Dolomitization and porosity evaluation of the Cretaceous Upper Qamchuqa (Mauddud) Formation, Khabbaz oil field, Kirkuk area, northern Iraq

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ABSTRACT

The Khabbaz Field in northern Iraq produces oil and gas from the Albian Upper Qamchuqa Formation, which corresponds to the Mauddud Formation of southern and central Iraq and the Arabian Gulf. The Formation is layered into Units A, B and C, of which Unit A is the main reservoir zone characterized by correlatable flow units and barriers/baffles. Units B and C generally have lower overall reservoir quality compared to Unit A. A detailed examination of cuttings, cores, and wireline logs from ten wells in the field revealed an important link between sedimentary facies, dolomitization, and heterogeneity of reservoir characteristics. The wide range of dolomite fabrics include microcrystalline, planar-e, planar-s, planar-p, non-planar as well as saddle and cement types. These fabrics imply successive phases of dolomitization, which profoundly influence the enhancement of reservoir character. Intercrystalline, micromoldic, and microvuggy porosity are the most influential byproducts of this dolomitization. Fracturing and stylolitization, in addition to the uniform network of intercrystalline pore systems, especially of the fine- to medium-crystalline dolomite, effectively contributed to the collective porosity and permeability of the reservoir.

INTRODUCTION

The Khabbaz Field is one of the Iraq’s giant oil fields with multiple pay zones similar to most of the northern Iraq oil fields. The first seismic investigation in the Khabbaz area (Kuna Rewi Valley) started in 1995 by the Iraqi Petroleum Company (IPC) and showed a NW-plunging structure. A second seismic survey was conducted between July and October 1971 and indicated the presence of the Khabbaz prospect. The first discovery well (Kz-1) was drilled in August 1976, and development was started in 1987 by France’s Technip Geoproduction for the North Oil Company. Work was interrupted in August 1990 due to political circumstances and the field was brought on stream four years later in March 1994 by the North Oil Company. Surface facilities include a 70 million cubic feet/day (MCF/d) compression and dehydration plant, and a pipeline linking the field to the main export network. Khabbaz Field can produce about 25,000 barrels of oil per day and 45 MCF/d of gas.

The field’s reserves are estimated between 0.5 and 1.0 billion barrels in three formations: (1) Oligocene Jerribe Formation with 36° API oil in a 130-m column; (2) Upper Qamchuqa (Mauddud) Formation with 29° API oil in a 125-m column; and (3) upper part of Lower Qamchuqa (Shu’aiba) Formation with 42° API oil in a 175-m column. So far 30 wells have been drilled; the majority targeted the Oligocene reservoir, and more than half penetrated the Upper Qamchuqa (Mauddud) Formation. The field is an anticlinal structure (4 x 20 km in extent) located between Jambur and Bai Hassan oil fields (Figures 1 and 2), which are all parallel to the Kirkuk Field trend. Tectonically the field is located in the Foothill Zone (Hamrin - Makhul subzone) of the Zagros folded zone, which represents part of the Arabian unstable shelf (Buday and Jassim, 1987). A major fault intersects the structure in its southeastern nose and influences reservoir performance (Figures 2 and 3).

This study is focused on the thick carbonate section of alternating limestone and dolostones within the Upper Qamchuqa (Mauddud) Formation. These carbonates developed over an extensive ramp along the margin of the Arabian Plate, which evolved during the Albian time (Jassim and Goff, 2006). The present work is intended to evaluate the relationship between reservoir lithologic characteristics and petrographic properties with emphasis on the dolomitized units. The ultimate goal is to establish a porosity-permeability prediction tool to enhance the reservoir characterization. Wireline logs were
Figure 1: General location map showing oil fields and key wells in Iraq. The Khabbaz Field is located southwest of Kirkuk Field.

Figure 2: Structural contour map of Khabbaz Field on top of the Upper Qamchuqa (Mauddud) Formation.
integrated with petrographic examination of cores and cuttings samples from 10 wells (Kz-1 to Kz-5, Kz-7, Kz-11, Kz-13, Kz-14 and Kz-16, Figure 2). These wells were chosen because they completely penetrated the Upper Qamchuqa (Mauddud) Formation and provide control for lithostratigraphic correlation. Scanning electron microscope (SEM) photographs are used to demonstrate the relationship between the dolomite fabric and the type and size of the pore system.

**STRATIGRAPHY**

The Qamchuqa Limestone Formation was first defined in van Bellen et al. (1959–2005) from the Qamchuqa Gorge, east of the Dokan Dam site, to the northeast of Sulaimaniah city. Due to lateral variation in the formation, Al-Sadooni (1978), following unpublished remarks of McKinley (1959), raised the status of the formation into the Qamchuqa Group. His proposed group includes from bottom to top: Lower Qamchuqa Formation, Upper Sarmord Formation and Upper Qamchuqa Formation. This new scheme was adopted by most petroleum geologists working in the Kirkuk area and amended by Buday (1980).

Further southwestwards and westwards, in central Iraq, the equivalents of these three formations become better differentiated into (Figure 4):

- Lower Qamchuqa Formation to the Hauterivian – Early Aptian Zubair and Early Aptian Shu’aiba formations,
- Upper Sarmord Formation to the Albian Nahr Umr Formation,
- Upper Qamchuqa Formation to the Late Albian Mauddud Formation.

These latter names are commonly used in southern Iraq and the Arabian Gulf area.

The Upper Qamchuqa (Mauddud) Formation is a widespread Late Albian unit, which extends over most of the Arabian Platform (Sadooni and Alsharhan, 2003). In Iraq its thickness varies due to lateral facies changes and erosional truncation. In Figure 5 the isopach map shows that the thickness of the formation decreases around the Mosul area and rapidly increases toward the west (Sinjar Trough) where its thickness reaches 125 m in Well Butma-1 and 198 m in well Tal Haji-1 (Sahar, 1987). The thickest area of the formation is located to the southeast of Kirkuk, where it increases from 170 m in the Khhabbaz Field, to 237 m in Kirkuk-107 Well, to 250 m in Chemchemal-1 Well, to about 350 m in Kor Mor-3 Well (Figure 1).

