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ORIGINAL PAPER

Dolomite textures in the Upper Cretaceous carbonate-hosted Pb–Zn deposits, Zakho, Northern Iraq

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Abstract In the northeast of Zakho City, Northern Iraq, the host rocks of Pb–Zn deposits are composed predominantly of dolomites with subordinate dolomitic limestone intervals. This study is focused on the dolomites of the Bekhme Formation (Upper Campanian) carbonate-hosted Pb–Zn deposits. The amount of dolomites, however, increases toward the mineralized zone. Dolomites are dominated by replacement dolomite with minor dolomite cements. Petrography study allowed identification of six different dolomite textures. These are (1) fine crystalline, planar-s (subhedral) dolomite, RD1; (2) medium to coarse crystalline, planar-e (euhedral) to planar-s (subhedral) dolomites, RD2; (3) medium crystalline, planar-s (subhedral) to nonplanar-a (anhedral) dolomites, RD3; (4) coarse crystalline, planar-s (subhedral) to nonplanar-a (anhedral) dolomites, RD4; (5) planar (subhedral) void-filling dolomite cements, CD1; and (6) nonplanar (saddle) void-filling dolomite, CD2. The RD1, RD2, RD3, and RD4 dolomite textures are replacive in origin and are volumetrically the most important types, whereas CD1 and CD2 dolomites with sparry calcite are commonly cements that fill the open spaces. Although the dolomites of the Bekhme Formation are not macroscopically observed in the field, their different types are easily distinguished by petrographic examination and scanning electron microscopy. It was observed that the dolomites of the Bekhme Formation are formed in two different diagenetic stages: the early diagenetic from mixing zone fluids at the tidal–subtidal (reef) environments and the late diagenetic from basinal brines which partially mixed with hydrothermal fluids at the shallow-deep burial depths. The latter occurs often with sphalerite, galena, and pyrite within mineralized zone. These dolomite types are associated base-metal mineralization (Mississippi Valley type).

Keywords Dolomite · Pb–Zn deposits · Paragenesis · Bekhme Formation · Zakho · Iraq

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Introduction

Detailed investigation of the dolomitization in the carbonate-hosted Pb–Zn deposits of the Bekhme Formation (Upper Campanian) at Lefan Valley in the extremely northern part of Iraq has been conducted in the present work. In the Lefan locality, the zone of mineralization extends for several tens of meters parallel to the bedding plane and exposes on the southern limb of Khamtur Mountain. The Lefan area is located about 4.5 km east of Shiranish Islam Village and 25 km northeast of Zakho, Northern Iraq (Fig. 1). The Cretaceous sedimentary sequence, particularly its upper carbonate unit, and the Bekhme Formation contain some Pb–Zn deposits in the North Zakho area (Jassim and Goff 2006; Awadh 2006). Pervasive dolomitization occurs in the Cretaceous carbonate sequences in the Zakho area, Northern Iraq (Jassim and Goff 2006; Awadh et al. 2008). The formation of dolomite in carbonate sequences and the nature of dolomitization have been some of the most intensively debated and extensively studied problems in limestone (Chen et al. 2004; Hardie 1987).

Dolomite/Pb–Zn associations are widely known in many parts of the world (Gómez-Fernandez et al. 2000; Velasco et al. 2003), and most belong genetically to the Mississippi Valley-type (MVT) deposits (Leach and Sangster 1993). Thus, an understanding of the origin of the dolomite can provide important information on the evolution of basinal fluids, fluid–rock interactions during diagenesis, and processes of mineralization, which in turn can further improve mining. In

