



## Mechanism of Hydrothermal Dolomitization in Shallow and Deep Burial Diagenesis: Implications for Hydrocarbon Migration in the Cretaceous Formation, NE-Iraq

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### ABSTRACT

Hydrothermal dolomitization (HTD) is a major diagenetic process of carbonate rocks, significantly impacting reservoir storage, reservoir quantity, and hydrocarbon migration. This paper adds a new insight in contrasting HTD mechanisms under shallow and subsurface deep settings, and focuses on dolomite characterization and properties in the Cretaceous Qamchuqa Formation. Shallow burial HTD produced four phases of saddle dolomites, SDI, SDII, SDIII, and SDIV. The deep burial HTD at least shows one type of saddle dolomitization phase, "SDs". The hydrothermal dolomitization in a shallow system, which is related to an open system, offers growth of large, well-formed dolomite crystals, forming massive dolomite bodies due to high fluid-rock interaction. In contrast, deep burial HTD occurring under elevated temperature is primarily driven by low fluid-rock interaction in a semi-open system. The semi-open system requires a high pressure that deformed the SD formation, which coincides with an increasing of the vertical stress. As a result, the SD formation is a transfer from a ductile phase to a brittle deformation, and led to an in-situ saddle brecciation, facilitating the creation of a conduit for fluid/hydrocarbon migration.

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# آلية الدلمة الحرارية المائية في عملية النشوء والتطور الضحلة والعميقة: الاستدلال على هجرة الهيدروكربونات في تكوين العصر الطباشيري، شمال شرق العراق

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معلومات الاشارة	الملخص
تاريخ الاستلام: 03- فبراير - 2025	تعد عملية الدولوميت الحرارية المائية عملية تشخيصية رئيسية للصخور الكربوناتيّة، وتؤثر بشكل كبير على تخزين الخزانات وكميتها وهجرة الهيدروكربونات. تضيف هذا البحث نظرة ثاقبة جديدة في مقارنة آليات عملية الدولوميت الحرارية المائية في البيئات الضحلة والعميقة تحت السطح، وتركز على وصف الدولوميت وخصائصه في تكوين قمجوكا الطباشيري. أنتجت عملية الدولوميت الحرارية المائية للدفن أربع مراحل من الدولوميت السرجي: SDI و SDII و SDIII و SDIV. أظهرت عملية الدولوميت الحرارية المائية للدفن العميق على الأقل نوعاً واحداً من مراحل الدولوميت السرجي SDS. توفر عملية الدولوميت الحرارية المائية في النظام الضحل، والتي ترتبط بنظام مفتوح، نمو بلورات دولوميت كبيرة جيدة التكوين، وتشكل أجسام دولوميت ضخمة بسبب التفاعل العالي بين السوائل والصخور. على النقيض من ذلك، فإن عملية الدولوميت الحرارية المائية التي تحدث في درجات حرارة مرتفعة، مدفوعة في المقام الأول بتفاعل منخفض بين السوائل والصخور في نظام شبه مفتوح. يتطلب النظام شبه المفتوح ضغطاً عالياً يؤدي إلى تشوه تكوين SD، والذي يتزامن مع زيادة الإجهاد الرأسية. ونتيجة لذلك، فإن تكوين SD هو انتقال من مرحلة بلاستيكية إلى الحالة الهشة، مما يؤدي إلى كسر سرج في الموقع، مما يسهل إنشاء قناة لهجرة السوائل/الهيدروكربون.
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## Introduction

In recent years, petroleum exploration has progressed from shallow to deep reservoirs within worldwide petroliferous basins. Carbonates serve as the primary reservoirs for petroleum exploration, drilling, and production. Carbonate reservoirs comprise porous dolomites, which are partially of hydrothermal origin (Davies and Smith, 2006; Salih et al., 2019a). To develop a model for the dolomitization process, particularly hydrothermal dolomitization, which may be of major economic importance (Shah et al., 2012), Comprehensive integration tools are necessary. Hydrothermal dolomitization (HTD) is typically influenced by basement faults and is extensively examined as a unique phenomenon on a worldwide scale (Davies and Smith, 2006; Barale et al., 2016; Salih et al., 2019b; Salih, 2023; Koeshidayatullah et al., 2020). HTD generally occurs in extensional tectonic settings and can result in the development of remarkable porosity oil and gas reserves (Friedman, 2007). Meanwhile, the hydrothermal impact on carbonate reservoirs is complex, including constructive and destructive of any texture, including fracturing (Slater and Smith, 2012; Zhou et al., 2018). Hydrothermal fluids infiltrate the reservoirs, inducing substantial fluid/rock interaction that ultimately influences reservoir growth (Yang et al., 2024). The dissolution of carbonate rocks caused by these fluids

normally occurred in the vicinity of migration pathways (faults or others), which can enhance good porosity/permeability zones leading to valuable reservoirs (Liu et al., 2017). The hydrothermal alteration of carbonates has been documented in various basins, and its characterization is crucial for distinguishing conventional diagenetic evolution from hydrothermal processes that may positively or negatively influence the quality and performance of reservoirs (Machel et al., 2004; Davies and Smith, 2006; Wang et al., 2025).

Saddle dolomite is considered one of the major products and a key indicator of hydrothermal fluid involvement in a late diagenesis setting (Davies and Smith, 2006, Du et al., 2018). Variations in temperature and Mg<sup>2+</sup> concentrations of the hydrothermal fluids result in diverse textures and filling sequences of dolomite precipitation (Guo et al., 2021). The saddle dolomites in the subsurface are linked to the matrix dolomites, which include two genetically distinct varieties: One is silt-fine crystalline dolomites (dolomudstones), resulting from early seepage-reflux dolomitization, for example, reported by Guo et al. (2021) in the Late Cambrian seawater in Tarim Basin, China. Recently, the origin of the HT dolomitization fluids in carbonate reservoirs attracted many researchers to characterize the diagenetic fluids in heterogeneous carbonate rocks. Many scholars provided a deep understanding of sources and paleo-temperature of HT fluids based on the geochemical data (Salih et al., 2021, Su et al., 2021, Li et al., 2024, Xu et al., 2025). The sources derived from high temperature and brine fluids, related to evaporative rocks (Carpenter, 1978, Zhang et al., 2009, Azmy and Conliffe, 2010), reflux of cold-meteoritic fluids (Iannace et al., 2012) or microbial activity in environments conducive to sulfate-reducing species (Vasconcelos and McKenzie, 1997, Bontognali et al., 2010). However, the origin of HTD fluids remains debatable. Several researchers follow the abovementioned fluid sources to establish the paragenetic sequence (Salih et al., 2021, Li et al., 2024).

Paragenesis serves as a crucial indicator for understanding the intricate diagenetic phases, referred to as "subsequent events," occurring during the dolomitization process under subsurface settings. Comprehensive optical microscopy and supporting results from oxygen-carbon isotopes of saddle dolomite demonstrate the influence of hot fluids under the subsurface resulting from deep burial conditions. The fluids are directed through the fractures and pore spaces, corresponding with hydrocarbon migration (Salih, 2023). The dolomitization pathway significantly influences the formation, development, and distribution of dolomite, as well as dolomite reservoirs, resulting in an impact on the determination of exploration directions in targeted oil and gas fields (Shen et al., 2022). The Lower Cretaceous Qamchuqa Formation represents a significant reservoir in the Middle East, associated with the development of fracturing and dolomitization processes (Salih, 2022). The initial porosity of sedimentary successions filling a basin is controlled by depositional processes. To develop a diagenetic setting model in the Qamchuqa Formation, it is crucial to comprehend the origin and timing of fluid movement through the sedimentary rocks.

The Upper Qamchuqa Formation in NE Iraq is part of an extensive dolomitized carbonate platform developed during the Barremian – Albian over the passive continental margin of NE Arabia. The Hydrothermal (HT) in the Qamchuqa Formation has been studied well in exposed sections from the Kirkuk oil field, and might have a significant influence on reservoir petrophysics and quality (Salih, 2023). Therefore, HT is essential for carbonate reservoir formation, which could increase or decrease the HT fluid-rock interaction. This interaction usually produces typical saddle dolomites in hot setting conditions. To conduct any evaluation for secondary porosity in a reservoir, a deep petrographical observation has been carried out to characterize the diagenesis and establish the whole paragenesis to qualify the reservoir enhancement. The previous scholars have studied well the characteristics of HTD in shallow diagenetic settings, but not extended them to deep burial settings. Therefore, the novelty of our study is to show and present a comprehensive set of data comparing HTD in shallow and deep subsurface conditions. In brief, understanding the HT interaction with host reservoir rocks will