The general lithology of the Upper Qamchuqa (Mauddud) Formation within the Kirkuk area shows no significant variation. It is generally characterized by intercalations of limestone, dolomitic limestone, and dolostone with infrequent marl intercalations (Figure 6).
| Stage     | Western Iraq | Central Iraq | Northwestern Iraq | Northeastern Iraq | Iran       |
|-----------|--------------|--------------|-------------------|-------------------|------------|
| Cenomanian| Rumaila      | Jawan        | Nahr Umr          | Upper Qamchuqa    | Lurestan   |
|           |              |              |                   | Upper Sarmord     | Khuzestan  |
| Albian    | Maudud       |              |                   |                   | Sarvak     |
|           |              |              |                   |                   | Kazhdumi   |
| Aptian    | Shu’aiba     |              |                   |                   | Dariyan    |
| Barremian | Zubair       |              |                   |                   | Garau      |
| Hauterivian| Yammama     | Yammama      |                   |                   | Gadvan     |
|           |              |              |                   |                   | Fahliyan   |
| Valanginian| Zangura     |              |                   |                   |           |
|           |              |              |                   |                   |           |
| Berriasian| Makhul       | Karimia (Sarmord) |               |                   |           |
| Portlandian| Gotnia       | Chia Gara    |                   |                   | Surmeh     |

Figure 4: Regional stratigraphic correlation chart of Lower Cretaceous units across the northeastern margin of the Arabian Plate (modified after van Bellen et al., 1959-2005)

Figure 5: Isochore of the Upper Qamchuqa (Mauddud) Formation (after Sahar, 1987). Contour interval 50 meters.
In the Khabbaz Field the lower contact of the Upper Qamchuqa (Mauddud) Formation is conformable and gradational with the Upper Sarmord (Nahr Umr) Formation. The upper contact with the Dokan Formation is marked by a break corresponding to either non-deposition or an erosional unconformity.

**SEDIMENTARY FACIES**

The limestone section in the study area reveals the occurrence of biotic communities generally of shelf environments. The regional facies spectrum of the Qamchuqa Platform indicate tidal flat, lagoon, shoal, patch reef, fore-slope to ramp, and basinal environments (Al-Sadooni, 1978; Sahar, 1987; Al Shhdidi et al., 1995; Al-Pfryadi, 2002; Al-Juboury et al., 2006; Ameen, 2008). The locally recognized facies in the Kirkuk area are briefly reviewed here based on general observations and previous studies. The review is taken from west towards the eastern-northeastern part of the sedimentary basin (Figure 7).

**Tidal Dolostone Facies:** It is characterized by the occurrence of stromatolitic dolostone microfacies, which occur as thin layers punctuating the lagoonal facies and developed as marginal tidal-flat complexes of the lagoonal environment. Relics of fenestral fabric are characteristic but commonly obliterated by intensive dolomitization.

**Lagoonal Facies:** This facies is commonly found in the western part of Kirkuk area and characterized by dolomitic limestone and dolostone of peloidal-miliolid packstone to grainstone. Other grains include fragments of algae and mollusks. Early cementation of this facies reduces dolomitization effects; however, selective dolomitization is frequently recognized and lagoonal dolomudstone can be found alternating with the limestone.
Orbitolina-bearing Facies: This is a dark grey orbitolina-rich limestone, which is variably dolomitized. Grains are dominated by large benthic orbitolinids. Microfacies ranges from whole-foram grainstone to wackestone to fragmented packstone to wackestone. Other subsidiary grains include bioclasts of algae, rudists and mollusks.

Rudist Bioclastic Facies: It is characterized by high-energy bioclastic packstones. The majority of grains are rudist fragments intermixed with fragments of open-shelf faunas. It is highly bioturbated and interlayered with thin shaley seams.

Basinal Foraminiferal Argillaceous Facies: This is the most eastern facies of the area. It is characterized by planktonic foraminifera intermixed sporadically with calcispheres forming bioclastic packstone to wackestone microfacies. Intermixture with open-shelf bioclasts is common. The matrix is argillaceous micrite and marl.

**SUBSURFACE LITHOLOGIC UNITS**

The Upper Qamchuqa (Mauddud) Formation in Khabbaz Field ranges between 156–180 m in thickness, with an average of 167.6 m (Table 1). It shows variable lithologic characteristics, which are recognized by examining core and cutting samples from the 10 studied wells. Wireline log interpretation assisted lithologic interpretation of uncored or poorly sampled intervals as well as the determination of thickness of these units. Final well report documentation of some of these wells was also considered in reviewing the general lithologic characteristics of the reservoir. Three lithologic units are recognized in all the studied wells, and generally are persistent across the field.

Unit A represents the upper lithologic part of the reservoir. It ranges in thickness from 62 to 69.5 m, with maximum thickness of 69.5 m in Well Kz-13 in the central part of the field (Table 1). This good reservoir unit is easily recognized from the combined neutron-density porosity log, which is characterized by high porosity intervals. It is generally characterized by alternation of light gray, hard, dense, fossiliferous and occasionally bioturbated limestone with buff brown, soft, sucrosic-to-vuggy and fine- to medium-crystalline dolomite and dolomitic limestone (Figure 8). The dolomite horizons are occasionally vuggy. Dolomitic horizons are frequent and exceed six in some wells.
Unit B represents the middle and the thickest part of the reservoir. It ranges in thickness between 66.5 and 79.5 m with a maximum thickness in Well Kz-11 (Table 1). The limestone and the dolomitic limestone are generally gray to light gray, hard, bioturbated and include dark green shale or marl intercalations. Occasionally, white irregular patches or inclusion of anhydrite are recognized. It consists of alternations of dolostone, dolomitic limestone and limestone with subsidiary intercalations of marly limestone. The dolostones are represented by irregular horizons of buff, medium hard, sucrosic, fine to coarse crystalline dolomite. It is commonly vuggy and saturated with oil (Figure 8).

Unit C is the thinnest zone and ranges between 19.5 and 42.0 m (Table 1). It generally consists of alternating light gray to whitish gray, hard, bioturbated, fossiliferous, and occasionally marly or dolomitic limestone and dolostone, with dark gray to black fissile and friable shale or marlstone (Figure 8). The argillaceous content is usually variable but generally increases downward. The shaliness of this unit indicates the influence of underlying Upper Sarmord Formation, and can be easily recognized on the gamma-ray log (Figure 6). The carbonate portion is usually dense and fractured. The argillaceous limestone sections are occasionally laminated and bioturbated. This is the only unit of the three that shows significant thickness changes within the small area of the Khabbaz Field (Table 1).

