



Original Paper

Dolomitization of the lower cretaceous carbonate reservoir in the Euphrates Graben, Syria

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ABSTRACT

Results of this study are based on core materials description, thin sections, Cathodoluminescence (CL), and Scanning Electron Microscope (SEM) examinations. The Lower Cretaceous over the Euphrates Graben area was characterized by carbonate sedimentation in shallow marine environments. The low energy lagoonal to inner shelf sediments of the Judea Formation includes micritic mudstone to wackestone texture, dolomitic limestones and dolostones. Two types of dolomites recognized in the carbonates of the Judea Formation, the preserving microcrystalline dolomites which commonly founded in the partially dolomitized micritic limestones, and the destructive coarsely crystalline dolomites which commonly founded in the dolostones and dolomitic limestones. Petrographic examinations indicate that the preserving microcrystalline dolomites represent subtidal cycles developed in a shoal to open marine depositional environments, they probably formed under conditions of the shallow burial diagenesis. The destructive coarsely crystalline dolomites may develop in more basinward, open marine environments under conditions of the deep burial diagenesis that accompanied by rising in temperature, pressure, and burial depth. It is believed that evolution of the diagenetic history of the Judean Formation sediments occurred in two diagenetic stages; the shallow burial diagenesis, and the deep burial diagenesis. Compaction processes, early fracturing, micritization, early calcite, and the early phase of dolomitization were part of the multiple diagenetic alterations during the shallow burial diagenesis. The deep burial diagenesis was marked by dissolution, late stage of dolomitization and replacement, mechanical and chemical compaction, and the late calcite precipitation. It is believed that dolomitization of the Judea Formation carbonates in the Euphrates Graben has contributed to improving the reservoir properties by increasing the porosity and thus the permeability.

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1. Introduction

From the geological and sedimentary point of view, dolomites and/or dolomitic rocks are very important as potential hydrocarbon reservoirs (Rong et al., 2012; Li et al., 2015), this what made them attract the interest of many researchers around the world, especially in the matters that are related to their origins, mechanism, and environments of deposition (Vandeginste et al., 2013; Jacquemyn et al., 2014).

Dolomitization processes of the carbonate rocks usually occur shortly after their deposition, additionally, they are developing during the different burial diagenesis stages. Dolomitization

processes lead in general to partial or complete destruction of the original dispositional texture of the host limestone rocks (Melim and Scholle, 2002). The sources of the Mg-rich, dolomitizing fluids include marine, evaporative seepage reflux, hydrothermal, and dissolution of the local limestone (Antao 2004).

Dolomite reservoirs usually have values of porosities higher than in the limestone (Sun, 1995). Additionally, dolomitization process itself is believed to alter the petrophysical properties (the porosity and permeability) of the host limestone rocks (Machel, 2004).

Quality of the dolostones reservoirs is mainly related to types and sizes of the resulting dolomite crystals, this is in addition to ratios of the cement and their distribution between the dolomite crystals (Mazzullo, 2000). Over the stratigraphical section of the Euphrates Graben, dolomitization process mainly affected the carbonate sediments of the Triassic Kurrachine Dolomite Formation,

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and the Lower Cretaceous Judea Formation (Kinga and Gizella, 2007; Ibrahim et al., 2020).

In the case of the Judea Formation, which is considered as an important reservoir has been detected recently during expansion of the hydrocarbon exploration over the graben area, dolomitization of the carbonate sediments occurs slightly in the upper part of the formation “the Carbonate Zone” and extensively in the lower part of the formation “the Dolomite Zone” and leads to generate a prospective dolostone and dolomitic limestones reservoir rocks in many fields over the Euphrates Graben.

The available information about dolomitization processes and mechanism of the carbonate rock of the Judean Formation over the Euphrates Graben fields are relatively scarce so far. From this standpoint, the integrated petrographic investigations in this study may allow an understanding of the dolomitization process of the studied formation rocks and how contributed to the development of the petrophysical properties (Wendte, 2006; Kinga and Gizella, 2007).

One of the most effective methods to investigate and ensure the dolomitization process of the carbonate rocks are the geochemistry analyzes. Unfortunately, we were unable to use the geochemistry data in this article due to the confidentiality issue by the host company. This paper focuses on dolomitization process of the carbonate rocks and aims to investigate and describe the dolomitic limestones and dolostones lithofacies that encountered in the Lower Cretaceous Judea Formation over the studied field in the Euphrates Graben area. Petrographic investigations were used to (1) detailed description of the petrography features of the encountered limestones, dolomitic limestones, and dolomites, (2) characterize dolomitization processes of the host limestones rocks and (3) summarize the diagenetic events that influenced sediments of the Judea Formation and (4) evaluation the impact of dolomitization process on improving the quality of the resulting dolomitic limestones and dolostones reservoir intervals.

2. Geological settings

Syrian lands occupy a part of the northern slope of the Arabian plate (Brew et al., 2001). They are located near the collision border between the Eurasian and Arabian plates (Fig. 1a).

This collision manifests itself by Zagros fault which has a northwestern extension passing through eastern Iraq and western Iran (Litak et al., 1998). Tectonic blocks in Syria, which recorded uplifts and subsidence, include Palmyrides fold zone, Euphrates Graben, Rutbah and Sinjar-Abd Elaziz uplifts (Fig. 1b). The studied area lies in Euphrates Graben in the eastern part of Syria (Fig. 1b). The Euphrates Graben is one of the most important geological units in Syria, additionally, it is one of the most important sedimentary basins rich in oil and gas over the eastern part of the Syrian territory (Yousef et al., 2016).

The Euphrates Graben system is a rift basin with 160 km long elongated in the northwest to southeast. It is developed over most of the eastern part of Syria as illustrated in Fig. 1b. Euphrates Graben system is characterized by an intricate pattern of interlocking faults. Regional information and references about Syria (Litak et al., 1997; Yousef et al., 2016) indicated that the Euphrates Graben system formed during the Middle to Late Cretaceous time. Most of the normal and reverse faults over the graben area were developed during the Cretaceous time. Structural inheritance through the re-activation of the pre-existing basement anisotropies contributes largely to the complex structural architecture of the Euphrates Graben. In the Euphrates Graben, more than 45 hydrocarbon fields (Yousef and Morozov, 2017). Many oil and gas reservoirs were discovered in the stratigraphic section of the Euphrates Graben that extending from the Paleozoic to the Neogene. All those

reservoirs are of a high degree of importance. Generally, the Paleozoic, Cretaceous, and the Triassic reservoirs are among the most important reservoirs due to their high potential of hydrocarbons (Brew et al., 2001).

3. Samples and methodology

Results of this study are based mainly on 350 m of core materials analyses from seven wells of the Judea Formation, and wireline logs data from 37 wells (Fig. 2). More than 300 thin sections from the different lithofacies of the Judea Formation were prepared and investigated using a polarizing microscope to distinguish the different components of the carbonate lithofacies of the studied formation, additionally, to investigate and identified the different diagenetic features of the formation sediments, and distinguish the different porosity types and their evaluations.

In order to study and understand developing of the replacement dolomites and precipitated calcite, many of the thin sections were investigated using a Cathodoluminescence (CL) microscope. Additionally, many selected samples were examined using the technique of the Scanning Electron Microscope (SEM).

Petrophysical measurements were imported from the host company. Porosities of the different samples were measured from the core plugs using a Helium Porosimeter, the horizontal permeability was measured using a Gas Permeameter. The application of the Rock Physics Model (Anifowose 2016) was used to calculate the vertical distribution of the dolomite or the vertical dolomite content within the Judea Formation sediments section, this was based mainly on PEF (photoelectric factor in barns per electron) and GR logs for the S-15 well (Fig. 3b). This taking into account that the main components of the Judea Formation sediments are calcite and dolomite based on well logs interpretations as shown in Fig. 3b.

4. Results

4.1. Sedimentary evaluation of the Judea Formation

Stratigraphically, the studied section covers the Lower Cretaceous Judea Formation (Fig. 3a and b) which varies in thickness from 7 to 57 m (Fig. 4b), and vary from mud-dominated limestones in the upper half of the section “the Carbonate Zone” to dolomitic limestones and dolostones in the lower half section “the Dolomite Zone” (Fig. 3b). The obtained results based on well logs interpretations of the penetrating wells of the Judea Formation sediments over the studied field showed that sediments of the “Carbonate Zone” did not contain any interesting hydrocarbon indicators, while sediments of the “Dolomite Zone” contains hydrocarbons in a good commercial quantity which makes this zone as the main reservoir zone in many fields over the Euphrates Graben area.

The regional information (Yousef et al. 2017, 2018, 2019, 2019) indicates that sediments of the Judea Formation over the Euphrates Graben and locally over the studied field were affected and eroded partially or completely by the regional Base Upper Cretaceous unconformity (BKU) (Fig. 4a), (see Fig. 3a), which resulted in varying thicknesses of the formation sediments over Euphrates Graben fields.