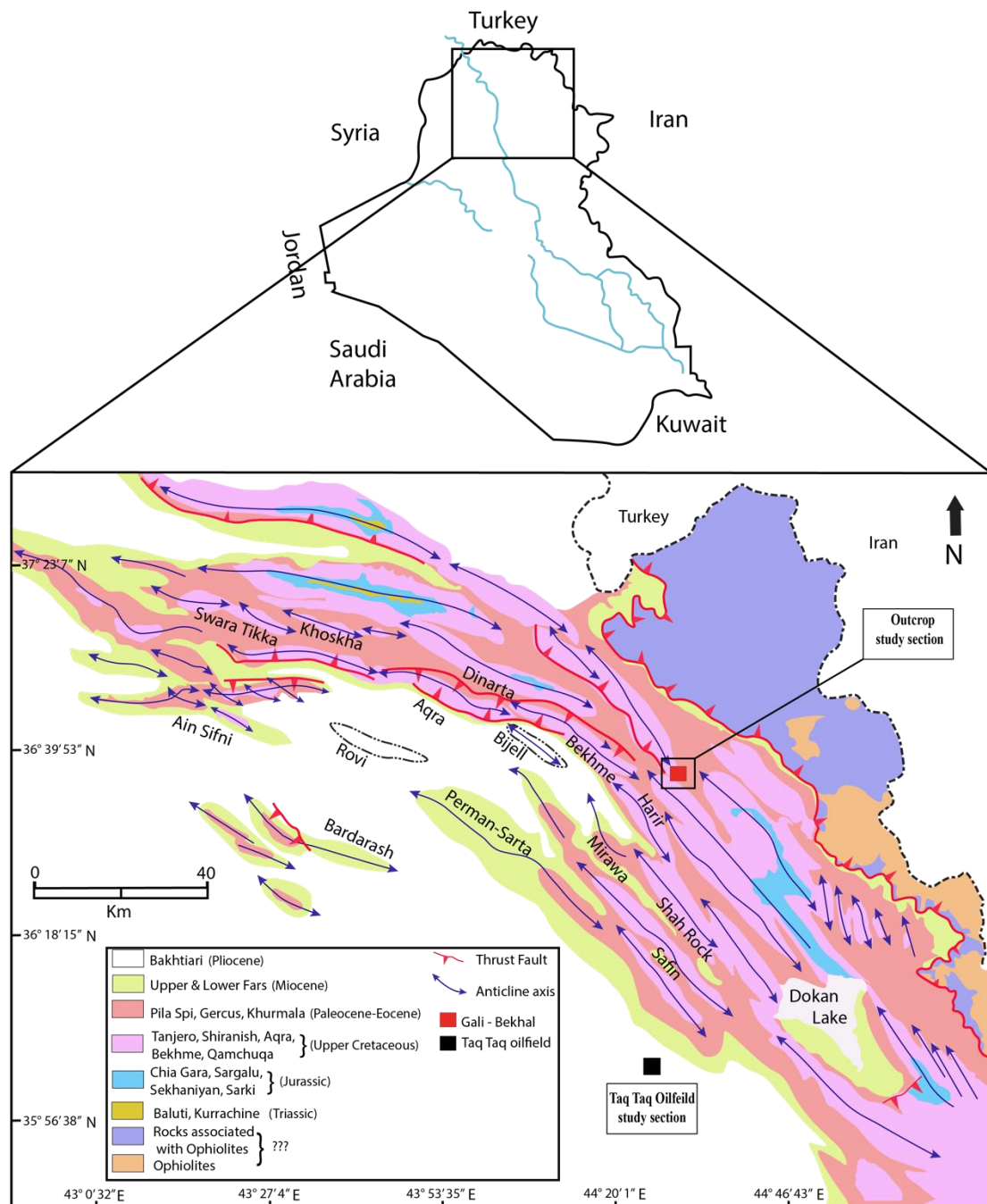
define the target in deep settings wells during exploration and even throughout the whole lifetime of any petroleum field.

### **Geological and geo-tectonic setting**

The Early Cretaceous Arabian platform comprises a substantial sequence of dolomites and limestones. This sequence covers the majority of Iraq, a portion of southwestern Iran, the Arabian Gulf, and Saudi Arabia. In the Albian period, the Qamchuqa Formation was formed in a shallow water, low-energy lagoonal environment covering Dohuk, Mosul, Erbil, and Kirkuk. (Buday et al., 1980, English et al., 2015), with several sub-environments such as tidal flat, reef (barrier reef), lagoon, shoal, patch reef, and fore slope to ramp environments (Al-Juboury et al., 2006, Ameen, 2008; Al-Qayim et al., 2010). The Qamchuqa formation is one of the main reservoir rocks and displays a highly intercrystalline porosity with important large vuggy porosity linked to fracturing (Sadooni and Alsharhan, 2003).

The Taq Taq oilfield lies within the Zagros Sedimentary Basin along the Zagros thrust belt, which is a world-class hydrocarbon province located on the NE margin of the Arabian Platform. The structural characteristics in this field consist of an asymmetric double plunging anticline. The structure trends NW-SE, parallel to the main axis of the Zagros fold belt, and the structures at the Khabbaz, Chemchemal, Kirkuk, and Bai Hassan fields (Aqrabi et al., 2010). To the NE, a narrow syncline separates the Haibat Sultan ridge of the Khalakan anticline from the Taq Taq structure, with outcrop of Miocene, Eocene, Paleocene, and Late Cretaceous units. The basin is a characteristic foreland compressional basin created by the collision of the Afro-Arabian and Euro-Asian plates during the Late Cretaceous and Cenozoic times. The Qamchuqa Formation is the main reservoir at the Taq Taq oilfield and presents different thicknesses between 213 m and 219 m. It overlies the Cenomanian Dokan Formation (Al-Qayim and Rashid, 2012).

The Qamchuqa Formation at the Gali Ali Bag Gorge is located in the High Folded Zone within the NW segment of the Zagros Fold Thrust Belt (Al-Kadhimi et al., 1996, Machel et al., 2004, Jassim and Goff, 2006). This zone is considered to be a vast number of sub-parallel high amplitude anticlines and synclines. The fold trends exhibit an abrupt variation from NW-SE trend in the east of the study area to E-W oriented folds, curved trends toward the western part of the Zagros basin within the part of Zagros Fold Thrust Belt, accompanied by stresses that generated many thrust and transverse faults and fault-related folds. Moreover, several gorges in the high folded zone occur along the traverse normal and strike-slip faults (Alavi, 2004). The Lower Cretaceous Qamchuqa Formation (Barremian to Early Cenomanian) is a significant rock unit in terms of outcrop, thickness, and regional distribution in the NE Iraq-Kurdistan Region (Sissakian et al., 2015). In the Gali Ali Bag gorge, the exposure carbonates formed of several hundred meters of neritic, thickly-bedded shallow water platform settings of the Qamchuqa Formation (Fig. 1). The study area is located in the NW plunge of Korak anticline in High Folded Zone in NE-Iraq (Fig. 1). The Qamchuqa Formation is considered as a giant Cretaceous reservoir in Taq Taq and Kirkuk Oilfields, thickness is estimated to be nearly 600 m in the main reservoir region. This region is affected by diagenetic fluids of highly fractured and faulted dolostones of the Lower Cretaceous carbonates of the Qamchuqa Formation in the subsurface.



**Fig 1.** The geological and tectonic map illustrates the precise location of the studied sections, depicted as a (Green and black cubic) (Salih et al., 2019a).

## Materials and Method

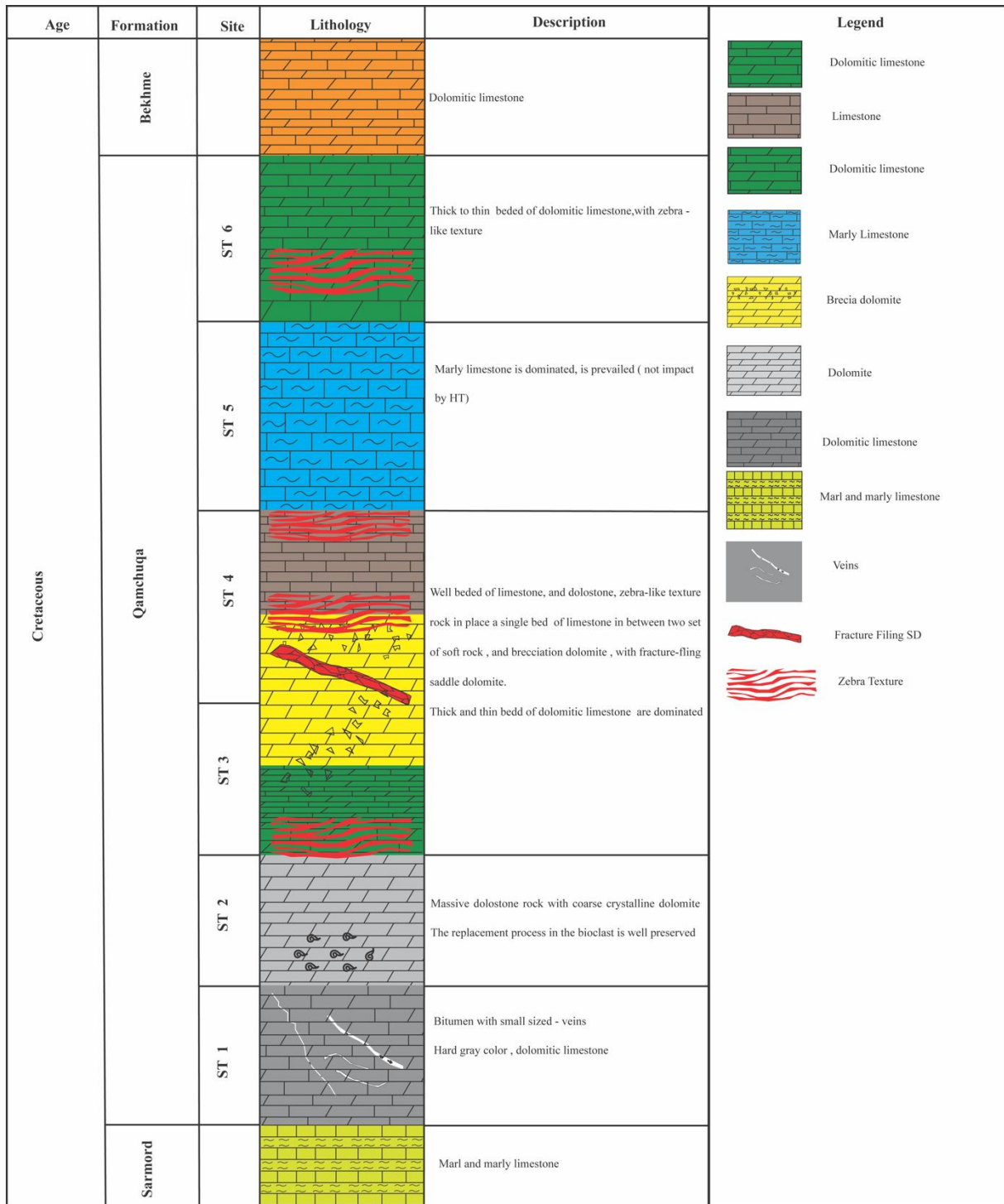
Extensive fieldwork was carried out at the studied outcrops in the Gali-Bekhal region (Fig. 1). Twenty-two samples belonging to the Qamchuqa Formation were collected from dolomites, limestones, and zebra dolomites to infer the direction of the hydrothermal fluid body that caused the dissolution and also the cementation at the origin of significant variations of diagenesis, which influenced the reservoir quality. In well 16 at Taq Taq Oilfield, 11 core samples were also collected from the Qamchuqa Formation. Thirty-nine thin sections (need a stratigraphic log of the well with location of samples and thin sections), prepared within the standard thickness of around 30  $\mu\text{m}$ , for classical petrographic analysis (facies and diagenesis) utilizing an optical microscope (LEICA DM2700P), were utilized at the scientific research center in Soran University, Erbil, Iraq

