Journal of Earth Sciences & Environmental Studies (ISSN: 2472-6397)

Scanning the Lower Cretaceous carbonate rocks utilizing stable isotopes and petrographic records

DOI: 10.25177/JES.6.1.RA.10787

Research

Accepted Date: 25th Jan 2022; Published Date:25th Feb 2022

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CITATION

Namam M. Salih, Scanning the Lower Cretaceous carbonate rocks utilizing stable isotopes and petrographic records (2022) Journal of Earth Sciences & Environmental Studies 6(1): 148-163

ABSTRACT

The study is carried out on the Lower Cretaceous carbonate rocks along Zagros basin, NE-Iraq, allowing the recognition of syn-depositional and post-depositional microfacies. The paper recognized three mains microfacies: lime mudstone, fossiliferous wackestone, and orbitolinid wackestone/packstone microfacies. Orbitolinid wackestone/packstone comes in the base of the studied area, follows by argillaceous unit. Orbitolinid wackestone/packstone contains orbitolinid foraminifera, indicates a shallow-water carbonates. lime mudstone microfacies comes repeatedly at top of argillaceous unit, then followed by fossiliferous wackestone that contains *Cuneolina* sp and miliolids. The repetition of fossiliferous wackestone, in between argillaceous unit with anhydrite grains mark a change of marine conditions and fluctuation of sea level that persisted through Early Cretaceous.

Paragenetically, post-depositional products include: 1) replacive dolomite, 2) transparent, rhombohedral dolomite crystal, 3) saddle dolomites that postdate replacive and rhombohedral dolomites. Saddle formation suggest that late dolomitizing fluid is originated from hot circulating fluid during an intensive fracturing system and is associated with hydrocarbon migration. Zebra/breccia textures development are explained by focused fluid flow. Hydrothermal fluids in structure controlled by tectonic activity produced hydro-fractures that significantly filled by saddle dolomites during the hydrothermal dolomitization.

The C isotope record shows two major positive excursions of $\delta^{13}C$ (phase 1 & 3) precedes and predates the phase 2 negative excursion of $\delta^{13}C$ from argillaceous limestone deposits. The O isotope variation values in phase 3 is consistent with influx of hydrothermal fluids and zebra/breccias textures.

Keywords: Stable isotopes, petrography, argillaceous limestone, hydrothermal dolomitization, Lower Cretaceous.

1.INTRODUCTION

The Lower Cretaceous Qamchuqa Formation includes one of the major reservoirs in the Middle East. Fracturing, dolomitization and other diagenetic processes affected the carbonates could contribute and add a qualified characteristics of reservoir development, which make the foreland basin Qamchuqa Formation one of the main targets for oil exploration in most of the oil fields of Iraq. The role of tectonics in a foreland basin setting as related to fracturing, fluid flow and dolomitization have not been investigated in details of the region before (Kareem et al., 2021). Structurally controlled hydrothermal dolostone hosts many hydrocarbon reservoirs worldwide and hence have been of high interest for exploration by oil companies (Davies and Smith, 2006).

Depositional processes control initial porosity in basin filling sedimentary successions. Primary conditions determine how diagenesis modifies the hydraulic properties of sediments as they undergo burial and lithification. Therefore, combining sedimentology, stratigraphy and diagenesis to understand the evolution of fluid flow in sedimentary sequence is necessary to understand the secondary alternation on synsedimentary rocks, which in this study we called post -depositional setting conditions.

Understanding the source and timing of fluid flow through sedimentary rocks is necessary for the development of diagenetic setting model in Qamchuqa Formation. Delineating temporal relationships requires integration of sedimentology and diagenesis through paragenetic relationships to constrain fluid flow associated events, including those related to petroleum migration and formation of mineral deposits (Hiatt and Kyser, 2000). Although depositional processes establish initial porosity and permeability relationships, diagenesis can completely modify or invert these original relationships (Hiatt and Kyser, 2000). As a consequence, it becomes critical to determine how reservoirs evolved as diagenesis progressed during the time mineralizing fluids were flowing through basin filling sedimentary rocks (Davies and Smith, 2006).

The goal in defining the depositional and diagenetic parts are to provide an overview of depositional controls exerted on initial porosity and diagenetic controls during fluid evolution, and to understand the source and type of fluid flowed after the deposition, therefore the stable isotope signals are the direct indicator for tracking the fluid evolution during and after the deposition (Salih et al., 2019)

The studied area is located in the northwestern plunge of Korak anticline in High Folded Zone in NE-Iraq (Figure 1). The formation is considered as a giant Cretaceous reservoir in Tak Tak and Kirkuk Oilfields, thickness is estimated to be approximately 600 m in the main reservoir region.

The main key addressed in this paper is to define the depositional environment, and intensive diagenesis and drawing paragenetic sequence, and finally solving the syn/post-depositional conceptual model of this formation.

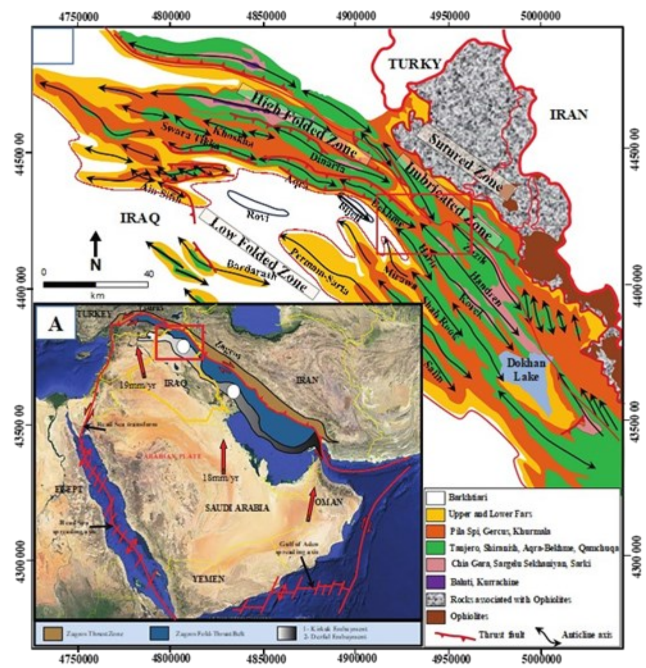

Figure 1. Geological map, showing the general location of the studied area (rectangle) and the tectonic unit of NE-Iraq (After Kareem et al., 2021).

2. MATERIALS & METHODS

2.1. Sampling and Material

Detailed fieldworks were carried out at the studied outcrop (Figure 1). 17 samples were collected from the limestones, dolomites, and calcites at different litho-stratigraphic levels, in places following the NW –SE direction. Lateral and vertical samplings were carried out in order to follow the direction of fluids causes the dissolution and cementation, and to outline any significant variations in term of diagenesis.