Sediments of the Judea Formation are spread over several tilted horsts defined at the formation top and deeper levels by an interlocking system of west southwest to east northeast, east northeast to west southwest and east to west trending boundary faults (Fig. 4a). There is stratigraphical evidence for major south to southeasterly tilting and erosion of the Early Cretaceous Judea Formation sediments due to the influences of the BKU unconformity, this unconformity limits the top of the Judea Formation which is not

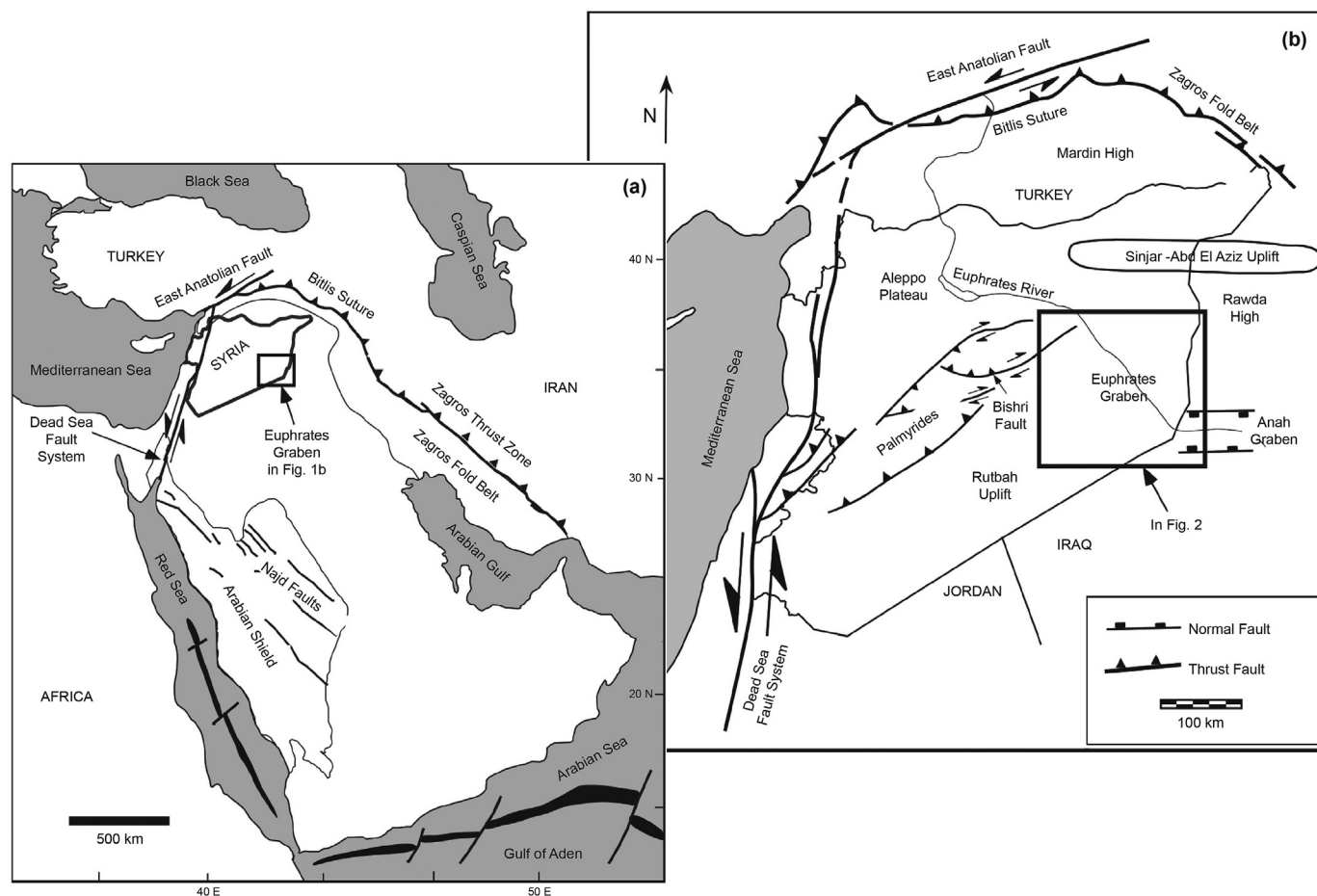


Fig. 1. Regional tectonic and topography maps showing: a Map illustrates the Arabian plate tectonic settings (Litak et al., 1998) and b Location of the Euphrates Graben map within Syrian lands (Litak et al., 1998).

overlain by sediments of the Post Judea Sandstone Formation (Fig. 4a).

The non-uniform thicknesses of the Judea Formation sediments over the studied area indicate a period of relative strong tectonic activity, which ended with a phase of subtle tilting during the deposition time of the Post Judea Sandstone Formation, pinching out over the field in a west-northwesterly direction (Fig. 4a).

The present-day complex horst and graben were generated during the Late Cretaceous rifting phase of the Euphrates Graben system. The influx siliciclastic sediments of the Post Judea Sandstone Formation (PJS) (Fig. 4a), (see Fig. 3b) heralds a period of major normal faulting and erosion by the BKU unconformity over the area of the studied field and is the most apparent record by rapid stratigraphic thickness variations of the Ere, Derro, Post Judea Sandstone, Judea, and Mulussa F formations (Fig. 4a). The correlation between the penetrated wells indicates that distribution of the Judea Formation is locally limited to some wells, whereas in other wells sediments of the formation are absent due to the erosion activities (Fig. 4a).

4.2. Carbonate lithofacies of the Judea Formation

Based on sedimentological investigations and interpretations of the cored intervals from sediments of the Judea Formation over the studied field in the Euphrates Graben, four carbonate lithofacies were defined including; 1). Interbedded limestones and calcareous mudstones. 2). Limestones with thin mudstone interbeds. 3).

Homogeneous lime-mudstone. 4). Dolostones and dolomitic limestones. Below is a brief description of each lithofacies of the Judea Formation.

4.2.1. Interbedded limestones and calcareous mudstones

Sediments of this lithofacies occur mainly within the “Carbonate Zone” (Fig. 5a). The limestone beds are of 15–60 cm thick, and the mudstone beds are up to 1 m thick (Fig. 5b and c). The limestones are light to medium grey; bioturbation is intense including small (up to 1 cm) sub-horizontal to sub-vertical burrows (Fig. 5b). The mudstones interbedded are calcareous throughout, mostly medium to dark grey (Fig. 5b and c). Bivalve fragments are present, the degree of the bioturbation is moderate to weak or absent, with visible horizontal burrows, horizontal lamination is frequently preserved (Fig. 5c), development of the horizontal lamination reflect concentration of the straight pressure solution seams (Miall, 1985).

4.2.2. Limestones with thin mudstone interbeds

The limestones are light to medium grey, brownish grey, or greenish-grey (Fig. 5d, e, f, g). Stylolites are not common throughout. Bioturbation is pervasive including simple about 1 cm wide Chondrites burrows (Fig. 5d and e). The associated mudstones are a minor component occurring in laminae and beds that reach a thickness of 25 cm (Fig. 5f and g). It is mostly medium to dark grey and are always calcareous and marks the boundary between sediments of this lithofacies and sediments of the underlying

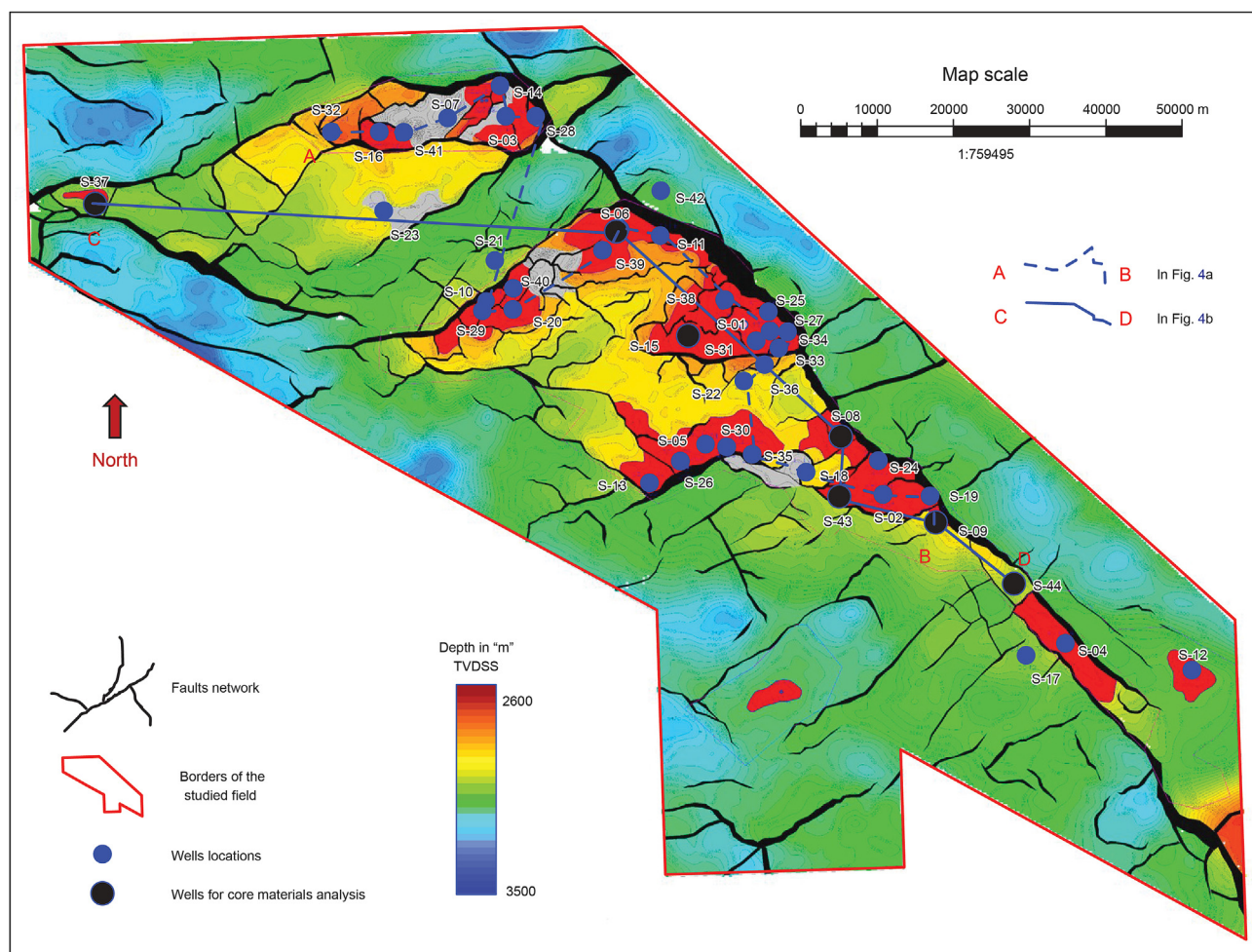


Fig. 2. 2D window showing a structural map flattened on Judea Formation top over the studied field. See Fig. 4a for the cross sections A-B, and Fig. 4b for the cross sections C-D. TVDSS (True Vertical Depth Subsea).

homogeneous lime-mudstone lithofacies (Fig. 5g).