## Field observation

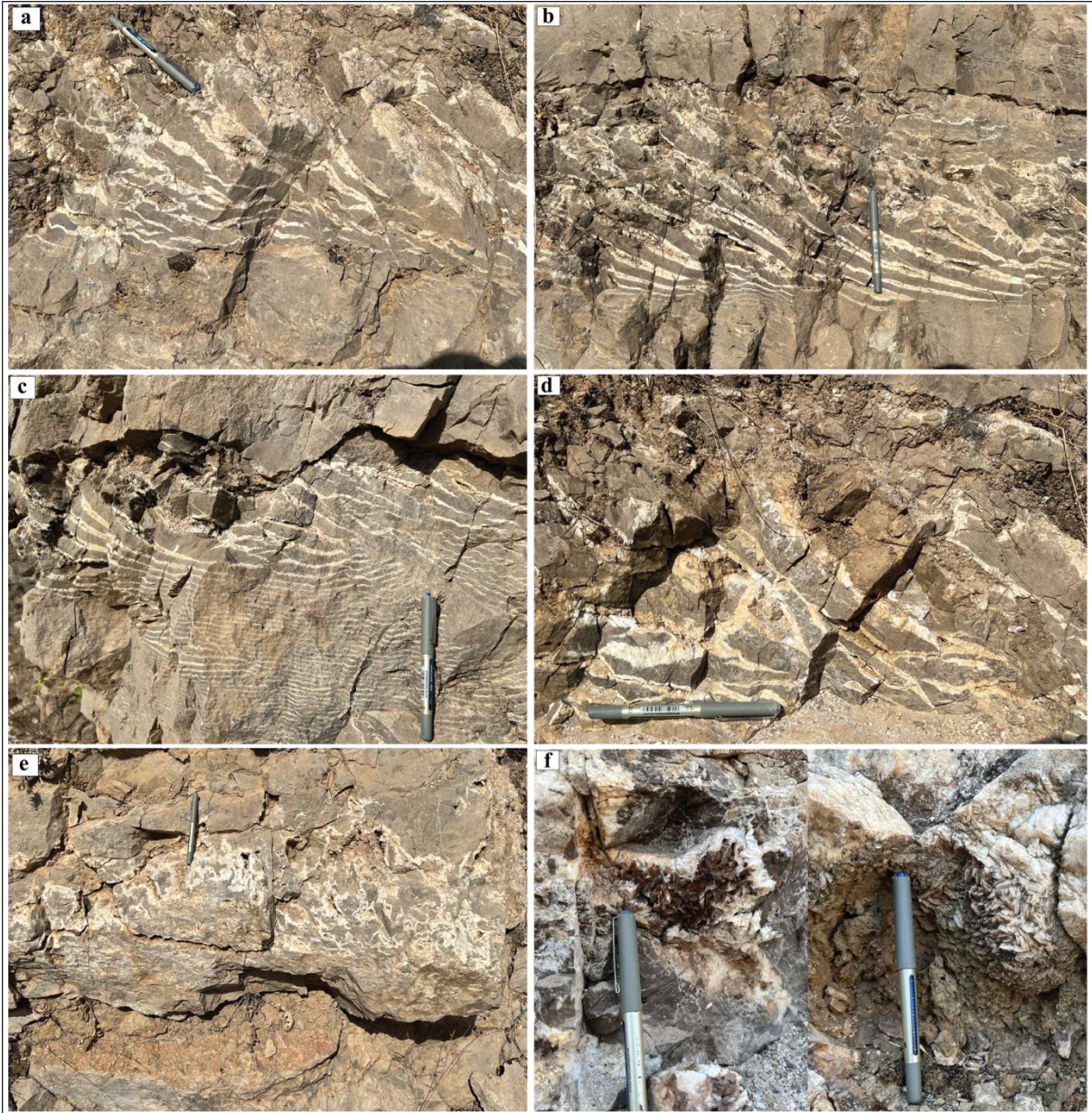
The Qamchuqa Cretaceous formation presents a diverse geological facies and textures, characterized by a variety of sedimentary and diagenetic processes influenced by tectonic activities. In the studied regions, such as the Zagros Foreland Basin in Iraq, the Cretaceous Qamchuqa Formation has been extensively altered and produced a complex diagenetic history. The main alteration is likely caused by hydro-fracturing and hydrothermal fluids (Fig. 2). Field observations in the studied section (Gali-Bekhal) frequently show an intermittent occurrence of zebra-like texture, hydro-brecciation texture, and voids and fractures-filling saddle dolomites following the horizontal direction of the formation along the whole road direction from Gali to Bekhal areas.

Six sites were sampled and investigated intensively for tracing the distribution of hydrothermal fluids and hydrothermal dolomitization (Fig. 3a-f). Starting from Gali, site 1 is started with dolomitic limestone and dolostone rocks, the rocks in places are cross-cut by several vines and small-sized fractures, and vuggy structures are also observed. The rapid changes were recorded in Site 2, where very coarse calcite crystalline cementation filled the chambers and void spaces inside the bioclasts, like rudists, forams, bryozoan, etc. Besides the cementation, the replacement process within the matrix of the rock is more prevalent and dominant. Obviously, in Site 3, the alternative occurrence of white and gray bands, named zebra texture, is the main signature that appears in this site. The white band-like layers are the fractures giving a parallel appearance to the bedding planes, these fractures filled by coarse crystalline dolomite, named saddle dolomite (Fig. 3a-d). The new HT indicator in Site 4 is the hydro-fracturing features, the host dolomite grains are floating within this texture and cemented by saddle grains (Fig. 3e-f). Site 5 is lacking any traces of hit dolomitizing fluids, only represented by host limestone and Marly limestone as well. While at the final Site (6), the HT fluid signatures again occurred, mostly zebra texture interbedded with thick-bedded dolomitic limestone. The Qamchuqa Formation at Taq Taq oilfield lacks any textural features of HT diagenetic fluids under a subsurface deep setting.

In the context of the high folded zone region of NE-Iraq, the Cretaceous formations, particularly the Qamchuqa Formation, have been identified as significant reservoirs for the reasons behind the undiscovered large part of oil and gas resources for this formation. The stratigraphic and diagenetic complexity and the presence of various lithologies and textures suggest a dynamic depositional and diagenetic environment influenced by both hydrothermal and tectonic processes during the Cretaceous interval.



**Fig 2. Columnar litho-facies of Qamchuqa Formation and the contact boundaries in the Gali-Bekhal section (not to scale).**



**Fig. 3. Field photographs showing Qamchuqa Formation: (a) Massive dolomitic limestone affected by hydrothermal dolomitization, causing a zebra-like texture and hydro-fracture, (b, c) Fracture filling saddle dolomite.**

## Result and Discussion

### Carbonate microfacies

Mudstone microfacies contains benthic foraminifers (miliolids) and is partly dolomitized. It is the predominant facies in the lower and middle parts of the Qamchuqa Formation, which consists mainly of micrite, slightly influenced by recrystallization processes; the percentage of grains is less than 10%; all the contained grains belong to skeletal grains and have been documented by Salih (2022). This microfacies was identified in both outcrop and subsurface samples.

The second microfacies is wackestone, which is characterized by sand-sized bioclasts, varying between 10% to 45%, floated in micritic groundmass. The skeletal grains are represented by miliolids, globogirina, and foraminiferal, with dominate of pressure solution. In the core samples subsurface, the fossiliferous wackestone is also recognized as a marine facies. No clear evidence of porosity is visible, suggesting it might have undergone compaction or cementation. While episodic hydrocarbon migration linked to hydrothermal fluids is

predominantly observed in the Qamchuqa Formation (e.g., Salih, 2023). This diagenetic stage significantly influences reservoir porous media, which demonstrates the enhancement of pore spaces following the injection of host limestone with hot fluids. Packstone is the major facies in the Qamchuqa Formation and consists mostly of Globogerina, Rotalina, miliolids, bioclasts, and foraminiferal limestones. The grains are broken down by physical compaction and cement formation, and recognized within the chamber of miliolid. The boundstone microfacies is represented by bryozoa and rudist clasts, and other secondary components are gastropod, rotaliids, and miliolids (Fig. 4a-d). The rudists are filled with cement (silica or dolomite) and are cut by stylolites.