Finally, 20 thin sections were prepared and later on petrographically studied under standard polarizing microscope.

The oxygen and carbon isotopic compositions of (23) samples were analyzed from powders, after selective micro drillings of the different recognized carbonate phases. However, the co-occurrence of fracturefilling calcite and dolomite, and also evaporites in the host limestones, made it difficult to avoid a mixing between these phases. As a consequence, the dolomite and calcite are considered as one group, and host limestone and evaporite as a second group.
Carbonate powders were reacted with 100% phosphoric acid at 70 °C using a Gasbench II connected to a Thermo Fisher Delta V Plus mass spectrometer. All values are reported in per mil relative to V-PDB (Table 1). Reproducibility and accuracy were monitored by replicate analysis of laboratory standards calibrated to international standards NBS19, NBS18 and LSVEC. Laboratory standards were calibrated by assigning $\delta^{13}C_{VPDB}$ values of +1.95‰ to NBS19 and −46.6‰ to LSVEC and by assigning $\delta^{18}O_{VPDB}$ values of −2.20‰ to NBS19 and −23.2‰ to NBS18. The analyses (23) were performed in the University of Erlangen (Germany, M. Joachimski).

2.2. Geological setting

The study area is located within the High Folded Zone in the Northwestern segment of the Zagros Fold (Figure 1), which is a part of the unstable shelf of Arabian Plate, this plate is a part of AlpineHimalayan belt and tectonically considered an active plate by convergence with Iranian plate (Jackson et al., 1995). Because of the Zagros Orogeny, convergence continent-continent collisional events between the Arabian and the Eurasian plates caused the final closure of the Neo-Tethys and formed the Zagros Fold-Thrust Belt, which occurred during Late Cretaceous to Cenozoic (Alavi, 2004). The area is the Northeastern deformed part of the Arabian plate (Alavi, 2004) that has been deformed intensely on all scales and characterized by the presence of a vast number of sub-parallel high amplitude anticlines and synclines, mostly have two major trends, a NW-SE trend paralleling the Zagros orogeny and an E-W trend paralleling the Taurus Mountains (Csontos et al., 2012). The fold trends show an abrupt change from NW-SE in the east of study area to E-W oriented folds curved toward the western part of the study area.

Within the part of Zagros Fold Thrust Belt stresses generated many thrust and transverse faults and a number of fault-related folds. A number of gorges in the high folded zone occur along traversal normal and strike slip faults (Alavi, 2004). In the Zagros foldthrust belt, the prominent physiographical features developed along transversal normal and strike-slip faults is Galley Ali Bag gorge. This unique gorge is one of the longest, narrowest, deepest gorges (canyon like the gorge consists of massive thickly bedded Cretaceous carbonates (Sissakian et al., 2015).

The most of High Folded Zone structures are covered by Upper Cretaceous rocks (Buday, 1980). The early Cretaceous Qamchuqa Formation is an important rock unit in terms of exposure, thickness, and regional distribution (Sissakian et al., 2015). In Gali Ali Bag gorge, the formation comprised of several hundred meters of neritic, thickly-bedded shallow water– platform carbonates, underlain conformably by the thinly interbedded soft, basinal marl and marly limestones of the Sarmord Formation, and overlain by the thickly-bedded Aqra-Bekhme Formation (Sissakian et al., 2015). The Qamchuqa strata is one of the main reservoir rocks (Sadooni and Al-sharhan, 2003), have highly intercrystalline porosity, and significant large vuggy porosity associated with fractured dolostone facies.

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3. RESULT AND DISCUSSION

3.1. Field observation

The Lower studied part of the Qamchuqa Formation is partly exposed to the surface, composed of host limestone, rich of gastropods, pelecypods, and benthic foraminifera (Figure 2AB). The middle and upper parts are completely altered were mostly destructed by dolomitization fluids in addition to calcite filling pore-spaces and different textures caused by dolomitizing fluids were recognized following the continuity of the bedding planes (Figures 3 & 4). Therefore, the current exposed rocks are sampled based on vertical and lateral facies changes. The formation undergone a complex diagenetic history; however, the original depositional facies are partly preserved. The studied section is focused around ~ 6m thickness due to difficulties to reach the whole section. The altered part is dolomitized that filling abundant pore-spaces and fractures parallel to the stratification of host layers and sub -vertical fractures (Figure 2 A, B).

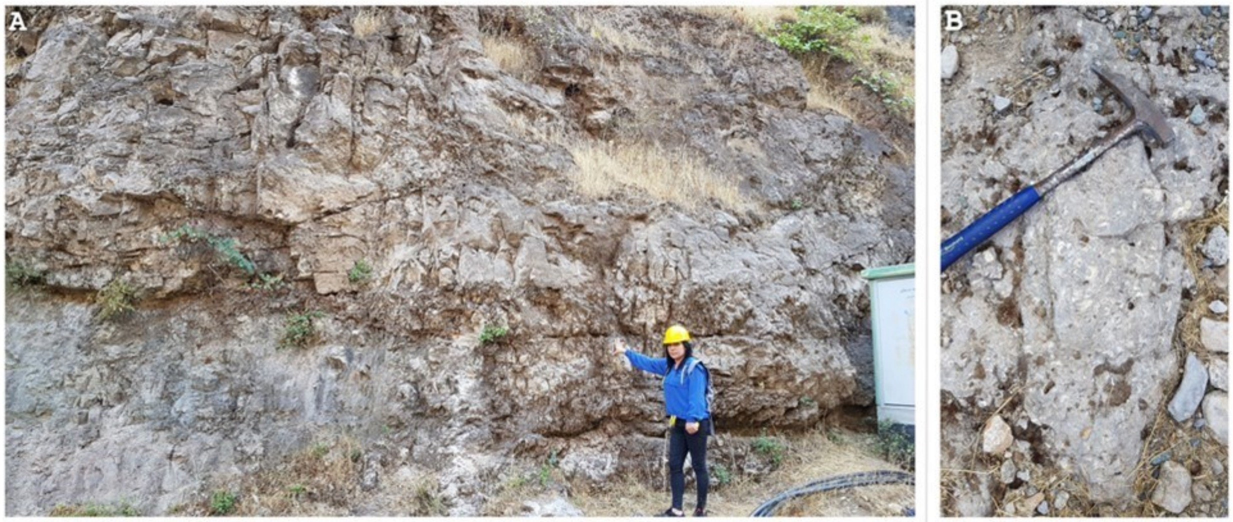

Figure 2. Field photographs: (A) the studied section of the Qamchuqa Formation showing massive bedding of host limestone that later exposed to hydrothermal fluids, were flowed up through some parts of this formation and altered the original facies of limestone. (B) Host limestone of the Qamchuqa Formation illustrates the diversity of organisms, bivalves, forams, and gastropods.