4.2.3. Homogeneous lime-mudstone

Sediments of this lithofacies extend along the lowermost part of the “Carbonate Zone” (Fig. 5a). The lime-mudstones are homogeneous, cream, and pervasively bioturbated including Chondrites burrows, bivalve, and other shell fragments are locally present in minor quantities.

Stylolites locally are common (Fig. 5h). Dolostones occasionally occurs as thin beds and marks the boundary between sediments of this lithofacies and sediments of the underlying dolostones and dolomitic limestones lithofacies (Fig. 5k), the changes in color between these two lithofacies may reflect the changes in the clay materials content (Miall, 1985).

4.2.4. Dolostones and dolomitic limestones

Sediments of this lithofacies occur mainly within the “Dolomite Zone” in the lower part of the Judea Formation (Fig. 5a). The dolostones and dolomitic limestones are cream to light brown or grey (Fig. 5l, m, n). Foraminifera are common, including Miliolids which indicate low energy, inner shelf to lagoonal depositional environments. Other skeletal components include Brachiopods, Gastropods, and Bryozoa. Poorly developed, irregular, streaky laminae and stylolites are present (Fig. 5m). The contacts between sediment of this lithofacies with sediments of the other lithofacies

are abrupt (Fig. 5n) and often stylolitized. Internally, the beds are largely massive, although many are cut by sub-horizontal and, in some cases, sub-vertical pressure solution seams (Fig. 5o). The visual porosity of the dolostones is generally low. However, macroscopic vugs occurs within the most coarsely crystalline horizons (Fig. 5p). Towards the base of the Judea Formation section, the dolostones are characterized by intense and pervasive of the dolomitic veining and the local brecciation (Fig. 5o).

4.3. Depositional environments interpretation

Interpretations of the depositional environments of the Judea Formation sediments are based entirely on the evidence contained within the micritic limestone lithofacies. Sedimentological investigations of the cored intervals suggested that sediments of the Judea Formation were deposited in mostly low to moderate energy in origin, lagoonal to inner shelf depositional environments (Fig. 6), this is indicated by presence of the bivalve, Brachiopod debris, Miliolid, Bryozoa, Gastropods, cryptalgal lamination, and the other benthic foraminifera, additionally by the microscopy texture of the sediment (wackestone to wackestone/packstone).

Presence of the algal laminae, in particular, testifying to the development of the lagoon margin and shallow open marine/lower intertidal flat conditions (Pomar and Kendall, 2008). The transition to the homogeneous lime-mudstone probably reflects deepening

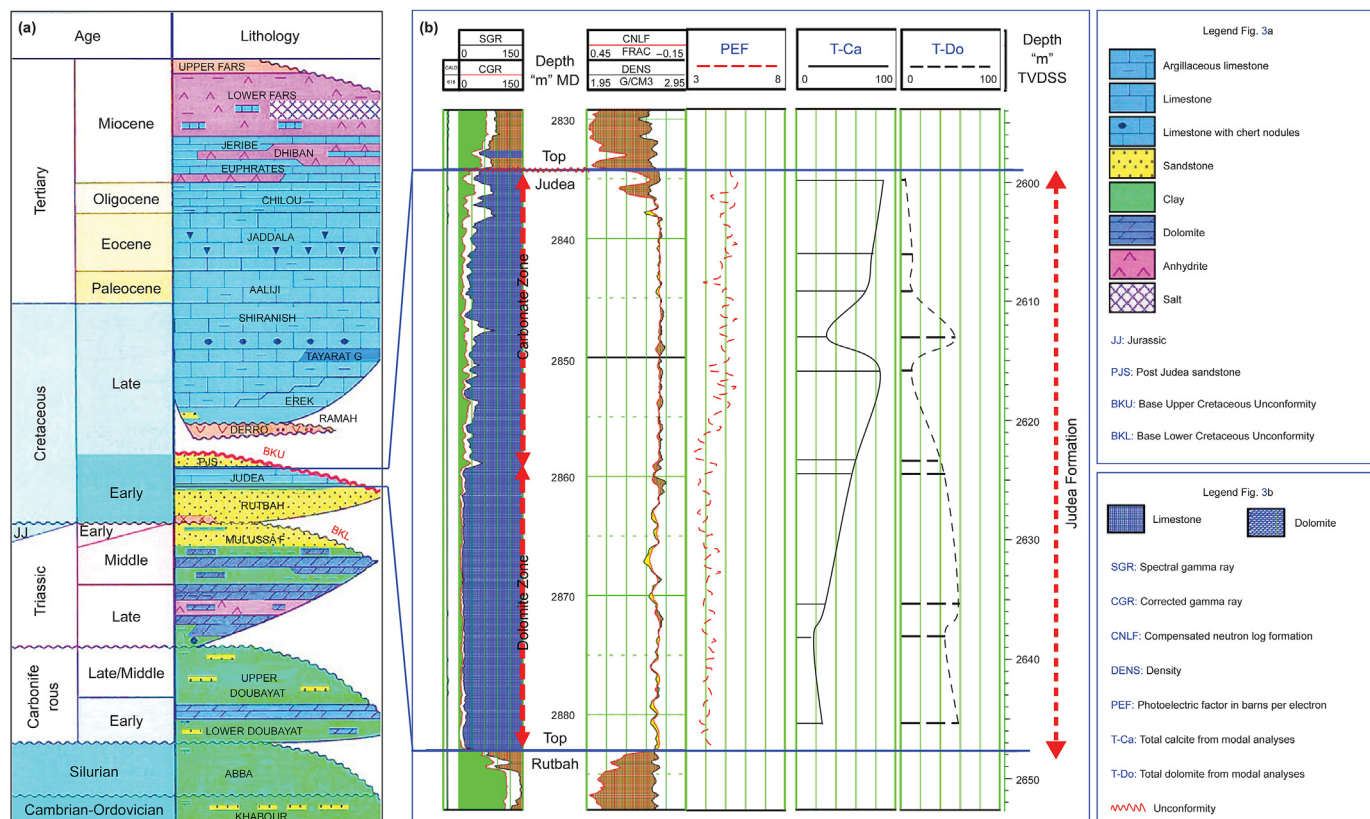


Fig. 3. Composite stratigraphy and geophysical panel showing. **a** General stratigraphic section of the Euphrates Graben area. **b** Typical of the S-15 well logs showing the logging response of the Judea Formation, limestones are characterized by low SGR and narrow separation between DENS and CNLF logs, and PEF values of about 5, dolomites and dolomitic limestones have very low SGR values and wide separation between DENS and CNLF logs but have values of PEF less than 4 (Lucia, 2004). T-Ca is the total calcite, and T-Do is the total dolomite. See Fig. 2 for the S-15 well location.

with establishment of the low energy, shallow marine conditions with negligible elastic input, and slightly dolomitization effects. The thin claystone intervals probably represent a flooding surface, and the succeeding development of lime-mudstones to wacke-stones with thin beds of mudstone point to shallow marine, low energy conditions with some elastic input, possibly storm or flood derived (Lucia, 2004). The proportion of the mudstones is increased with the development of lithofacies (interbedded limestones and calcareous mudstones). This may reflect deepening within a shallow marine, low energy environment, or just an increase in the supply of the siliciclastic mud (Lucia, 2004). The abundance of the mud sediments may suggest the protracted accumulation of fines below the fairweather wavebase (Pomar 2001).

Thus, in summary, sediments of the Judea Formation in the studied field in the Euphrates Graben appears to have deposited in a low-energy, offshore marine environments, possibly analogous to carbonate ramp setting characterized by a slow accumulation of micrite and episodic influxes of skeletal material in response to the storm events.

Processes suggested as the origin of the micrite include inorganic precipitation, bioerosion, biochemical precipitation, and the mechanical disintegration of skeletal debris (Shinn et al., 1989).

4.4. Petrography

Sediments of the Judea Formation in the studied field in Euphrates Graben consists of carbonates deposited in shallow marine environments, these included the pure limestones lithofacies in the upper part of the formation to the dolomitic

limestones and dolostones in the lower part of the formation section (see Fig. 3b). Thin section examination (Fig. 7) showed that the pure limestone lithofacies that contain less than 5% of the dolomite are dominated by micritic muds (mudstones and wackestones) with variable amounts of skeletal fragments include poorly sorted, subangular to subrounded bivalves, with scattered Echinoderm and small bioclasts (mainly foraminifers). Locally, the sparry calcite fills most of the vugs, mouldic, and the intragranular pores after dissolved algae, Gastropods and other skeletal fragments (Fig. 7a and b). The peloids and the sparry calcite cement that partially replaced the mudstones pockets and are therefore classified as pelsparite packstones (Fig. 7c), the sparry calcite infilling the vug, cavities, or mouldic pores that possibly after the incomplete leaching of mud intraclasts (Fig. 7d).

Sediments of the Judea Formation were slightly and/or pervasively dolomitized and replaced by the dolomites. The micritic limestones lithofacies still retain the original dispositional texture when the dolomite content is more than 5% and less than 40%. Rarely finely crystalline dolomites (Fig. 7e) are formed within the micritic matrix (Mm). Some of the microbioclasts are still preserved (Fig. 7a and b).

The micritic limestones that are slightly replaced with the finely crystalline dolomites are usually characterized by no to very pore porosities (Fig. 7e and f). The original limestone textures have been almost completely destroyed with increasing the dolomite content (when the dolomites contents are less than 90% and more than 40%) (Fig. 7g, h, i).

