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Microfacies and diagenesis of the reefal limestone, Callovian Tuwaiq Mountain Limestone Formation, central Saudi Arabia

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ABSTRACT

In order to document the microfacies and diagenesis of the reefal limestone in the uppermost part of the Callovian Tuwaiq Mountain Limestone Formation at Khashm Al-Qaddiyah area, central Saudi Arabia, scleractinian corals and rock samples were collected and thin sections were prepared. Coral framestone, coral floatstone, pelloidal packstone, bioclastic packstone, bioclastic wacke/packstone, algal wackestone and bioclastic foraminiferal wacke/packstone were the recorded microfacies types. Cementation, recrystallization, silicification and dolomitization are the main diagenetic alterations affected the aragonitic skeletons of scleractinian corals. All coral skeletons were recrystallized, while some ones were dolomitized and silicified. Microfacies types, as well as the fossil content of sclearctinian corals, bivalves, gastropods, brachiopods and foraminifera indicated a deposition in environments ranging from shelf lagoon with open circulation in quiet water below wave base to shallow reef flank and organic build up for the uppermost reefal part of the Tuwaiq Formation in the study area.

1. Introduction

The Jurassic succession in Saudi Arabia is subdivided into seven formations. These are from older to younger: Marrat, Dhruma, Tuwaiq Mountain Limestone, Hanifa, Jubaila, Arab and Hith formations. Jurassic outcrops in central Saudi Arabia are arranged in a convex arc hinged in Al-Riyadh region with the horns of the arc oriented to the northwest and to the south. The total outcrop length is in excess of 1000 km, the width nowhere exceeds 85 km and with a greatest outcrop thickness of 1100 m (El-Asa'ad, 1989; El-Sorogy et al., 2014; El-Sorogy and Al-Kahtany, 2015; Al-Dabbagh and El-Sorogy, 2016).

The Callovian Tuwaiq Mountain Limestone Formation is one of the most organic rich rocks that form the major source formation in the anoxic basins of the Middle East in central Saudi Arabia near Riyadh city (Powers, 1968; Powers et al., 1966; Vaslet et al., 1983; Al Sharhan and Magara, 1995; El-Sorogy et al., 2014; Youssef and El-Sorogy, 2015). It was deposited on a carbonate platform developed across the intra-shelf basin (Ziegler, 2001). Fischer (2001) divided this formation into three main paleoenvironments: outer lagoon paleoenvironment which is corresponded to the lower part of the Formation, back-reef paleoenvironment which is corresponded to the middle part and the reef paleoenvironment which is corresponded to the upper part. Also, Al-Qahtani (2013) divided the Tuwaiq Mountain Limestone Formation to three main paleoenvironments (open platform, high energy shoals and restricted carbonate platform). He mentioned also that these three paleoenvironments have been distributed in the whole section.

Many workers have been studied Tuwaiq Mountain Limestones from the geological, paleontological and paleoecological points of view, among those are, Steineke et al. (1958), Powers et al. (1966), Powers (1968), Moshrif and El-Asa'ad (1984), Manivit (1987), Al-Dabbagh (2006), Hughes (2002, 2004a, 2004b, 2005, 2008), Hughes et al. (2009), Al-Husseini and Matthews (2005), El-Sorogy et al. (2014), Youssef and El-Sorogy (2015).

Previous works on the Tuwaiq Mountain Limestone have focused mainly on lithostratigraphy, biostratigraphy, paleoecology and paleontology; however, detailed sedimentological, microfacies and diagenetic works are still needed. Therefore, the main objective of the present work is to document microfacies and diagenetic alterations affected reefal limestone in the uppermost part of the Callovian Tuwaiq Formation at Khashm Al-Qaddiyah area, central Saudi Arabia.

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2. Materials and methods

Khashm Al-Qaddiyah is located about 35 km from the city of Riyadh. A section was measured in detail at 24° 38′ N and 46° 40′ E (Fig. 1). Scleractinian corals and rock samples were collected from the upper most reefal limestone of Tuwaiq Formation at the study area (Figs. 1–3). 79 thin sections were prepared for microfacies analysis, coral identification and diagenetic alterations. Due to high porosity of coral samples, they impregnated with resin under vacuum. Thin sections are investigated and photographed using Polarizing Microscope. The classification of carbonate rocks followed the nomenclature of Dunham (1962), Embry and Klovan (1972) and the energy index classification of Plumely et al. (1962).