**MICROFACIES ANALYSIS**

Microfacies analysis is the microscopic evaluation of the total of all the paleontological and sedimentological criteria of carbonate rocks using thin sections, peels, and polished slabs (Flugel, 1982). Microfacies analysis was applied here for both limestone and dolostone lithologies to:

- investigate the type and distribution of microfacies to define the rock types,
- define sedimentary facies and interpret paleoenvironmental settings,
- recognize type and influence of various diagenetic processes, specifically dolomitization, on reservoir quality,
- identify the type and distribution of pore spaces and its relation to reservoir characterization.

| Wells | Unit | Intervals (m) | Thickness (m) |
|-------|------|---------------|---------------|
| Kz-1  | A    | 2,752.5 - 2,821 | 68.5          |
|       | B    | 2,821 - 2,888   | 67            |
|       | C    | 2,888 - 2,924   | 36            |
| Kz-2  | A    | 3,025.5 - 3,091.5 | 66         |
|       | B    | 3,091.5 - 3,163  | 71.5          |
|       | C    | 3,163 - 3,205    | 42            |
| Kz-3  | A    | 3,202 - 3,250    | 48            |
|       | B    | 3,202 - 3,250    | 48            |
|       | C    | 3,202 - 3,250    | 48            |
| Kz-4  | A    | 2,979 - 3,047    | 68            |
|       | B    | 3,047 - 3,120    | 73            |
|       | C    | 3,120 - 3,150    | 30            |
| Kz-5  | A    | 2,832 - 2,895    | 63            |
|       | B    | 2,895 - 2,969    | 74            |
|       | C    | 2,969 - 2,991    | 22            |
| Kz-7  | A    | 2,931 - 2,975    | 44            |
|       | B    | 2,975 - 3,010    | 35            |
|       | C    | 2,975 - 3,010    | 35            |
| Kz-11 | A    | 2,885.5 - 2,950.5 | 65          |
|       | B    | 2,950.5 - 3,030  | 79.5          |
|       | C    | 3,030 - 3,057    | 27            |
| Kz-13 | A    | 2,805.5 - 2,875  | 69.5          |
|       | B    | 2,875 - 2,947    | 72            |
|       | C    | 2,947 - 2,982    | 35            |
| Kz-14 | A    | 2,811.5 - 2,873.5 | 62           |
|       | B    | 2,873.5 - 2,948.5 | 75           |
|       | C    | 2,948.5 - 2,968?  | 19.5          |
| Kz-16 | A    | 2,905 - 2,968.5  | 63.5          |
|       | B    | 2,968.5 - 3,035  | 66.5          |
|       | C    | 3,035 - 3,061    | 26            |
| Formation | Lithologic Unit | Lithology |
|-----------|----------------|-----------|
| Upper Qamchuqa | A (65 m) | Cyclic alternation of fossiliferous, bioturbated shelf limestone, and dolomitic limestone with fine to medium crystalline sucrosic dolostone |
|           | B (75 m) | Alternation of thick massive sucrosic mainly coarse crystalline dolostone with thin horizons of bioturbated and bioclastic dolomitic limestone |
|           | C (30 m) | Alternation of bioclastic limestone with sucrosic dolostone and dark gray basinal marlstone |

Figure 8: Detailed lithologic characteristics and representative cores of the lithologic units of Upper Qamchuqa (Maudud) Formation, Khabbaz Field. Unit A, Well Kz-2, 3,038–3,048 m; Unit B, Well Kz-11, 2,964–2969 m; Unit C, Well Kz-11, 3,040–3,058 m.
The analysis was conducted based on petrographic studies of ca. 400 thin sections selected from core and cutting samples of 10 wells for the examined interval. Staining of dolomitized samples was attempted following Dickson (1966) to differentiate between calcite and dolomite. Identification of important microfossils was assisted by using previous related studies and literature. Nomenclature for depositional texture followed Dunham (1962) with slight modification especially for dolomitized samples. Textural description of dolomite and terminology is conducted following Sibley (1982), Sibley and Gregg (1987) as reviewed by Machel (2004), and explained in Figure 9.

For crystal size classes the scheme of Lucia (1995) is adopted as follows: < 20 µm is fine, 20–100 µm for medium crystalline, and > 100 µm for coarse crystalline dolomite. Attempts were made to restore original fabric and sedimentary microfacies of dolomitized samples by using relict fabric and original undolomitized components. Terminology of pore types and classification is adopted after Choquette and Prey (1970) and Pittman (1992). Microfacies analysis is done for the three basic rock types: limestone (L1 to L4), dolomitic limestone (DL1 to DL5) and dolostone (D1, D2, etc.). Symbols were used as such to simplify references to different microfacies in diagrams and text.

**Limestone Microfacies (L)**

**Bioclastic Wackestone to Packstone (L1):** Grains of this microfacies are dominated by fine sand to silt size skeletal fragments and debris, commonly made up of rudist bioclast fragments (Figure 10a). Other bioclasts includes algae (Figure 10b), mollusks, miliolids and forams. The matrix is recrystallized micrite, locally cryptocrystalline and, or replaced partially to completely by sparry calcite or dolomite. Porosity is generally low and characterized by dissolution of the already cemented intergranular spaces, intraskeletal pores, vugs and rare moldic pores.

**Peloidal Bioclastic Wackestone to Packstone (L2):** Peloids are the characteristic grain types of this microfacies. Other grains include lumps, molluscan fragments and miliolids (Figure 10c). The matrix is dominated by recrystallized micrite or replaced by fine crystalline dolomite. Sometimes the grain-to-matrix ratio increases to grainstone especially with rounded bioclasts. Porosity is developed mainly by leached interparticle, matrix and locally moldic porosity.

![Planar-e (euhedral)](image1)
![Planar-s (subhedral)](image2)
![Planar-c (cement)](image3)
![Planar-p (porphorotopic)](image4)
![Planar-e to nonplanar-a](image5)
![Non-planar-a (anhedral)](image6)
![Non-Planar (saddle)](image7)
![Planar-p (porphorotopic)](image8)

**Figure 9:** Dolomite textures and classification from Machel (2004) after Gregg and Sibley (1984), Sibley and Gregg (1987) and Wright (2001).
Miliolid Peloidal Packstone to Grainstone (L3): Miliolids and peloidal grains are commonly associated together to form packstone to grainstone texture (Figures 10d and 10e). Miliolids are often micritized and commonly intraskeletal pores are filled by calcite cement. Other types of grains include bioclasts of gastropods and several types of benthic foraminifera. Matrix is less common and often leached with isolated intergranular pores. In other cases sparry calcite replaces part of the micritic matrix. Other less common porosity types are moldic and intercrystalline within some dolomitized burrow fills.

