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Ghazaleh R., Kazimirov E.T.
Gubkin Russian State University of Oil and Gas (National Research University), Moscow, Russia, ghazalirama@gmail.com, egorcasual@yandex.ru

DOLOMITIZATION MECHANISMS OF THE MIDDLE TRIASSIC KURRACHINE DOLOMITE FORMATION, PALMYRIDES (SYRIA)

Comprehensive research of the properties and structure of productive Middle Triassic section of the Kurrachine Dolomite Formation in the Palmyra Rift Basin is currently of remarkable importance for the petroleum activity in Syria.

In this study, the main rock types, associated sedimentary environment and dolomitization mechanisms were identified. The void space distribution in the studied rocks basically depends on the sedimentation settings that control early diagenetic dolomitization processes. Within the sabkhas and lagoons, non-porous microcrystalline dolomites were formed by recrystallization of mud material. In shallow marine environments with an active hydrodynamic regime (peloid banks and microbial mounds), the distribution of primary voids generally preserved during pervasive early diagenetic dolomitization which led to the formation of extremely fine-to-fine and fine-to-medium crystalline dolomites. Tectonic cracks observed in the rocks were filled with saddle dolomite cement, which subsequently occluded their connectivity. Mineralization of fracture occurred by deep burial diagenesis due to transformations of clay minerals from the underlying Amanous Shale Formation source rocks, as a result of the development of Palmyra folding.

Accordingly, it is suggested that the main reservoirs of the Kurrachine Dolomite Formation are not predominantly confined to fracture zones, but rather to areas of intercrystalline porosity development of the dolomites in specific facies zones.

Keywords: *dolomitization, Kurrachine Dolomite Formation, Triassic, Palmyrides, Syria.*

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Introduction

Exploration activities in Palmyrides area began in the late 1970’s looking for oil at stratigraphic Cretaceous and Jurassic levels. In the early 1990’s Marathon Company made the fields gas discoveries in the Triassic Kurrachine Dolomite Formation. After that, numerous companies such as the Syrian Petroleum Company (SPC), INA-Naftaplin, PetroCanada, and others intensified the exploration program in Palmyrides to investigate, discover, develop, and evaluate oil and gas fields.

The Palmyrides is divided into two northern and southern tectonic domains by the approximately east–west oriented Jihar fault and overlying Al Daww depression [Searle, 1994].

The Palmyride fold-thrust belt is an intracontinental transpressive mountain belt and represents the most significant structural chain in central Syria [Chaimov et al., 1992; Barazangi et al., 1993; Brew et al., 2001]. It strikes N45°E from the Anti-Lebanon mountain chain and the Dead Sea fault system to the Euphrates Graben in the NE, beneath which it plunges. It is 400 km long and 100 km wide with a maximum elevation of 1300 m [Lučić, 2001].

The primary reservoir in Palmyrides is Kurrachine Dolomite Formation (Middle-Upper Triassic) bearing fractured carbonate, underlain by deep seawater clays of Amanous Shale Formation (Lower Triassic), and sealed by shallow-water salt-bearing sediments of Kurrachine Anhydrite Formation (Upper Triassic). Secondary reservoirs associate with the Markada (Carboniferous) and Amanous Sand (Permian) Formations, both clastic with stacked reservoirs [Lučić, 2001].

Kurrachine Dolomite contains more than 50% clean to argillaceous dolomite with fewer limestones and intercalated anhydrite halite/sylvite layers (400 m). The subdivision based on reservoir properties consists of 3 main zones from bottom to top: D2, D1 and C2 [Gazale, 2024; Gazale, Kazimirov, Postnikov, 2023]. This classification, provided by INA and the SPC, is currently used in Syria (Fig. 1).

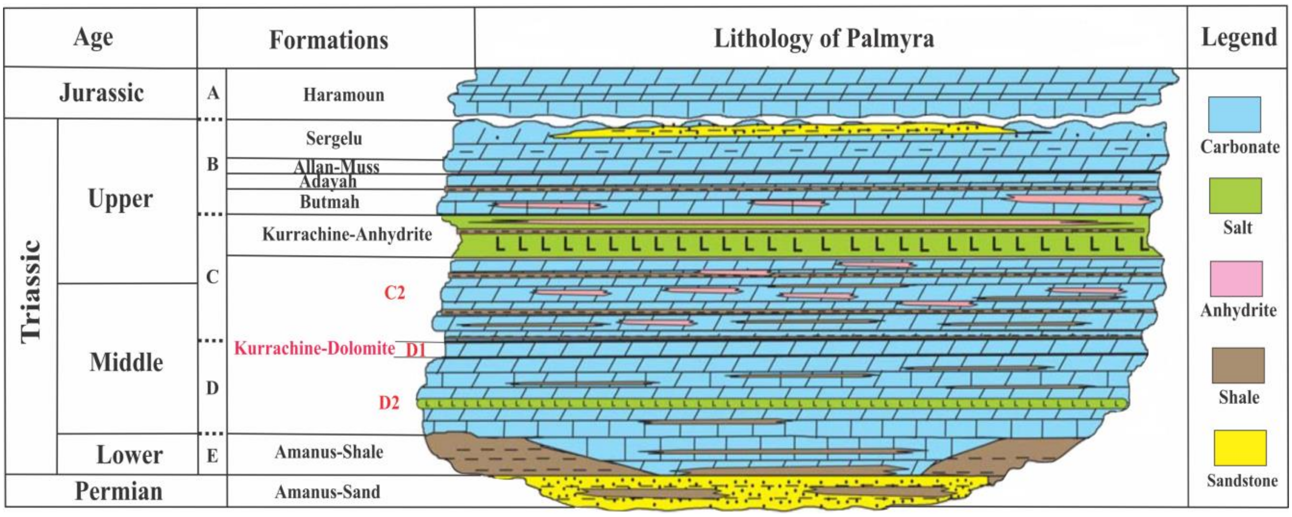

Fig. 1. Schematic lithostratigraphy of the Palmyra Basin formations (modified after [Lučić, 2010])