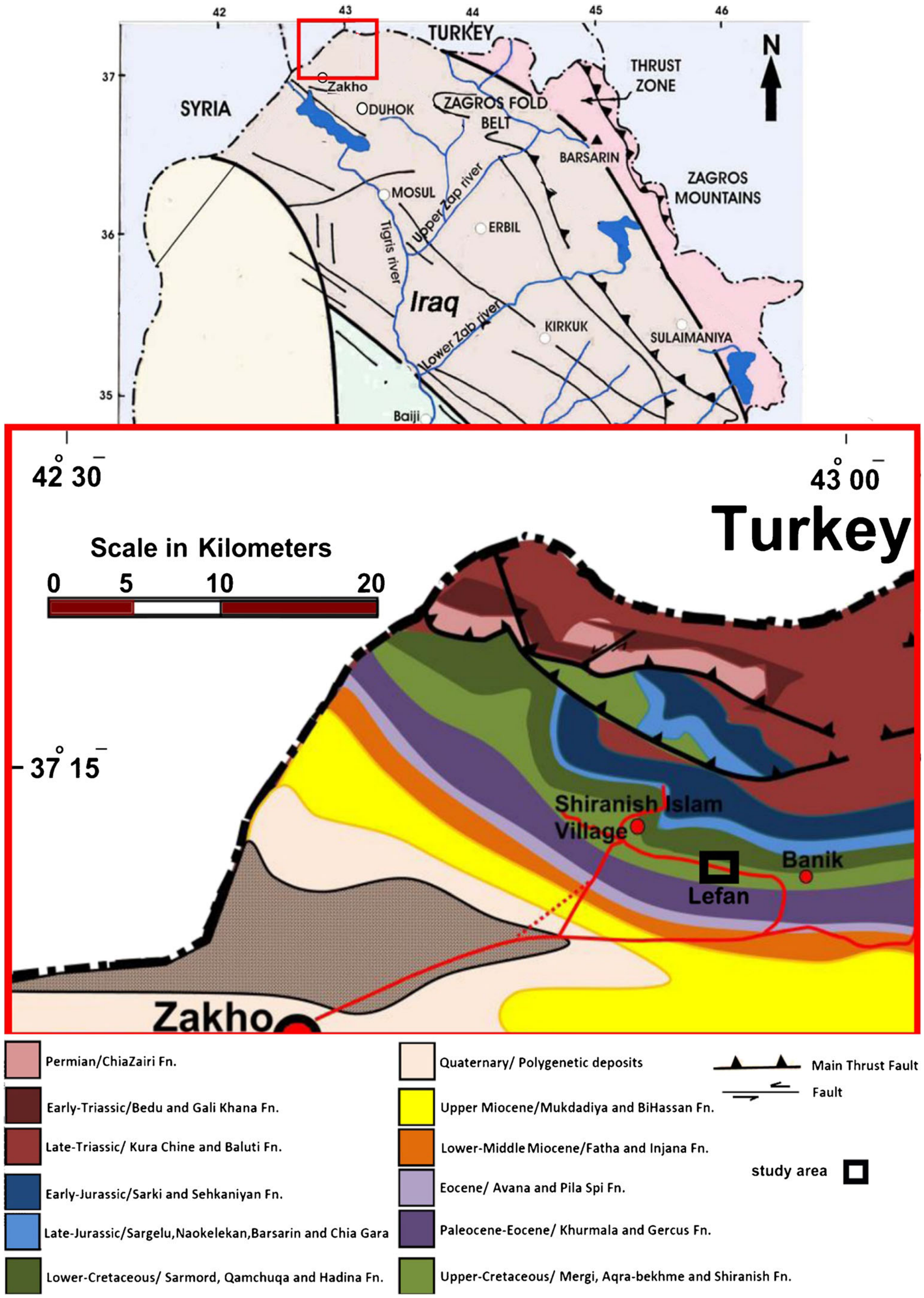


Fig. 1 Location and geological map of the study area

this study, the textural description of dolomite is conducted with terminology following Sibley (1982) and Sibley and Gregg (1987). For crystal-size classes, the scheme of Lucia (1995) is adopted with slight modification, due to the large difference in crystal size of the crystalline dolomite of the Bekhme Formation. These classes are as follows: <30 μm is fine, 30–150 μm for medium crystalline, and>150 μm for coarse crystalline dolomite. In this study, the classification of dolomite rock textures is based on petrographic studies, aided by analysis of scanning electron microscopy (SEM) images.

The study aims to determine the textural characteristics, diagenetic development, and origin of the dolomites associated with Pb–Zn deposits within the Bekhme Formation.

Geological setting

Northern Iraq is characterized from the metallogenic point of view by presence of Pb–Zn deposits, mostly accompanied by barite and exceptionally by fluorite (AI-Bassam et al. 1982).

The formation of these mineral deposits is associated with the geological and tectonic development of Tethys and movement of the Arabian Plate. In the Lefan area in the extremely northern part of Iraq, a mineralization zone is exposed on the southern limb of Khamtur Mountain, striking E–W, dipping of about 45° S, and existed parallel to the bedding plane. This zone is considered by Jassim and Goff (2006) and Awadh (2006) as Pb–Zn deposits in the upper carbonate unit of the Cretaceous sedimentary sequence and particularly in the Bekhme Formation. The study area generally is composed of sedimentary succession of Paleozoic, Mesozoic, and Cenozoic ages (Fig. 1). The rocks are thrusted, folded, and faulted, the fold having sublatitudinal strikes. All these structural features led to distortion in the stratigraphic succession of the area.

No intrusive igneous rocks were found in the area. Extrusive rocks are present but rarely. All the localities of Pb–Zn deposits in Iraq were recorded in the Northern Thrust Zone of Iraq. The main parts of the lead–zinc deposits exist within massive limestones of the Bekhme Formation (Upper Campanian).

Stratigraphy and sedimentation

In the studied section, the Bekhme Formation reaches up to 110 m thick (Fig. 2). The formation is composed in its lower part of light gray, well-bedded (somewhat thin), recrystallized limestone rich in larger fossils such as rudist, gastropods, benthic forams, and nonskeletal pisoids. No effect of mineralization in this part of the Bekhme Formation was observed. The middle part of the formation consists of dark gray, hard, dense, and massive dolomitic limestone to yellowish gray dolostone toward the top. This massive dolostone represents the mineralized zone in the formation (Fig. 2). Dolomite occurs as small rhombic grains in limestone, and their content increases toward mineralized zone whereas micrite decreases. Consequently, the permeability appears to be increased with dolomite. The fossils and their bioclasts are predominantly dislocated, deformed, and recrystallized. Unequivocally, the sulfide minerals seem to have epigenetically deposited with cementing dolomite and locally secondary calcite grains, filling interstitial spaces, voids, and microfractures (Fig. 3a). Dolomite and rudist shells are preferable media for replacement than calcite (Awadh et al. 2008). The upper part is characterized by medium- to thick-bedded bioclastic limestone to dolomitic limestone which shows the local dissolution, dolomitization, and recrystallization. This part of the Bekhme Formation is highly affected by mineralization.

The Bekhme Formation is overlain by the marl and marly limestone of the Shiranish Formation (Upper Campanian-Maastrichtian) with conformable and gradational contact and underlain by thick limestone beds of the Mergi Formations (Middle Cretaceous) with a layer of basal polymict conglomerate (Fig. 2). The massive carbonate rocks of the Bekhme Formation form the high mountains and cliffs in the area, whereas the marls and marly limestones of the Shiranish Formation form the lower plains.

Methods

A total of 80 samples of the carbonate host rocks were collected from the Upper Cretaceous carbonates of the Bekhme Formation in the Lefan locality. Petrographic and textural investigations using reflected and transmitted light microscopy aided by SEM images are conducted. All thin sections of carbonate rocks were stained with alizarin red solutions according to the method of Dickson (1965) to distinguish dolomite from calcite. Representative samples were analyzed for their mineralogical characteristics by X-ray powder diffractometry (XRD, Rigaku Geigerflex). XRD analyses were performed using CuKα radiation and a scanning speed of 1° 2θ/min to determine mineralogical composition of the bulk samples. Representative samples were also prepared for SEM analysis by adhering the fresh broken surface of the sample onto an aluminum sample holder with double-sided tape and thinly coating with a film (~350 Å) of gold using a Giko ion coater. Both XRD and SEM were carried out at Wollongong University, Australia.