### **Diagenetic Facies**

#### **Micritization and Microspar**

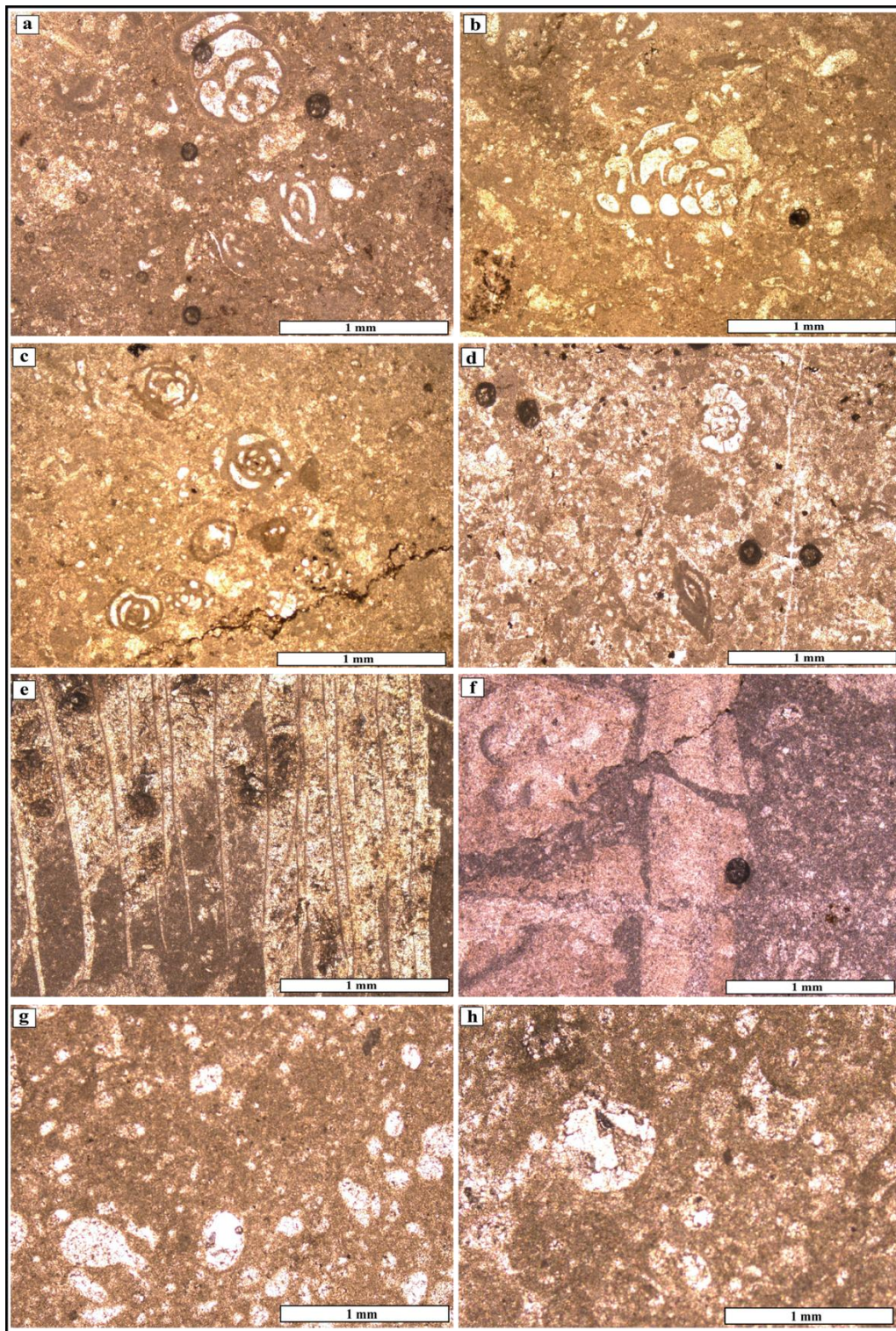
Micritization is an early diagenetic facies formed by the activity of (micro)organisms. Due to the small size of grains in the micrite, the identification of their origin is difficult. Dunham (1962) selected 0.02mm as a boundary between sand and mud. The present study shows that micritization in the surface preferentially affects the thin edge of foraminifera (Globigerina and miliolids). The early diagenesis of the micritic groundmass that was changed by the replacement process still preserved the remnant of the original facies of mudstone. The facies are commonly linked to early fractures and stylolitization. Micritization is a fundamental diagenetic process characteristic of the shallow marine environment (Flügel, 2004). This process leads to destroying the original structures of the grains. Continual micritization leads to the formation of carbonate muds (Flügel, 2004). The micrite is mostly slightly affected by early dolomitization, and these grains undergo chemical compaction, which causes the pressure solution. The packstone microfacies consists of a micrite matrix that is affected by neomorphism to microspar.

#### **Microspar**

Microspar is the early diagenetic stage with very fine grains, and the crystal size is less than 10 $\mu$ m, and is dominated by closely packed grains. Microspar can be distinguished from micrite by its larger size and clarity, and from carbonate grains by their crystal shapes and lack of internal texture (Flügel, 2004). Longman (1977) has been suggested that the main factor affecting microsparite formation is the Mg ions, which are removed by meteoric water, forming microsparite and sparry calcite.

#### **Equant calcite cement**

This cement is one of the most abundant cements in the Qamchuqa Formation. This cement occludes fracture or vein spaces, with crystal sizes slightly larger than 100 micrometers, and this cement usually fills the void spaces within the miliolid shell. This equant cement is characterized by euhedral to subhedral crystals, and the crystals exhibit high relief. The equant cement crystals are relatively large compared to the surrounding matrix, indicating later-stage cementation compared to the microspar phase, and the crystals display bright interference colors, suggesting they are likely composed of calcite cement. Equant cement is formed in early diagenesis after the neomorphism of microspar. This type of cement is found in meteoric-vadose, meteoric-phreatic, and shallow burial environments, while originating from the re-crystallization of preexisting cements (Flügel, 2004).



**Fig. 4. (a-h) Photomicrographs showing carbonate depositional microfacies: the main components are micrite and skeletal grains that are considered the majority of the grains, including *globigerina*, *rotalina*, *miliolids*, and other bioclasts.**

### **Early Dolomitizing fluids**

The following diagenetic phases are recognized in both sections, outcrop and core samples. The description and classification of dolomite grains were based on Sibley and Gregg (1987):

### **Anhedral replacive dolomitization (DI, DI<sub>s</sub>)**

The dolomite of this type, surface dolomite (DI) and subsurface dolomite (DI<sub>s</sub>), is the first phase that belong to early dolomitization, characterized by fine, non- or anhedral, non-planar dolomite crystals (ranging from 130 to 320 μm) observed from Gali-Bekhal section (DI) (Fig. 5a, b) and Taq Taq well section (DI<sub>s</sub>) (Fig. 5c, d).

The same properties of anhedral dolomite crystals having the same characterization in subsurface sample (DI<sub>s</sub>). Replacive dolomite (DI<sub>s</sub>) is the earlier diagenetic phase consist of a very fine crystalline dolomite replacing partially the wackstone microfacies. Intercrystalline porosity is often found associated with the (DI<sub>s</sub>) that filing with hydrocarbon. The same replacive dolomite is reported in the literature and characterized by very fine- to medium-crystalline, planar-subhedral to nonplanar-anhedral texture (Györi et al., 2020).The remnants of precursor micrite or bioclasts were observed in the replacive dolomite, which suggests that the replacive phase was not completely fabric-destructive, and both micrite and bioclasts dissolved before dolomitization and reprecipitated as an early cement in the micrite, and these phases were subsequently replaced by anhedral dolomite.

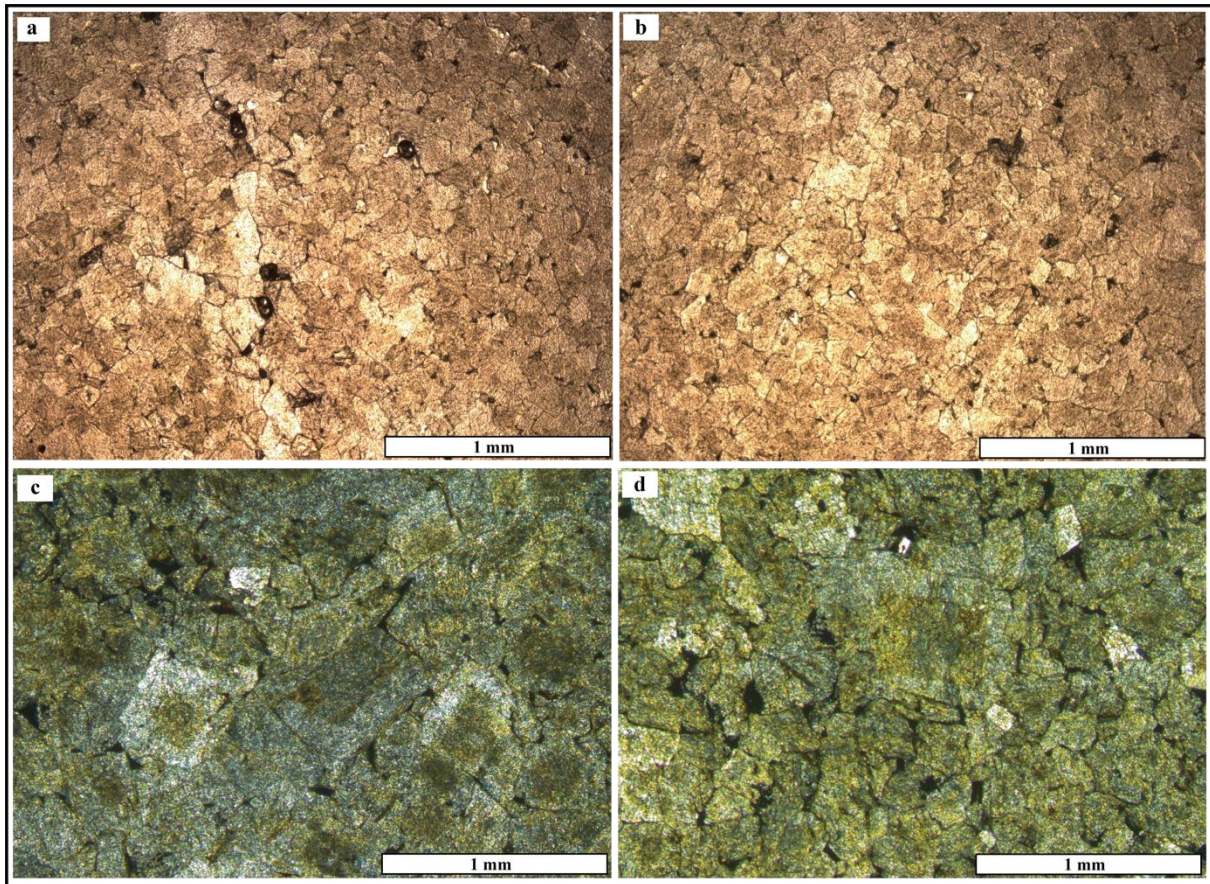
### **Subhedral growing dolomitization (DII-surface, DII<sub>s</sub>-subsurface)**