Three distinctive diagenetic features are recognized in the fieldwork: (1) zebra-like texture (Figure 3); (2) fractures and pore-spaces fillings, and (3) the breccia-like texture (Figure 4). The zebra-like texture is characterized by alternating of dark grey and white colour bands, the size of bands is considered as a horizontal extension of pluridecimeters to meters (Figure 3). The alternation is highlighted by the dark grey colour of dolomite matrix and white coloured fractures filled by coarse grains of dolomite and calcite. They are nearly parallel to the bedding plane, giving a stratified fabric to the texture. However, in places these bands arranged sub-vertical to bedding planes.

Figure 3. Photograph shows the abundant zebra texture that arranged parallel and sub-vertical to bedding planes, close up of the inserted photo that reveal a zebra texture in Lower Cretaceous outcrop

Figures 4 & 5 show spherical and elliptical voids filled with dolomitic cement. These voids are always accompanied by bitumen or hydrocarbon seepage. They left no traces for the host limestone, and the voids cemented by coarse grain-sized dolomites. These voids formed interconnected, up to 25 cm, allowing a good lateral continuity parallel or subvertical to the bedding planes and are associated with the seepage of hydrocarbon products. The oval-rounded vugs are filled with curved dolomite and are often associated with fractures stacked in a circle or random order. The voids and zebras are abundant in Gali Bag area, and also reported in Bekhme Formation (Salih et al., 2019a, b). The fracture-filling dolomites were previously documented as a result of hot fluids called hydrothermal fluids that structurally controlled by tectonic activity (Salih et al., 2019a).

Figure 4. photograph showing the extensive brecciation and void filling by saddle dolomite. The inserted photo shows on the upper left top part of this photo the percolate of hydrocarbon within the breccia and along the secondary porosities.

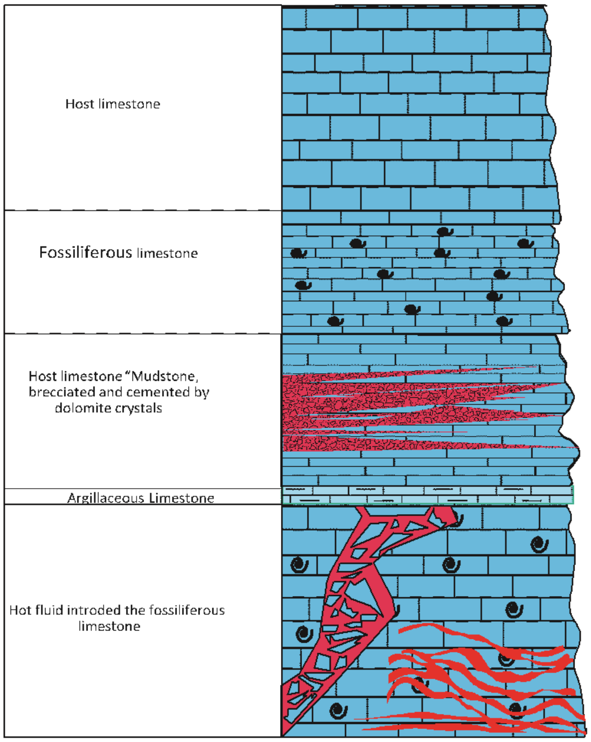

Figure 5. litho-log of the studied section of the Qamchuqa Formation (not to scale).

3.2. Optical observation "Syn-depositional"

3.2.1. Lime Mudstone Microfacies

These facies are the major facies in the lower and middle parts (Figure 6 A), consists mainly of micrite, which is slightly effected by recrystallization processes, the percent of grains is less than %10, all the contained grains are belong to skeletal grains. It contains Miliolids, Textularia,Nummulites.

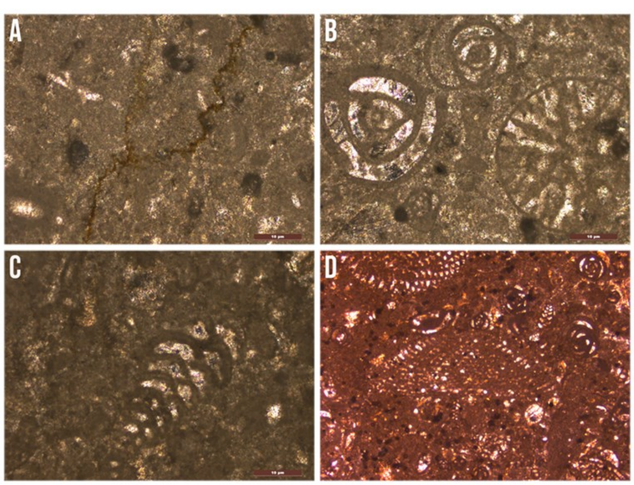

Figure 6. Photomicrographs showing: (A) The micritic groundmass with abundant needle like porosities filled by anhydrite mineral. Q1.XPL. (B) Majority of skeletal grains are miliolids in a wackestone microfacies. Q1.XPL. (C) The skeletal grains are considered the majority constitutes, the obvious grain in the most central part is Cuneolina sp. Q1.XPL. (D) Orbitolinid wackestone/packstone microfacies with abundant of benthic foraminifera (orbitolinid) and miliolids. Q2.XPL.

3.2.2. Fossiliferous Wackestone Microfacies

The constitutes of wackestone is usually varies between 15 % and 50% of grains in a micrite groundmass (Figure 6 B, C). The skeletal grains are considered the majority, the most obvious grains are miliolids, *Cuneolina sp*, gastropods, pelecypods, and foraminiferal bioclasts embedded in micritic groundmass (Figure 6 B-D). The grains are usually dissolved and filled by drusy cement. The drusy cement is filling the intraparticle porosity, in places the drusy cement filling the fractures, and other pore spaces. The early digenesis of the micritic groundmass that altered by replacement process still preserved the remnant of pristine facies. The spare micrite grains is replaced progressively by larger crystal, till turned to rhombohedral crystals. The facies are commonly associated with early fractures filled by anhydrite crystals, which imply that this anhydrite is contemporaneous with early diagenesis and could be linked to fluctuation of sea level during Cretaceous period (Read and Horbury, 1993).