Pb–Zn mineralization

Pervasive dolomitization characterizes the Mesozoic carbonate rocks of the study area, whereas Pb–Zn deposits occur mostly in the Upper Triassic and Upper Cretaceous sequences. Texturally and mineralogically, the Pb–Zn deposits are simple and are consist predominantly of sphalerite, galena, and minor pyrite (Fig. 3b). Ore emplacement ranges from replacement feature to open space filling. Ore appears to be as small veins and veinlets (Fig. 3c). Disseminated clusters of crystals that occupy intergranular pore spaces around dolomite are the common microfeature. Most of the primary sulfide ores were altered to secondary ores by influence of supergene solutions. Sphalerite was altered to smithsonite, galena to cerussite and anglesite, and pyrite altered to goethite (Awadh et al. 2008). Gossan consists mainly of iron oxides (goethite and limonite). Smithsonite and cerussite were detected by XRD (Fig. 4).

In general, the ore minerals are highly deformed, recrystallized, and oxidized. The sulfides are intermixed with dolomite, whereas calcite is more frequent in the oxidized zone. This simple mineral assemblage is similar to the MVT deposits as noted by Leach and Sangster (1993) and Leach et al. (2005).

Fig. 2 Stratigraphic column of the Bekhme Formation, Lefan area, Zakho

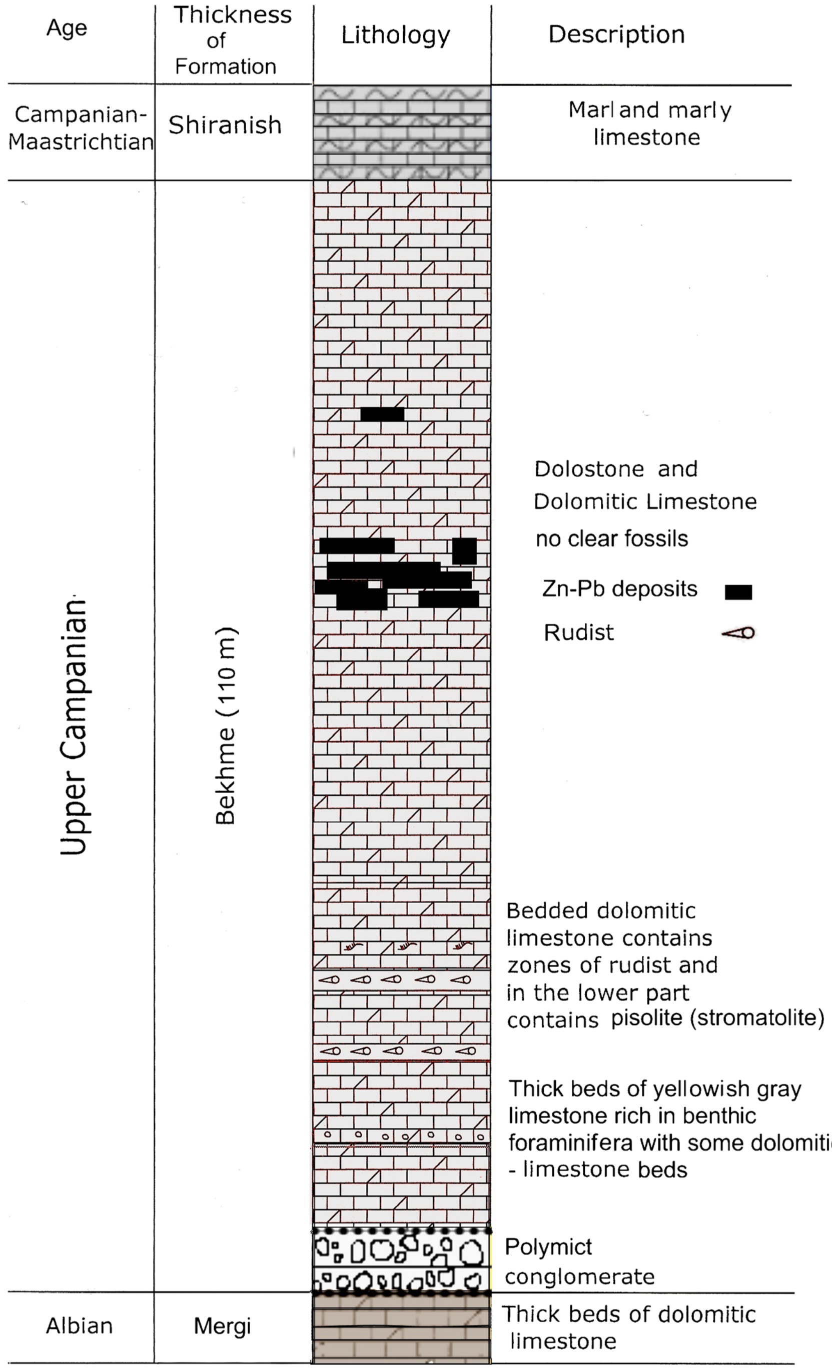
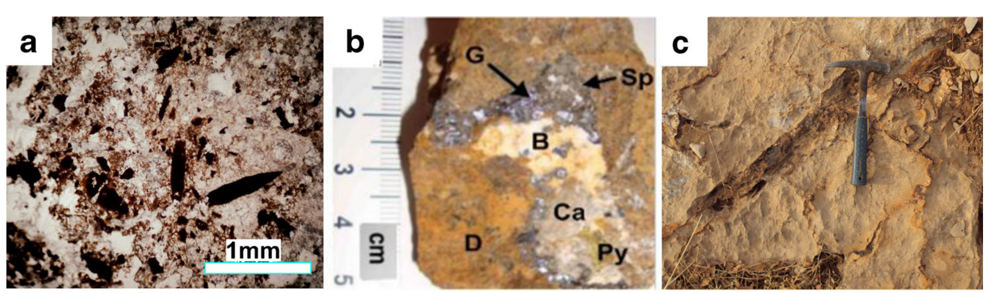


Fig. 3 **a** Sulfide minerals (*dark area*) filling interstitial spaces, voids, and fractures. **b** Lead–zinc minerals at the studied area (Lefan): galena (*G*), sphalerite (*Sp*), pyrite (*Py*), barite (*B*), and secondary calcite (*Ca*) hosted by dolomite (*D*). **c** Vein and veinlets of ore deposits in dolomitic limestone of the Bekhme Formation