This phase of dolomite grains replaced the microspare in aggrading growth, and precipitated in a condition of non-hydrothermal dolomitization as they lack the definition of saddle dolomite characteristics, which also shown by its textural evolution and crystal properties. This type of dolomite in both sections post-date the previous replacive dolomite. DII and DII<sub>s</sub> phases are characterized by fine-grained, subhedral dolomite crystals (ranging from 120 to 300 μm) originated from a shallow depth and considered as an early diagenetic phase (Fig. 5a, b and c). DII<sub>s</sub> also appear in pore-space and has the same properties as DII. DII<sub>s</sub> dolomite crystals show a preservation of the original facies of the rock despite there being no remaining micrite develop, and sometimes known as mimicking or mimetic dolomites.

The subhedral dolomitization in the subsurface depth shows the complete replacement of dolomite characterized by very tight and compact dolomitization due to burial weight, with obvious zonation texture on the surface of crystals. The solubility boundaries between the grains, “the contact between compacted grains of dolomite,” indicate that the porosity and permeability are decreasing because the grains are very close and pressure increases due to burial weight.

### **Euhedral dolomite DIII-surface and DIII<sub>s</sub>-subsurface**

The dolomite exhibits a typical rhombohedral shape between anhedral and subhedral dolomite crystals (up to 200 μm) in both exposed (Fig.5a) and core sections (Fig. 5c, d). In cases, this rhombohedral dolomite is considered the replacement process, and the tiny crystals of dolomite can be seen floating in a micritic matrix, which indicates a high number of nucleation points and/or high supersaturation. Similar dolomitization patterns in sediment succession have been described in Jurassic and Cretaceous carbonates from France, Switzerland, and Italy (Rameil, 2008, Iannace et al., 2013). The crystal size varies slightly, with most of the crystals appearing to be medium and coarse-grained. The co-occurrence of pre-dated dolomites (DI and DII) suggests that dolomite likely formed as early diagenetic dolomitization; however, the amount of nucleation of dolomite rhombs is quite low, therefore, the replacement process becomes limited at this stage. This texture indicates that the dolomite was not significantly recrystallized or changed by subsequent hydrothermal processes, maintaining its initial rhombohedral form. These textures are typically observed in shallow marine to subtidal environments where micrite facies predominate, and dolomitization has been documented by Ramadan (2014).



**Fig. 5. Photomicrographs (a and b) showing the early dolomitization processes in outcrop sample; (c and d) illustrate the early dolomitization under subsurface setting.**

### Late Dolomitizing fluids

The following phases of dolomite postdated the early diagenetic processes in the Cretaceous reservoir formations (Qamchuqa and Bekhme formations):

Elongate-sized dolomite crystals are the first and earliest saddle dolomite formation ( $SD_I$ ); this type of dolomite predominantly occurs in the alternating white and dark bands from zebra-like texture (Fig. 3a-d). while the next phase of saddle dolomite ( $SD_{II}$ ), dirty dolomite, or dark saddle dolomite postdates the  $SD_I$  and predates the  $SD_{III}$ .  $SD_{III}$  is considered translucent saddle dolomite ( $SD_{III}$ ). The dolomitization fluids produced a final phase of coarse-crystalline saddle dolomite ( $SD_{IV}$ ). The late dolomitization in the Taq Taq subsurface section, at least one phase of saddle dolomite was identified ( $SD_s$ ). In addition to saddle dolomite, a radiaxial dolomite cement filling the pore spaces and fractures is also considered as a product of the late diagenetic stage.

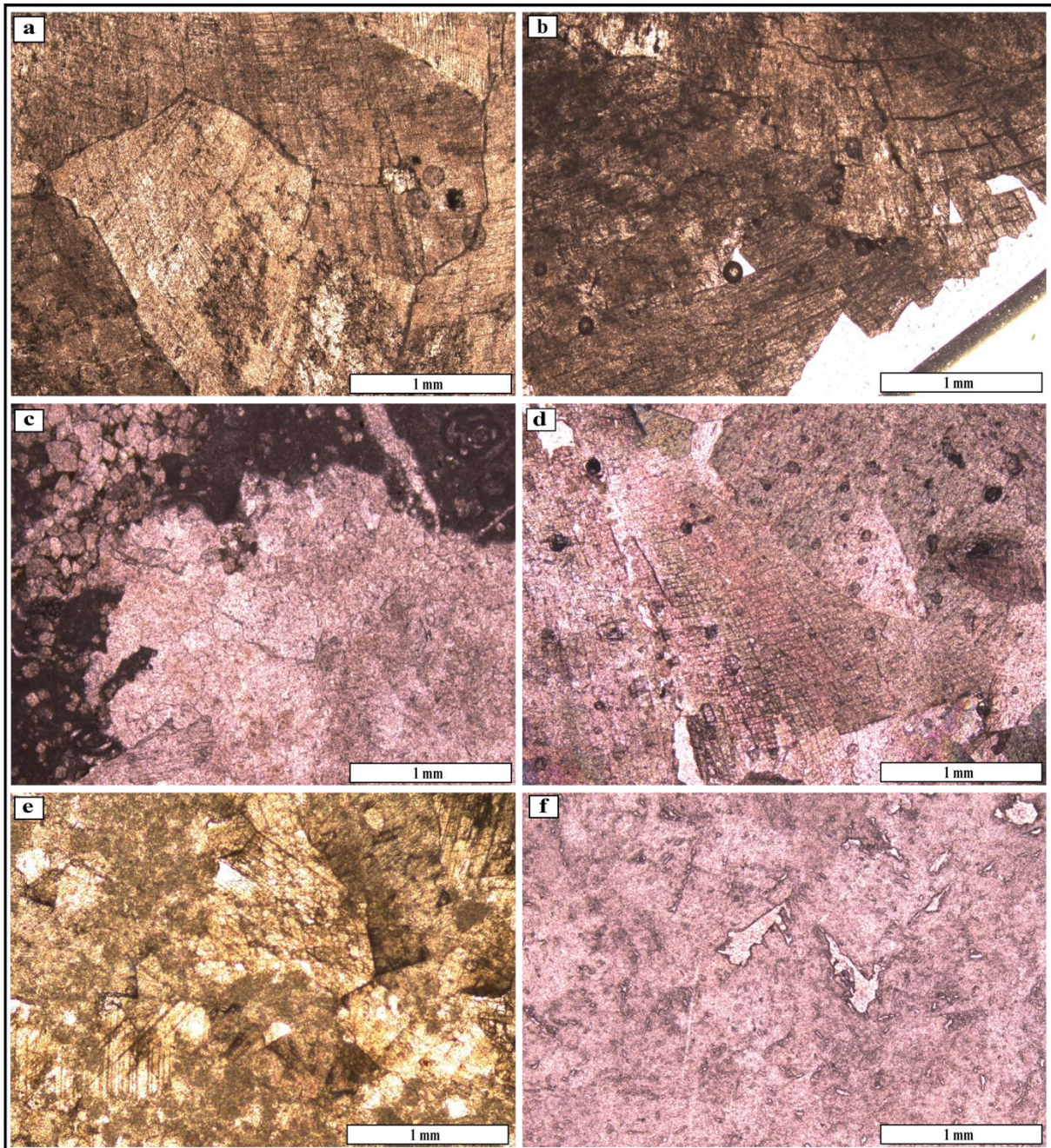
Characteristic types of these dolomites are assigned to the various conditions of burial realm, which includes saddle and radiaxial dolomites (Fig. 6a-f). Saddle dolomites characterized various shapes and properties, often anhedral, but euhedral morphologies are dominant in this study. The main properties of saddle dolomitization have been described in the literature as well (e.g., Radke and Mathis, 1980; Salih et al., 2019b). Saddle dolomite is characterized by a warped crystal face, curved cleavage, and undulous extinction in cross-polarized light (cf., Searl, 1989; Warren, 2000; Salih et al., 2021). Saddle dolomite crystals can vary in size, color, and properties, and occur as void and fracture filling cement and as replacement minerals (Radke and Mathis, 1980). Therefore, the recent paper demonstrates and classifies the saddle dolomite accordingly into various phases. Saddle dolomite formation commonly originates from high temperature fluids and salinities (Salih et al., 2019), although it may also be associated with sulphate-reduction processes. Various fluid and formation

temperatures that are responsible for saddle dolomite formation are reported and range from ca 50–320°C (Davies and Smith, 2006; Liu et al., 2014; Salih et al., 2021). The characteristics of burial dolomite fabric are zebra dolomite (Vandeginste et al., 2005), while zebra-like texture associated with HTD is well recognized in the exposed rocks. The zebra-like texture in the Gali-Bekhal section (Fig.3) characterized a banded carbonate texture formed by rhythmic millimeter to centimeter-scale alternations of dark and translucent laminae, which is indicative of voids in the context of late burial tectonic stress and hydrothermal formation fluids (Wallace and Hood, 2018; Mueller et al., 2020).