3.2.3. Orbitolinid Wackestone/Packstone Microfacies and argillaceous limestone

The large sized-skeletal grain is common in the lower part and particularly the orbitolinid are the dominant one, and miliolid are represented these facies as a second major component. The grains are linked up by micrite. Orbitolinid (Figure 6 D; Figure 7) is the most important groups for Early-Mid-Cretaceous biostratigraphic studies in the Tethyan realm, including the Middle East (Simmons et al, 2000). The structure of the embryonic apparatus of Orbitolinid is a significant feature for taxonomic subdivision. Differences in the structure of the embryonic apparatus allow for several evolutionary lineages to be recognized, each lineage typically containing a number of stratigraphically restricted species (Simmons et al, 2000).

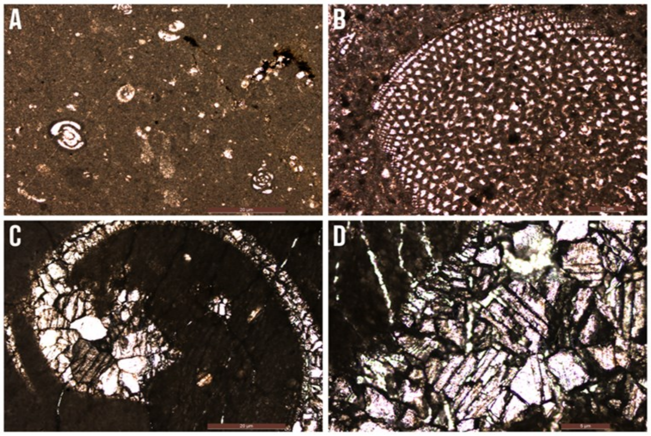

Figure 7. Photomicrographs of precursor limestone showing the depositional microfacies of the Qamchuqa Formation, the Orbitolinid (A, B, C, D) and miliolids (C). Axial section through megalospheric embryonic apparatus (initial chambers seen in microphotograph A). The type of microfacies in these figures is orbitolinid wackestone/packstone microfacies. Q2. PPL.

The Orbitolinidae are extinct family of Large Benthic Foraminifera. Orbitolinidae were present in the warm, shallow marine waters from the Early Cretaceous to the Early Oligocene, however, they were most diverse during the Mid-Cretaceous (BouDagher -Fadel and Price, 2019). In contrast to other large benthic foraminifera, the Mesozoic orbitolinids originated in the warm tropical shallow platforms of Tethys (BouDagher-Fadel and Price, 2019). The paleogeographic migration of orbitolinid members from one group to another during the global sea level low stands of the Aptian, moving from Tethys westward to the Americas, and also eastward into the Western Pacific region. Their migration stopped after rising sea level in the Albian. During storms, bioclastic material was transported from shallow to deep-water environments that were dominated by pelagic sedimentation (Husinec et al., 2000). The Repetition of small-scale of foraminiferal wackestone microfacies, and in between the quite low energy of mudstone microfacies with appearance of argillaceous limestone probably could demonstrate the periodic flooding of platforms (Figures 6 & 7 A-D), and that the studied part of the Qamchuqa formation precipitated in a shallow warm-water carbonate platform. Furthermore, Shirazi and Abedi, 2013 added that this family flourished in shallow marine carbonate facies deposited under subtropical to tropical conditions. The species have relatively short temporal ranges and thus provide valuable chronostratigraphic information (Schroeder et al., 2010).

Based on above observation and related literatures, the studied section of Qamchuqa Formation is deposited in a shallow neritic environment during Early Cretaceous time where the biotic components and their microfacies association indicate shallow carbonate facies characterized warm water conditions with different degrees of water energy that change to relatively more quiet condition during the deposition of mudstone microfacies.

The Orbitolinid microfacies is followed the 10-20 cm thick unit of argillaceous limestone (Figure 5). The mudstone facies were significantly observed and repeated in the lower part and upper part of the argillaceous limestone unit. These periodic changes from benthic wackestone/packstone to mudstone microfacies and fossiliferous wackestone microfacies to mudstone at the base and top of argillaceous unit mark a change in sea level.

3.3. Diagenesis and Post-depositional setting

3.3.1. Reservoir Diagenesis characteristics

A. Dolomitization

The recent study shows that dominant alteration on host rocks is the dolomitization process, characterized by absence of any predominant fossils and skeletal components in samples where the dolomitization is extensive. dolomite is common result and could be recognized easily by naked eyes under optical microscope:

***a. Replacive matrix dolomite*:** occurred in different shapes and colors, ranging from dark gray to brown color (Figure 8 A-D). Replacive matrix dolomite crystals are bimodal size distribution and possesses fine to medium coarse crystalline texture, usually preserve the precursor limestone and in places occurred as a destructive dolomite. The dolomite crystals are non-planar to s-planar (Figure 8 A-C).

b. Rhombohedral dolomite: show a transparent color, rhombohedral shape and in places nucleated around a rhombohedral dolomite crystal ghost (Figure 9 A). The latter can be easily recognized by cloudy cores and free rims. Thus, the transparent rims could be related to relatively slow mechanism of dolomitization formation that did not preserve any limestone inclusion.

c. Saddle dolomite**:** this type of dolomite classified into two categories based on their characteristics: SD1 and SD2. Saddle dolomite is mainly found inside fracture, dissolved vugs, zebra, and cemented the clasts of breccia fragments. This dolomite characterized by curved faces and sweeping or wavey extinction under optical microscope (Figure 9 C-D). Few published works documented that these secondary dolomites and bitumen filling open spaces from the reservoir rocks originated from hydrothermal brine fluids that precipitated saddle dolomites (Davies and Smith, 2006). Two phases of saddle dolomites precipitated, SD1 is beige colour, coarse crystals, usually occupied a large fracture and vugs than SD2. SD2 is dissimilar to SD1 by having two set cleavage and similar in their sizes and have a grey colour giving a dirty colour to the crystal lattice (Figure 9 B-D).

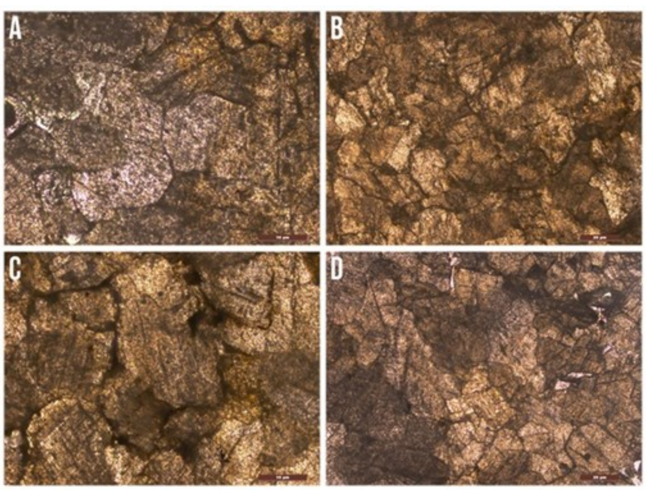

Figure 8. Photomicrographs of: (A) early and replacive dolomite crystals, close up of s-planar and sometimes planar “see the central part of the photo”. Q5. PL. (B) Replacive dolomite with different sizes of dolomite crystals. Q6. XPL. (C) Replacive dolomite, close up the tight arrangement of dolomite grains and hydrocarbon preservation between grain boundaries. Q6. XPL. (D) The dolomite crystals usually show a unit extinction under cross nicols. Q6. XPL.