All diagenetic studies were carried out on thin sections of the scleractinians, *Actinastraea pseudominima* (Koby, 1897), *Enallocoenia crassoramosa* (Michelin, 1843), *Isastrea hemisphaerica* Gregory, 1900, *Ovalastraea caryophilloides* (Goldfuss, 1826), *Stylina kachensis* Gregory, 1900 and *Collignonastraea grossouvrei* Beauvais, 1972 (Fig. 4), which have been previously identified with other benthic invertebrates from the study area (El-Sorogy et al., 2014). Fossils are stored in the Museum of the Geology and Geophysics Department, College of Science, King Saud University.

3. Geologic setting

The Tuwaiq Mountain Limestone Formation overlies unconformably the Bathonian-Callovian Dhruma Formation and consists mostly of shallow-marine lagoon and stromatoporoid carbonates of Middle to Late Callovian age with a combined thickness of 295 m and is disconformably overlain by the Oxfordian Hanifa Formation with apparent paraconformity in the outcrop (Manivit et al., 1990; Al-Qahtani, 2013). Vaslet et al. (1983) has divided the Tuwaiq Mountain Limestone Formation into three informal members comprising Baladiyah (T1), Maysiyah (T2) and Daddiyah (T3). However, Powers et al. (1966) and Powers (1968) have subdivided it into two informal members.

At Khashm Al-Qaddiyah, the Tuwaiq Formation (Figs. 2 and 3) attains about 190 m thick, mostly of shallow-marine lagoon and stromatoporoid carbonates. The upper part is massive bedded, chalky limestone intercalated with chert layers and lenses. The upper most 25–40 m thick of the studied section (Fig. 3B) is coral bearing bioturbated limestones with isolated coral heads hemispherical and globular forms, reaching 20–50 cm in diameter (Fig. 3C, D)

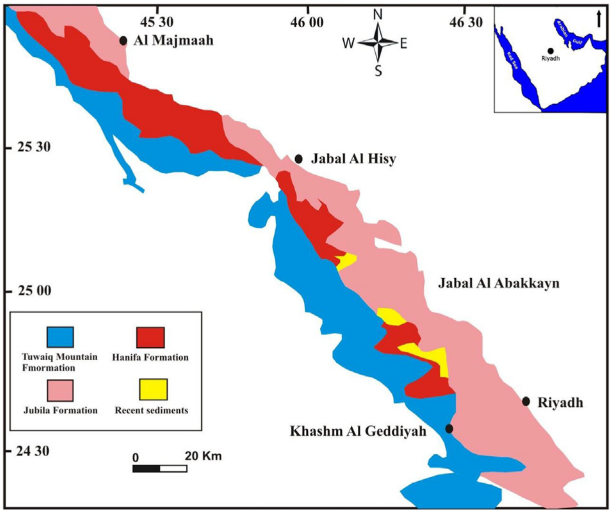

Fig. 1. Location map of the study area.

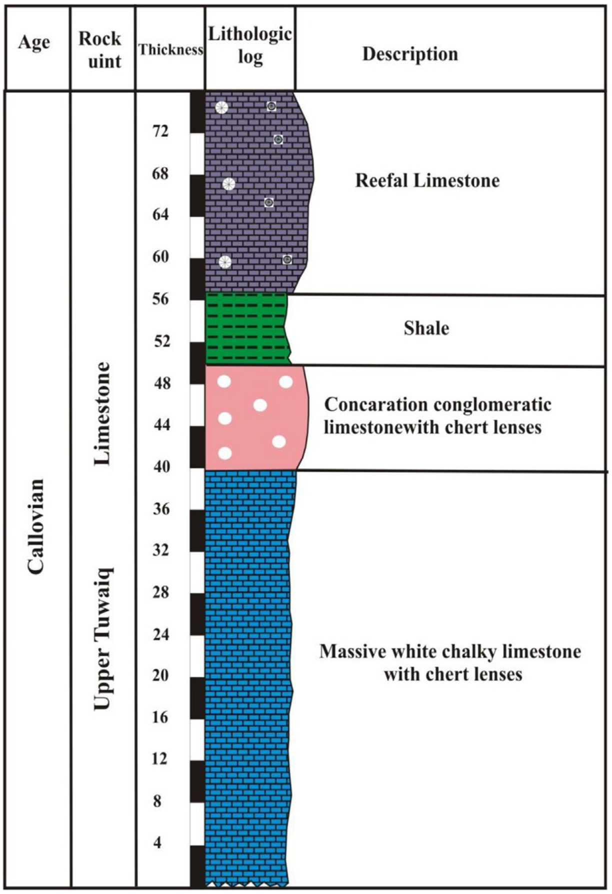

Fig. 2. Composite section of Tuwaiq Mountain Limestone at Khashm Al-Qaddiyah section.

Power et al. (1966) on the basis of ammonites and foraminifera, allotted the lower beds of the Tuwaiq Mountain Limestone to the Callovian but the upper beds of the Formation, depending on distinctive foraminifera, to the Oxfordian. Also, Al Sharhan and Magara (1995), Al-Dabbagh (2006), Basyoni (2003) accepted the Power et al. (1966) opinion.