Elongate-sized saddle dolomite crystals (SD<sub>I</sub>) composed of coarse euhedral to subhedral crystals with non-planar tight, cemented dolomite, with sizes growing up to a few millimeters, displaying a typical wavy extinction observed under cross-polarized light. These latter characteristics are characteristic of saddle dolomite, and probably could prove a recrystallization under high-temperature conditions, which is typical of hydrothermal dolomitization processes. The tight cementation and the occurrence of these dolomites within fractures support their genesis from hydrothermal fluids. These fluids enriched in magnesium and carried through the rock matrix, likely replaced pre-existing carbonate matrix and/or filled fractures and cavities (Immenhauser, 2021). Coarse crystalline dirty and dark saddle dolomite (SD<sub>II</sub>) usually precipitates in open cavities and fractures and indicates the hydrothermally rich fluids, and could suggest a late diagenetic environmental setting with hot fluid movement. Translucent saddle dolomite (SD<sub>III</sub>) observed in zebra-like texture composed of coarse anhedral to subhedral crystals with non-planar tight cemented dolomite that is postdate SD<sub>I</sub> and SD<sub>II</sub> in zebra-like and predate (SD<sub>IV</sub>)

Coarse to very coarse-crystalline saddle dolomite (SD<sub>IV</sub>) has curved crystal faces with two sets of cleavage, wavy extinction, and curved faces, with sizes up to millimeters. This indicates precipitation from late hydrothermal fluids (Fig. 6d). Planar-euhedral dolomite vugs and fractures occur as predominant void-filling dolomite, thus decreasing the pore spaces and fractures. This type includes dolomite cement, which substitutes the precursor cement (Fig. 6d). The replacement and cementation of SD filled the fractures and voids/vugs were distinguished in the absence and existence of precursor limestone (Fig. 6d). These dolomites in the Gali-Bekhal section did not show any keys for supporting a deep burial setting. While the subsurface samples and deep burial HTD are rarely described in the literature, if so, the scholar relied on geochemical analyses without referring to any comparison study for SD properties, “physical properties of HTD” in the shallow and deep burial realm. In addition to the multi-phase dolomitizing rock, another phase of late diagenesis is represented by blocky calcite. Blocky calcite crystals have a euhedral planar crystal with growing up to centimeter size, meaning they have well-formed, distinct crystal faces but may also have some irregularities and a transparent color with clear fluid entrapment. The irregular boundaries are probably linked to the post-dating dissolution fluids (Fig. 6f). This coarse-crystalline, blocky calcite may extend as veins and patches into adjacent host limestone and dolostone. The dark and large inclusion within the surface of blocky calcite and corrosion of saddle grains due to blocky calcite aggregation suggest that the calcite is the final stage of diagenesis, post-dated the saddle formation.

In the subsurface setting of Qamchuqa Formation within >2km depth, the formation at least injected one episode of dolomitizing fluid, producing a dolomitizing product SD<sub>s</sub>. In the subsurface section, the SD<sub>s</sub> phase is usually formed within matrix dolomites (dolostones) with low nucleation points. This dolomite shows very coarse rhombs and clear zonation growth with a transparent rim and a cloudy core (Fig. 5c-d). Since this dolomite is absent in fractures and other void spaces, and is only observed within matrix facies that occupied a very low volume of the total dolostone matrix, this phase is probably formed due to a replacement process and in a closed or semi-open system. Consequently, SD<sub>s</sub> require a deep closed system (Fig. 7a, b).

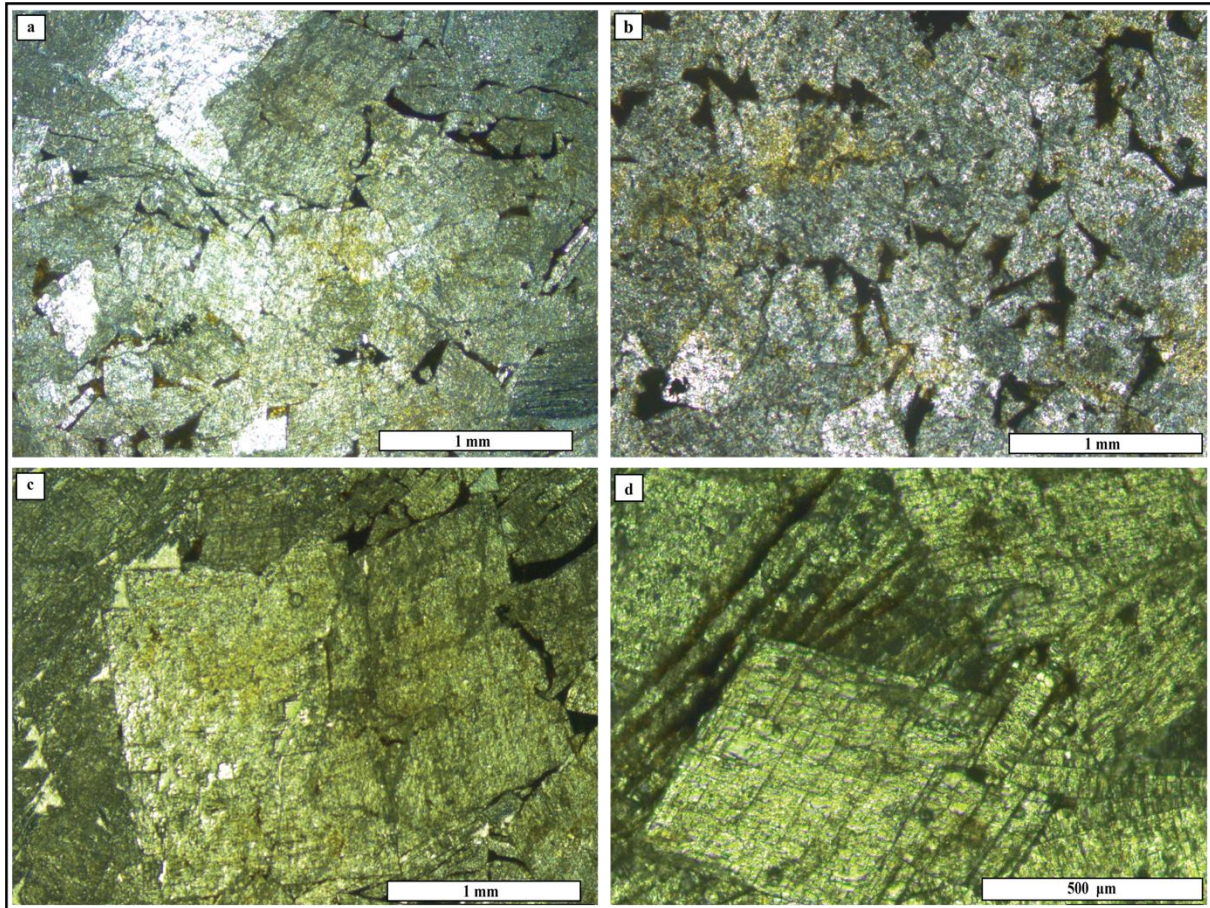


**Fig. 6. Photomicrographs of various phases of saddle dolomite, polarized light. (a, b) Coarse crystalline dirty and dark saddle (SD<sub>I</sub>) dolomites.Q8c.XPL. (c) Translucent saddle dolomite (SD<sub>III</sub>). Q8a.XPL (d) Coarse to very coarse-crystalline saddle dolomite (SD<sub>IV</sub>). Q7b.XPL (e) Radiaxial cement. Q8a.XPL. (f) Blocky calcite.Q6c.XPL Gali-Bekhal section.**

Under subsurface settings, one of the distinctive features associated with the saddle dolomite is the distortion. This distortion is the evident feature from SD that characterizes the curved nature of crystal faces and has 2 sets of cleavages, in addition to their sweeping extinction in cross-polarized light. The distortion of saddle dolomite is more affected by corrosion and solubility than the suture contact between the saddle dolomite grain formed by the burial weight. This distortion of saddle dolomite is a direct indicator of increasing burial weight and subsidence rate. This kind of saddle dolomite, which shows twisting out of the SD shapes, could be directly linked to the mesogenesis phase (Fig. 7c, d).

The early diagenetic fluids produce a sequence of growing various dolomite generations from both sections, starting with non-planar, anhedral dolomite grains, which occur as a replacement of the pristine facies. Even the replacement phase destroys the original features of pristine facies except for the traces of micrite product. The non-planar, anhedral dolomite could

result from temperatures higher than those that form a dolomitic crystal with planar and euhedral shape characteristics. This suggestion has been reported by Gregg and Sibley (1984, 1987) and added that these dolomites originated from burial diagenetic conditions. However, in our study, the progressive generation of dolomite phases, intercrystalline truncation, corrosion, and zigzag suture contact between grain boundaries are well recognized, particularly starting with the formation of planar, rhombohedral dolomite crystals. These features are more shaded in subsurface samples than in surface sections (Figs. 5 -7).