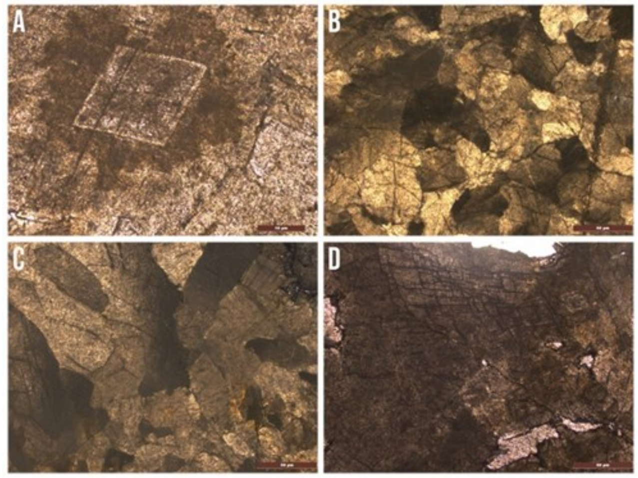

Figure 9. (A) The remanant of rhombohedral dolomite crystals inside the fracture filling saddle dolomite. Q5. XPL. (B) Fracture-filling saddle dolomite SD1. Q6. XPL. (C) Saddle dolomite SD1 inside fracture. Q12. XPL. (D) Dark brown saddle dolomite SD2, showing coarse crystals, curvature faces and sweeping extinction under cross nicols (XPL) with two sets of cleavages, see the upper most part. Q11. XPL.

B. Dissolution

The dissolution of the host limestone leads to the formation of typical secondary voids which is common in Qamchuqa Reservoir Carbonates. The dissolution is identified from field and under optical properties, characterized by geometrical voids, a few tens of microns to several millimeters to centimeters in size, sometimes evoke the typical shape of bioclast, the lager voids having often a rhomboedral periphery as does the dolomite crystal. Fine crystals of calcite crystals are observed on the walls of secondary voids. The dissolution voids are significant for interpretation and reconstruction of carbonate history and the understanding of carbonate diagenesis (Salih et al., 2020) since this secondary porosity is the only evidence for an earlier and later stages of dolomitization (Figure 10).

The identification of these voids may precisely help the reconstruction of initial and final geometry of dolomitic bodies (Purser and Aïssaoui, 1985). Distribution of dissolution features in carbonate of the Qamchuqa Formation is easily can be detectable by naked eyes, while the very fine dissolution can be detected at the microscopic or even at the ultramicroscopic scale. The process itself starts at a very early stage and could be finalize the scenario of diagenesis. Large-scale dissolution features in carbonates are known during sea-level low stands through the exposure of the marine carbonates to meteoric waters, this leading to the formation of karstic framework and cavities especially under prevalent humid tropical climatic conditions (Hopley, 2011). These macro- to mesoscale dissolution features are distributed at specific horizontal intervals in the ancient reef carbonates and are characterized by open voids, chalky facies, and so on. Nevertheless, the large-scale and the wide distribution of such dissolution is often seen in the host carbonates and dissolution of early fracturing (Figure 4). The dissolution was accompanied by a features like zebra and hydro-breccia, which could be in agreement with the observation of dolomite formation from Bekhme Formation (Salih et al., 2019a,b). The authors reported these features as a result hydrothermal flowing up through carbonates.

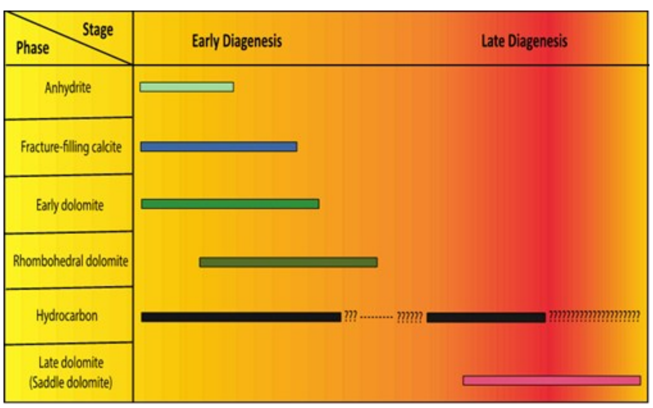

Figure 10. Diagram showing the early and late digenetic events during the syn-deposition and postdeposition of the Qamchuqa Reservoir Carbonates.

C. Fracturing

Diagenesis and fracture network development are complex and mutually dependent processes. Diagenesis significantly affects fracture network properties and contributes to the heterogeneity of the reservoir (e.g., Hood et al. 2003). Circulating hot fluids in the fractures is another source of diagenesis and can either increase or decrease the initial fracture and fracture network properties, which were generated by mechanical and associated hydrothermal fluids (Salih et al., 2020; Figure 11). These hot fluids are controlled fracture porosity and permeability, can increase by dissolution or decrease by the precipitation of cements. Hydrothermal fluids controlled by fault are commonly associated with dissolution, and the dissolution tends to be localized and often generates 'vuggy fractures' (e.g., Nelson 2001). Fractures represent a preferential pathway for diagenetic fluids, so the fracture network strongly controls the location, geometry and extent of diagenetic processes. Hence, open fractures contribute to changes in rock matrix properties as observed in this study. Fluids flowing along the fracture network can react with the host rock and change the petrophysical properties of the matrix Salih et al., 2020, which created different sizes and shapes of dolomite (Figure 11). These reactions can increase or decrease matrix properties by dissolution, replacement or cementation in the vicinity of the fractures (Figure 11). An example is hydrothermal dolomitization, where hot magnesium-enriched fluids are provided via the fault and fracture network (e.g., Davies & Smith 2006; Sharp et al. 2010). The hot fluids are evidenced by the mechanism of curved faces saddle dolomites formation. These fluids when invaded the Qamchuqa Formation make a major diagenetic change in the host rocks and invoke the alteration on petrophysical properties of the Qamchuqa Carbonatse properties, which control the development and characteristics of younger fractures. Consequently, the saddle dolomite, and in cases blocky calcite are precipitated in the Qamchuqa Formation (e.g., Kareem et al., 2021).