Methodology

The authors had collected the available data from the SPC's Exploration Department and the field directorate offices in Damascus for the wells drilled in the Northern Palmyra and Al Daww basins. Research was carried out in the laboratory of the Department of Lithology of the Gubkin Russian State University of Oil and Gas (National Research University) in Moscow as follows.

Seventy-five thin sections from core samples of the Kurrachine Dolomite Well Sd-2 (Core 1: 3,495.0-3,508,5 m; Core 2: 3,551-3,567 m; Core 3: 3,780-3,789 m) (Al Daww), and fifteen thin sections from Wells N.H-2 (Core 2: 2,172-2,180 m) and N.H-3 (Core 2: 2,130-2,137 m) (Northern Palmyra) were examined by optical microscopy (OM) and impregnated with blue epoxy to easily observe voids and micropores. Dolomite textures were determined using the Wright (1984) and Sibley and Gregg (1987) method (Fig. 2). The micropetrographic classification of dolomite crystal size was established using the Chatalov (2013) scheme: < 0.004 mm (cryptocrystalline), 0.004-0.032 mm (microcrystalline), 0.032–0.063 mm (extremely fine crystalline), 0.063-0.125 mm (very fine crystalline), 0.125-0.25 mm (fine crystalline), 0.25-0.5 mm (medium crystalline), 0.5-1 mm (coarse crystalline), and >1 mm (very coarse crystalline). These terminologies are important for a better understanding of the dolomitization process. Dolomitization mechanisms were interpreted according to the models of Land (1985) and Tucker and Wright (1990).

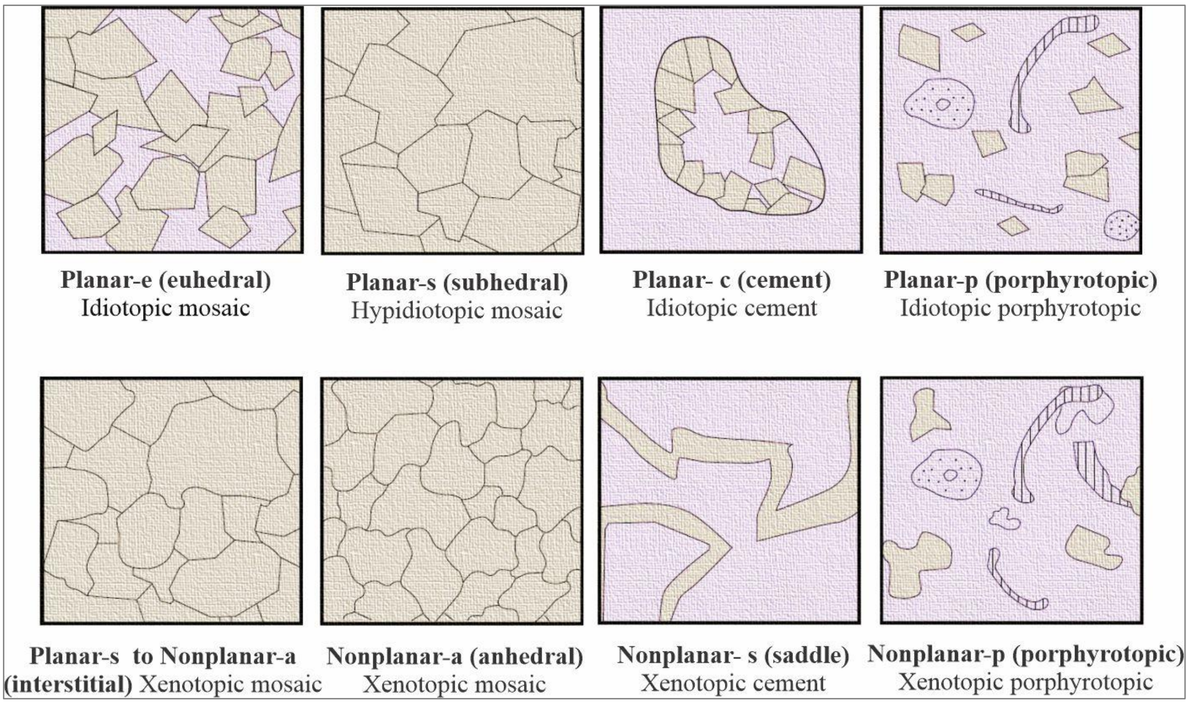

Fig. 2. Dolomite textural classification system, planar (rhombic) and nonplanar (nonrhombic) dolomite ([Wright, 1984; Sibley and Gregg, 1987], slightly modified)

Results

Dolomite textures

Microcrystalline, non-planar (anhedral) dolomite matrix (type 1)

This type of dolomites was found in two samples (Fig. 3).