**Fig.7. Photomicrographs show the deformation and textural evolution of saddle dolomite (SDs) under subsurface burial conditions. (a–d) show saddle dolomite crystals characterized by distortion, including curved and twisted crystal faces, two cleavage sets, and sweeping extinction under cross-polarized light. These crystals exhibit dissolution along crystal boundaries and the development of zigzag sutured contacts between adjacent grains, indicating the breakdown of saddle dolomite along grain boundaries and cleavage sets. W16.TT 2296m and 2394m XPL. Taq Taq Oilfield.**

### **Fluid evolution in burial dolomitizing**

The burial dolomitization is formed due to the alteration of limestone, which is deeply buried during the later diagenetic stage. This process is driven by the migration of Mg-rich fluids, typically expelled from compacting sediments or basinal brines. The burial dolomite (SDs) forms as void-filling cement, often leading to porosity reduction, which is considered a common feature in deeply buried carbonate rock as a distortion SD. In the subsurface case, the diagenetic SD condition evolved from a semi-open deep-burial mesogenesis stage that ascended from the hydrothermal fluid along faults and fractures. These fluids promoted dolomitization, and recrystallization expanded the reservoir distribution and improved the reservoir quality, mostly developing a pore-vug reservoir (Zhang et al., 2012).

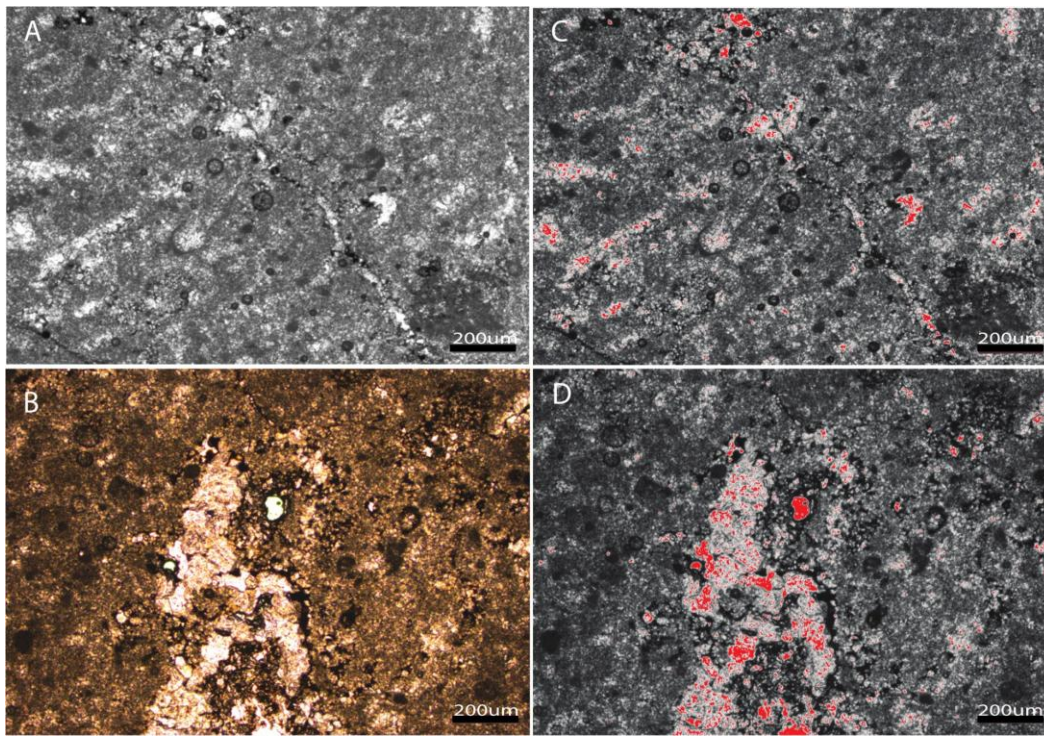
The zigzag and suture contact between the SD grains due to compaction and compacted grains is the direct indicator of the deep burial diagenetic stage (Fig. 7a, b). The SDs contained samples show a clear distortion, probably due to increasing of burial depth. Furthermore, the compaction in the subsurface conditions is driven by sutured grain contact and the tightened

grains of dolomite filling the fracture. During burial, pressure dissolution occurs along grain contacts, reducing porosity and creating tightly interlocking grain textures, and concavo-convex sutures are also dominant in the Taq Taq Oilfield. These processes are indicative of a burial diagenetic condition involving both mechanical compaction and chemical processes. Such compaction-related textures are widely reported in carbonate systems undergoing burial diagenesis (Tucker and Wright, 1990).

During the entire burial process, the rocks adjacent to the vugs and fractures shared the hydrostatic formation pressure, largely leading to the increased compaction of the adjacent rocks. The intracrystalline porosity within the pore spaces continued to remain intact and was semi-filled with calcite cement and bitumen (Jiang et al., 2023). Hydrothermal activity is another critical factor in dolomitization, often associated with the movement of magnesium-rich fluids along faults and fractures. Davies and Smith (2006) have reported that the hydrothermal dolomite formed at shallow depths and originated from very saline fluids with temperatures and pressures higher than the ambient temperature and pressure of the host formation. The occurrence of saddle dolomite in our series indicates elevated temperature conditions during late diagenesis. Saddle dolomite formation linked to hydrothermal systems suggest a fluid involvement not lower than 60-80°C, and mostly ranging from suggested most saddle dolomite formed in temperature between 100-180°C, by Davies and Smith (2006). In this study, if we consider that the geothermal gradient for one kilometer is 25 to 30°C, the ambient formation where the saddle dolomite is formed (up to 2300m), then the ambient temperature is not higher than 60 °C.

SD crystals in the subsurface are characterized as tight and more highly compacted than the shallow “surface setting”; the shape of the grain is more distorted and shows a smaller grain size compared to the shallow setting because the mechanism of the SD formation is closely related to temperature and pressure. The SD in shallow setting forms under hydrothermal conditions with relatively open system fluid dynamics and moderate compaction, subsurface SD forms under more constrained, closed or semi-closed systems, characterized by intense compaction and higher temperature-pressure regimes. This distinction explains the differences in crystal size, morphology, crystallization rate, and structural features. The restricted fluid movement has been documented in the surface and in the subsurface (Roger Ngia et al., 2019; Salih, 2023).

The contrasting characteristics of saddle dolomite crystal in surface and subsurface conditions reflect the interplay between temperature, pressure, system openness, and fluid dynamics. In surface settings, hydrothermal fluid activity dominates the process, leading to the formation of large crystal sizes, while in subsurface conditions, the combination of increasing compaction, high pressures, and semi-closed-system behavior prefers the formation of small-grain-size saddle dolomite, more increasing of dolomite filling fractured. Understanding these mechanisms is critical for interpreting diagenetic histories and fluid migration pathways in sedimentary basins and for future oil and gas exploration. The hydrothermal alterations have a strong impact on the porosity and permeability enhancement (Fig. 8a-d). The enhancement of the porous media has been linked to the fracturing and dissolution of precursor rock, and was reported as an excellent production performance of hydrocarbon reservoirs (Lima et al., 2020; Salih, 2023). The distribution of HTD aligned with the direction of the fracture and open space system, as evidenced by the destructive dolomite fabric. The Qamchuqa Reservoir Formation exhibits significant dolomitization through two mechanisms: fracture and dissolution by hot fluids. This process resulted in increased porosity during both early and late dolomitizing phases, indicating that hot fluids facilitate the enhancement of porous media and the migration of hydrocarbons (Fig. 8a-d) (Salih, 2023).



**Fig 8. Thin section photomicrographs: (a) early diagenesis microfacies and (b) Late diagenesis microfacies, pre-analysis. (C, D) Post-analysis, the red contrast shows the porous media that range from 1.7% to 2.6%, respectively.**

### **Hydrothermal fluids and non-hydrothermal diagenesis controlled the formation and alteration of the Qamchuqa Cretaceous Reservoirs**

The Cretaceous reservoir is a widely distributed exploration target, a storage, and an economically significant hydrocarbon-bearing formation in various sedimentary basins (Naji et al., 2009; Al-Nafie et al., 2022; Aladwani and Diab, 2022; Asadi Mehmandosti et al., 2022). These reservoirs are common in both carbonate and sandstone formations. The Cretaceous reservoirs are usually injected by hydrocarbons generated from underlying Jurassic and Cretaceous source rocks that have undergone thermal maturation and migration (Abeed et al., 2013; Al-Khafaji et al., 2022). The timing of hydrocarbon generation and migration is usually recorded during the Late Cretaceous and Paleocene periods, utilizing maturity modeling and fluid inclusion (Scotchman et al., 2006; Xu et al., 2017). The reservoir quality of Cretaceous formations can vary significantly, with some exhibiting good porosity and permeability characteristics (Sajed and Glover, 2020; Yinguo et al., 2022), while others are considered low-quality, low-porosity, and low-permeability reservoirs (Yinguo et al., 2022; Marghani et al., 2023). The reservoir properties are influenced by various factors such as depositional facies, diagenesis, and structural features. Therefore, a deep understanding of lithological variation, timing of diagenetic stages, and the influence of lithological variation on reservoir quality is necessary for drawing the conceptual modelling of any reservoir.

The earliest alteration, “diagenetic phase” in Qamchuqa Formation from subsurface and surface samples, is characterized by micritization; the micrite envelope is a distinctive feature in surface samples, where it was absent in subsurface samples. However, the marine facies share the same globigerina limestone, but the formation in outcrop contains, in places, a large benthic foraminifer, which was absent in subsurface conditions. Consequently, a less porous medium is observed in subsurface samples than in surface samples within marine and earlier alteration (Fig. 4). This could be linked to compaction and tightened grains in deeper conditions.