Foraminiferal Marly Wackestone to Packstone (L4): This is a typical basinal or deep-marine microfacies. Characteristic features include abundant pelagic planktonic foraminifera and their skeletal debris, as well as ostracods, echinoderm fragments and mollusks in a sparse to very argillaceous micritic matrix (Figure 10f). This microfacies is common in lithologic Unit C of the Upper Qamchuqa (Mauddud) Formation. The argillaceous content of this microfacies marks the influence of the Upper Sarmord Formation, which underlies this unit and is dominated by shale and marl. Porosity is ineffective in this microfacies.

Dolomitic Limestone Microfacies (DL)

Bioclastic Dolowackestone to Dolopackstone (DL1): This microfacies is originally the same as microfacies (L1) but partially to completely dolomitized (Figure 11a). Dolomite is characterized
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by either medium crystalline (20–100 µm), planar-e to planar-s type, or by fine crystalline mosaic especially when it is associated with bioclasts of quiet environment (Figure 11d). Dolomitization selectively affects matrix, or both matrix and grains simultaneously. Porosity is intercrystalline in dolomitic parts, and in the nondolomitized parts consists of moldic, vuggy, intraskeletal pore types.

Miliolid Bioclastic Porphyrotopic Dolowackestone to Dolopackstone (DL2): Grain types of this microfacies are dominated by miliolids and/or bioclasts of mollusks and other forams (Figure 11b). Matrix is micritic with slight recrystallization. Dolomite is distributed as fine to medium crystalline (10–40 µm), euhedral rhombs of planar-p type. Both matrix and grains are affected by this type of dolomitization, which shows low intensity in a relatively dense limestone. Fracture porosity is the common porosity type.

Peloidal Bioclastic Dolowackestone to Dolopackstone (DL3): Peloids are the dominant grain types with partially to completely dolomitized matrix (Figure 11c). Miliolids, algae, and mollusks fragments are locally concentrated. Preservation of fossil fragments is generally good indicating a relatively quiet environment and early stabilization/cementation. Dolomite occurs either as selectively replacing matrix by finely crystalline mosaic texture, or as isolated, euhedral, and planar-p, dolomite rhombs. Porosity commonly occurs as leached intergranular spaces (Figure 11d).

Figure 11: All photomicrograph are crossed nicols.
(a) Bioclastic dolowackestone with medium crystalline dolomite mosaic, Kz-16-2917.
(b) Porphyrotopic dolomite (unstained crystals) of the miliolid bioclastic dolowackestone microfacies. Note the oil shows in microfracture, Kz-16-2975.
(c) Peloidal dolowackestone with intergranular porosity resulted from dolomitized matrix, Kz-14-2842.
(d) Bioclastic dolopackstone forams and pellets are the most abundant grains. Common replacement by finely crystalline dolomite, Kz-11-2971.
(e) Fenestral doloboundstone stromatolite fenestral porosity is abundant, Kz-16-3068.
(f) Foraminifera bioclastic dolopackstone, Kz-11-3049.

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Fenestral Doloboundstone (DL4): The origin of this microfacies is seemingly stromatolitic boundstone of tidal flat environment (Flugel, 1982). The usual early dolomitization of this facies yields an intensely dolomitized microfacies with relics of the original biogenic fabric (Figure 11e). Dolomite is of fine to medium crystalline texture. Porphyrotopic dolomite occasionally are recognized overprinting biogenic fabric with retained fenestral porosity.

Foraminiferal Bioclastic Argillaceous Dolowackestone to Dolopackstone (DL5): Planktonic foraminifera are the characteristic skeletal grains of this microfacies. Grains are usually embedded in an argillaceous micritic matrix (Figure 11f). Other skeletal grains include fine bioclasts of forams and other deep-marine fauna. Lamination can be recognized in thin sections. Coarse bioclasts are sporadically concentrated and leached yielding a moldic porosity. Dolomite is represented by floating rhombs of medium crystalline mosaic.

Dolostone Microfacies (D)

Dolomudstone (D1): This microfacies is characterized by a very finely crystalline dolomite mosaic (< 10 µm). It either replaces a lime mud facies (Figure 12a) or replaces the lime mud filling intergranular spaces of a bioclastic packstone facies (Figure 12b). Grains are bioclasts, miliolids, algae and rare peloids. Microvugs and fractures are present. This type of dolomite replaces micritic matrix in what may be an early stage of diagenesis (Amthor and Friedman, 1991).

Fine Crystalline Planar-s Dolomite Mosaic (D2): The dolomite of this microfacies is characterized by finely crystalline (10–20 µm) of planar-s type. It commonly forms a homogenous ground mass with dark sporadic clouds, and occasionally ghosts of fine shell bioclastic fragments (Figure 12c). Dolomite crystals are anhedral in shape especially when finely crystalline (> 10 µm) with no relics of the original fabric (Figure 12d). Another special form of dolomite in this microfacies is coarser crystalline (10–20 µm), euhedral dolomite mosaics showing considerable amounts of moldic to microvugular porosity (Figure 12e). Other textures are characterized by finely crystalline planar-s type of dolomite, which incompletely replaces the original limestone matrix (Figure 12f). Pores in this microfacies are rarely intercrystalline.

Medium Crystalline Planar-e-s Dolomite Mosaic (D3): This dolostone is characterized by medium crystalline (20–50 µm) and locally even coarsely crystalline planar-e (Figure 12h) to planar-e to planar-s mosaic (Figure 12g). In some cases the texture is underdeveloped patches of fogged or cloudy nonplanar-a mosaic with relics of original micritic matrix mosaic (Figures 12g and 12h). In other cases relics of the original micrite developed as a peloidal fabric. Ghosts of skeletal grains such as orbitolinids, miliolids, and other forams and skeletal debris are also present. The most common type of porosity is intercrystalline (Figure 12h). In the more coarsely crystalline fabric inter-crystalline porosity becomes larger and coalesces to isolated microvugs (Figure 12i). Additional porosity comes from unhealed fractures (Figure 12h). This facies represents the best reservoir facies based on its excellent petrophysical properties.