The first sample (Fig. 3a, b) is basically represented by microcrystalline dolomite with a crystal size from 0.005 to 0.01 mm. The rock texture is indistinctly layered with intermittent wavy relicts of cryptocrystalline structure observed in individual layers. The layers are occasionally accentuated by microstylolitization areas and jagged-vertical stylolite seams, filled with brownish clay-organic material (kaolinite areas). This dolomite contains a few inclusions of organogenic detritus up to (1-3%), especially fragments of echinoderms, sea ourcin needles, and rare whole ostracod shells. In individual layers, there are attenuating wedge-shaped desiccation cracks, filled with large anhydrite crystals – 2.5 mm (3-4%) with rare inclusions of cubic-shaped pyrite – 0.3 mm (1%).

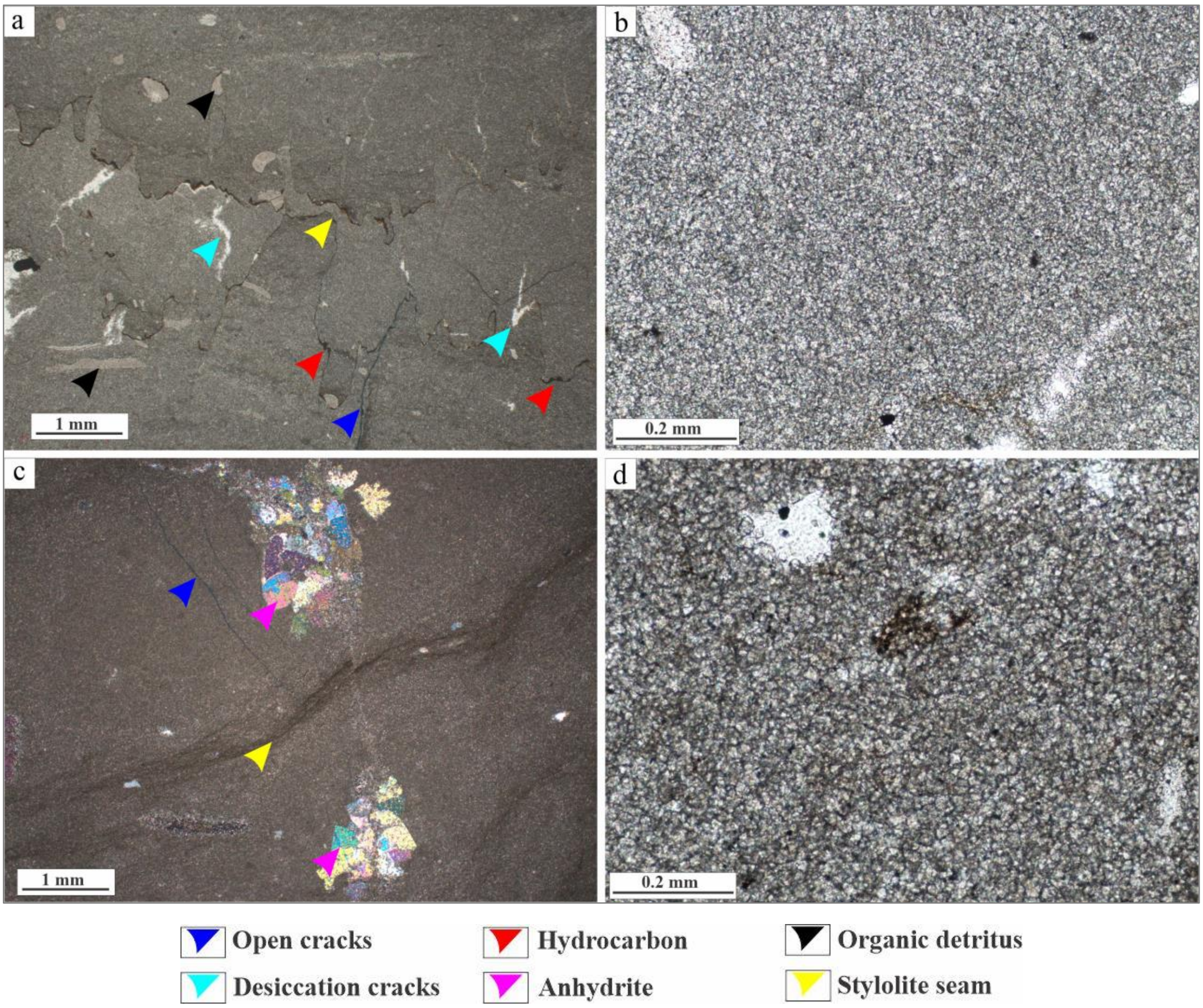

Fig. 3. Thin-section microphotographs of microcrystalline dolomite

(a) Microcrystalline slightly dolomitized limestone with rare organic detritus (ghosts of fine shell bioclastic fragments); (b) Magnified view of (a), N.H-3, C2, 2130.54 m; (c) Microcrystalline dolomites with nests of anhydrite; (d) Magnified view of (c), Sd-2, C2, 3500.85 m. a, b and d: PPL; c: XPL.

Rock crystals are predominantly closely packed; however, there are isolated layers with elliptical voids smaller than 0.03 to 0.2 mm (2-3%), not impregnated with painted epoxy and possibly mineralized with halite, whereas the isolated ones are mineralized with anhydrite. Some scattered inclusions of pyrite (1%) – 0.01-0.03 mm are observed.

The second sample (Fig. 3c, d) is basically represented by microcrystalline dolomite with a size of 0.01 to 0.02 mm. The texture is nodular, emphasized by subparallel wavy areas of microstylolitization. The nodules are massive and the microstylolitization areas have scarce intercrystalline microporosity (2-5%) filled with organic matter.