Based on dolomite crystal sizes, two main types of the dolomites and/or dolomite crystals were distinguished in the carbonate

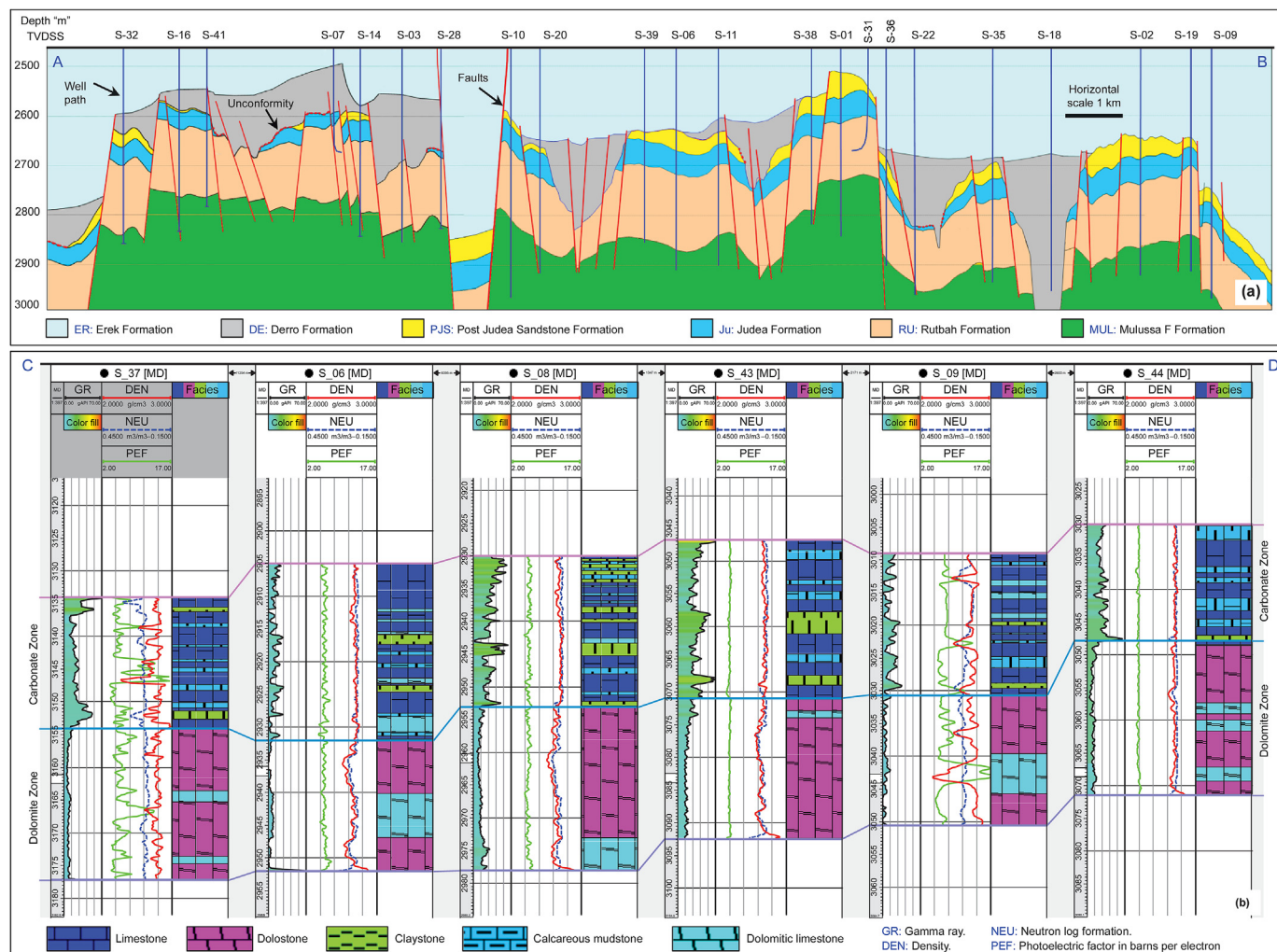


Fig. 4. Composite stratigraphy and a tectonic panel showing. a Cross-section A-B and, b correlation panel C–D across the studied field showing in the Euphrates Graben area. See Fig. 2 for the S-15 well location. See Fig. 2 for the locations of the cross sections A-B, and C-D.

sediments of the Judea Formation, these include; the preserving microcrystalline dolomites, and the destructive coarsely crystalline dolomites. The preserving microcrystalline dolomites are generally less common, they are mainly founded within the micritic limestone lithofacies, they consist of small crystals of dolomites that are not exceeding 5 μm in size and mainly fill the secondary pores that resulting from dissolution activity of the bioclasts (Fig. 7c). The preserving microcrystalline dolomites are also limited to the micritic limestones lithofacies, they composed of small to medium-sized of dolomite crystals with dimensions ranging between 5 μm and 50 μm (Fig. 7e and f). The small and medium sizes of the dolomite crystals are sometimes intertwined to form a distinctive texture that closes all the pores between the crystals (Fig. 7f). Some of the stylolites fracture shows replacement by the finely to occasionally coarsely crystalline dolomites (Fig. 7f).

The destructive coarsely crystalline dolomites (Fig. 7g, h, i) are most commonly founded in the dolomitic limestones and in the pure dolostones lithofacies that occupy the lower part of the Judea Formation sediments section.

The destructive coarsely crystalline dolomites consist of large dolomite crystals, ranging in size from 50 to 100 μm (Fig. 7g, i) and may reach up to 200 μm (Fig. 7h). This type of dolomite replacement destroys completely the original limestone fabric and texture. The coarse crystals of dolomites occasionally exhibit rarely ghost

structures which probably represent relict bioclasts (Fig. 7i). The cores of the rhombs' dolomite are infrequently composed of authigenic pyrite (Fig. 7h).

Some of the pores between the dolomite crystals are filled with residual clays (the brown to black spots in the thin section photomicrographs in Fig. 7g). Other pores are open and clean (Fig. 7h). Precipitation of the dolomite cement between the dolomite crystals in the late stage of the burial diagenesis leads to a partial and almost complete closure of the pore network between the dolomite crystal (Fig. 7i). Many samples were selected for preparation as polished thin sections and analyzed using a Cold Cathodoluminescence (CL) microscopy. Samples from the dolomitic limestones (Fig. 8a, b, c) displays a precursor lithology of lime mudstone slightly replaced by microcrystalline rhombic dolomite crystals with a uniform texture. Between the dolomite crystals, lie residual clayey micrite (dark background in Fig. 8b) which has an even, dull orange luminescence in Fig. 8a.

The cathodoluminescence examination signature of the dolomite crystals seems to be a fairly simple two-stage growth zonation from bright yellow-orange crystal nuclei to duller crystal rims, this suggests a transition from non-ferroan to ferroan dolomites (Cazenave et al., 2003).

The brightness and color of the dolomite crystals nuclei also suggest selective manganese (activator) ion incorporation in

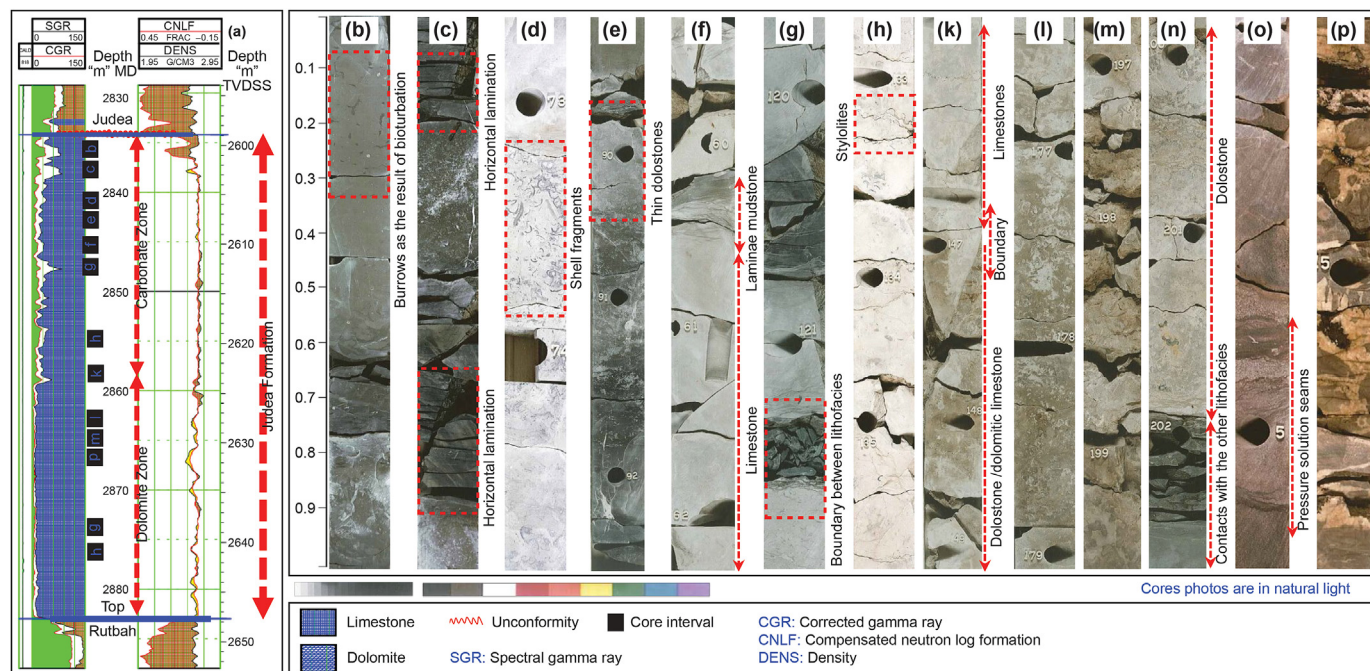


Fig. 5. Representative core photographs showing. a Typical of the S-15 well logs. b, c Representative cores photographs from S-15 well showing the petrographically characterizes of the interbedded limestones and calcareous mudstones. d, e, f, g Representative cores photographs from S-06 well showing the petrographically characterizes of the limestones with thin mudstone interbeds. h, k Representative cores photographs from S-08 well showing the petrographically characterizes of the homogeneous lime-mudstone. l, m, n Representative cores photomicrographs from S-43 well showing the petrographically characterizes of the dolostones and dolomitic limestones. o, p Representative cores photographs from S-09 well showing the petrographically characterizes of the dolostones and the dolomitic limestones. See Fig. 2 for wells locations.

calcium sites, possibly inherited from the precursor calcium carbonates (Budd et al., 2000). Samples from the micritic limestones lithofacies indicate biomicrite wackestone with dull luminescence (orange color) in the matrix (Fig. 8d, e, f, g, h, i). Several mouldic and vuggy pores are calcite spar-filled and show vague cathodoluminescence properties. Large areas of very coarse blocky calcite cement exhibiting long, strongly alternating cathodoluminescence patterns giving a good impression of cement growth stratigraphy (Fig. 8d and e). Very precise correlation of the cement between the crystals and the pores is possible based upon both growth and sector zone signatures in different areas of individual crystals.