Fischer (2001) studied the gastropod zones in the Jurassic rocks in Saudi Arabia with great accuracy and he concluded that all beds of the Tuwaiq Mountain Limestone belong to the middle and upper Callovian. Hughes (2008) stated that the Tuwaiq Mountain Limestone Formation is Middle Callovian based on ammonites, nautiloids, brachiopods and nannoflora. Also El-Sorogy et al. (2014), and Youssef and El-Sorogy (2015) reached the same conclusion as Fischer (2001) and Hughes (2008). Thus, in this paper, depending on the deep field and laboratory studies, we agree that all the beds of the Tuwaiq Mountain Limestone Formation are of Middle and late Callovian age.

4. Results and discussion

4.1. Microfacies

Seven microfacies types were distinguished from the reefal limestone of the Tuwaiq Mountain Limestone Formation, these are: coral framestone, coral floatstone, pelloidal packstone, bioclastic packstone, bioclastic wacke/packstone, algal wackestone and bioclastic foraminiferal wacke/packstone (Figs. 5 and 6). The coral

Fig. 3. A, The studied section at Khashm Al-Qaddiyah area; B, Close up view of the upper most reefal part of the studied section; C, D, Callovian scleractinians in living position from the studied section.

framestone and coral floatstone were recorded from the hemispherical and globular coral heads spreading in the upper reefal part. Carbonate grains are formed of recrystallized and micritized large fragments of corals, that act as frame builders or may float in a bioclastic matrix (Fig. 5A–C). The pelloidal, bioclastic packstone, wacke/packstone, algal wackestone and bioclastic foraminiferal wacke/packstone were recorded in the internal sediment among coral framework and the lower part of the reef. They composed of pellets, foraminiferal tests, sponge spicules, dasycladacean algae, shell fragments (Fig. 5D, Fig. 6A–D). All were embedded in micritic matrix. The carbonate grains, in general, act as essential rock builders.

The skeletal grains are dominated by foraminifera (*Nautiloculina* sp., *Riyadhella* sp., *Redmondoides* sp., *Praekurnubia* sp., *Verneuilinoides* sp., *Haplophragmoides* sp., *Steinekella* sp., *Trocholina* sp. and *Palorbitolina* sp.), reworked corals (*Thamnasteria* sp. *Ovalastraea* sp.), domal and branched stromatoporoids, many epifaunal brachipods (*Rhynchonella* sp., *Somalirhynchia* sp., *Terebratula* sp., *Valvulina* sp. and *Habrobrochus* sp.), gastropods (*Purpuroidea* sp., *Arcomytilus* sp. *Erymnoceras* sp.), bivalves (*Exogyra* sp., *Pinna* sp., *Homomya* sp., *Lima* sp., *Lopha* sp.) and dascycledean algae. Matrix among coral colonies is made up of peloidal micrite with abundant aggregate grains. Most aggregate grains are micritized exhibiting the characteristic lobate outline. Most skeletal grains have rims of thin early-marine cement and micritization.

The presence of these fossil assemblages suggests well oxygenated water with normal salinity in the open sea back-reef and shallow lagoon shelf (Holzapfel, 1998; Sepkoski, 2002; Clark and Boudagher-Fadel, 2001; Ivanova et al., 2008; Neagu and Cirnaru, 2004; Masse et al., 2004; El-Sorogy et al., 2014; Youssef and El-Sorogy, 2015). Stromatoporoids requires moderately low energy conditions in order to avoid breakage, and are considered to have best developed in the distal part of the lagoon or in back banks, where the direct higher wave energy would be inhibited (Hughes et al., 2009). The presence of aggregate grains and peloids indicates submarine erosion of lithified carbonates adjacent to a reef zone inner platform behind the platform edge (Flügel, 2010). The occurrence of reworked bioclasts may indicate occasional storm events. The seven recorded microfacies types are similar to SMF 5, 7–9 of Flügel (1982) and facies belts 4, 5 of Wilson (1975), indicating an environment ranging from shelf lagoon with open circulation in quiet water below wave base to shallow, reef flank and organic buildup of in situ sessile organisms that grow on a carbonate shelf. The high coral contents in the uppermost part of the Tuwaiq Mountain Limestone Formation and the collected fossils imply framework in an open marine environment with moderate to high energy conditions (Ahmad, 1998; Pandey et al., 2009; Flügel, 2010; Cestari and Laviano, 2012).