This sample has scattered nests of anhydrite (occasionally stellate, rarely tabular) with crystal size from 0.2 to 2 mm of acicular idiomorphic and hypidiomorphic habitus. Anhydrite crystals often contain scattered inclusions of rhombohedral dolomite microcrystals – 0.02 mm. Some anhydrite nests are connected by intermittent subvertical cracks, completely filled with anhydrite and microcrystalline dolomite.

Open attenuating thin cracks are observed. They are 0.015 mm wide, and presumably have technogenic origin (Fig. 3c).

Extremely fine to fine crystalline, non-planar to planar (anhedral to subhedral) dolomite matrix (type 2)

The sample (Fig. 4) has a spotted texture due to the uneven distribution of areas of different structure. The areas of the first type have dolomite crystals of 0.05-0.15 mm, and are distinguished by the presence of shadow relicts, possibly due to the recrystallization of pelitomorphic microbial-algal limestone, forming columnar spots. The areas of the second type have dolomite crystals of 0.03-0.25 mm. They are characterized by the absence of shadow relicts and the presence of a few inclusions of recrystallized detritus up to 0.8 mm in size, apparently due to the recrystallization of limestone of the packstone type. In both cases, dolomite crystals are subhedral and have a pelitomorphic admixture of calcite.

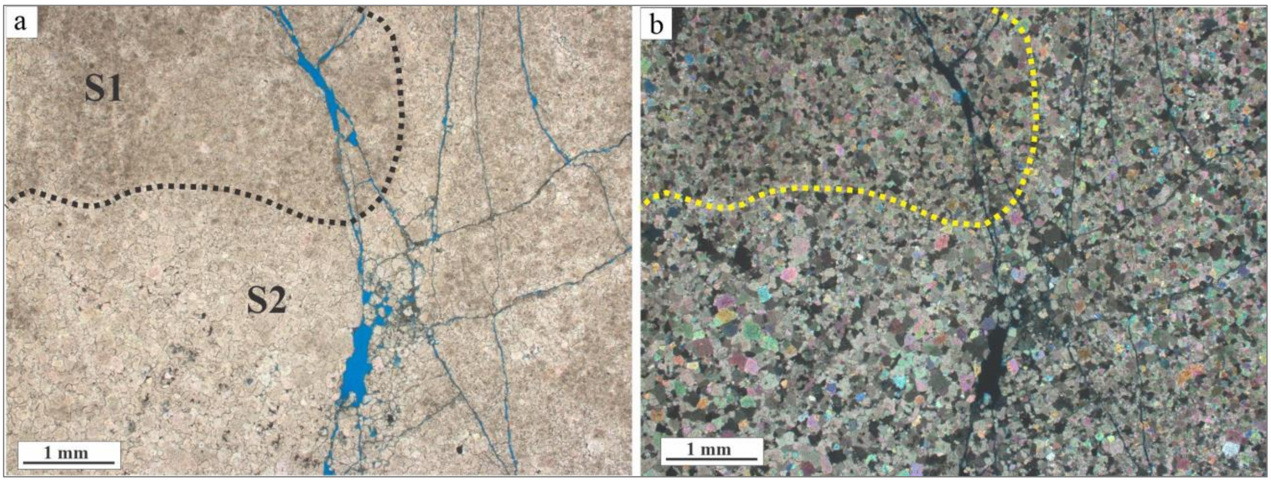

Fig. 4. Microphotographs of extremely fine to fine crystalline dolomite
(a, b) Mottled dolomite texture: relicts (remains) of recrystallized algal-microbial forms (dark, S1) and packstone (light, S2), the sample is penetrated by a network of dense random fractures, N.H-2, D1, 2172.94 m. a: PPL; b: XPL.

The rock contains multiple branching, intersecting open cracks, predominantly of subhorizontal and subvertical inclined orientation, with an opening from the hairline to 0.25 mm (due to leaching), probably of tectonic origin.

Fine to medium crystalline, non-planar to planar (anhedral to euhedral) dolomite matrix (type 3)

This type of dolomites was found in two samples (Fig. 5).

The first sample (Fig. 5a, b) is replacive dolomite with a massive texture composed of fine to medium dolomite crystals – 0.05-0.4 mm with predominantly fine crystals – 0.125-0.2 mm in section.