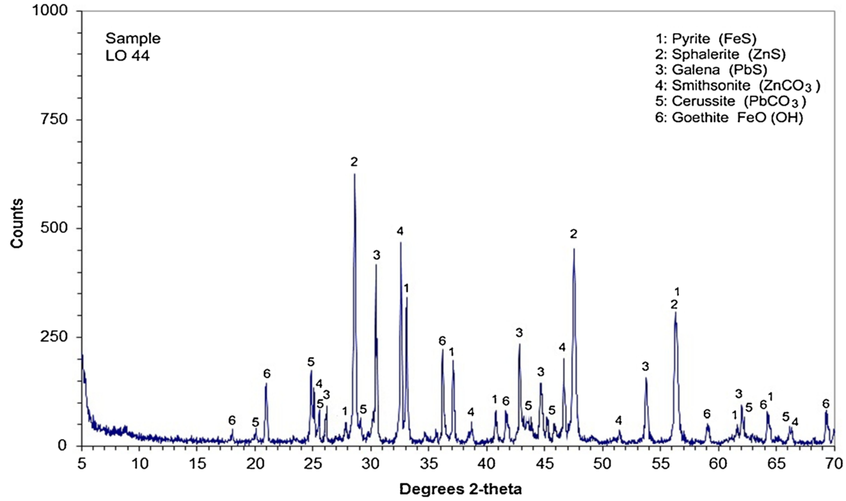


Fig. 4 XRD pattern of bulk ore sample from Lefan

Facies analysis

Limestone facies

Limestone in the Bekhme Formation is bedded and recrystallized, white to light gray, and yellowish. It is about 60 m in thickness and represents the lower and partially the middle part of the formation. Interfingering between limestones and dolomites locally interrupted by faults occurs in the middle part of the formation. Limestone rarely is affected by mineralization. Microfacies analysis reveals that three microfacies could be recognized, and these include the following: rudist boundstone, in which rudist shells are locally rounded and floating in mud matrix (Fig. 5a); foraminiferal wackstone, which is composed of well-preserved shells of miliolids, alveolinids, and orbitiods (Fig. 5b). Corals and gastropods are also common (Fig. 5c) and pelloidal, bioclastic dolowackestone to dolopackstone (Fig. 5d). Theses facies reflect the reef environments, in which relatively low-energy conditions prevail (Flügel 2004).

In some samples, the original texture is easily recognized as wackestone microfacies, whose grains are dominated by different species of well-preserved forams (Fig. 5b). In other

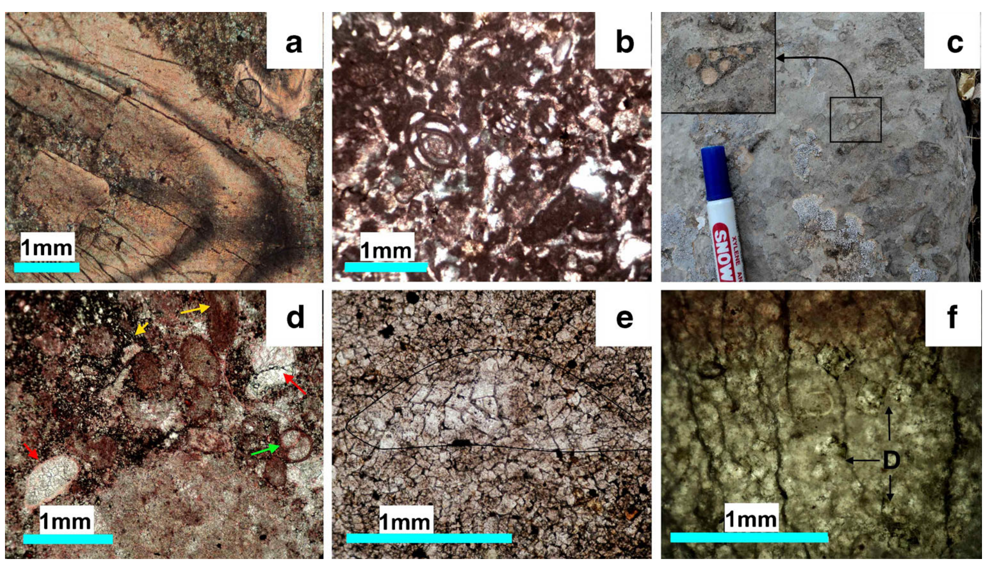


Fig. 5 **a** Rudist boundstone microfacied, the rudist shells are locally rounded and floating in mud matrix. **b** Foraminiferal wackstone microfacies display well-preserved shells of benthic forams. **c** Well-preserved shells of gastropods in dolomitic limestone of the Bekhme Formation. **d** Pelloidal bioclastic dolowackestone to dolopackstone microfacies, peliods (*yellow arrows*), ostracods (*red arrows*), and gastropod (*green arrow*). **e** Ghost of fossil fragments (ostracod?) occurred due to intensive dolomitization of limestone. **f** Floating dolomite rhombs occurred due to a low degree of dolomitization in lime mudstone. Note the planktonic foram in the *center*

cases, intensive dolomitization obliterates original component of the rock, leaving ghosts of fossil fragments (Fig. 5e). In these cases, the whole rock is changed into dolostone with vague relics of original component or fabric. Sometimes, dolomitization occurs in low degree, which affects part of the micritic matrix in the form of floating rhombs or partially dolomitized skeletal grains (Fig. 5f).

Dolomite facies

The dolomite facies dominate the carbonate succession of the Bekhme Formation in the study area. It occurs in different types and fabrics. The dolomite facies differ markedly from the limestone facies in their dark gray to yellowish gray color. These facies are hard, dense, massive, fractured, and locally brecciated. The massive dolostone at the top of the middle part represents the mineralized zone, which is highly effected by mineralization. The thickness of the dolomite facies is about 50 m. Dolomite occurs as rhombic grains, and their content increases toward mineralized zone, while micrite decreases consequently. Dolomitization is typically pervasive. Preservation of peloids and fossil fragments (such as planktonic and/or benthic forams) is usually poor (Fig. 5f). Grains and surrounding matrix are sometimes differentiated by variations in dolomite crystal size. Some relics of undolomitized limestone are locally observed within dolomites and at boundaries with limestones. Dolomites were formed as a result of various degrees of dolomitization from the precursor limestones. Dolomite facies are considered as a diagenetic facies. However, the environmental interpretation of these lithofacies is quite controversial. Al-Karadakhi (1989) and Ali (2010) suggested that this type of dolostone might deposit in fore-reef environments. Since the most important microfacies in dolomite are bioclastic dolowackestone to dolopackstone and dolograinstone, these facies reflect a fore-reef environment (Flügel 2004).

