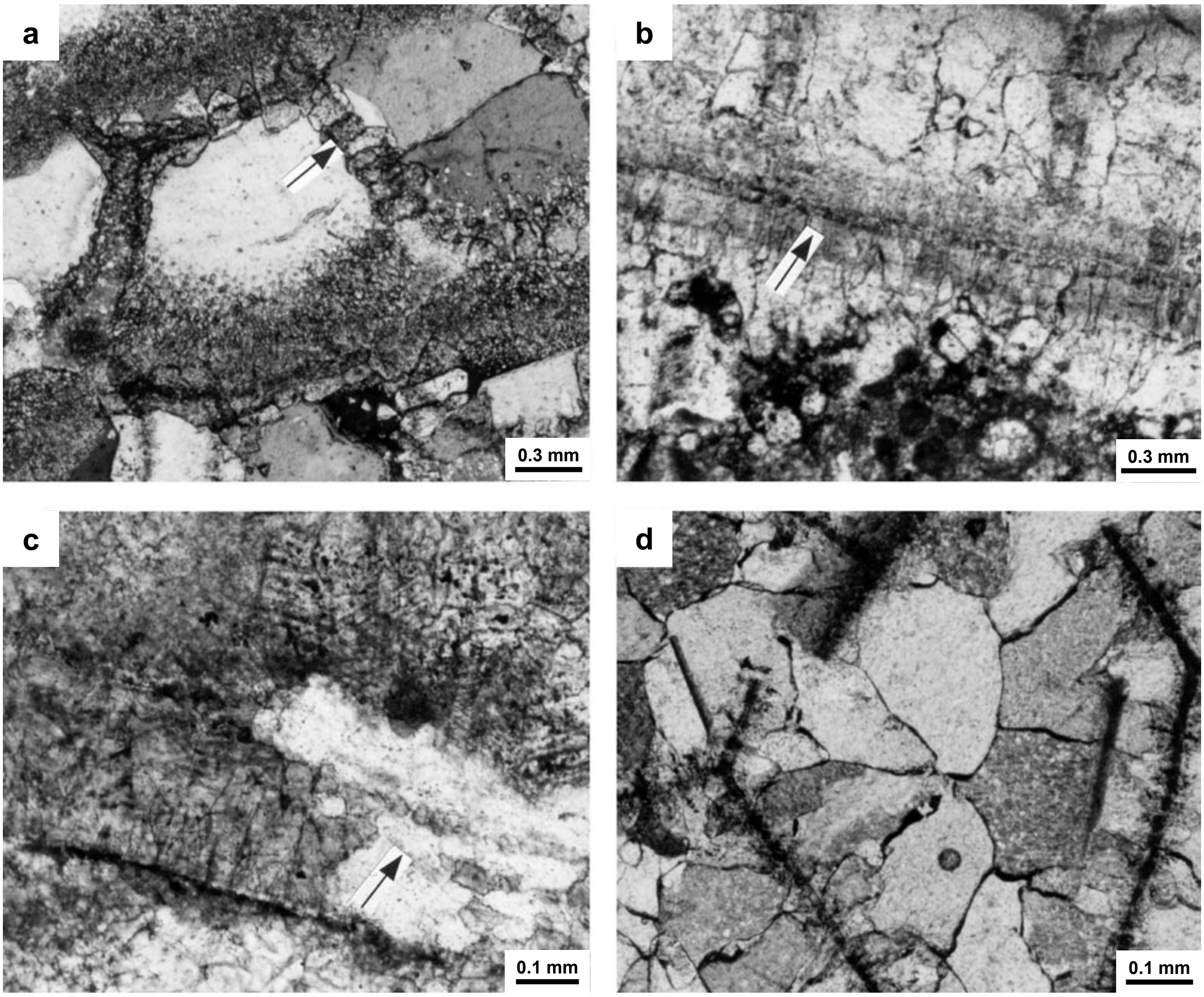

Fig. 5 (a) Photomicrograph of the outer cellular–prismatic layer of a radiolitid showing the recrystallization of the cell walls to coarse crystallized calcite. Note the presence of the dark relics of the original microstructure (arrow). The intraskeletal pores are filled with coarse equant quartz crystals. Crossed nicols. (b) Radiolitid shell, showing the thick outer cellular–prismatic and the thin inner prismatic layers. Note the partial preservation of their microstructure. Plane light. (c) Radiolitid shell showing partial silicification of the prismatic layer (arrow), with complete obliteration of the original microstructure in the silicified parts. Plane light. (d) Break up of a cell wall in the cellular layer due to early mechanical compaction. The cells are filled with equant calcite cement. Crossed nicols.