Two sets of very dull luminescent bands are particularly conspicuous in most crystals, these enable confident cement correlation. In very large crystals, the zoned structure becomes fainter towards pore centers, culminating in a uniform mid-range, moderately bright cathodoluminescence in the youngest areas of the crystal (Fig. 8d and e).

The complex growth zonation observed records dramatic fluctuation in pore fluid chemistry or, conceivably, crystal growth rate resulting in variable uptake rates of manganese (activator ion) and ferrous iron (quench ion) (Budd et al., 2000). These variations would be expected in pore fluids undergoing variable recharge (seasonal, say, in a groundwater system) and consequent fluctuation in Mn: Fe and redox conditions (Dromgoole and Walter, 1990).

The zoned cement may thus be of relatively near-surface diagenetic origin. The evolution towards a faintly zoned or unzoned structure could indicate burial and gradual change to a steadier rate of crystal growth in pore fluid of more persistent chemical conditions.

Presence and distribution of the replacive dolomite crystals as pin-point (rarely aggregated), many of dolomite crystals that different in shape from euhedral to subhedral occur almost randomly in the micritic matrix (Fig. 8a, b, g, h), in some cases

clustered preferentially along argillaceous solution tracts (Fig. 8j and k). Individual dolomite crystals show euhedral growth zonation as alternate dull and bright bands.

5. Discussions

5.1. Dolomitization of the host rock

Sediments of the Judea Formation over the studied field in the Euphrates Graben area consists of pure to non-dolomitized limestones lithofacies in the “Carbonate Zone” in the upper part of the formation, these followed by units of dolomitized mudstones (wackestones, grainstones, and packstones) reflect lagoon and/or shoal lithofacies, they gradually passing into dolomitic limestones and dolomites dominant in the “Dolomite Zone” in the lower part of the formation. Based on petrographically examinations of the thin sections, two types of dolomites replacement have been identified within the carbonates of the Judea Formation; the preserving microcrystalline dolomites that encountered within the micritic limestones lithofacies, and the destructive coarsely crystalline dolomites that encountered and dominant the dolostones and dolomitic limestones.

The relationship between the original depositional environments of the carbonate sediments of the Judea Formation and dolomitization processes as evidenced by the different types of the encountered dolomites and/or dolomitization degree (Kinga and Gizella, 2007; Bai et al., 2016). The preserving microcrystalline dolomites based on the interpretations are suggested to represent subtidal disposition cycles probably developed in a shoal to open marine depositional environments (Fig. 9).

Sedimentology and diagenetic interpretations based on the available information in this study indicate that the preserving microcrystalline dolomites may have formed in conditions of the shallow burial diagenesis before the carbonate sediments of the

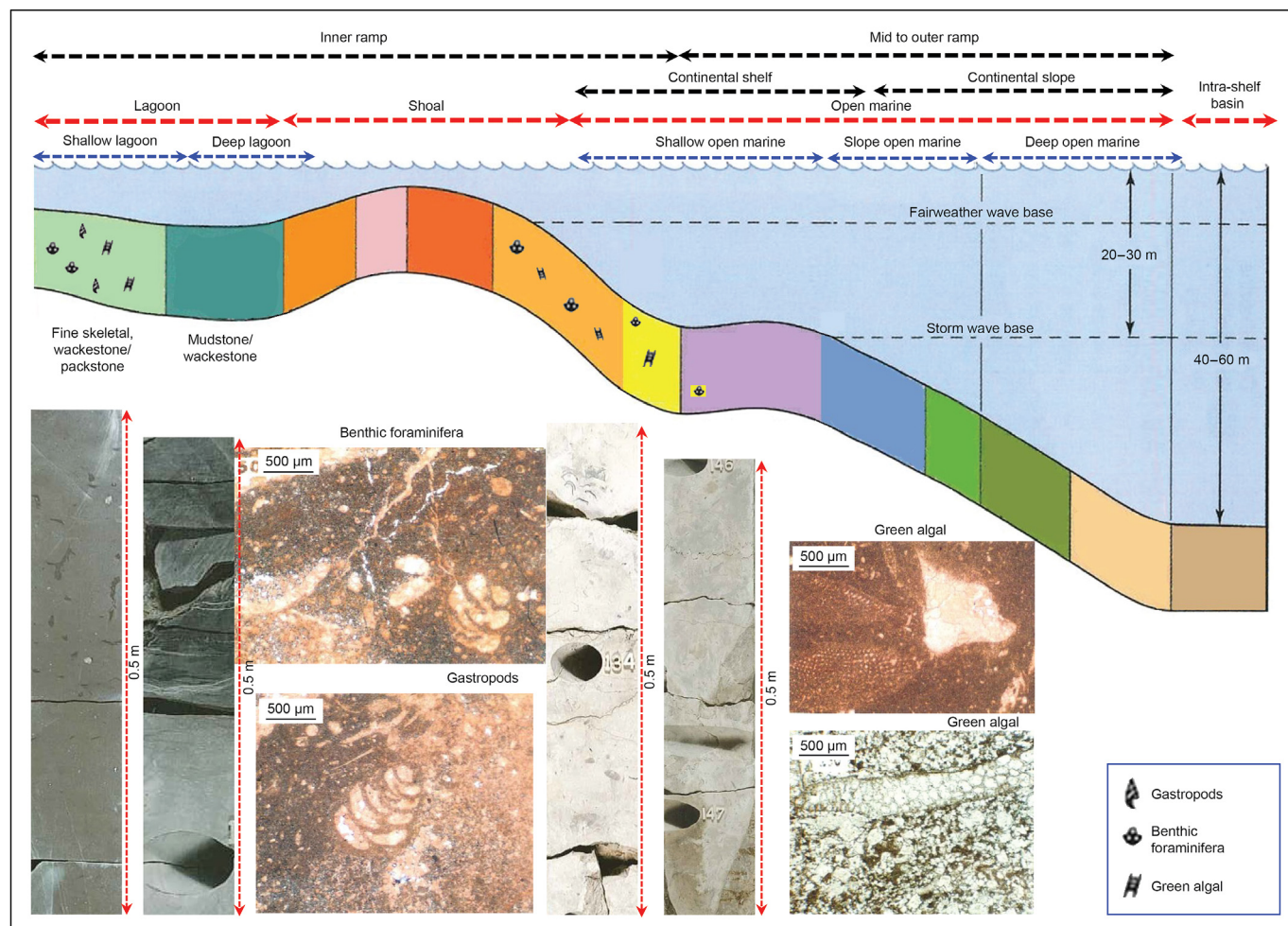


Fig. 6. The suggested disposition environments of the Judea Formation sediments in the studied field in the Euphrates Graben area.

Judea Formation were subjected to any significant diagenetic modifications in the deep burial diagenesis stage. We have adopted the following observations to support this suggestion: (1) the preserving microcrystalline dolomites occupies most of the early formation pore spaces where the limestones preserve their original texture before any extensively dolomitization processes (see Fig. 7e), some of the preserving microcrystalline dolomites are randomly distributed in the dolomitized micritic matrix (Fig. 8a and b); (2) the early phase of dolomitization processes are characterized by persevering of the original sedimentary texture of the limestones sediments, additionally, dolomitization processes does not affect the early diagenetic modification processes that occur in the early stages of the diageneses which includes; bioturbation, micritization processes, and precipitation of the different cements between the granular components of the rock and in the pore spaces (see Fig. 8g, j); (3) stylolites microfractures and/or microfractures that expanded by dissolution activity of the bioclasts inhibits growth of the preserving microcrystalline dolomites and restricts them (see Fig. 7f), not only the dolomites, but also, they inhibit and restricts growth of the precipitated calcite crystals in these pores (see Fig. 7c); (4) precipitation of the calcite crystals within the pore spaces and/or within the fractures voids occurred probably coincided with or after precipitation of the replaced microcrystalline dolomites (see Fig. 7c), (see Fig. 8g and h); (5) stylolites microfractures and/or microfractures that expanded by dissolution activity cross-cut both of the precipitated calcite and

the replaced microcrystalline dolomites (see Fig. 7c).

Sedimentology and diagenetic interpretations indicate that the destructive coarsely crystalline dolomites (see Fig. 7g, h, i) that dominate the “Dolomite Zone” probably are formed in more open marine depositional environments (see Fig. 5) and are mainly produced during conditions of the deep burial diagenesis stage under the high temperature that resulted from increasing the burial depth of the sediments and increasing of the sediment pressure (Ehrenberg et al., 2007).

Thin section investigations showed that the microcrystalline dolomites are sometimes excited within the core of the coarsely crystalline dolomites, or stick to it without any clear and/or sharp boundaries (see Fig. 7f, g, i), (see Fig. 8a, j, k), these features refer to the processes of recrystallization of the microcrystalline dolomites and their incorporation with the coarsely crystalline dolomites during the late stages of the burial diagenetic modifications (Aqrabi et al., 1998; Abboud et al., 2005).

As a result, dolomitization processes of the micritic limestones lithofacies that dominant the upper part of the Judea Formation over the studied field in the Euphrates Graben area are probably started in conditions of the shallow burial diagenesis shortly after limestones deposition in intertidal to the leeward shoal depositional environments, dolomitization processes of these sediments continued to the end of the shallow burial diagenesis stage.