Dolomite textures

Dolomitization is typically pervasive. Grains and surrounding matrix are sometimes differentiated by variations in dolomite crystal size and unidentified inclusions in grains, resulting in a browner color than the surrounding dolomite.

Six dolomite rock textures have been recognized, based on the crystal-size distribution and crystal-boundary shape (planar or nonplanar), and classified using the dolomite rock classification scheme of Sibley and Gregg (1987). The types are (1) fine crystalline, planar-s (subhedral) dolomite, RD1; (2) medium to coarse crystalline, planar-e (euhedral) to planar-s (subhedral) dolomites, RD2; (3) medium crystalline, planar-s (subhedral) to nonplanar-a (anhedral) dolomites, RD3; (4) coarse crystalline, planar-s (subhedral) to nonplanar-a (anhedral) dolomites, RD4; (5) planar (subhedral) void-filling dolomite cements, CD1; and (6) nonplanar (saddle) void-filling dolomite, CD2. RD1, RD2, RD3, and RD4 dolomite textures are replaced in origin and are volumetrically the most important types, whereas CD1 and CD2 dolomites commonly exist as cements that fill the open spaces.

Dolomite texture 1: fine crystalline, planar-s (subhedral) dolomite (RD1)

The dolomite of this type (RD1) is characterized by a fine crystalline texture (10–30 μm) of planar-s type. It consists of scattered crystals distributed irregularly through the host limestone (Fig. 6a). Planar-s dolomite has straight and rarely curved intercrystalline boundaries (Fig. 6b). The crystals tend to be subhedral (Sibley and Gregg 1987). The other minor amounts of dolomite texture of this type are anhedral crystalline dolomite. Most of dolomite crystals are subhedral to anhedral with straight compromise boundaries at many crystal face junctions (Sibley and Gregg 1987). Fine crystalline dolomite (predominantly 10–20 μm and up to 35 μm in size) replace unfossiliferous or scarcely fossiliferous mudstone often with irregular fenestral voids and with laminated mudstone–microbialite- and/or bioclast-bearing wackstone/packstone (Fig. 6a, b).

Dolomite texture 2: medium to coarse crystalline, planar-e (euhedral) to planar-s (subhedral) dolomites (RD2)

This type of dolomite texture (RD2) is pervasive and increases toward the mineralized zone, but it is fabric-destructive and has obliterated the original depositional and early diagenetic features. The RD2 dolomite is generally composed of medium to coarsely crystalline (sucrosic) mosaic dolomite with size ranging from 60 to 300 μm (Fig. 6c, d). Dolomite crystals are planar euhedral to subhedral (locally anhedral) with straight and rarely curved intercrystalline boundaries (Fig. 6c). Both idiotopic and xenotopic textures are common. Almost all crystals are cloudy in appearance with clear rims, and they show sharp extinction. In most cases, tiny crystals are observed in the cloudy central part of euhedral dolomite rhombs; they are probably relics of the RD1 type after recrystallization and/or replacement. The samples with a xenotopic texture seem to be a mosaic of subhedral to anhedral dolomite crystals with irregular crystal boundaries. This type of dolomite texture probably formed through recrystallization and/or replacement; the relics of original fabrics are absent or sparse except for some traces of few fossil fragments. In this type, zoning classification is observed. In addition, late diagenetic stylolites truncate the dolomite crystals (Fig. 6c). The most common type of porosity is intercrystalline. In the more coarsely crystalline fabric, intercrystalline porosity becomes larger and rich in bitumen and iron oxides to isolated microvugs. SEM images show the presence of medium to coarse crystalline,

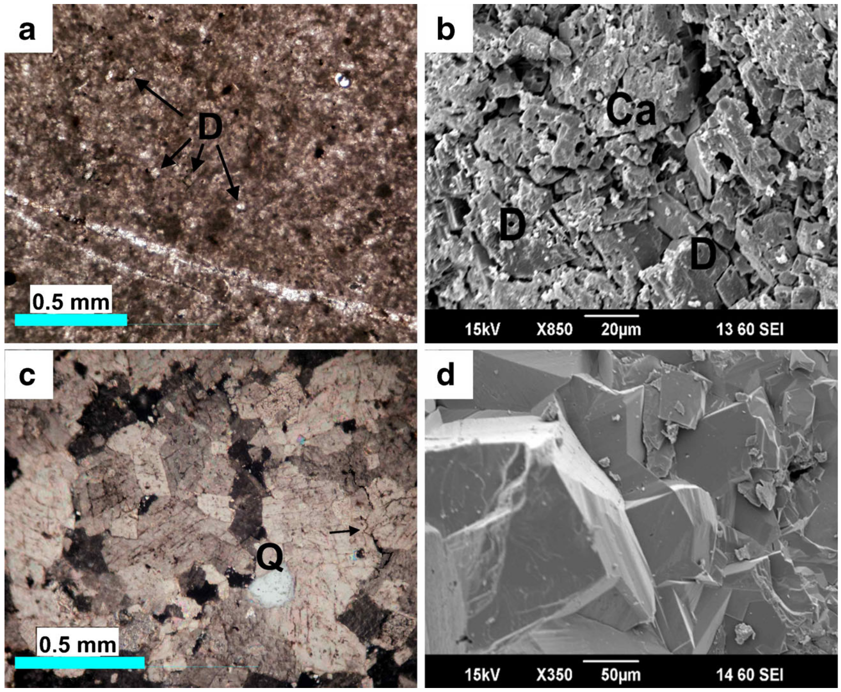


Fig. 6 **a** Fine crystalline, planar-s (subhedral) dolomite (RD1) represented by scattered dolomite rhombs (*D*) distributed irregularly in unfossiliferous lime mudstone. **b** SEM image of fine crystalline, planar-s (subhedral) dolomite (RD1) showing straight to rarely curved crystalline boundaries of planar-s dolomite (*D*) surrounded by calcite (*Ca*). **c** Medium to coarse crystalline, planar-e (euhedral) to planar-s (subhedral) dolomites (RD2). Note the quartz grain (*Q*) and how the stylolite (*arrow*) truncates the dolomite crystals. **d** SEM image of medium to coarse crystalline, planar-e (euhedral) to planar-s (subhedral) dolomites (RD2) showing straight to rarely curved crystalline boundaries, dolomite appears slightly dissolved

planar-e rhombic dolomite; dolomite appears slightly dissolved (Fig. 6d).