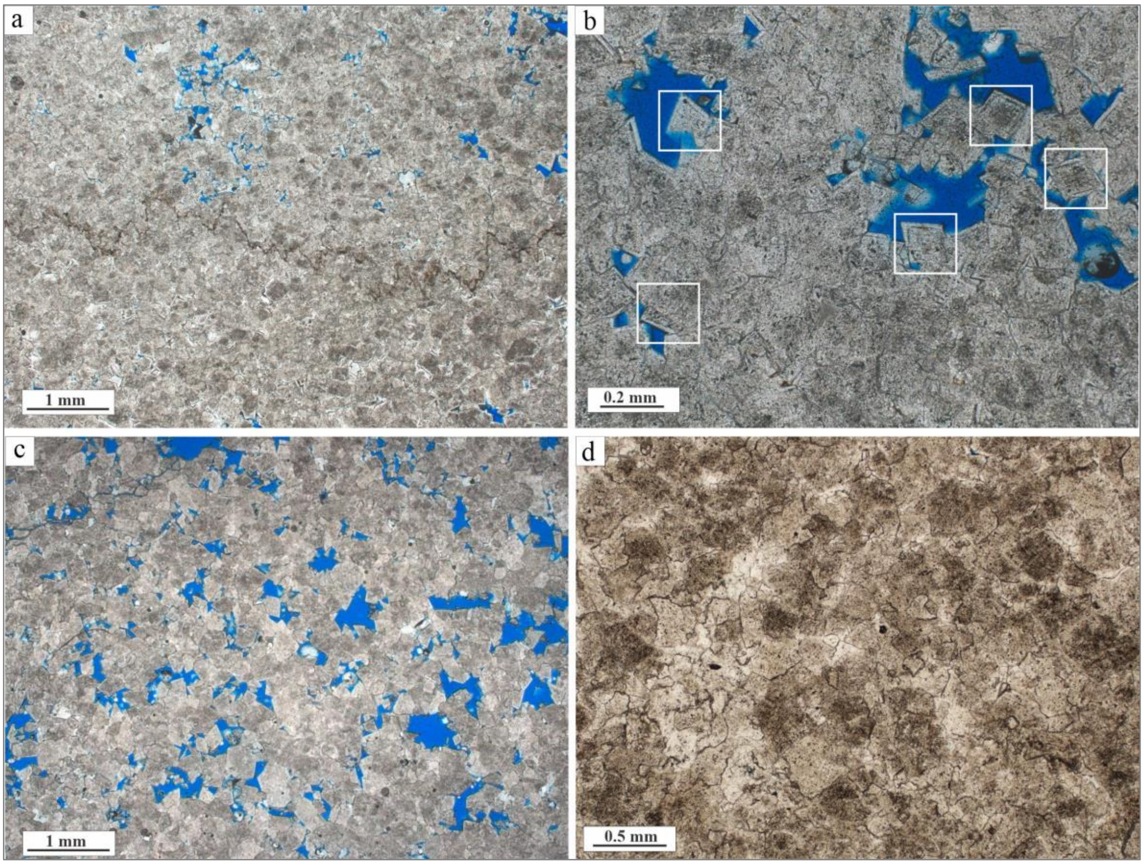

Fig. 5 Thin-section microphotographs of fine to medium crystalline dolomite
(a) Minor porosity (blue) in fine to medium crystalline replacement dolomite, N.H-2, D1, 2179.58 m; (b) Enlarged image of (a) displaying euhedral rhombohedral crystallites with white overgrow edges (in white squares) close to porous space (blue); (c) A porous area of dolomite that presumably replaced peloidal grainstone, N.H-2, D1, 2174.34 m. (d) A dense area of dolomite that presumably replaced algal-microbial limestone, N.H-2, D1, 2174.34 m. All microphotographs were captured in PPL.

Crystals are anhedral but in areas with residual intercrystalline voids they are subhedral with white overgrowth edges.

A serrated stylolite impregnated with dark organic matter, isolated fragments of quartz, and independent inclusions of pyrite is observed.

The rock has low porosity (up to 2-5%). The pores have irregular, round, and slit-like shape. The distribution of void space is extremely unequal. Dolomite is likely to have replaced microbial mud limestone (a few fenestrae microbial mat).

The second sample (Fig. 5c, d) is spotted texture dolomite composed of crystals – 0.1-0.6 mm with predominantly crystals – 0.22-0.36 mm.

The texture of the rock depends on the uneven development of dense and porous areas. In dense areas – anhedral dolomite crystals predominate, in porous areas – subhedral to euhedral with the development of white edges. Most crystals have shadow relicts with an admixture of calcite.

In porous areas, intercrystalline voids and caverns (up to 1.5 mm, on average 0.15-0.35 mm) are present, amounting to 8-12% and unevenly distributed. Occasionally, subhorizontal open cracks (from hairline to 0.25 mm) are observed, connecting individual void systems with each other.

The dolomites are presumably replaced areas of algal-microbial limestones (dense areas) (Fig. 5c) and peloidal grainstones (porous areas) (Fig. 5d).

Coarse to very coarse crystalline, non-planar (anhedral) saddle dolomite cement (type 4)

Saddle (baroque) dolomite (Fig. 6a) is characterized by predominance of coarse crystals > 1-2 mm in size, with undeveloped nonrhombic shape, curved crystal faces, and sweeping undulatory extinction in cross-polarized light with nonplanar xenotopic texture. It occurs in tectonic fractures that cross the host-rock matrix (in sample Fig. 6a, the crystals of the microcrystalline host matrix are of 0.01-0.03 mm in size).

The mineralization of the cracks apparently occurred in three stages (Fig. 6): mineralization of the walls by saddle dolomite (first stage), then by coarse-crystalline calcite (second stage) and, in the residual voids – by anhydrite (third stage). Hydrocarbon spots are occasionally observed in the residual isolated voids (Fig. 6b).