El-Sorogy et al. (2014) attributed the low diversity of taxa in the present study area to inimical paleoenvironmental conditions that have prevailed during the Callovian such as high rate of sedimentation, which caused turbidity and consequently decreased light penetration. Also the muddy facies might lead to unfavorable soft substrate for coral colonies to grow into large sizes and therefore did not provide adequate space for the buildup of a true reefal barrier system in central Saudi Arabia.

4.2. Diagenesis

Skeletons of scleractinian corals of Callovian Tuwaiq Mountain Limestone Formation at Khashm Al-Qaddiyah area underwent different types of diagenetic alterations under both marine and

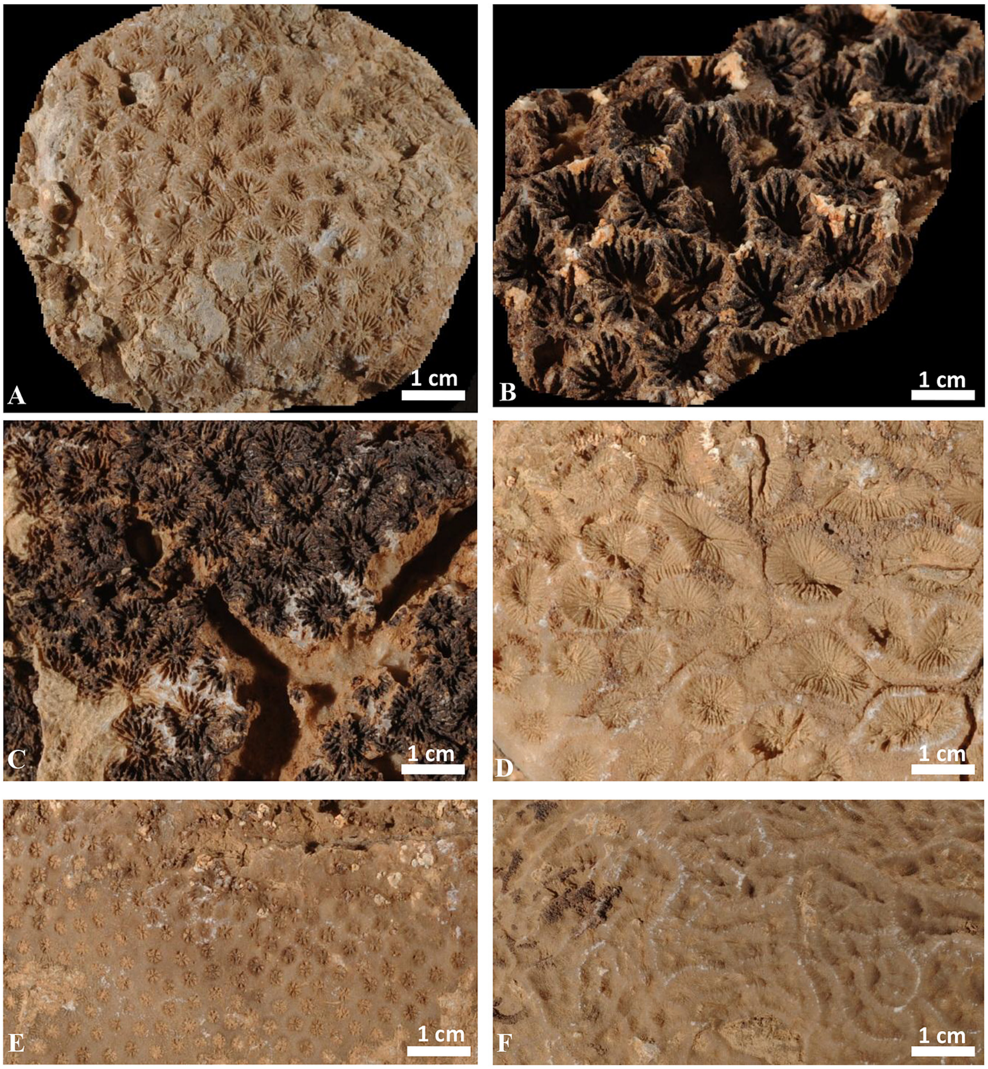

Fig. 4. Calicular views of the studied corals (El-Sorogy et al., 2014). A, *Actinastraea pseudominima* (Koby, 1897); B, *Enallocoenia crassoramosa* (Michelin, 1843); C, *Isastrea hemisphaerica* Gregory, 1900; D, *Ovalastraea caryophilloides* (Goldfuss, 1826); E. *Stylina kachensis* Gregory, 1900; F, *Collignonastraea grossouvrei* Beauvais 1972.

meteoric-diagenetic environments. The following is a detailed study on these diagenetic processes:

4.2.1. Cementation

The early phase of cementation occurred in Holocene reefs of the Red Sea coast are aragonitic needles and high-Mg calcite (El-Sorogy, 1997; El-Sorogy et al., 2013). Most of the marine cement is recrystallized into microspar. Microspar originates from recrystallization of lime-mud (micrite) which is only possible after the removal of Mg ions (Folk, 1965). Similar diagenetic alterations of rudist shells are reported (e.g. Al-Aasm and Veizer, 1986; Woo et al., 1993; Mansour, 2004). Dissolution of aragonitic skeletons generate types of porosity including vuggy, moldic and enlarged intergranular porosity (Flügel, 2010; Özer and Ahmed, 2016). Also Boggs (2011) stated that, dissolution of aragonite and high-magnesium calcite may saturate the waters in calcium carbonate with respect to calcite, causing calcite to precipitate.