Dolomitization processes of the limestones that dominant lower part of the formation “the Dolomite Zone” that are deposited in

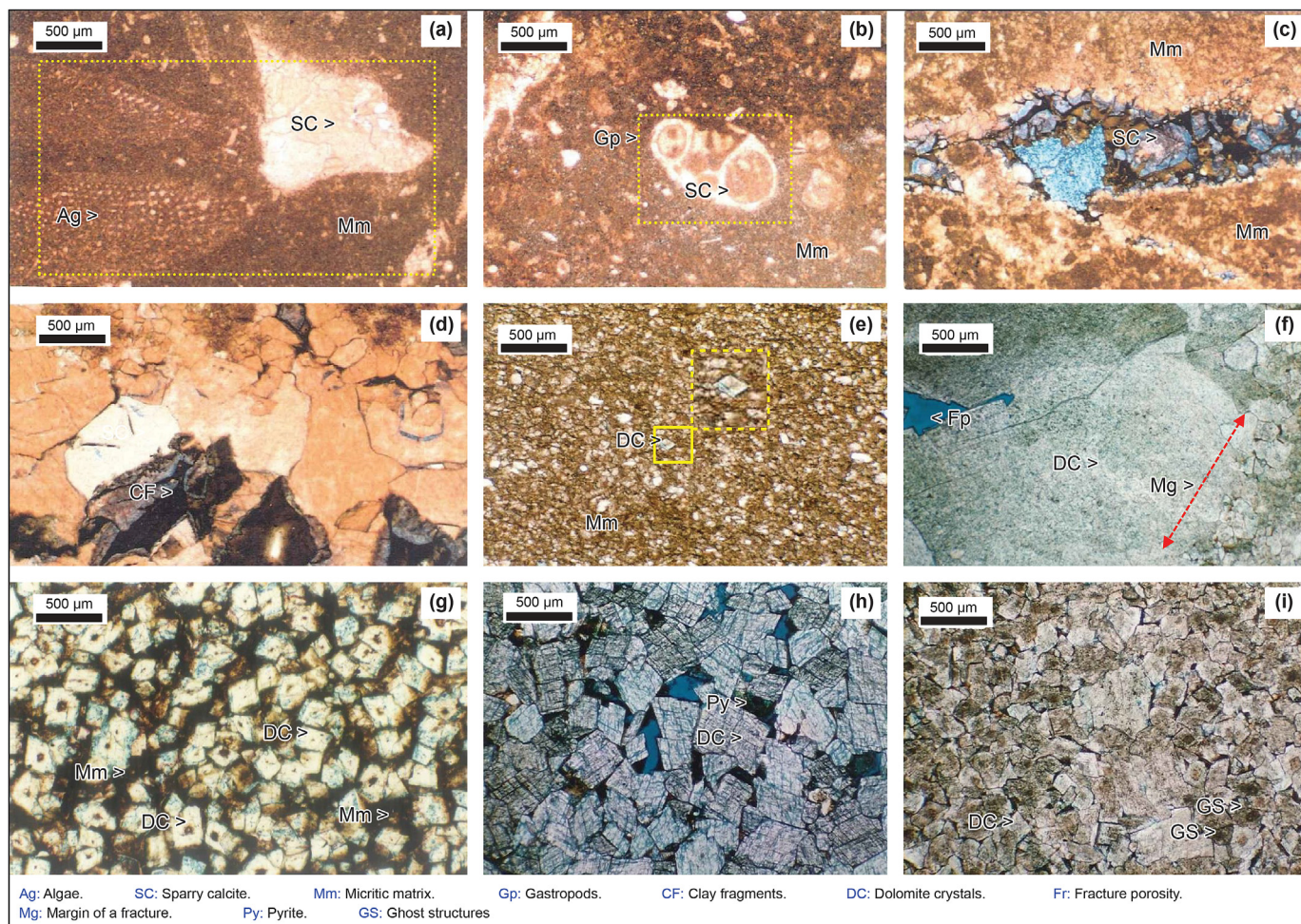


Fig. 7. Representative optical photomicrographs from S-37, 06, 15, and 08 wells showing, a Biomicrite wackestone, the chambered green algae (Ag) within the carbonate matrix, sparry calcite (SC) infilling the vug and mouldic pores, PPL. b Biomicrite wackestone, some Gastropods (Gp) and other skeletal fragments within the micrite matrix (Mm) are replaced by the precipitated calcite, PPL. c Pelsparite packstone, some of the mudstone pocket are replaced by the precipitated calcite and slightly by the cryptocrystalline dolomites, the carbonate matrix consists of common micritic peloids and micritic intraclasts, PPL. d Pelsparite packstone illustrates cavities, possibly after the incomplete leaching of the mud intraclasts (CF), the cavities are extensively cemented by the sparry calcite, PPL. e Micrite matrix (Mm) containing indeterminate microbioclasts, rarely rhomb finely crystalline dolomites (DC), PPL. f The margin of a fracture (Mg) which cuts finely crystalline dolomites, the fracture is partially sealed by the dolomites. However, note the isolated relict fracture porosity (Fp), PPL. g Dolomitization of the micritic matrix (Mm) by rhombic coarsely crystalline dolomites (DC) vary in size from 50 to 100 μm , PPL. h Dolostones consist of rhombic coarsely crystalline dolomites (DC) varies between 100 and 200 μm in size, locally pyrite (Py) nodules within the matrix, some of the pore's networks are open and clean, PPL. i Rhombic coarsely crystalline dolomites (DC) vary in size from 100 to 200 μm , pores networks are occluded by dolomites and ghost structures, PPL. See Fig. 2 for the S-37, 06, 15, and 08 wells locations.

slightly open marine depositional environments are continued during the deep burial diagenesis stage which was accompanied by an increase in the temperature and pressure.

5.2. Paragenetic sequences

Many diagenetic processes affected the original dispositional rock fabrics and textures of the Judea Formation carbonates over the studied field. These include; dolomitization processes, leaching activity or dissolution, and early and late calcite and/or dolomite cementation. Diagenesis processes of the Judea Formation carbonates started with the inversion of the primary aragonite matrix to calcite (micrite), followed by the minor dissolution of the unstable bioclasts creating localized secondary porosity (Fig. 10a).

Authigenic pyrite locally precipitated within some of the open vugs or secondary porosity that resulted from dissolution activity (Fig. 10a). Localized fracturing of the carbonate matrix under compaction occurred, these fractures were later infilled by calcite cement that probably sourced from the dissolved bioclasts, calcite

cement also occluded the primary and secondary porosity (Fig. 10b). Localized early dolomitization (Fig. 10c) or extensive (Fig. 10d) of the carbonate matrix occurred in the Judea Formation.

The early dolomitization process that occurred in micritic limestones was the main process according to which the process of replacement with dolomites began, although some of the micritic limestone samples retain the original dispositional texture and some fragments of skeletal in the host micritic limestone rocks (Fig. 10a, c). Fractures are common within sediments of the Judea Formation; they are extensive in the Dolomite Zone but are not so in the Carbonate Zone.

Most of the fractures exhibit a stylolitic fracture (Fig. 10e), the common stylolitic fractures contain no visible porosity being sealed by the stylolitic clay and the ferroan dolomite (Fig. 10e). It is therefore concluded that these fractures do not enhance reservoir quality. Fracture fills are mainly sparry, ferroan calcite (Fig. 10f). Some of the fractures have a zoned fill of marginal calcite and/or dolomite (Fig. 10d, f).