Coarse Crystalline Planar-e-s Dolomite Mosaic (D4): This type of dolomite is characterized by coarse (> 100 µm), euhedral to subhedral dolomite crystals of planar-e to planar-s type with low intercrystallite but high vuggy porosity (Figures 13b and13c). Crystals sometimes occur as nonplanar-a with cloudy centers which show noticeable low porosity (Figure 13a). Microvugs also occur but are sometimes filled by anhydrite (Figure 13c). Dolomite crystals in some cases are very coarse and show progressive dissolution and successive replacement by other cements such as anhydrite. Undolomitized bioclasts can be occasionally recognized.

Planar-e-s Dolomite Cement (D5): This is a special type of coarse crystalline dolomite with a patchy distribution. It is characterized by very coarse, clean, planar-c crystals. It sometimes forms a veinfilling dolomite cement. In other cases it shows dedolomitization due to successive calcite replacement and cementation (Figure 13d) or filling fractures by partly dedolomitized dolomite cement into late diageneric calcite cementation (Figure 13f). This dedolomitization and its textural association to vein and fracture-filling dolomite cement is of local occurrences. It could be related in part to extra-basinal fluids, which had not equilibrated with host dolomite and incorporated during successive deformational phases (Budai, 1984).
Figure 12: All photomicrograph are crossed nicols. (a) Dolomudstone microfacies of extremely finely crystalline dolomite mosaic, Kz-2-3183.
(b) Dolomitic limestone (red), packstone to grainstone with grains largely preserved as calcite and selectively dolomitized intergranular cements and mud, Kz-16-2926.
(c) Fine crystalline dolomite partly replacing skeletal grain of bioclastic limestone, Kz-16-2916.
(d) Uniform finely crystalline dolomite mosaic of planar-s type with sparse microvugular porosity, Kz-1-2832.
(e) Finely crystalline mosaic of planar-s with common moldic porosity, Kz-11-2896.
(f) Dolomitic limestone of fine crystalline dolomite mosaic of planar-s type showing partial replacement of original bioclastic fabric, Kz-16-2918.
(g) Medium crystalline, planar-s type dolomite mosaic of uniform intercrystalline microporosity, Kz-1-2850.
(h) Planar-s type, medium crystalline dolomite mosaic with good uniform network of intercrystalline pores. Note the fracture is partially healed by dolomite, Kz-1-2835.
(i) Medium crystalline planar-e dolomite showing intercrystalline pores ranging to microvugs, Kz-16-2988.
Figure 13: All photomicrograph are crossed nicols. Scale bar for a to h is 0.5 mm.
(a) Planar-a coarse crystalline dolomite mosaic with inclusion-rich areas (cloudy clusters). Intercrystalline porosity is low, Kz-1-2869.
(b) Coarse crystalline, planar-e to planar-s dolomite with very good intercrystalline porosity, Kz-14-2930.
(c) Coarse crystalline, planar-e type with intercrystalline microvugs occasionally filled by anhydrite, Kz-14-2980.
(d) Coarse crystalline cement of vein-filling dolomite, which show partial dedolomitization, Kz-16-2967.
(e) Dolomite cement lining and filling moldic pores, Kz-14-2909.
(f) Coarse euhedral dolomite cement partially replacing calcite matrix, Kz-16-2973.
(g) Bimodal mosaic of fine and medium crystalline dolomite, Kz-1-2885.
(h) Bimodal dolomite mosaic ranging from medium to coarse crystalline. High intercrystalline porosity associated with finer part of the mosaic, Kz-16-2979.
(i) SEM photograph of the previous sample showing mixed modal dolomite crystal size.
Dolomite cement is similar to the saddle dolomite of Sibley and Gregg (1987). Sometimes it lines pore walls or partly fills moldic pores (Figure 13e), or completely fills pores (Figure 13g). It is characterized by uniform planar-e dolomite, which shows a size increase towards the center of the vuggy pore. In many cases dolomite cement is usually recognized in association with other types of dolomite forming a bimodal association.

**Bimodal Dolomite (D6):** This type of dolomite is characterized by a mixed mode of dolomite crystal sizes. It shows a mixed association of fine and medium crystalline mosaic (Figure 13g), or coarse and medium crystalline mosaic (Figures 13h and 13i); in both cases the finer part is characterized by anhedral to subhedral crystal shape, and the coarsest fraction is commonly euhedral.

## DOLOMITE AND DOLOMITIZATION

The vertical distribution of microfacies was plotted for each studied well and interval against the general lithology and porosity log to assist in correcting inferred lithologic characters as well as to help predict reservoir facies.

The dominant lithology of the Upper Qamchuqa (Mauddud) Formation is dolostone, which occurs in various types, fabrics, and association to the precursor limestone. Moreover, the dolostone directly controls the type, distribution, and origin of the reservoir characteristics.

The dolomitization of the Qamchuqa Group had been examined by many workers in an attempt to evaluate the reservoir quality. Al-Shakiry (1977) and Al-Sadooni (1978) gave very general description of the dolomite rocks. Sahar (1987) in his study of the Qamchuqa reservoir in northern Iraq suggested a late diagenetic origin in a mixing zone setting. Al-Shididi et al. (1995) gave a detailed account of the dolomitization in Jambour Field in the Kirkuk area. They showed that the dolomitization is part of a long diagenetic history of four different stages of which dolomitization produces varieties of dolomitic fabrics having taken place at a moderate burial depth. The mixing zone’s origin was reviewed by Werdi (2001) in his study of the pervasive dolomite of the Qamchuqa reservoir in Bai Hassan, Khabbaz and Jambour fields. The regional study of Sadooni and Al-Sharhan (2003) on the Mauddud Formation gave a detailed classification of the dolomite types. They grouped the dolomite into two major groups: (1) selective dolomitization, which includes post-fracture, post-stylolite, local source, water-controlled types; and (2) extensive dolomitization, which includes aphanitic, limpid, and saddle types. This classification is generally adopted here with considerable modification.

### Classification of the Dolomite

#### Early Diagenetic Dolomite

**Selective Dolomite (D1):** Selective dolomitization affects all types of carbonate facies and both matrix and grains. Dolomite usually occurs as disseminated floating rhombs of 10–100 µm size with variable percentages. It is similar to the floating rhombs fabric of Gregg and Sibley (1984) and Randazzo and Zakhos (1984), or the porphyrotopic type of Sibley and Gregg (1987). This type is interpreted to represent an early stage of dolomitization (Randazzo and Zakhos, 1984; Sibley and Gregg, 1987; Machel, 2004), and represented by different types of dolomitic limestone microfacies.