(1979), these conditions can allow the concurrent precipitation of dolomite during silicification. HESSE (1987) suggested that microdolomite formation was independent of silicification and that it is produced during the stabilization of high-Mg calcite components to low-Mg calcite. GIMENEZ-MONTSANT et al. (1999) related the presence of dolomite crystals within the cherts to early diagenetic interaction between the silica-rich fluids and the host sediment before chert formation. The occurrence of the dolomite rhombs, in both the studied carbonate matrix and in the silicified parts of the rudist shells and corals suggests that the formation of the dolomite is related to the silicification process, but the magnesium originated and was released from the calcareous components during their stabilization and dissolution. Accordingly, it can be proposed that the silicification process took place in the mixing-zone environment and was associated with minor late diagenetic dolomitization.

On the other hand, the presence of authigenic quartz in the silicified rudist shells in two forms, equant megaquartz and fibrous chalcedonic quartz, is highly controlled by the rate of nucleation and crystallization, which in turn is mostly dependent on the degree of saturation (FOLK & PITTMAN, 1971). With high silica concentrations and rapid precipitation, chalcedony is formed, while equant megaquartz usually forms at slower rates of precipitation from solutions having low degree of silica supersaturation. Thus, it can be proposed that the silicification of the rudist shells might take place either in more than one stage, and each stage was characterized by different conditions of the degree of saturation and rate of crystallization, or the two quartz-phases were precipitated concurrently with the presence of micro-variability in the concentration of dissolved silica in the fluids.

Diagenetic event	Diagenetic Stage				
	Marine	Early meteoric	Mixing zone	Late meteoric	Shallow burial
Micritic and bladed cement	------				
Cells wall breakage	------				
Isopachous rim cement		———			
Intraskeletal equant cement		———			
Shell recrystallization		———			———
Silicification			———		
Vuggy-filling cement				------	
Shell break and quartz cracking					------

Fig. 6 Chart of the paragenetic sequence of the studied rudist shells. Straight lines indicate clearly observed processes; dash lines indicate minor processes.

4.3. Neomorphism of the shell layers

The bimineralic and polylayered rudist shells underwent diagenetic alteration during the meteoric diagenetic stages. The cells wall of the outer thick cellular–prismatic calcite layers have been highly recrystallized to coarse crystalline, more stable diagenetic low Mg-calcite, with the presence of micritic relics (Fig. 5a). However, the cell walls preserved their original microstructures and identities. Also, the thin prismatic calcite layer probably suffered some recrystallization, but their original microstructure is mostly preserved (Fig. 5b). In contrast, the original aragonitic inner thin layers of crossed-lamellar microstructure are not observed in the studied rudist shells. They have been either dissolved and subsequently infilled by equant calcite cement or by internal sediments, or were neomorphically transformed to the more stable low-Mg calcite, without preservation of the original microstructure during periods of exposure to meteoric waters. Similar diagenetic alterations of rudist shells are reported by AL-AASM & VEIZER (1986a) and WOO et al. (1993). The primary microstructures of the layers have been highly destroyed when the layers were subjected to silicification and replaced by fibrous chalcedony (Fig. 5c).

4.4. Compaction

The rudist shells were subjected to fragmentation, after settling in the shallow marine conditions, by the effect of current and waves resulting in the reduction of some shells to coarse and fine debris, and breaking up of the cell walls of the cellular–prismatic layer of some shells before the introducing of the equant meteoric calcite cement (Fig. 5d). Also, the rudist shells were subsequently subjected to compaction in shallow burial conditions, resulting in some mechanical compaction fabrics, including breaking up of some shells, orientation of some rudist shell fragments, and cracking of some quartz crystals and their exhibition of wavy extinction.