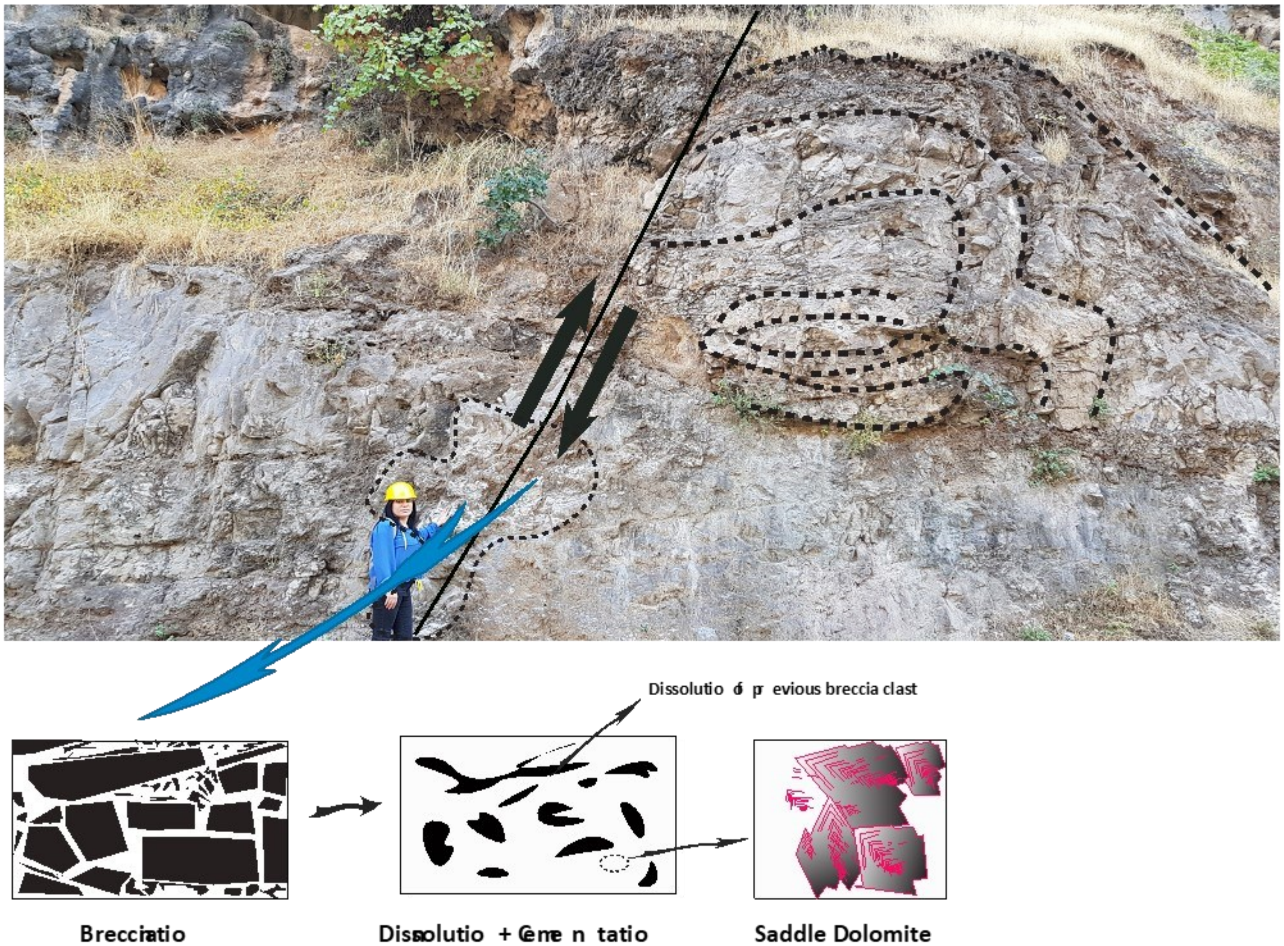

Figure 11. Model showing the mechanism of flowing up the hydrothermal fluid through the Qamchuqa Formation and sequence of late diagenetic events, especially in areas close to breccia texture. The diagram below the field photograph illustrating the mechanisms of diagenetic event that post-date the onset of early dolomitization “brecciation zone” which is influenced by sudden hydrostatic pressure and reset of hydrothermal fluid through these breccias which dissolved the previous brecciated angular clasts “fragments”. Both mechanisms of flowing up hot fluids were enhanced by tectonic activities: folding and faulting systems.

D. Breccias

Breccias form features with various geometries, consisting of mainly tabular parts, at a random angle with respect to bedding, a few centimeters to some meters wide, which can be followed vertically for up to some tens of meters (Figure 2). The breccia texture from Upper Cretaceous carbonate rocks represented by floating of angular fragments of matrix has reported that the timing of brecciation is consistent with saddle dolomite formation and fault activity. Breccias are important lithotype feature in the study of hydrothermal dolomitization, due to the precious information they provide about the dynamics and evolution of the hydrothermal system (Salih et al., 2020), although volumetrically they constitute a minor part of the dolomitized rocks. Breccias commonly consist of floated clasts which cemented by saddle dolomite, with a common subvertical or high-angle orientation with respect to the host-rock bedding.

In our case, the brecciated dolomite matrix is cemented by the saddle dolomites, which could be formed as a result of tectonic-hydrothermal brecciation related to a sudden, explosive pressure from the migrating fluids (e.g., Katz et al., 2006). The floated angular fragments giving evidence that the fracturing was contemporaneous with the hydrothermal fluids (cf. Salih et al., 2019b). However, the angular fragments are accompanied by sub-rounded fragments in the brecciated zone, this is the first case can be reported these two types of fragments together. The only scenario for this type of feature could be linked to reinflux hydrothermal fluids during mechanical movements “fault” and hydro-pressure fluids, where geometrically the rounded fragments are postdating the angular ones (Figure 11). Cement-supported textures “angular clasts’ are indicative of high fluid-flow rates and rapid precipitation; a similar case has been reported in the literature (Davies and Wendte, 2005; Lopez-Horgue et al., 2010), due to reaction of fault activity that simply open the barrier for fluid to flow in the direction of fracture and open-space system. The slow hydrothermal flux is dissolved the previous spaces “fractures” and etched the previous angular fragment to develop the rounded fragment in the brecciated zone (Figure 11).

E. Zebra-like texture

The zebra-like texture is the abundant feature in Qamchuqa Formation and is a typical of the Lower Cretaceous-aged sediments (Figure 12), arranged in horizontal and sub-vertical bands to the bedding planes, giving structures similar to the zebra-like texture. In macro-scale, the texture appears as an alternation of the grey bands of the dolomite matrix and the white bands of the saddle dolomites and are genetically related to the fracturing mechanism that occurred during the influx of the hydrothermal fluids (Kareem at al., 2021). These bands created the zebralike texture. The latter formed where the hot fluids intruded horizontally and in places obliquely to the layers of carbonate rocks (cf. Salih et al., 2020).