**Pervasive Dolomite (D2 and D3):** This dolomite is represented by the extensive and pervasive dolomite mosaic of different fabrics and crystal sizes of shallow burial but post-dates submarine cementation. Generally the crystal size ranges from 1.0 to > 100 µm and planar-e to planar-s morphology. The mosaic has unimodal distribution and usually retains a uniform intercrystalline pore network. This type of dolomite is equivalent to the sucrosic texture of Sibley (1982), or the sutured mosaic of Randazzo and Zakhos (1984). It is believed that these dolomites were developed after considerable burial and are of early diagenetic origin replacing subtidal to supratidal mudstones to wackestones (Amthor and Friedman, 1991), possibly during mixing of a meteoric phreatic wedge with marine waters (Machel, 2004).
Late Diagenetic Dolomite

Pervasive Dolomite (D4): This type is characterized by a coarsely crystalline dolomite mosaic of planar-e (D4), to planar-a fabrics. Original fabric is usually destroyed and occurrence of crystals possess a cloudy-centered clear rim textures may indicate the late replacive nature of dolomitization event. This type of dolomite, however, may occlude intercrystalline porosity (Amthor and Friedman, 1991). In some cases it occurs as nonplanar-a crystals, which usually display an interlocking fabric with coarsely crystalline mosaic. In this case it retains ghosts of the original fabric, which may indicate that dolomitizing fluids are Mg++ deficient to complete dolomitization (Amthor and Friedman, 1991; Machel, 2004). The paragenetic relations of this type of dolomite and its association to the surrounding rocks indicate late diagenetic processes (Sibley, 1982; Amthor and Friedman, 1991).

Dolomite Cement (D5): This is a late diagenetic dolomite with localized occurrences and commonly reported as vein filling, or fracture healing or pore fillings after late diagenetic calcite cementation. It is common as pore lining or filling with euhedral, equant, coarse dolomite crystals, which increase in size inwards. Other types of this dolomite cement include saddle dolomite of late diagenetic origin. The coarsely crystalline fabric, the microfracture healing, and the moldic pore filling nature of this dolomite all indicate a late diagenetic event in a deep-burial environment (Amthor and Friedman, 1991, Machel, 2004).

DOLOMITIZATION AND POROSITY TYPES EVALUATION

Due to the intensive dolomitization of the Upper Qamchuqa (Maudud) Formation the most effective porosity is secondary intercrystalline dolomite. Within the reservoir, dolomite interlayeres frequently alternate with undolomitized limestone and argillaceous limestone lithologies. Different types of porosity were recognized amongst the intercrystalline dolostone reservoirs. These are divided into two main groups: (1) fabric-selective porosity, which is controlled by the components of the original rock, and (2) non-fabric selective porosity where the pores are developed independent of original textures or fabric. The types of porosity associated with each group are discussed below.

Fabric Selective Porosity

Interparticle porosity is uncommon in the dolomitic parts and common in the limestone and dolomitic limestone rock types. Its occurrence, if any, is commonly in the packstones microfacies, which often escapes severe dolomitization (Figures 10b, 10c and 10d).

Intraskeletal porosity is common in both limestone and dolostone and when occurring it is associated with foraminifera especially Orbitolina chambers in foraminiferal bioclastic wackestone to packstone microfacies (Figure 12c). Pores are usually poorly connected and thereby ineffective.

Intercrystalline porosity is the most common and influential type and is classically developed in the sucrosic dolomite. Pores are found between crystals of dolostone mosaic of all sizes and forms. However, high and effective porosity is found to be associated with fine to medium crystalline dolostone classes of planar-e to planar-s type (Figures 12e, 12h and 12i). These types furnish the most uniform, well-connected network of dolostone intercrystalline pore system. Despite the importance of other types of porosity, this type seems to control the distribution of the potential reservoir subunits.

Moldic pores are the voids left by removal, usually through dissolution, of original carbonate grains. Shapes of the original grains especially bioclastic are preserved and help in identifying the original components. These pores, however, are not generally connected and permeability in this case is limited. Moldic porosity is common in dolostone rock types of the dolomudstone type of early diagenetic origin (Figure 14a).

Fenestral pores are ellipsoidal or deformed, and tend to be aligned parallel to laminations of the dolomitized stromatolitic boundstone facies (Figure 11e). This type of porosity also has restricted distribution.
Figure 14: All photomicrograph are crossed nicols.
(a) Dolomudstone microfacies with fine moldic pores, Kz-2-3188.
(b) Plug photo showing microvugs developed in sucrosic dolostone, Kz-2-3050.1.
(c) Microvugular porosity evolved from overdolomitization of moldic dolostone, Kz-11-2895.
(d) Microvugs resulting from recrystallization of finely crystalline dolomite into a coarse crystalline mosaic, Kz-1-2977.75.
(e) Plug photo of vugs resulting from dissolution of dolomite, Kz-13-3123.
(f) Irregular fracture system in tight dolomite, Kz-16-2968.
(g) Core photo showing a large vug in sucrose dolostone, Kz-1-2334.
(h) Oil-saturated stylolite in sucrose dolostone, Kz-14-3214.
(i) Stylolite in tight dolostone, Kz-16-2976.1.
Microvugs are small (< 2 mm in width) cavities or voids developed mainly by dissolution of original material (Figure 14b). In most cases these microvugs resulted from progressive dolomitization of moldic dolostone whereby the original molds were modified by additional dissolution and dolomite pore-filling cementation (Machel, 2004). In this case they usually occur as isolated small (< 1 mm in width) irregular pores (Figures 12e, 13e and 14c). In other cases, they formed enlarged intercrystalline pores (Figure 14d).

| Reservoir Unit | Thin-section Photo | Core | Depth (m) | Porosity (A) Core Porosity | Porosity (B) Core Porosity | Porosity (C) N-D Porosity |
|----------------|-------------------|------|-----------|---------------------------|---------------------------|--------------------------|
| A1             | 10d               |      | 2,905     |                           |                           |                          |
| A2             | 11b               |      | 2,905     |                           |                           |                          |
| A3             | 12b               |      | 2,905     |                           |                           |                          |
| A4             |                   |      | 2,905     |                           |                           |                          |
| A5             |                   |      | 2,905     |                           |                           |                          |
| A6             | 14f               |      | 2,905     |                           |                           |                          |
| B              |                   |      | 2,905     |                           |                           |                          |
| C              |                   |      | 2,905     |                           |                           |                          |

Figure 15: Comparisons of derived porosity from neutron-density (N-D) and sonic logs, with the core-measured porosities of the reservoir units in Well Kz-16.
Non-Fabric Selective Porosity

Fractures are produced in response to stress. They usually represent minor increases in secondary porosity but greatly increase permeability. Small fractures can be modified and enlarged into macrovugs upon dissolution (Figure 14e) or remain tight linear and/or irregular especially in dense limestones (Figure 14f). In other cases fractures are partly to completely healed by progressive dolomitization events (Figure 12h).