The margins of the fracture locally have been partially

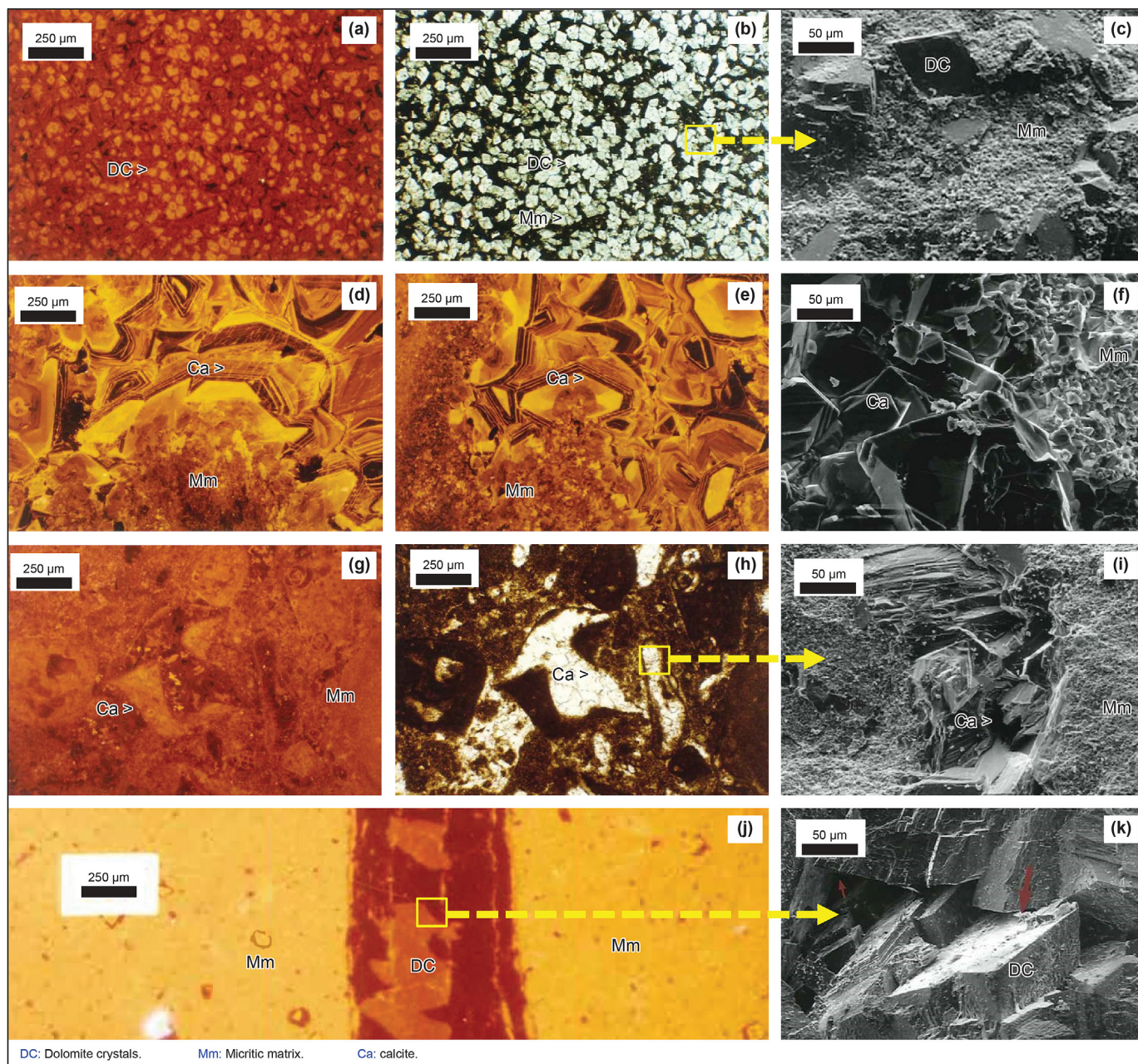


Fig. 8. Representative cathodoluminescence, optical, and SEM photomicrographs from X-06, 15, 08, 43, and 09 wells showing a Cathodoluminescence of replacive dolomite crystals in a precursor lime mudstone lithofacies. b The same view as the previous sample but in transmitted light, the micrite matrix forms the dark background to clear dolomite crystals, PPL. c SEM photomicrograph showing replacement of the micritic matrix (Mm) by dolomite crystals (DC). d, e Cathodoluminescence of coarse sparry calcite in mouldic pore, CL. f SEM photomicrograph showing the secondary calcite (Ca), consisting of coarse and tightly interlocking subhedral crystals inferred to have replaced a skeletal fragment following dissolution and reprecipitation. g Cathodoluminescence of bioclastic limestone, CL. h The same view as the previous sample but in the transmitted light, calcite cement tracts are seen as clear sparry areas, PPL. i SEM photomicrograph showing micritic matrix dominated by calcite. j Luminescence of micritic matrix and fracture infill, the bright orange micrite matrix is very homogeneous and features small, replacive dolomite crystals that are marked by dull luminescent rims, two-stage cement infill of fracture comprises ferroan dolomite (very dull red/brown) which is overlain by calcite (red/orange), CL. k SEM photomicrograph showing large and interlocking crystals of dolomite, coated by drilling mud residues (arrowed). See Fig. 2 for the X-06, 15, 08, 43, and 09 wells locations.

dolomitized and filled by the dolomites (Fig. 10e). Fracture infilling rarely seems to have been incomplete, allowing for the only local later migration of hydrocarbons into the occasional remnant, isolated voids (Fig. 10c). Existing fractures may have been utilized as fluid conduits for the necessary magnesium-rich pore fluids.

Accordingly, many fractures appear subsequently to have been cemented by coarsely crystalline baroque dolomite (see Fig. 7h and i). The termination of a group of calcite-filled fractures at a boundary between the micrite lithofacies and the dolostone

lithofacies (Fig. 10d) mostly indicates that these fractures were formed in the early stage of the diagenetic modification of the Judea Formation sediments, most likely in the shallow burial diagenesis stage. The suggested diagenetic events sequence with porosity evaluation of the Judea Formation sediments over the studied field in the Euphrates Graben based on the available petrographic investigations are illustrated in Fig. 11, although it is emphasized that many aspects remain speculative due to the limited database and due to confidential issue of the geochemistry data from the host

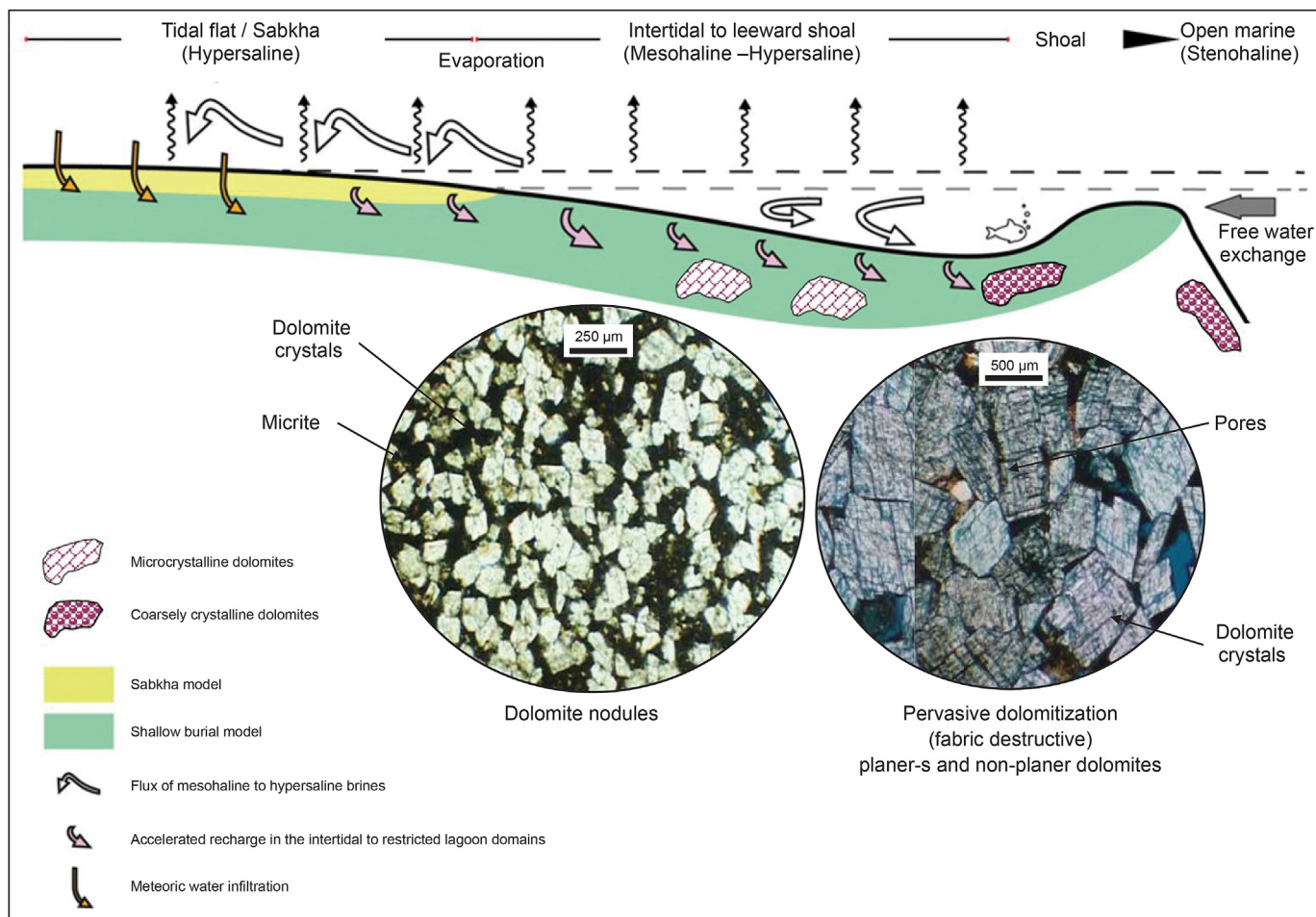


Fig. 9. Proposed mechanism of dolomitization for the Judea Formation in the Euphrates Graben.

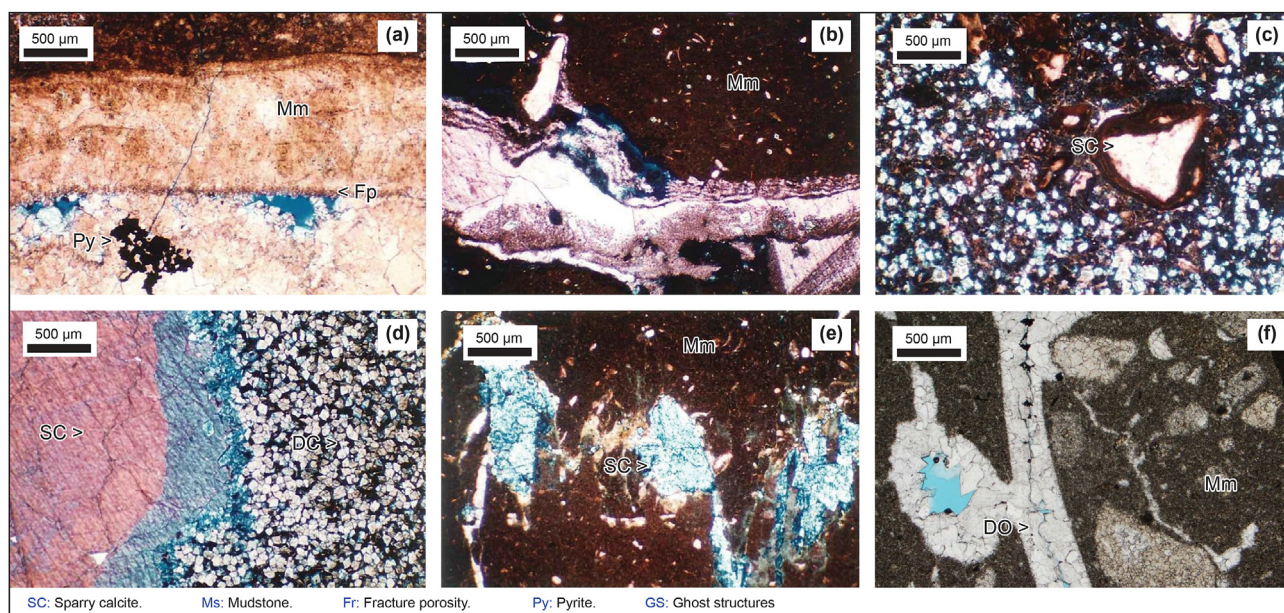


Fig. 10. Representative optical photomicrographs from X-37, 06, 15, and 44 wells showing, a Biomicrite wackestone, a large bivalve fragment within a micritic matrix creating a geopetal structure infilled by calcite, pyrite nodule present, PPL. b Fractured micritic mudstone, the calcite fills the fracture which crosses a micritic matrix with rare skeletal fragments, PPL. c Dolomitic micrite wackestone, the micritic matrix extensively dolomitized by rhombic dolomite crystals, the calcite infilling the skeletal fractures, PPL. d Fractured dolostone, the matrix of rhombic dolomite crystals crossed by a fracture, notice the zoning within the fracture. The walls are lined by dolomite, enclosed by calcite, PPL. e Fractured dolomitic micrite mudstone, well-developed stylolite partially replaced by dolomite, the matrix is occasionally crossed by calcite filled crystals, PPL. f Fractured micritic mudstone, dolomite fracture crossing the micritic matrix, PPL. See Fig. 2 for X-37, 06, 15, and 44 wells locations.