Dolomite texture 3: medium crystalline, planar-s (subhedral) to nonplanar-a (anhedral) dolomites (RD3)

The RD3 dolomite makes up about four-fifths of the dolomite phase volumetrically based on visual estimation of thin sections and SEM images. In general, the abundance of RD3 dolomite increases, similar to RD2 type, toward the mineralized zone. This type forms mosaic of planar-subhedral to anhedral crystals (30–100 μm) that have straight (locally curved) crystal faces and display a sharp to slightly undulatory extinction (Fig. 7a, b). The dolomite crystals commonly have a cloudy core (subhedral) and clear rim texture (Fig. 7a). The cloudy centers of the crystals result from the presence of inclusions, which may be bubbles or unreplaced inclusions of calcite or other minerals, whereas the clear rims are nearly inclusion-free (Boggs 2009). The most characteristic feature of this type is nonmimic replacement of allochems (ooids, peloids, and bioclasts). These allochems can be recognized as ghost textures (Fig. 7a). SEM images reveal the presence of medium crystalline, planar-s rhombic dolomite, which is slightly dissolved (Fig. 7b). Owing to the large amount of intercrystalline, moldic, and microvug porosities, this type of dolomite texture might be developed by intensive dolomitization of a limestone with originally bioclastic packstone type (Randazzo and Zachos 1984).

Dolomite texture 4: coarse crystalline, planar-s (subhedral) to nonplanar-a (anhedral) dolomites (RD4)

This type of dolomite texture is not common and it is characterized by coarse crystalline (>100 μm) dolomite mosaic. Dolomite crystals are cloudy in appearance, having rare clear rims with curved (locally straight) and rarely embayment intercrystalline boundaries (Fig. 7c). Crystals are of planar-s (subhedral) to anhedral type with low intercrystalline but high vuggy porosity (Fig. 7d). The RD4 dolomites have changed locally from idiotopic to xenotopic, indicating an increase in temperature and salinity of the solutions (Gregg and Sibley 1984). The dolomite crystals show intragrain microfractures filled with bitumen and iron oxides. The crystals become more filthy (cloudy) from the center outward. This filthiness may be caused by relics of undolomitized lime mud and/or presence of iron oxide inclusions. As a result, the rock gained a cloudy appearance. They commonly show sharp to slightly undulatory extinction. This texture is occasionally associated with secondary calcite and/or silica cement filling pores and spaces between the coarse crystalline dolomite.

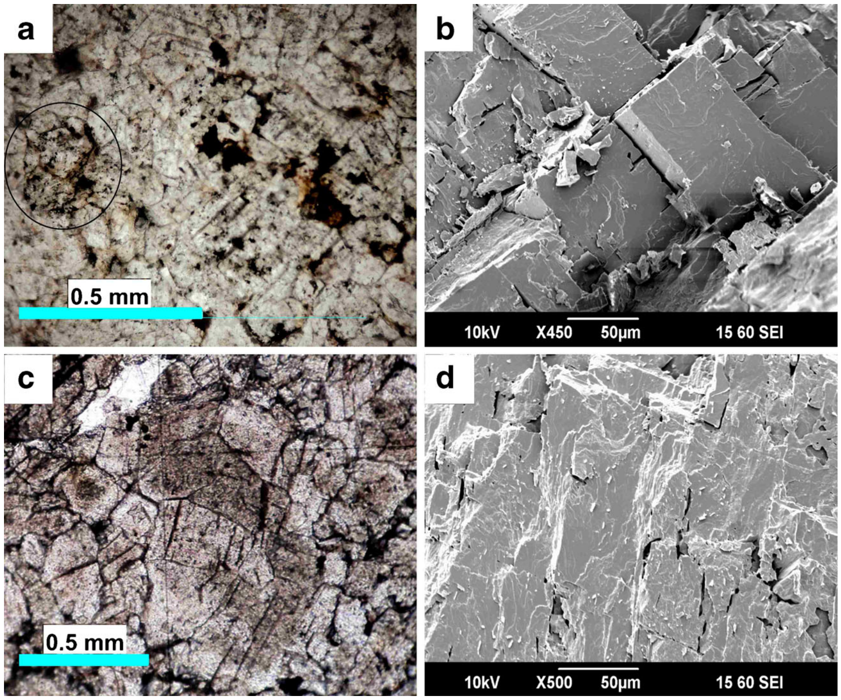


Fig. 7 **a** Medium crystalline, planar-s (subhedral) to nonplanar-a (anhedral) dolomites (RD3) display the cloudy core (subhedral), clear rim dolomites and nonmimic replacement of allochems which can be recognized as ghost textures (the *circle*). Dark patches represent the sulfide minerals and Fe oxides. **b** SEM image of medium crystalline, planar-s (subhedral) to nonplanar-a (anhedral) dolomites (RD3) showing planar rhombic dolomite with slightly dissolved boundaries. **c** Coarse crystalline, planar-s (subhedral) to nonplanar-a (anhedral) dolomites (RD4) display the cloudy core, rarely clear rim dolomites with curved (locally straight) and rarely embayment intercrystalline boundaries. **d** SEM image of coarse crystalline, planar-s (subhedral) to nonplanar-a (anhedral) dolomites (RD4) showing low intercrystalline but high vuggy porosity