Macrovugs are single irregular large cavities characterized by relatively high porosity values but low permeability because the vugs are poorly/non connected. Macrovugs are also common in the dolostone units especially those with intensive, sucrose, coarse crystalline massive horizons, which links their origin to a possible dolomite dissolution (Figure 14g).

Stylolites are another secondary fabric independent of porosity types, which are developed in homogenously dolomitized rocks (Figure 14h). The uniform and tight texture of the sucrosic dolostone units seems to assist in the development of these deep-burial dissolution features (Figure 14i). Again these secondary porosity features, with their linear and zigzag pattern connecting isolated pores, enhance permeability as well as porosity.

Porosity Evaluation

The porosity and permeability data are measured from plugs of selected wells for various intervals (provided by Iraq North Oil Company) using Boyle’s Law. The core data were used for correlation with the predicted data calculated from logs of the studied wells for a validation check. The results show good correlation in the case of the selected Well Kz-16 (Figure 15). Some core data were depth
shifted to match log depths, and reference to certain microfacies and representative samples were indicated for the cored interval. Conventional logs for all wells are available including gamma-ray, density, neutron, sonic, spontaneous potential and resistivity.

The predicted porosities were measured from sonic, density, and neutron logs using the program “getdata 222.exe”, which is produced by GetData Software Development Company. The total derived log data were converted to digitized data sets with six points per meter (or 16 cm interval) for each log. Plotting of these porosity values against the litholog led to the prediction of several porosity subunits within the main lithologic units of the Upper Qamchuqa (Mauddud) Formation.

Two sections were constructed across the field along selected wells to show the correlation of the porosity subunits to the lithologic variation of the reservoir. The first one along the strike (Figure 17), the other is along the dip of the structure (Figure 18). Both cross-sections show that Unit A of the reservoir includes six important and distinctive porosity subunits, which are generally consistent in their distribution and thicknesses over the Khabbaz Field. These high porosity subunits are associated with the dolostone horizons and referred to from the top as A1 to A6. Subunits A1 and A2 have the highest average porosity values of 19%. The remaining subunits are of average porosity ranging between 15–17%. The drilled depths and thicknesses of these subunits and their average porosity

Figure 17: Correlation of porosity subunits of Unit A in wells along a dip cross section of the Khabbaz Field using neutron-density porosity logs.
Litho.
Unit | Reservoir Sub-Unit | Kz-1 | Kz-2 | Kz-4 | Kz-5 | Kz-3 | Kz-11 | Kz-13 | Kz-14 | Kz-16
--- | --- | --- | --- | --- | --- | --- | --- | --- | --- | ---
A1 | Intervals (m) | 2,752.4-2,754.9 | 3,025.9-3,027.4 | 2,979-2,985 | 2,832-2,834.7 | 3,202.5-3,206.7 | 2,885.3-2,890 | 2,806-2,810.5 | 2,811.6-2,815.6 | 2,905.7-2,907.3
| Thickness (m) | 2.5 | 1.5 | 6.0 | 2.7 | 4.2 | 4.7 | 4.5 | 4.0 | 1.6
| Porosity | 0.20 | 0.18 | 0.22 | 0.21 | 0.19 | 0.26 | 0.25 | 0.14 | 0.10
A2 | Intervals (m) | 2,756.8-2,765.4 | 3,032-3,037.8 | 2,985-2,995.4 | 2,838.4-2,844.3 | 3,208.3-3,219.2 | 2,894-2,899.7 | 2,814.2-2,820.7 | 2,817.9-2,824.5 | 2,911.3-2,917.6
| Thickness (m) | 8.6 | 5.8 | 10.4 | 5.9 | 10.9 | 5.7 | 6.5 | 6.6 | 6.3
| Porosity | 0.19 | 0.27 | 0.16 | 0.18 | 0.17 | 0.21 | 0.21 | 0.13 | 0.24 | 0.20
A3 | Intervals (m) | 2,772-2,779.9 | 3,044.2-3,052.9 | 3,000-3,004 | 2,849.6-2,857.6 | 3,219.2-3,228.4 | 2,906.1-2,908.4 | 2,826.7-2,835.8 | 2,826.3-2,828.2 | 2,923.8-2,932.1
| Thickness (m) | 7.9 | 8.7 | 4.0 | 8.0 | 9.2 | 2.3 | 9.1 | 1.7 | 8.3
| Porosity | 0.15 | 0.17 | 0.12 | 0.16 | 0.18 | 0.15 | 0.13 | 0.18 | 0.11
A4 | Intervals (m) | 2,787-2,798.6 | 3,059-3,069.2 | 3,014.2-3,028.4 | 2,863-2,873.5 | 3,235.4-3,244.9 | 2,919.8-2,931.6 | 2,842-2,854 | 2,829.2-2,850.4 | 2,939.1-2,948.3
| Thickness (m) | 11.8 | 10.2 | 14.2 | 10.5 | 9.5 | 11.8 | 12.0 | 21.2 | 9.2
| Porosity | 0.17 | 0.14 | 0.19 | 0.16 | 0.14 | 0.22 | 0.22 | 0.20 | 0.12
A5 | Intervals (m) | 2,799.2-2,810.5 | 3,069.4-3,081.9 | 3,028.4-3,037.2 | 2,873.5-2,885.5 | 2,931.6-2,940.1 | 2,854-2,866.7 | 2,850.9-2,862.8 | 2,949.3-2,959.8
| Thickness | 11.3 | 12.5 | 8.8 | 13.0 | 8.5 | 12.7 | 11.9 | 10.5
| Porosity | 0.17 | 0.17 | 0.14 | 0.16 | 0.19 | 0.20 | 0.15 | 0.15
A6 | Intervals (m) | 2,810.5-2,822.7 | 3,082-3,091.2 | 3,038.2-3,064.3 | 2,887.5-2,896.1 | 2,944.6-2,951.5 | 2,866.9-2,876.4 | 2,867.4-2,873.2 | 2,962-2,968.1
| Thickness | 12.2 | 9.2 | 26.1 | 8.6 | 6.9 | 9.5 | 5.8 | 6.1
| Porosity | 0.18 | 0.13 | 0.11 | 0.19 | 0.17 | 0.14 | 0.10 | 0.17