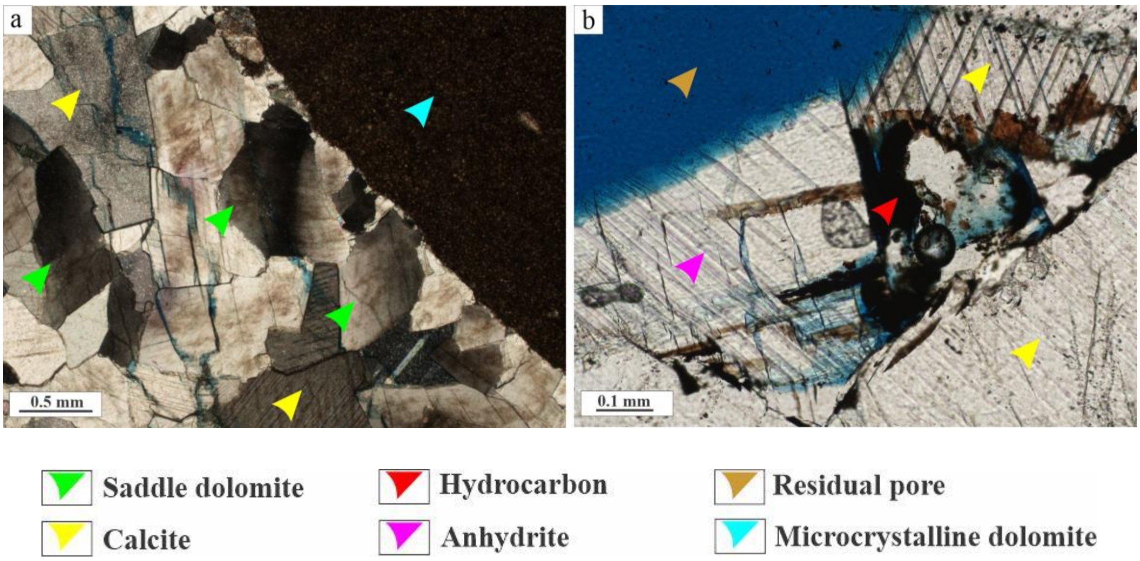

Fig. 6. Microphotographs of fracture mineralization

(a) Mineralization of crack in microcrystalline dolomite host matrix (yellow arrow): coarse and very coarse saddle dolomite (first stage) and calcite (second stage) crystals in host microcrystalline dolomite; (b) Isolated residual void in fracture partly filled with anhydrite (third stage), calcite and with some black-brownish hydrocarbon spots, Sd-2, C2, 3497.89 m. a: XPL, b: PPL.

Interpretation

Dolomitization mechanisms

Sabkha-evaporation mechanism

Type 1 dolomite (formed in the sabkha facies) (Fig. 3a, b) can be traced back to the sabkha evaporation model (Fig. 7a).

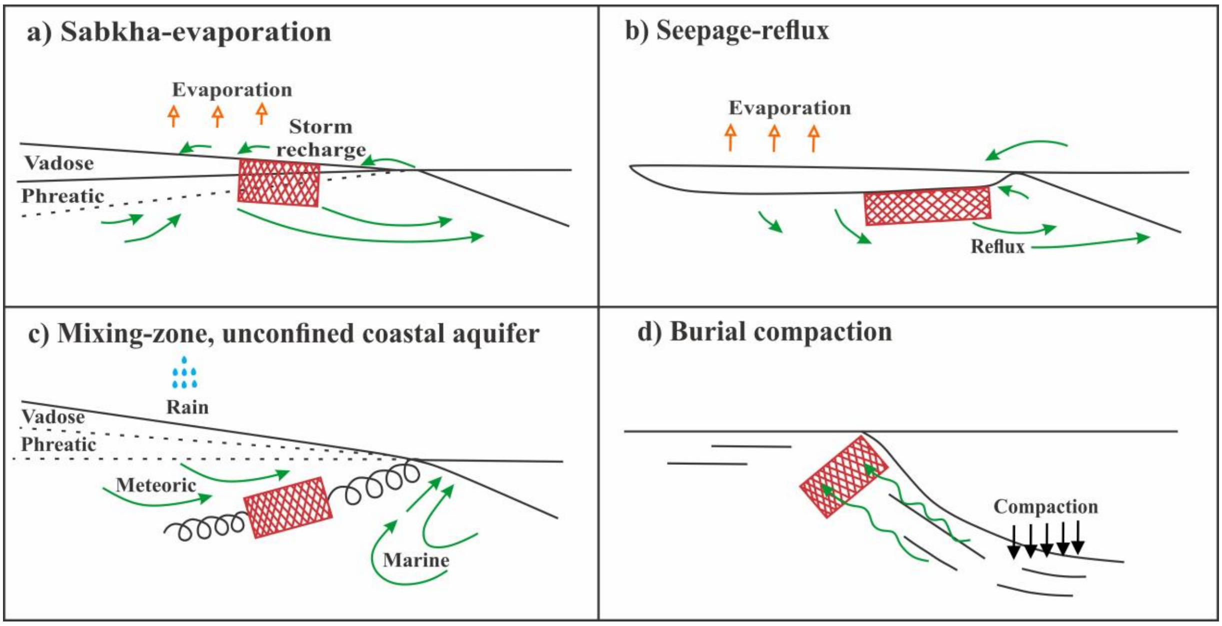

Fig. 7. Models of dolomitization mechanisms for the studied formation
(After [Land, 1985; Tucker and Wright, 1990])
Red - dolomitization area.

It could be formed by synsedimentary dolomitization under conditions of hypersaline water and intense surface evaporation [Patterson, Kinsman, 1982] according to the following two models:

1. Seawater-flooding model [Kinsman, 1969; Patterson, Kinsman, 1982]: when rainfall, storm and flash flooding occur, the seawater flows inland and recharges the aquifer underlying the sabkha. This model has been criticized because the density of sabkha water is higher than that of seawater and thus will settle under the water and not mix.

2. Evaporative-pumping model [McKenzie, Hsu and Schneider, 1980; Müller, McKenzie and Mueller, 1990]: under arid conditions, high temperatures cause a strong evaporation process of water to occur from the capillary fringe to the surface. This evaporation leads to the accumulation of salts, which over time form sabkha sequences.