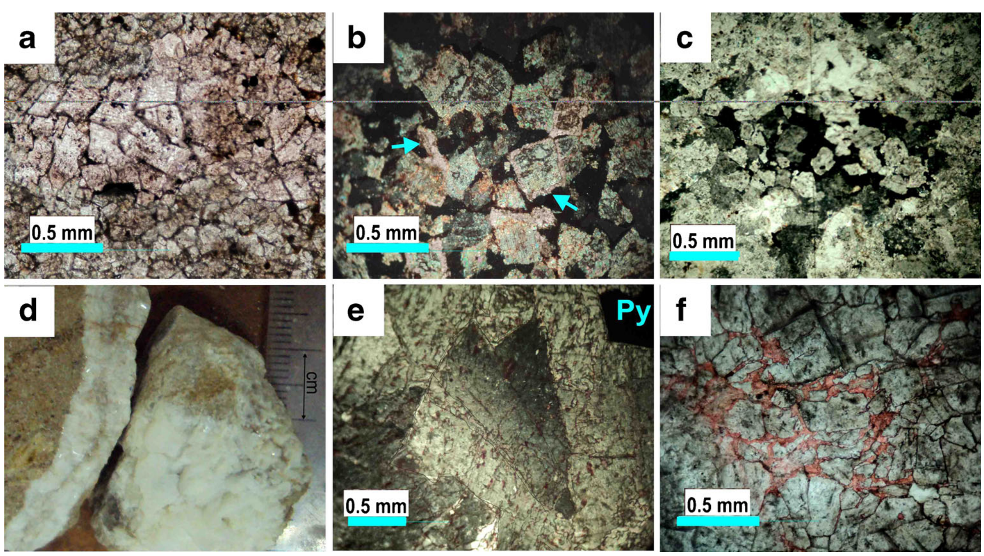


Fig. 8 **a**–**c** Planar (subhedral) void-filling dolomite cement (CD1). **a** CD1 with cloudy and rich in inclusions. **b** CD1 precipitated as a thin and clear outer rim or zone (*arrows*) around a single or cluster of dolomite rhombs as overgrowth. **c** CD1 precipitated as cements filling pores and dissolution vugs. **d**–**f** Nonplanar (saddle) void-filling dolomite (CD2). **d** Milky white to creamy vein of nonplanar crystals of saddle dolomite. **e** Irregular lobate faces of CD2 (saddle dolomite) with sweeping extinction associated with sulfides (pyrite, *Py*). **f** CD2 shows dedolomitized dolomite cement into late diagenetic calcite cementation (*reddish/pink area*)

Dolomite cements

Planar (subhedral) void-filling dolomite cement (CD1)

This type of dolomite cement consists of planar, subhedral to anhedral void-filling crystals, ranging from 100 μm up to 2 mm in size. They generally are cloudy and rich in inclusions (Fig. 8a). All crystals show sharp extinction, slightly undulatory. The type of dolomite cement (CD1) is precipitated in intercrystalline pores as a thin and clear outer rim or zone around a single or cluster of dolomite rhombs (replacement dolomites) as syntaxial overgrowths (Fig. 8b). These dolomite crystals precipitated also as cements lining pores and dissolution vugs or/and surrounding patches of secondary calcite (Fig. 8c). The CD1 is volumetrically of minor importance.

Nonplanar (saddle) void-filling dolomite (CD2)

This type of dolomite cement appears as milky white to creamy, nonplanar crystals in hand specimens, ranging from 200 μm up to 5 mm in size (Fig. 8d). The crystals of the CD2 have irregular, curved, or lobate faces and sweeping extinction and are mostly associated with sulfides (Fig. 8e). They are also characterized by very coarse, clean, nonplanar, rich in inclusions crystals. The CD2 type forms a vein-filling dolomite cement. In other cases, it shows dedolomitization due to successive calcite replacement and cementation or filling fractures by partly dedolomitized dolomite cement into late diagenetic calcite cementation. This dedolomitization and its textural association to vein and fracture-filling dolomite cement are of local occurrences (Fig. 8f). It could be related in part to extrabasinal fluids, which had not equilibrated with host dolomite and incorporated during successive deformational phases (Budai 1984).

Calcite and silica

The main gangue minerals of the Pb–Zn deposits in the study area are calcite and minor quartz. Different generations of calcite exist with relationships to dolomites. A first generation of calcite (calcite 1) predates all dolomite, including early diagenetic generations, except RD1dolomites. Calcite 1 is locally replaced by dolomite crystals (Fig. 9a). A second generation of calcite (calcite 2) is contemporaneous with the silica cement and main mineralization stage (Fig. 9b). This generation intersects all the diagenetic dolomite phases and occurs as cements lining vugs, fractures, and/or veins that postdate dolomite cements. Calcite 2 is characterized by large crystals occurring along fractures, faults, and karstic cavities as well as by white calcite veins (Fig. 9c). It postdates slightly the hydrothermal dolomites. Euhedral crystals of galena and sphalerite of large dimensions are associated with these calcite veins. Second-generation calcites (calcite 2) are intersected by a third-generation calcite (calcite 3, Fig. 9d). The latter calcite postdates mineralization; calcite 3 veinlets have been observed to cut both galena and sphalerite (Fig. 9d). This generation occurs together with Fe (hydro)oxides and smithsonite of the supergene mineralization.

Mechanism of dolomitization

Dolomites can form, theoretically, in three different ways (Machel 2004): (1) by *dolomitization*, which is the replacement of $CaCO_3$ by $CaMg(CO_3)_2$; (2) by *dolomite cementation*, which is precipitation of dolomite from aqueous solution in primary or secondary pore spaces; and (3) by precipitation from aqueous solution to form sedimentary deposits (*primary dolomite*). The volume of dolomite cement is small as compared to the total volume of dolomite, and primary dolomite appears to be rare and restricted to some evaporitic lagoonal and/or lacustrine settings (Boggs 2009). Thus, the great bulk of dolomite in the geologic record is apparently formed by dolomitization (replacement). Consequently, published discussion of the origin of dolomite has focused on mechanisms of dolomitization. Some modern/Holocene dolomites and most ancient dolomites are not directly associated with evaporites. Therefore, the hypersaline (reflux and sabkha) models do not appear to be appropriate for these dolomites (Boggs 2009). The absence of evaporite minerals from the studied samples is not reconciled with the model of dolomitization which takes place in evaporitic supratidal environments, discussed by Machel (2004) and Boggs (2009). Thin-section studies reveal that no evaporite minerals formed and no hollows which may be developed by leaching of evaporite minerals, as a result of influx of fresh water, are found. The formation model of the Upper Cretaceous dolomites generally fits the model of dolomitization by mixing water, common in reef facies (Land 1973). The Bekhme Formation is locally composed of rudist-bearing reefs. These rudistiferous reef facies host the Pb–Zn MVT deposits. These reefal carbonate-hosted Pb–Zn deposits are located in collisional orogenic belts, on active continental slopes. Also associated with orogens are MVT deposits that occur in fold and thrust belts (Leach et al. 2005). This activity provided favorable conditions for mixing of freshwater and seawater. It is most likely that a contemporaneous fault tectonics that had been active throughout the Upper Cretaceous played a role on this process. The areas that became shallower during sea level fluctuations (probably short-lived lowering and raising of sea level), which were triggered by fault tectonics concurrent with deposition, were invaded by freshwater. This freshwater was mixed with seawater to make brackish water favorable for dolomitization (Tucker and Wright 1990). The groundwater which becomes brackish by this process can cause dolomitization. On the other hand, the tectonic activity, marked by thrust and