The original intra-skeletal pores within the studied skeletons are partially or completely filled with more than one cement phase: (a) micritic calcite cement, rarely lined the inter-corallite cavities (Fig. 7A). The micritic crystals may be recrystallized to microspar during subsequent diagenetic stages. (b) equant calcite cement with crystals of clear subhedral, coarse crystalline texture completely filled the inter-corallite spaces (Fig. 7B). The fabric of this calcite cement suggests that it formed from phreatic-meteoric water after subaerial exposure of the Jurassic rocks, and (c) large blocky mosaics partially or completely filling spaced between septa (Fig. 7B, C).

4.2.2. Recrystallization

Recrystallization is a process by which crystals changing from fine to coarser crystals. In scleractinian corals, recrystallization means changing aragonite which forms the skeletal materials and cement into equant calcite. The term neomorphism has been introduced by Folk (1965) which includes aggrading and degrading recrystallization. It is also a process of replacement and recrystallization with possible change in mineralogy.

Aragonite and magnesium calcite are the most soluble carbonate polymorphs. The aragonite forming skeletons of the present samples have been highly recrystallized during the meteoric diagenetic stages to crystalline, more stable low Mg-calcite, with the presence of micritic relics in between (Fig. 7A, B). The original aragonitic microstructures are completely obliterated. They have been dissolved and subsequently infilled by equant calcite cement,

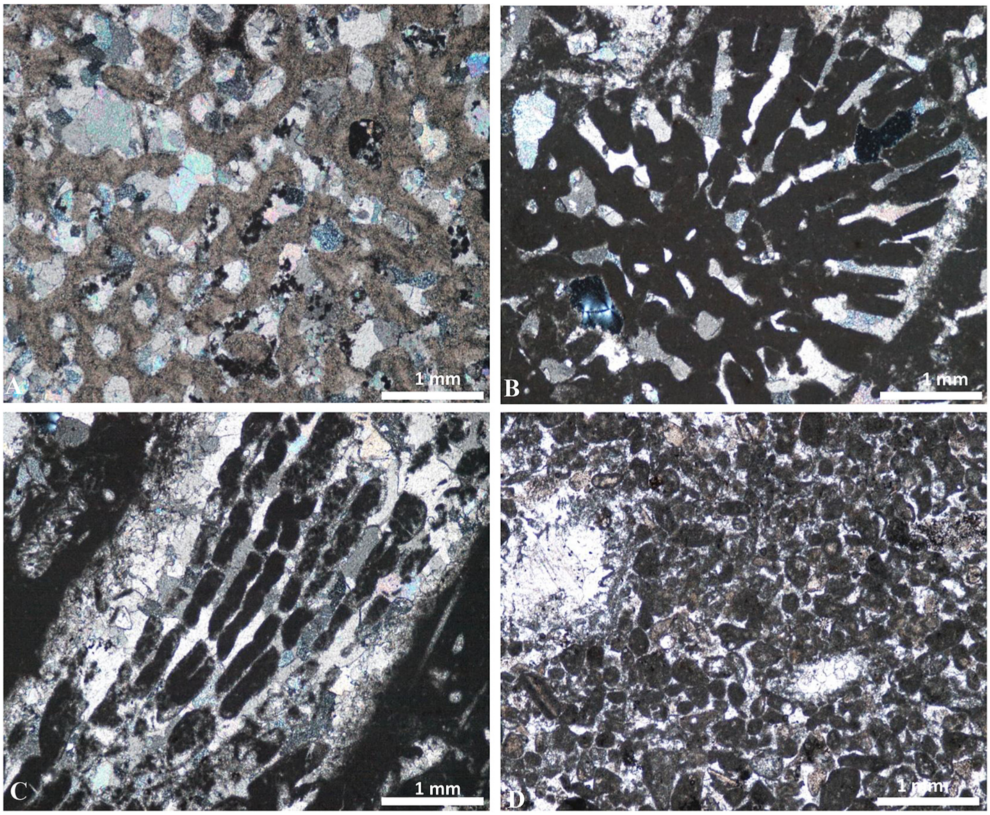

Fig. 5. Microfacies association in reefal limestone of Tuwaiq Formation (Crossed nicols). A, Coral framestone, with micritized transverse section of massive colony; B, Coral floatstone, with transverse section of single corallite; C, Coral floatstone, with longitudinal section of recrystallized coral colony; D, Pelloidal packstone, with small pellets and fossil fragments in micritic matrix.