The water lost by evaporation is compensated by the lateral flow of both seawater and groundwater with continental solutes to the aquifer below the sabkha surface. Here, carbonates are abundantly supplied with Mg^{+2} required for dolomitization through the vertical hydrological gradient, which contrasts with the natural horizontal hydrological gradient [Saeed, 2020]. Therefore, this model is also not suitable for the sabkha system as it is hydraulically unbalanced.

Similarly, for the sabkhas near the Abu Dhabi Emirate, the lateral facies belts within the sabkhas were interpreted to be a result of storm washover of marine flood water and/or evaporative pumping of marine groundwater [Kendall, Alsharhan, Whittle, 2020].

Notably, “Sabkha” is an Arabic term (سبخة), as numerous studies have confirmed, especially with regard to the Arab region, that microcrystalline dolomite belongs to sabkhas [Baniak, 2014; Kendall, Alsharhan, Whittle, 2020].

Although sequences of this type confirm deposition in the sabkha, this is not limited to the sabkha environment only, but rather indicates shallow, hypersaline lakes or salt ponds adjacent to the sabkha [Warren and Kendall, 1985], depending on several factors that affect the sedimentation mechanism, including the microcrystalline size, the morphology of anhydrite, and its presence in a wide range with dolomite.

According to Sibley [Sibely, 1982], this dolomite is produced primarily from the dolomitization of limestone mud in which small-sized dolomites are replaced by aragonite needles [Murray, Lucia, 1967] depending on many factors: suitable mineral composition of aragonite ($CaCO_3$), high dissolution of primary material (lime mud), availability sufficient space for ion exchange processes, abundance of organic matter within limestone mud, and existence of clay relatively rich in magnesium required for dolomitization [Purser, 1973].

The discovery of stratified rock stromatolite structures formed by cyanobacteria communities according to a recent study [Gazale, Kazimirov, Postnikov, 2023], explained their formation under hypersaline water conditions based on petrographic evidence such as microsized crystals and lamination. Thus, it confirms supratidal evaporate facies. This expands our understanding of the chemical composition of water in the Mid-Triassic.

Seepage-reflux mechanism

Type 1 dolomite (developed in lagoon facies near the shoreline) (Fig. 3c, d) is associated with seepage-reflux (Fig. 7b).

It is attributed to the early dolomitization or neomorphism of a penecontemporaneous or early replacement of the precursor peritidal calcite [Amthor and Friedman, 1992]. It reflects continuous chemical precipitation from seawater and Mg-enriched pore water (connate water) at low temperature, high salinity, shallow depth, and limited contact with open seawater [Land, 1985]. This assumption is supported by the presence of micro crystals of dolomite with a xenotopic mosaic texture and lack of fossils.

It is suggested that this dolomite was formed by a process of reflow and mixing of lagoon water and seawater [Purser, 1973]. For example, the study on Lake Pekelneer in the Netherlands [Deffeyes, Lucia, Weyl, 1965] where this lake is separated from the sea by a barrier coral reef and some dolomite on the edges of the lake. The presence of this dolomite may be due to the sea feeding the lake with Mg^{+2} rich water by leaching across the barrier [Land, 1985]. This led to an increase in Mg^{+2} and subsurface dolomitization. Thus, Mg-rich fluid resulting from evaporation of lagoon water or tidal flat pore water is the key factor in this mechanism because of leaching and seeping into subsurface carbonates.

The most effective evaporation occurs at the shoreline where sediments are directly in contact with air; this allows interpretation of dolomitization in relation to the ancient shoreline (buoyancy surface).

The reflux fluid source being the near-shoreline mesohaline lagoon instead of the far-shoreline hypersaline evaporative lagoon [Melim, 1991].

Types 2 and 3 were formed close to the lagoon facies on shoreline or backslope, in which case the dolomitization processes can be attributed to both the reflux and mixing models.

Mixing-zone, unconfined coastal aquifer mechanism

The mixing zone dolomitization (Fig. 7c) is mostly related to Dolomites of Types 2 and 3.

In this model, a mixture of marine water and subsurface meteoric water occurs [Badiozamani, 1973] within the vadose zone, forming a solution supersaturated with Mg and undersaturated with Ca [Adabi, 2011].

According to Magaritz and Peryt [Magaritz, Peryt, 1994], the easiest way to obtain dolomite is by mixing highly saline solutions with meteoric waters such as rainwater and hurricanes, or by reducing the salinity of seawater.

In types 2-3, crystals grow slowly as a result of precipitation of solutions saturated with high dolomitizing fluids Mg/Ca at critical temperature (below 60°C) [Mazzullo, 1992; Adabi, 2009]. Consequently, this may be explained as a product of diagenetic replacement of granomorphic limestone or recrystallization of very early dolomite.

We attribute these dolomites to a system of shoreline (and backslopes) as in the Bahamas, the Arabian Gulf, and Florida because of the presence of many accumulated porous granomorphic materials with some algal-microbial bioherms in the studied rocks.

Deep burial dolomitization

Saddle dolomite crystals (Type 4, Fig. 6) filling the space of large, subvertical, or inclined cracks could have formed in the deep burial diagenetic realm (similar to burial compaction mechanism in Fig. 7d.