Fig. 11. The suggested diagenetic sequence of the Judea Formation over the studied field in the Euphrates Graben area based on the available petrographic investigations.

company.

The diagenetic history of the Judea Formation sediments over the studied area is subdivided into two stages; the shallow burial diagenesis or the early diagenesis and the deep burial diagenesis (Fig. 11). Compaction processes, precipitation and presence of calcite, initiation of fine, sub-horizontal, and sub-vertical fractures within the micrite units, mobilization of the groundwater fluids supersaturated in CaCO_3 due to the early pressure solution, associated cementation of the fine fractures by calcite, and the slight recrystallization of the micritic matrix were part of the multiple diagenetic alterations during the shallow or the early burial diagenesis phase (Fig. 11). Fractures of early genesis occurred to the sediments under influence of the sedimentary stress. Micritization features of the mudstones were observed in many of the studied thin sections. The early phase of dolomitization or replacement with dolomite of the limestones of the Judea Formation (the microcrystalline dolomites) most likely has occurred during the shallow burial diagenesis.

Precipitation of the early calcite occurred in the shallow diagenesis, the precipitated calcites are mainly in the form of pore fillings of the pores that are resulting from dissolution and/or fractures fillings as observed through the petrographic investigations.

Sediments of the Judea Formation suffered diagenetic processes

in the deep burial diagenesis phase, dissolution, late stage of replacement and dolomitization (coarsely crystalline dolomites), mechanical and chemical compaction, late calcite cementation occurred also during this phase.

Deep burial and application of tectonic stress result in widespread mechanical compaction contributed greatly to reduce the porosity of the limestones, dolomitic limestones, and the dolostones. Solution seams and chemical compaction (stylolite) formed with further burial diagenesis leading to increase the porosity.

5.3. Diagenetic control on porosity evolution

The helium porosity values (core plugs measurements) of the Judea Formation range between 0.5% and 17% and horizontal permeability values range between <0.01 and 10000 mD (Fig. 12). The limestones of the “Carbonate Zone” generally exhibit non to very poor reservoir quality intervals. They are characterized by porosity values ranging between 0.05 and 11%, also they show permeability values ranging between 0.01 and 4 mD.

A significant change in the porosity and permeability values is observed when moving from the “Carbonate Zone” towards the “Dolomite Zone” where the dolomitic limestones and the dolostones are the main lithologies.

The dolostones and dolomitic limestones are of variable

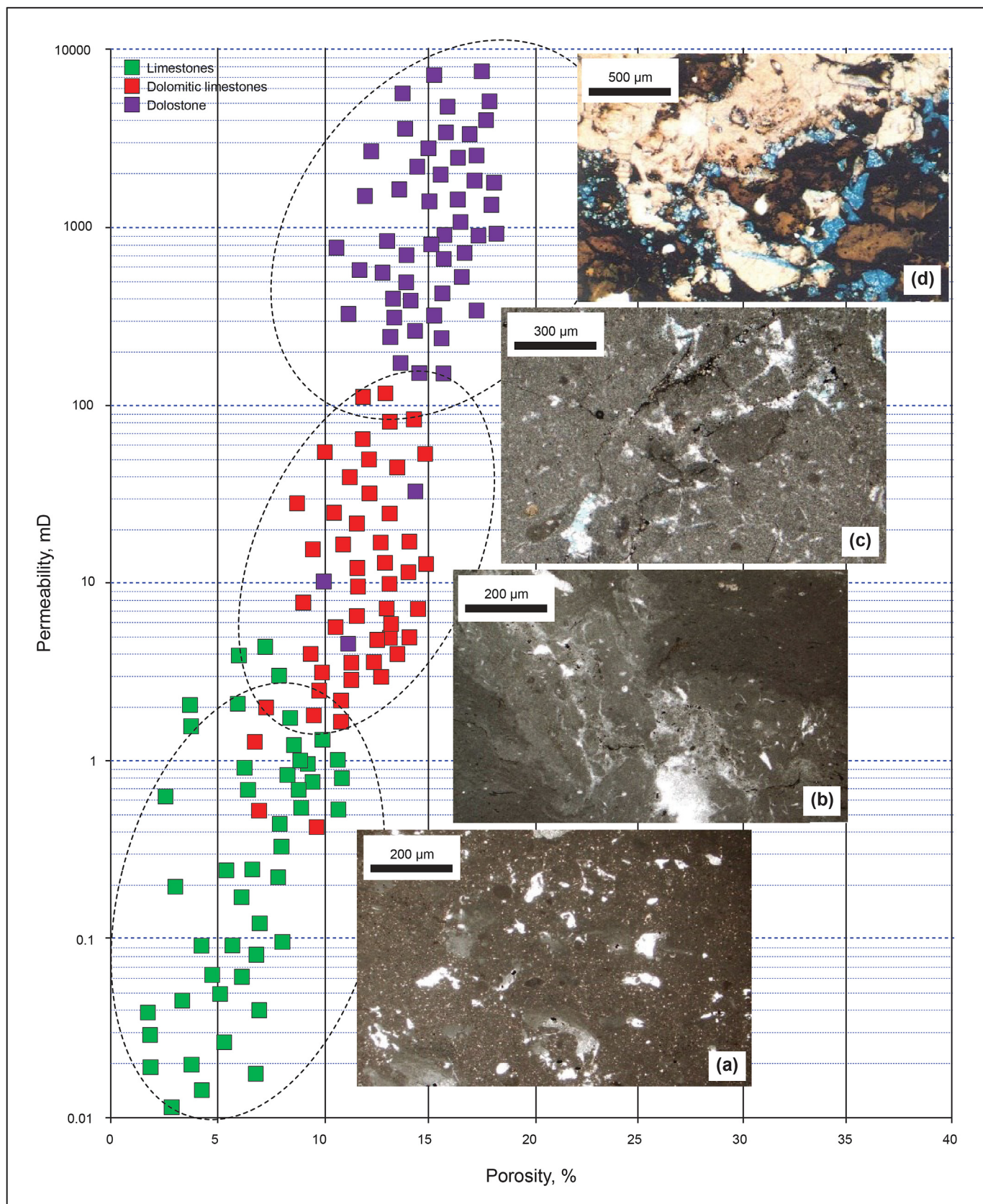


Fig. 12. Porosity and permeability of the different Judea Formation lithofacies.

crystallinity, and intercrystalline microporosities are developed. Porosity values of the dolomitic limestones range from 6 to 15%, and permeability values range from 1 to 100 mD. In the dolostone, porosity values range from 10 to 17%, and permeability values range from 100 to 10000 mD.

Reservoir quality of the Judea Formation has been modified by various factors. The initial porosity of the limestones and dolostones were little altered or reduced by the precipitated dolomites and calcite. Dolomitization processes and/or the partial replacement of the micritic matrix with dolomites lead to generating secondary dissolution porosity, mainly resulting from the dissolution of the fossils skeletal (Fig. 12a and b). This creates a vuggy porosity that remains ineffective porosity if they don't connect.

Besides, precipitation of the early calcite and/or the early dolomites in the early stage of the diagenetic modification plays as the main factor in closing many of these pores. The dolomites occur in many samples (absent to 80%), (according to thin section examinations) as extensive rhombic crystals exerting a severe detrimental control on reservoir quality.

The calcite generally occurs in many samples (see Fig. 7c), (see Fig. 8h), occasionally it partially occludes primary interparticle and secondary grain dissolution voids, the calcite has locally reduced both the pore volume and connectivity of the pore network, with a minor detrimental control on reservoir quality.

Optically non-resolvable clay (absent to 2% based on thin-section examinations in Fig. 7d) are locally observed as minor patchy deposits within the primary pores exerting a negligible detrimental control on reservoir quality. The stylolitic fractures that occurred in the late stages of the diagenetic modification processes helped to improve the reservoir quality of the dolomitic limestones and the dolostones intervals by creating new pathways for hydrocarbon materials through the reservoir rocks, observations from the petrographic study of the thin section improve this (Fig. 12c and d). Porosity of the dolostones appears to be enhanced by these stylolitic fractures, finely crystalline dolomitic stringers, and some partly open and steeply inclined fractures. Patchy, moderate oil shows are associated with vuggy porosity within the "Dolomite Zone" occurring amongst nodular and irregular algal laminated fabrics.

6. Conclusions

The scientific justification of this paper stems from the importance of the Judea Formation as a hydrocarbon reservoir over most of the Euphrates Graben fields, and additionally, from the lack of the information that explains the dolomitization processes and how they affect the formation rocks and generate the dolostones reservoirs. The obtained results of this paper increase understanding of dolomitization processes by answering many questions related to; how the texture of the precursor limestone and the resultant dolostones are critical to predicting the petrophysical properties of the dolomitized succession, and how the dolomitization processes affect the porosity and pore size of the reservoir rocks, and, thus, the quality of the limestone-dolostone reservoirs.

In general, it is very difficult to predict the origin and the source of the dolomitizing fluids, and the enrichment of Mg^{2+} and indicative information of refluxing dolomites since the geochemical data cannot be used in this research, and, thus, we strongly recommend on conducting geochemical analyses during the future development/exploration since these data are needed, together with petrographic observation to understand the dolomitization mechanism. Porosity within the dolomitized zone of the Judea Formation appears to be enhanced by the stylolitic fractures and finely crystalline dolomitic stringers, and, thus, we recommend to focus on the relationship between dolomitization and fracture since they enhance the quality of dolostone reservoirs.

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