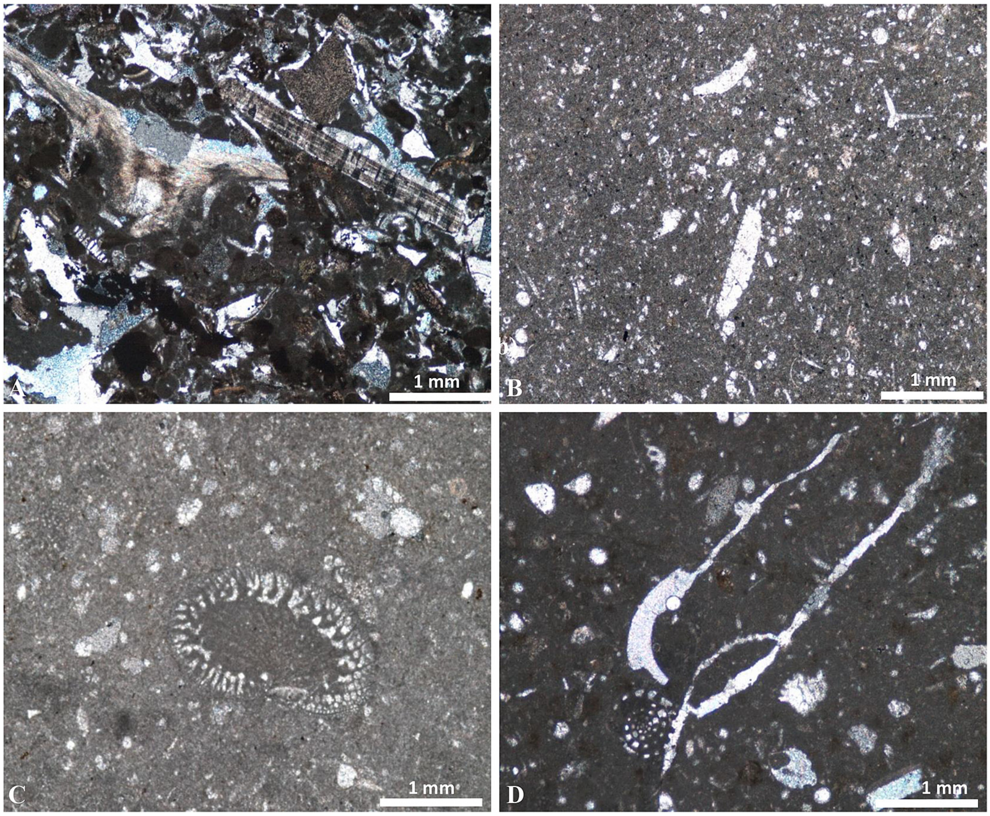

Fig. 6. Microfacies association in reefal limestone of Tuwaiq Formation (Crossed nicols). A, Bioclastic packstone, with packed shell fragments in micritic matrix; B, Bioclastic wacke/packstone, with different fossil fragments and spong spicules; C, Algal wackestnoe, with transverse section of dasyclad fragment and other bioclasts; D, Bioclastic foraminiferal wacke/packstone with foraminiferal test and shell fragments in micritic matrix.