The fracturing of the Kurrachine Dolomite Formation is due to tectonic activities during the formation of the Palmyride fold-thrust belt from the end of the Cretaceous to the Neogene [Brew et al., 2001]. This probably led to migration of hot fluids saturated with Mg^{2+} along the fractures that were mineralized by saddle dolomite.

For example, the diagenetic conversion of smectite-to-illite (illitization) [Boles, Franks, 1979]: smectite + K+ → illite + cations (Na^+, Ca^{2+}, Mg^{2+}, Fe^{2+}) + $Si(OH)_4$, while CO_3^{2-} ions are released due to diagenetic processes in organic-rich basal shale rocks. This conversion also occurs as a result of the thermal history of the basins, chemistry of the pore fluids, mineralogical composition of the mudrock, etc. The transformation of clay minerals occurs under conditions of increasing burial depth or tectonic pressure and temperature between 50-100°C [Eren, 2000].

Most likely, a major source of Mg^{2+} was the Amanous Shale Formation underlying the Kurrachine Dolomite Formation. This formation represents a period of regional marine transgression at the end of the Permian. It is a complex alternating sequence of calcareous shales, thin limestones, and sandstones, deposited in a shallow shelf environment. In analogy to the Amanous Sandstone Formation (see Fig. 1), it is postulated that the basin was partly fault-controlled, which led to the accumulation of significant amounts of kerogenous organic matter in isolated stagnant subbasins. Consequently, the Amanous Shale Formation is inferred to be one of the main sources of hydrocarbons in the Palmyrides [Brew et al., 2001].

On the other hand, saddle dolomite can be formed under hydrothermal conditions associated with the influence of Mg-enriched hydrothermal fluids [Davies, Smith, 2006].

Conclusion

Based on the conducted research, the following conclusions can be drawn:

The lithologies of the Kurrachine Dolomite Formation observed during the petrographic examination are microcrystalline nonplanar anhedral dolomite matrix (type 1), extremely fine to fine crystalline anhedral to subhedral dolomite matrix (type 2), fine to medium crystalline anhedral to euhedral dolomite matrix (type 3), and coarse to very coarse crystalline saddle dolomite cement (type 4).

Dolomitization models in the studied rocks are mainly confined to paleogeographic sedimentation settings, associated early diagenetic processes (types 1-3). Type 1 dolomite was formed by sabkha evaporation and seepage-reflux mechanisms, types 2 and 3 by seepage-reflux and mixing zone. Subsequent tectonic processes that cause deep burial diagenesis (type 4).

Pervasive replacement dolomitization through early diagenetic processes overwhelmingly preserves the distribution of primary voids, and consequently, dolomite reservoirs are predominantly spread in zone D1 of Kurrachine Dolomite Formation, where porous peloid banks and microbial algal build-up have accumulated.

The Amanous Shale Formation underlying the Kurrachine Dolomite Formation was the key source of Mg^{2+}-rich fluids to fill the saddle dolomite in fractures due to tectonic compression of the Palmyra Basin during the Cenozoic.

Mineralization of fractures negatively affects their connectivity. Therefore, despite the parallel migration of hydrocarbons from the Amanous Shale to the Kurrachine Dolomite Formation, not all fracture development zones should be considered as permeable; however, containing isolated hydrocarbons. Hence, the main oil and gas reservoirs of the Kurrachine Dolomite Formation are concentrated in the D1 zone, where unevenly fractured porous-cavernous reservoir rocks have formed. Nevertheless, there may be newer fracturing zones in which mineralization is less intense or absent, depending on changes in the composition of migrating fluids.

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Газале Р., Казимиров Е.Т.
Российский государственный университет нефти и газа (национальный исследовательский университет) им. И.М. Губкина, Москва, Россия, ghazalirama@gmail.com, egorcasual@yandex.ru

МЕХАНИЗМЫ ДОЛОМИТИЗАЦИИ СРЕДНЕТРИАСОВОЙ ФОРМАЦИИ КУРРАЧАЙН ДОЛОМИТ, ПАЛЬМИРИДЫ (СИРИЯ)

Детализация представлений о свойствах и строении продуктивных среднетриасовых отложений формации Куррачайн Доломит Пальмирского рифтогенного бассейна в настоящее время приобретает особую важность для нефтегазоносного комплекса Сирии.

Рассмотрены основные литотипы формации, для которых установлены фациальная принадлежность и механизмы доломитизации. Показано, что распределение пустотного пространства в породах напрямую зависит от обстановок осадконакопления, определяющих процессы раннедиагенетической доломитизации. В обстановках с преобладанием накопления сгусткового материала (себхи и лагуны) сформировались микрокристаллические доломиты, пористость в которых практически отсутствует. В мелководных морских обстановках с активным гидродинамическим режимом (пелоидные банки и микробиальные холмы) распределение первичной пористости часто сохраняется при полной доломитизации с формированием тонко-мелкозернистых и мелко-среднезернистых доломитов. Тектонические трещины, наблюдаемые в породах, часто минерализованы седловидным доломитовым цементом, ограничивающим их связность. Его формирование, по-видимому, происходило в условиях катагенеза за счет преобразования глинистых минералов из подстилающих нефтегазоматеринских пород формации Аманус Шейл вследствие развития Пальмирской складчатости.

На основании этого, высказано предположение, что основные породы-коллекторы формации Куррачайн Доломит приурочены не столько к зонам развития трещиноватости, сколько к участкам развития межкристаллической пористости доломитов определенных фациальных зон.

Ключевые слова: *доломитизация, формация Куррачайн Доломит, триас, Пальмириды, Сирия.*

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