The dolomites from the study area that display ‘‘zebra-like texture’’, consisting of the rhythmic alternation of mm-scale sheets of dolomites (Figure 12). Geometrically, these textures concordant with the stratification, may show a thickness controlled by fine layering, replacive dolomite with traces remaining of host limestones (e.g., Fontbote´ and Amstutz, 1983). Other studies reported dolomitized limestone display zebra structures with a sub-horizontal orientation, which is independent from the dip direction of the fold limbs and clearly exclude a facies-control on the development of the zebra structures. our studied zebra texture is in accordance with Tompkins et al. (1994) that the stratification of the host rock is the main control of distribution of the zebra-like texture, and in part could be connected to the pre-existing fissure planes: the fissures represent a ‘‘weakened’’ part of the rock through which fluids could more easily circulate (Wallace et al., 1994).

Grey bands are commonly considered as an older, replacement dolomite, white bands, on the contrary, have been both considered as sheet-like cavities, opened in response to tectonic stress and cemented by hydrothermal saddle dolomite (Vandeginste et al., 2005) or as displacive saddle dolomite veins (Merino et al., 2006). In this study case, whatever the origin of zebra structures, the replacive dolomite features seem to have exerted a strong control on their development “stratification”.

Figure 12. Diagram showing alternating bands of early dolomitization “grey colour” and late saddle dolomite “white coloured band”. This type of texture is very resembled to texture like zebra which is considered as a common feature of hydrothermal dolomitization structure.

Isotopic mapping (O-C stable isotopes) The oxygen and carbon isotopic compositions of the studied carbonates are compiled in Table 1 & Figure 13. The Cretaceous δ^{18}OVPDB and δ^{13}CVPDB values of the primary marine carbonates, estimated by Gradstein et al. (2012) in addition to Veizer and Hoefs (1976) and Pearson et al. (2001), range respectively between +0.8‰ and – 4.0‰; +1.8‰ and +2.7‰.

Table 1. δ^{13}C (% VPDB), δ^{18}O (% VPDB) values of selected samples from Qamchuqa Formation (n = 23).

Sample No.	δ^{18}O **permil V-**	δ^{13}C **permil V-**
QmR. 3	1.49	-9.02
QmR. 4	1.50	-9.86
QmR. 4	2.32	-8.25
QmR. 4	1.87	-9.51
glaconite	1.44	-4.91
glaconite	1.52	-5.16
QmR. 2	1.45	-9.23
QmR. 1	1.28	-8.28
QmR. 1	1.42	-8.18
QmR. 2	0.90	-8.27
QmR. 2b	1.23	-8.57
QmR. 2b	1.39	-8.60
QmR. 5	1.57	-8.74
QmR. 5	1.60	-8.81
QmR. 5	1.45	-9.08
QmR. 5	1.47	-9.08
QmR. 6	1.10	-9.06
QmR. 6	1.34	-8.91
QmR. 6	1.69	-8.71
QmR. 6	1.53	-8.71
QmR. 7	1.64	-8.65
QmR. 7	-1.25	-4.77
QmR. 7	-2.03	-4.61

δ^{18}OVPDB and δ^{13}CVPDB isotopes in carbonate are among the most important data to define the evolution of the paleofluids. δ^{18}OVPDB isotopes are used to evaluate the oxygen isotopic composition of seawater recorded in the marine sediments and the alteration of this primary seawater signature by meteoric waters, sea-level fluctuation and/or temperature influences as well. The δ^{13}CVPDB affected by biological processes and can indicate the original source of primary producers. Fluids precipitated calcite and dolomite will show specific limit of oxygen values in order to determine their origin whether marine, brine, meteoric, or mixed waters (Moore,1989).

where the δ^{18}OVPDB and δ^{13}CVPDB values are grouped in three excursion: phase 1, phase 2 and phase 3. The phase 1 is represented the host limestone with rich foraminiferal facies, phase 2 is represented the argillaceous limestone, and phase 3 is represented diagenetic cements. δ^{18}OVPDB values in phases 1 and 2 are overlapped and heavier in their oxygen composition than phase 3, suggesting involvement of distinct types of fluids/waters during the deposition and after deposition of these facies components. While the carbon isotope composition shift from high carbon values in phase 1 to low carbon values in phase 2, then at the upper part of the studied section were represented by phase 3, the carbon again shifted to a heavier value, in some overlapping with phase 1.

The limestone rich foraminiferal "orbitolinid" facies still could be influenced by imprint of diagenetic processes, even if few, however, the δ^{18}OVPDB values in this phase (1) displays a lighter value compare for those expected for Early Cretaceous marine carbonates (Veizer et al., 1999). The blocky and drusy cements filled the benthic foram pore-spaces are possibly required the oxygen values in phase 1 to be lower than Lower Cretaceous isotopic signals (Figures 6,7,13), while the carbon isotope is still preserved the original marine carbonate signal (Weissert and Ebra, 2004).

A remarkable negative excursion of δ^{13}CVPDB in phase 2, which is directly overlaid the foraminiferal facies "phase 1" and display a light oxygen and carbon isotopes. The phase 2 is dominant by argillaceous limestone and shows an abrupt facies change (Fig.), while in the upper most part of the studied section "phase 3", the δ^{13}CVPDB values are gradually re-emergence to normal values as in phase 1. According to reference curve for Early Cretaceous time intervals, three major positive excursions are attributed to Late Albian, Albian/Cenomanian, Middle Cenomanian (Keller, 2008). The falling and rising of δ^{13}C most likely follow eustatic sea-level (Jarvis et al., 2006), the increased δ^{13}C is associated with transgression and increased δ^{13}C is associated with regression (Jarvis et al., 2006).

The first positive excursion of δ^{13}CVPDB values is recorded in lower part of the studied section “phase 1” and this part is blanked directly by light carbon values “phase 2”, consequently the phase 2 is followed again by positive excursion of δ^{13}C values “phase 3”. However, the oxygen values for the first time in phase 3 severely decrease throughout the upper most part of the studied section (-9.9‰). The variation trend of δ^{13}C values is similar to δ^{13}C values from western Alps (Weissert and Erba, 2004). This negative excursion of δ^{13}C values from marly limestone can be correlated with the negative excursions that corresponding to Barremian marl package and Late Albian deposits from SE France (Papp et al., 2013). This oscillation in δ^{13}C values is marking major warming condition during Barremian time and then followed by cooling period (Kuhnt et al., 2011). The decreasing of oxygen δ^{18}O values could be explained by a major warming during the Lower Cretaceous times (Papp et al., 2013), however, the hydrothermal fluids are also involved in filling the pore spaces of zebra-like texture by saddle dolomite rocks (Salih et al., 2019). The significant observed trend toward lower carbonateδ^{18}O values during the flux of hydrothermal fluids and formation of saddle dolomites at the studied area coincide with those observed by (Kareem et al., 2021) in the same formation.