Micritization may decrease permeability by filling pore throats or reducing the grain sizes. Then, early micritization may prevent porosity decrease throughout burial compaction (Taghavi Rad et al., 2006). Micritization significantly influences the formation by destroying

the entire skeletal and bioclastic grains, making them lose their internal structures and the development of micritic envelopes. This process can be associated with the effect of microbial activity (Shammary and Kurkchi, 2023). The second significant event is the radial cement, which postdates the micritization and microspar, and one of the main criteria that Kendall and Tucker (1973) and Bathurst (1972) to argue that radial fibrous calcite was a replacement of fibrous aragonite or high-Mg calcite. According to James and Jones (2015). The general understanding is that both cements can originate from the precipitation of low-Mg and high-Mg calcite, and that crystal development exhibits asymmetry. High-Mg calcite varieties will be substituted by low-Mg calcite during burial. This cement formed as 0.5 to 1.5 mm thick isopachous or fan-shaped cements on internal sediments and skeletal grains. They show irregular composite crystal boundaries and acute crystal terminations.

Later diagenetic fluids produce a sequence of growing various dolomite generations from both localities, starting from non-planar, anhedral dolomite grains, which occur as replacement of pristine facies. Even the replacement phase destroys the whole original features of pristine facies except the traces of micrite product. The non-planar, anhedral dolomite could have resulted from temperatures higher than those that formed a dolomitic crystal with planar and euhedral shape characteristics. This suggestion has been reported by Sibley and Gregg (1984, 1987) and added that these dolomites originated from burial diagenetic conditions. However, with the progressive generation of dolomite phases, the intercrystalline truncation, corrosion, and zigzag suture contact between grain-grain boundaries features are well recognized, particularly starting with the formation of planar, rhombohedral dolomite crystals. These features are more shaded in subsurface samples than outcrop ones (Figs. 6 and 7).

The euhedral, rhombohedral shapes of dolomite cementation indicate a high number of nucleation points and/or high supersaturation. Similar dolomitization patterns in sediment succession have been described by (Iannace et al., 2013, Rameil, 2008). The crystal size varies slightly, with most of the crystals appearing to be fine to medium-grained. The dolomite is floating within a micrite matrix, a fine-grained carbonate mud, which indicates that it likely formed as early diagenetic dolomitization. This texture suggests that the dolomite was not extensively recrystallized or altered by later hydrothermal processes, preserving its original rhombohedral shape. Such textures are commonly found in shallow marine to subtidal settings where micrite facies dominate, and dolomitization

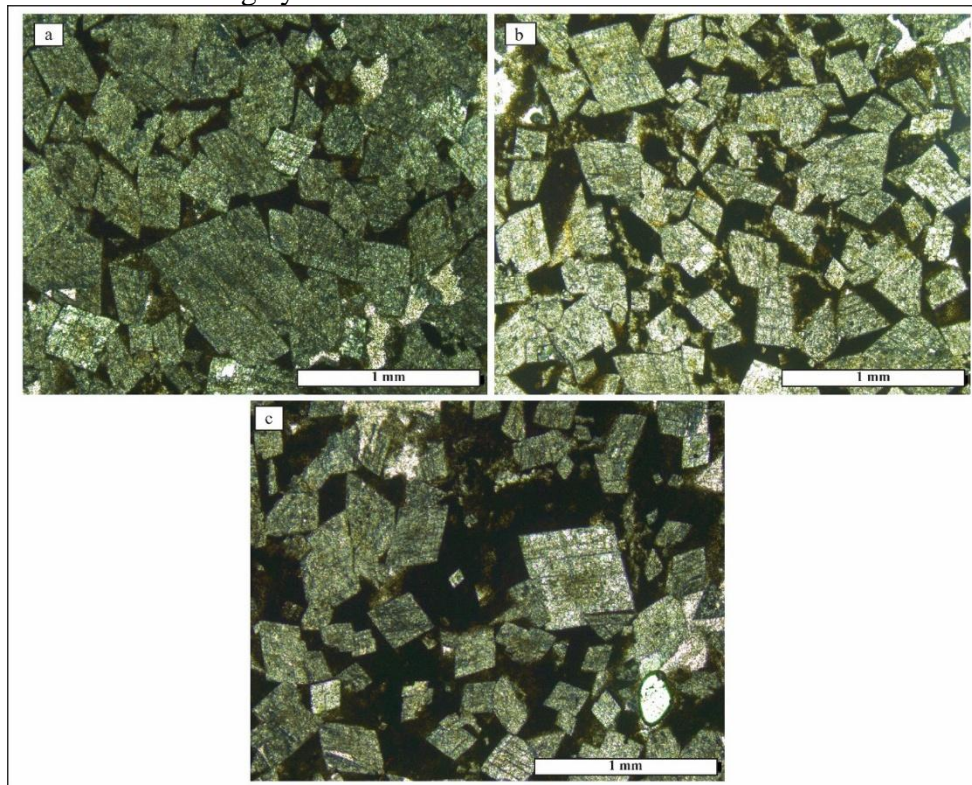
### **The inversion law of deep burial HT dolomitization**

In sedimentary reservoir rocks, porosity and permeability generally decrease with increasing burial depth and overburden pressure, a phenomenon extensively discussed in previous research for both clastic and carbonate reservoirs. In the subsurface of the Qamchuqa Formation within the Taq Taq oil field, hydrothermal fluids (HT) cause the formation of saddle dolomite (SD), which typically fills voids and fractures within the reservoir rock. Hydrothermal in the Bekhme Formation creates the cementation and fills voids and fractures, but does not completely block the pores and throats because the hydrocarbon migration was contemporaneous with the hydrothermal fluid. This migration of hydrocarbon filling a void and fracture prevents the primary porosity, but also creates dissolution and solubility of the formation (Salih et al., 2019a,b). Saddle dolomite in a subsurface setting formed under these conditions is characterized by two sets of cleavage and curved faces. With increasing vertical stress due to burial depth, the formation with subsequent behavior of SD produced a significant reduction in porosity and permeability. Previous research discussed that both SD precipitation and vertical stress contribute to the decreasing of petrophysical properties in carbonate and clastic petroleum reservoirs. Under conditions of high temperature and pressure, combined with increasing vertical stress, SD undergoes a clear change progressing from plastic phase to a brittle phase (Fig. 9a, b). This transition leads to crystal distortion, twisting of SD grains, and the formation of crystals (150 to 800  $\mu\text{m}$ ); however, the development of rhombohedral shapes due to breakdown under extreme vertical stress. In this brittle phase, SD dolomite often exhibits

a brecciated SD texture and floats within the HB phase, which is commonly associated with the charging episode of hydrocarbon migration and the inverse law of HT product (SD) (Fig. 9c).

The inversion law of hydrothermal dolomitization (HTD) becomes evident at this stage, increasing burial depth enables the SD crystals to further break down with increasing vertical stress, producing euhedral, rhombohedral grains along two sets of cleavage of SD. At this stage, the dissolution, enhancing secondary porosity and enabling hydrocarbon migration pathways are become dominate case in the subsurface realm. During the late diagenesis, the deep-sourced HT fluids, which migrate upwards, could indicate significant dissolution of carbonate and porosity increasing because the fluids became unsaturated with regard to calcite and dolomite as a gradual decrease in temperature and burial depth (Huang, 2010).

The inversion law is primarily associated with two mechanisms: first, decreasing porosity with increasing burial depth due to chemical and physical compaction; second, the porosity reduction caused by SD precipitation, which often fills pore spaces and fractures. During the brittle phase of SD, the breakdown and brecciation cause enhanced porosity and permeability, allowing hydrocarbon migration and accumulation. Two reasons influence this inversion law during HT dolomitization. first: is the increasing vertical stress, which increases the textural breakdown of SD crystals. Second: the characteristic of SD, where the presence of two sets of cleavage makes it particularly susceptible to brittle deformation, resulting in rhombohedral shapes and brecciated SD textures. This brecciated SD texture serves as a significant conduit for hydrocarbon migration during the charging episode, contributing to improved reservoir storage capacity. Consequently, the restoration of reservoir quality in the Qamchuqa Formation is essentially linked to the brittle phase of SD, where the textural breakdown and brecciation enable hydrocarbon migration and enhance storage of the reservoir. The latter emphasizes the importance of understanding hydrothermal dolomitization and burial stress in reservoir quality.



**Fig. 9. Photomicrographs showing: (a-c) the Brittle deformation of SD that opens the conduit for fluid migration (hydrocarbon migration). Hb migration is the last charging phase in the Cretaceous formations. So, the late diagenetic dolomitizing fluids “SD” are considered the most effective phase on HB migration, therefore increasing the storage of any reservoir. W16.TT 2293m. XPL. Taq Taq Oilfield.**

## **Conclusion**

This study shows the different characteristics and properties of saddle dolomite that was produced by elevated temperature fluids (HT) under shallow and deep burial dolomitization. The mechanisms of saddle dolomite formation are the key to understanding the diagenetic evolution of carbonate reservoirs. The findings indicate that shallow burial dolomitization primarily enhances reservoir quality through early fluid interactions and intensively during the dissolution process through injection of hot fluids into the Cretaceous formation. The vertical stress in the subsurface reservoir impacted by HT fluids caused a series of events on SD crystals, starting with distortion, breaking down of SD crystals, and ending with brittle deformation and SD brecciation. Deep burial processes contribute to the stability and decrease of porous media of dolostones under extreme conditions and low fluid-rock interaction. With increasing of vertical stress, the reservoir quality reverses the law of HT burial dolomitization in the context of hydrocarbon storage and exploration development, where the porous media increased due to extra-increasing of overburden weight and originated in-situ brecciation of saddle dolomites forming a rhombohedral dolomite crystal.

## **Conflict of Interest**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the recent work.

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