Table 2
Porosity subunits of lithologic Unit A, their drilled interval, thickness, and average porosity predicted from neutron-density combination logs.
### Table 3
Porosity subunits of lithologic units B and C, their drilled interval, thickness, and average porosity predicted from neutron-density combination logs

| Litho. Unit | Reservoir Sub-Unit | Kz-1 | Kz-2 | Kz-4 | Kz-5 | Kz-7 | Kz-11 | Kz-13 | Kz-14 | Kz16 |
|-------------|-------------------|------|------|------|------|------|-------|-------|-------|------|
| B1          | Intervals (m)     | 2.831-2.838 | 3.110-3.112 | 3.047-3.064 | 2.916.2-2.926.7 | ...... | 2.964.4-2.975.9 | 2.885.8-2.902.9 | 2.881.9-2.887.2 | 2.987.7-3.002 |
| Thickness (m) |                  | 7.0  | 2.0  | 17   | 10.5 | ...... | 11.5  | 17.1  | 5.3   | 14.3 |
| Porosity    |                   | 0.11 | 0.10 | 0.07 | 0.10 | ...... | 0.08  | 0.07  | 0.15  | 0.11 |
| B2          | Intervals (m)     | 2.840.6-2.863 | 3.127.7-3.131.1 | 3.070.5-3.084 | 2.930.1-2.937.5 | 2.931.9-2.934.2 | 2.977.9-2.983.4 | 2.906.5-2.911.3 | 2.893.1-2.895.2 | 3.014.9-3.018.5 |
| Thickness (m) |                  | 22.4 | 3.4  | 14   | 7.4  | 2.3   | 5.5   | 4.8   | 2.1   | 3.6  |
| Porosity    |                   | 0.10 | 0.11 | 0.06 | 0.07 | 0.11  | 0.11  | 0.15  | 0.08  | 0.10 |
| B3          | Intervals (m)     | 2.887.3-2.873.2 | 3.149.4-3.151.3 | 3.095.6-3.119.2 | 2.951-2.961 | 2.964.8-2.968.9 | 3.009.5-3.029.5 | 2.931.4-2.946.3 | 2.930.9-2.943.3 | 3.026.3-3.034.1 |
| Thickness (m) |                  | 5.9  | 1.9  | 23.6 | 18   | 4.1   | 19.0  | 14.9  | 12.4  | 7.8  |
| Porosity    |                   | 0.12 | 0.15 | 0.10 | 0.12 | 0.07  | 0.10  | 0.11  | 0.08  | 0.08 |
| C1          | Intervals (m)     | 2.888.7-2.894.9 | 3.188.2-3.196.8 | 3.120.4-3.138.6 | 2.971.4-2.973.6 | 2.983.6-2.989.4 | 3.029.6-3.037.5 | 2.951-2.954 | 2.957.3-2.959.3 | 3.044.3-3.046.1 |
| Thickness (m) |                  | 6.2  | 8.6  | 18.2 | 2.2  | 5.8   | 7.9   | 3.0   | 2.0   | 1.8  |
| Porosity    |                   | 0.12 | 0.10 | 0.08 | 0.12 | 0.03  | 0.09  | 0.08  | 0.11  | 0.10 |

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**Figure 18:** Cross-plot of intercrystalline (interparticle) porosity and permeability of a dolostone in relations to the crystal-size classes of Lucia (1995) in Lucia (2004).
Figure 19: Cross-plot of intercrystalline (interparticle) porosity and permeability of dolostone porosity subunits of Unit A in Well Kz-16 of Khabbaz Field showing their general association with crystal sizes of Class 2 and Class 3. (Port size means pore throat radius and refer to R35 parameter).
Figure 20: Porosity of units B and C in wells along a strike cross section in the Khabbaz Field using neutron-density porosity logs.
**Upper Qamchuqa Formation**

| Formation | Lithology          | Unit | Kz-2 Porosity | Kz-1 Porosity | Kz-5 Porosity |
|-----------|--------------------|------|---------------|---------------|---------------|
|           |                    |      | Depth (m)     | Depth (m)     | Depth (m)     |
|           |                    |      | 3.090         | 2.020         | 2.095         |
|           |                    |      | 3.100         | 2.030         | 2.100         |
|           |                    |      | 3.110         | 2.040         | 2.110         |
|           |                    |      | 3.120         | 2.050         | 2.120         |
|           |                    |      | 3.130         | 2.060         | 2.130         |
|           |                    |      | 3.140         | 2.070         | 2.140         |
|           |                    |      | 3.150         | 2.080         | 2.150         |
|           |                    |      | 3.160         | 2.090         | 2.160         |

**Figure 21:** Porosity of units B and C in wells along a dip cross section in the Khabbaz Field using neutron-density porosity logs.

- Dolomite, Dolomitic limestone, Marl, Shale
- Dolomite, Dolomitic limestone
CONCLUSIONS

The Upper Qamchuqa (Mauddud) Formation in the Khabbaz Field of northern Iraq mainly consists of alternating dolostone, dolomitic limestone, and limestone with subordinate amount of argillaceous limestone, dolomitic argillaceous limestone and calcareous shale. These lithologies can be grouped into three lithologic units. Parts of the reservoir are associated with the upper lithologic unit, in particular the dolostone horizons, which are characterized by sucrose dolomite of various crystal sizes and forms with high intercrystalline porosity. The highly porous layers, however, are linked within the pore system by fine- to medium-crystalline mosaic of planar-e to planar-s type. Fabric interrelations and paragenetic associations of the examined dolomite indicate development through long and multiple phases of diagenetic evolution, the influential types however, developed during moderate to deep burial.

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