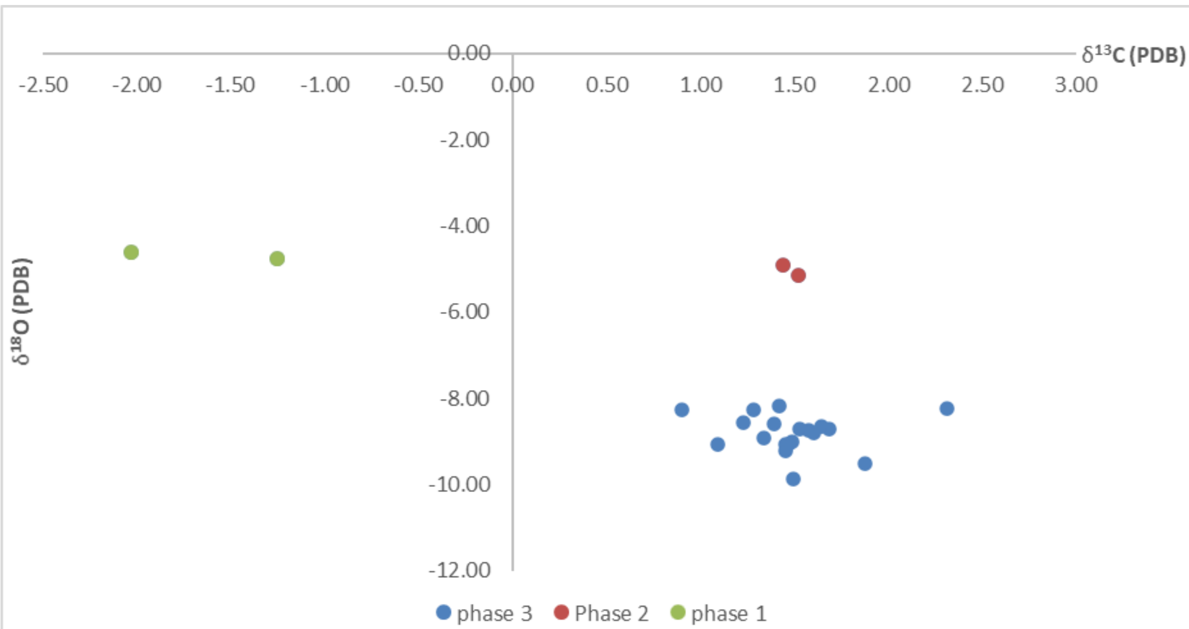

Figure 13. Oxygen versus carbon isotope composition of sedimentary rocks. The phase 1 is represented the host rocks, the phase 2 is represented the argillaceous limestone, and the phase 3 is post-depositional dolomites.

4. CONCLUSION

1. Samples from Barremeian-Albian in the northeast of Iraq-Zagros Basin were studied intensively in the field and under optical microscope and show three types of microfacies: lime mudstone microfacies, fossiliferous wackestone microfacies, and orbitolinid wackestone/packstone microfacies. Around 0.30m thick unit of argillaceous limestone is located in between the fossiliferous wackestone microfacies and the orbitolinid wackestone/packstone microfacies.
2. δ^{13}CVPDB fluctuation (Shifted from positive-phase 1 to negative excursions-phase 2) and abrupt facies changes are preserved within the lower part of the studied Qamchuqa Formation. The bulk-rock δ^{13}C values vary widely between 1.5 and -2.0‰ within the foraminiferal-rich carbonate rocks and argillaceous limestone, respectively. The positive excursion of δ^{13}C record is characterized by abundant and diversity of orbitolinid benthic foraminifera. The δ^{18}OVPDB values are relatively stays constant between these two differ-

ent facies, marking the short influence of these deposits by climate changes and eustatic sea-level.

3. Orbitolinids are associated with anhydrite mineral samples, which underlaid the argillaceous limestone bed. This bed is blanked and covered from top and bottom by mudstone. The argillaceous limestone in between fossiliferous wackestone microfacies and orbitolinid wackestone/packstone microfacies where the mudstone microfacies are repeated in the upper lower part of the argillaceous limestone as indicated in this work revealed to be deposited in a shallow marine carbonate that affected by a change in marine conditions: fluctuation in sea level during the depositional time.
4. Post-depositional alteration 'phase 3' on precursor limestone invokes three main types of dolomites:

- Replacive destructive and retentive dolomite crystals (Dr)
- Rhombohedral dolomite crystals (Drh)
- Saddle dolomites (SD1 and SD2)

5. Replacive/retentive and rhombohedral dolomites are usually precipitated as dolomite matrix, while saddle dolomites are developed and precipitated inside the geodes and fractures. Saddle dolomite crystals usually associated with replacive dolomite. In places rhombohedral dolomite crystals filled the vugs inside the groundmass and this suggest that the rhombohedral dolomite type is also could be precipitated as a cement.
6. The saddle dolomites under optical microscope show a typical characteristic of high temperature dolomitizing fluids: curved faces and sweeping extinction. Saddle dolomites are post-dated the replacive and rhombohedral dolomites in time, also well-developed inside the white bands of zebra structures and breccias, these dolomites always associated with hydrocarbon migration as they are easily recognized by naked ayes and under optical microscope.
7. The phase 3 is characterized by light oxygen isotope values (as low as -9.9‰) and carbon isotope values return to positive excursion (up to +2.3) in post-depositional dolomites. This consistent in oxygen-carbon variation suggesting an involvement of high temperature fluids during the alteration on the host carbonate.
8. The rhythmic zebra banding parallel-sub-vertical to bedding and cleavage planes is interpreted as reflecting preferential fracture development and that hydrothermal fluid injected along these planes. The zebra dolomites are thought to have developed by focused fluid flow, driven by tectonic stresses during Zagros Orogeny. Under these tectonic stresses, horizontal and sub-vertical displacements of zebra patterns and intra-crystal micro-fissures in the dolomite phases were formed.
9. For the first time, the study reports the remodified breccia texture and the geochemistry of the overlain and underlain the argillaceous limestone in the studied area. This type of texture characterized angular and rounded clasts together, and this prefer two mechanisms for the flowing up of repeated hydrothermal fluids in an area that tectonically active.

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