5. PARAGENETIC SEQUENCE

Petrographic observations of the studied Turonian rudists in the Abu Roash area show that the shells were subjected to different diagenetic alteration during marine, mixed marine–meteoric, and meteoric diagenesis and also during shallow burial diagenesis. Each diagenetic stage is characterized by certain diagenetic processes (Fig. 6). A paragenetic sequence reveals the different diagenetic events that can be proposed as follows:

(1) Early marine diagenesis: In this stage, a little micritic calcite cement was precipitated in the pores of the cellular layer and the body cavities of some shells and formed in submarine conditions. Subsequent meteoric alteration may affect this cement where it was recrystallized to microspar. Some bladed high Mg-calcite crystals were probably formed in this stage and precipitated as an isopachous rim, lining some pores of the cellular layer. Fragmentation and break down of cells walls of some shells took place in this stage.

(2) Early meteoric diagenesis: With the subaerial exposure of the sequence, the rocks were subjected to meteoric water diagenesis, including precipitation of two types of calcite cement that occluded the intra-skeletal pores of the cellular layers. The first type is the isopachous calcite rim, which was followed by precipitation of equant calcite cement as a complete infilling of the intraskeletal pores. Also in this stage the columnar calcite crystals, which lined the large body cavity of the shells, were precipitated. Stabilization and recrystallization of the shell components began.

(3) Mixing zone diagenesis: Partial silicification of the rudist shells and coral heads may have occurred in the mixing zone environment where meteoric water, which is the carrier of silica, mixed with marine water producing a solution of low pH, undersaturated with respect to $CaCO_3$ minerals but supersaturated with respect to quartz. This solution allowed the partial dissolution of both the shell components and the early meteoric equant calcite cement and the precipitation of authigenic silica. The presence of some disseminated euhedral dolomite rhombs within the silicified rudist shells and the corals and also in the matrix may support the idea of silicification in a mixing zone environment. From petrographic observations, silicification of the shells postdates the precipitation of the early meteoric cements and preceded the precipitation of the late meteoric vug-filling calcite cement.

(4) Late meteoric diagenesis: With the re-exposure of the beds to a freshwater lens, a few small irregular vugs were formed, cutting the shell components and were infilled by coarse crystalline calcite. This pore-filling cement postdated the formation of early meteoric intraskeletal equant calcite cement and also the silicification of the shells. Stabilization and recrystallization of the shell components probably occurred during this stage.

(5) Shallow burial diagenesis: represented by slight mechanical compaction resulting in the breakage of some shells, cracking of quartz crystals, and also recrystallization of the shell components.

6. CONCLUSIONS

Petrographic study of the rudist shells of the Upper Cretaceous rudist buildup at the El Hassana Dome, Abu Roash area revealed that the shells underwent different diagenetic modifications in variable diagenetic environments (marine, meteoric phreatic and mixing zones and also shallow burial setting). There were three major diagenetic stages that the rudist shells have passed through.

(1) Early submarine diagenetic stage, involving precipitation of a few micritic and bladed calcite cements and break down of some cell walls of the shells.

(2) Meteoric and mixing zones diagenetic stage during the subaerial exposure of the beds. It involved the precipitation of an early meteoric isopachous calcite rim followed by precipitation of equant and columnar calcite cements. Partial silicification of the rudist shells postdated the early meteoric calcite cements and occurred within a mixing zone environment where meteoric water, which is the carrier of silica, mixed with marine water producing a solution which allowed the partial dissolution of both the shell components and the early meteoric calcite cements, and the precipitation of authigenic silica. The silica is probably derived from pressure-solution of quartz and transformation of clay minerals during compaction of the underlying siliciclastic rocks and/or dissolution of silica-producing organisms. In later times, late meteoric vug-filling calcite cement was precipitated. Stabilization and recrystallization of the shell components probably occurred during this stage, where the aragonitic shell layers were dissolved or recrystallized to more stable diagenetic calcite and also the calcitic layers suffered some recrystallization.

(3) Shallow burial diagenetic stage, involving mechanical compaction which resulted in the break up of some shells, cracking of some quartz crystals, and also the recrystallization of the shell components.

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Manuscript received January 10, 2003.

Revised manuscript accepted May 04, 2004.