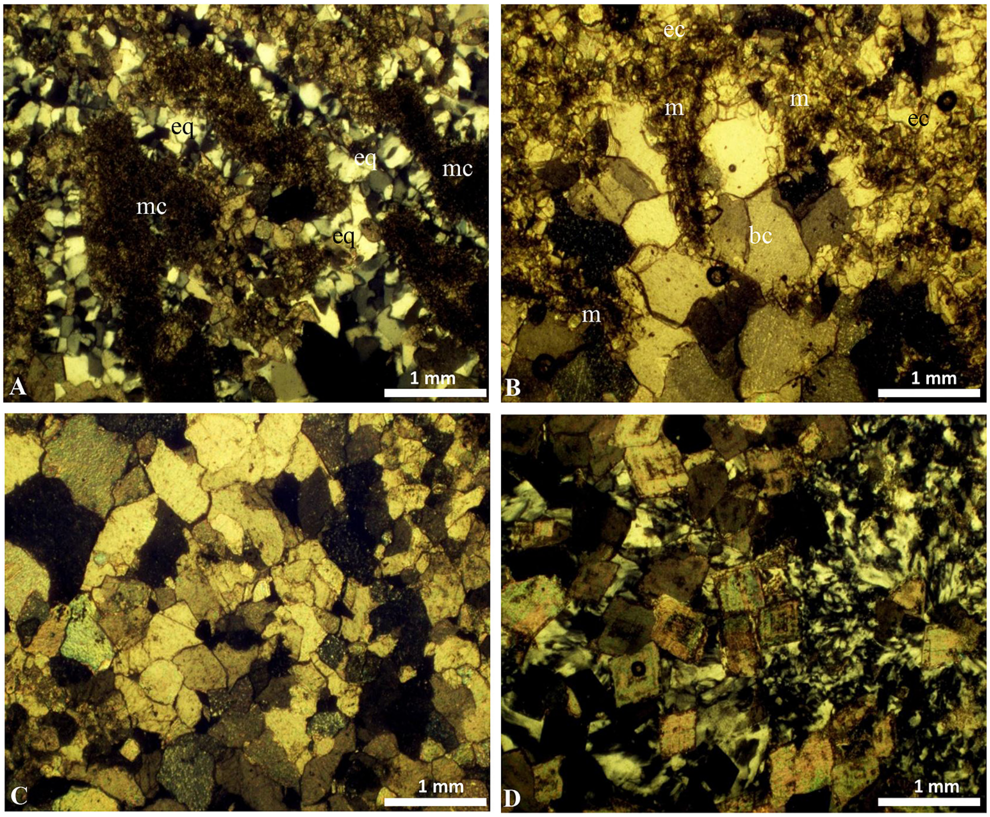

Fig. 7. Diagenetic alterations of the studied corals (Crossed nicols). A, Silicification of septa of *I. hemisphaerica* by equant quartz crystals (eq). Spaces among septa are filled with micritic calcites (mc); B, Skeleton of *C. grossouvrei* is mostly micritized (m), other parts of septa are changed into equant calcites (ec). Cavities among septa are filled with large blocky calcite (bc); C, All skeletal elements of *A. pseudominima* are changed to blocky calcite crystals in the late stage of diagenesis; D, Completely dolomitized and silicified *S. kachensis* with large typical zoned idiotopic dolomite rhombs. Note, increase intra-and inter-porosity due to dolomitization.

or were neomorphically transformed to the more stable low-Mg calcite, without preservation of the original microstructure during periods of exposure to meteoric waters.

4.2.3. *Dolomitization*

Dolomite rhombs replaced partially or completely scleractinians or calcitic cement (Fig. 7D). Basyoni and Khalil (2013) indicated that, such dolomitization took place during or after the introduction of late, post-compaction cement, and consequently the replacement process must be of burial diagenetic origin, though not necessarily at great depth.

The present dolomite rhombs consisted mostly of medium crystalline, nonferroan dolomites that exhibited slightly to strongly undulose extinctions under crossed nicols. It is also marked by typical zoning and iron oxide rims. Typical unit extinctions, normally associated with early near-surface dolomites, were uncommon. As demonstrated by Wendte et al. (1998), and Wierzbicki et al. (2006) undulose extinctions appear associated with dolomites that precipitated under deeper burial conditions or were altered by burial recrystallization. These typical dolomite crystals are anhedral to subhedral in shape. The euhedral crystals are normally associated with early formed dolomites.

4.2.4. *Silicification*

One of the most important diagenetic features observed in the studied corals is the authigenic silica, found either as pore-filling among scleractinian spaces (Fig. 8A, B) or as partial to complete replacement of skeletons (Fig. 8C, D). They precipitated in the form of equigranular microquartz and fibrous quartz as spherulitic chalcedony. Some of the crystals possess wavy extension and others are cracked. The contact of quartz crystals with the skeleton boundary is sharp and the boundaries are not dissolved or replaced by silica. This indicates that the quartz crystals were precipitated as cavity-filling cement after stabilization of the wall boundaries.

In general, the source of silica is unequivocal. The biogenic source of silica is considered as the common process by many workers (e.g. Lawrence, 1994; Gimenez-Montsant et al., 1999), where silica can be derived from dissolution of silica-producing organisms, such sponges in the studied formation. This intraformational source of silica for coral replacement is favored by many authors (e.g. Loope and Watkins, 1989; Maliva and Siever, 1988; Coniglio, 1987).

The time at which silicification affected scleractinian skeletons is difficult to determine from petrographic evidence alone. Most reports dealing with silicification suggest replacement that took place during early diagenesis before significant burial and compaction of sediments (Mansour, 2004; Schubert et al., 1997) or as proceeding lithification (Brunton, 1984). Carson (1991) indicated that silicification may occur at burial depths of 0–10 m. Noble and Van Stempvoort (1989) also suggested that quartz could be formed at a few meters to tens of meters burial depth. The presence of recrystallized calcite crystals floating in the chalcedony (Fig. 8D) suggests that silicification may have occurred after the recrystallization process. There are many studies concerning the development of dissolution and subsequent silicification (Holdaway and Clayton, 1982; Knauth, 1979; Schmitt and Boyd, 1981; Özer and Ahmed, 2016). Maliva and Siever (1988) proposed that the force of crystallization of silica increases the free energy and solubility of carbonate material and replacement by silica.

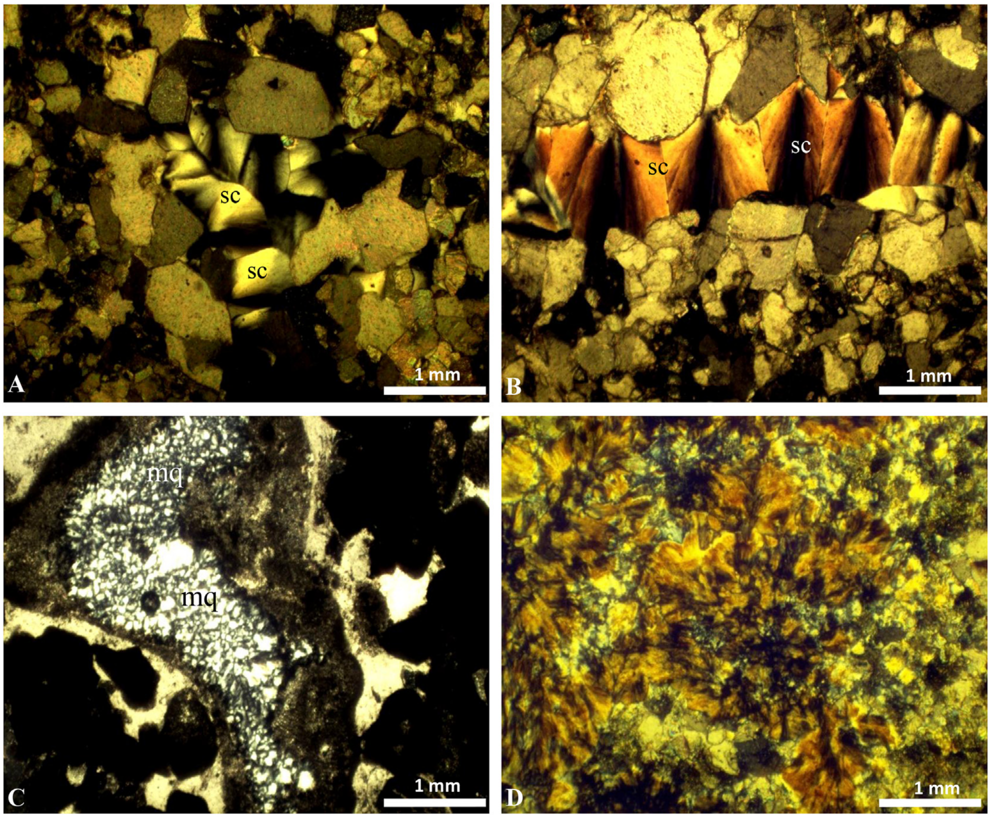

Fig. 8. Diagenetic alterations of the studied corals (Crossed nicols). A, Partial silicification by chalcedony (sc) in a dissolution cavity between recrystallized skeleton of *E. crassoramosa*; B, Partial silicification by calcedony vein (sc) in a dissolution cavity in a recrystallized *O. caryophilloides*; C, Scleractinian fragment is largely replaced by microcrystalline quartz (mq); D, Silicification of most *A. pseudominima* skeleton by chalcedony fans. Note, recrystallized calcite crystals floating in the chalcedony.

5. Conclusions

1 Reefal limestone in the uppermost part of the Callovian Tuwaiq Formation at Khashm Al-Qaddiyah area, Central Saudi Arabia yielded the following microfacies types: coral framestone, coral floatstone, pelloidal packstone, bioclastic packstone, bioclastic wacke/packstone, algal wackestnoe and bioclastic foraminiferal wacke/packstone.

2 The studied reefal limestone underwent the following diagenetic alterations: cementation, recrystallization, silicification and dolomitization. All original aragonitic skeletons of corals either dissolved or recrystallized to calcite. Silicification may be took place after recrystallization process.

3 The microfacies associations and fossil content of corals, bivalves, gastropods, brachiopods and foraminifera indicated an environment ranged from shelf lagoon with open circulation in quiet water below wave base to shallow reef flank and organic build up for the reefal limestone of the Tuwaiq Mountain Limestone Formation in Central Saudi Arabia.

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