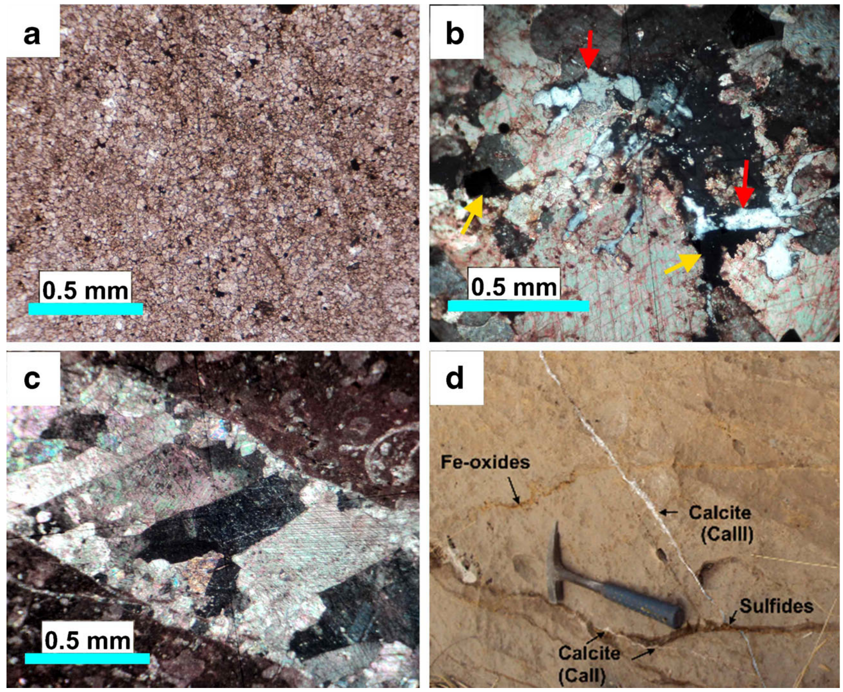


Fig. 9 Different generations of calcite with minor silica. **a** First generation of calcite (calcite 1) replaced by dolomite crystals. **b** Second generation of calcite (calcite 2) associated with the silica cement (*red arrows*) and mineralization stage; *yellow arrows* refer to sulfide minerals. **c** Large crystals of calcite 2 occurring along fracture. **d** Second-generation calcites (calcite 2) are intersected by a third-generation calcite (calcite 3). Note how calcite 3 cuts the sulfide and Fe oxides

other regional deep faults, coeval with the Eocene marine transgression, may have caused an increase of the thermal gradient in the whole area and circulation of formation and marine waters. These waters could have affected the Cretaceous succession along deep-seated faults and fractures. The presence of nonplanar crystals and of late-stage saddle dolomite may also indicate more elevated temperatures (Gregg and Sibley 1984). The relationship between major faults and dolomite distribution suggests that the fluids rose along or more probably diffused from these tectonic lineaments, extending laterally where permeability was greater. No intensive dolomitization has been observed within the highest (and again muddy) parts of the succession. The close association of dolomites and Pb–Zn ores suggests, also in the study area, that dolomitization and mineralization were temporally and genetically related and that dolomitization played an important role in the ground preparation for ore emplacement.

Bekhme Formation dolomites, in the studied Lefan area, have been formed as early diagenetic from mixing zone fluids at the subtidal (reef) environments and as the late diagenetic from basinal brines which partially mixed with hydrothermal fluids at the shallow to deep burial depths.

Paragenesis

Carbonate-hosted Pb–Zn deposits in the Bekhme Formation, Northern Iraq could be classified as MVT (Awadh 2006). Field evidence and petrographic studies have allowed outlining a detailed paragenetic sequence of the carbonate deposition. In the dolomitized carbonates, also the earliest diagenetic features are obliterated by dolomitization (Chen et al. 2004). However, the summary of paragenetic sequence of dolomite, calcite cement, and ore deposits is illustrated in Fig. 10.

The fine-grained dolomites or the first-generation dolomites (RD1) occurred as dolomite rhombs scattered in the carbonate matrix. These dolomite rhombs are formed shortly after deposition of the Upper Cretaceous carbonate of the Bekhme Formation. Fine-grained dolomites (RD1) could be considered as dolomites deposited in a very early diagenetic stage and became commonly the cores for later dolomites. In the study area, the RD1 occurs in association with the stromatolites of the peritidal zone, postdating early diagenetic features such as micrites and marine cements. The lowering of water table at the end of Lower Cretaceous caused partial emersion and a mixed marine–meteoric diagenetic environment, where the dissolution of carbonates was rendered, as well as a first karst generation. A first generation of calcite veins and bladed–syntaxial cement were deposited in a phreatic environment. Then, the dissolution of micrite and its recrystallization to microsparite and the calcification of carbonate fragments and ooids are followed. Dolomites of the RD2 and RD3 types were formed in this environment as well. These dolomites replace the calcites of the first generation and can be therefore considered as late diagenetic. RD2 and RD3 dolomite crystals commonly became the cores or the nuclei of late dolomite generations. The Bekhme Formation was influenced by Laramide orogeny during the Cretaceous and by the formation of the lower conglomerate unit of the formation including fragments of the Cretaceous succession (Ali 1989). These show reemergence in the Latest

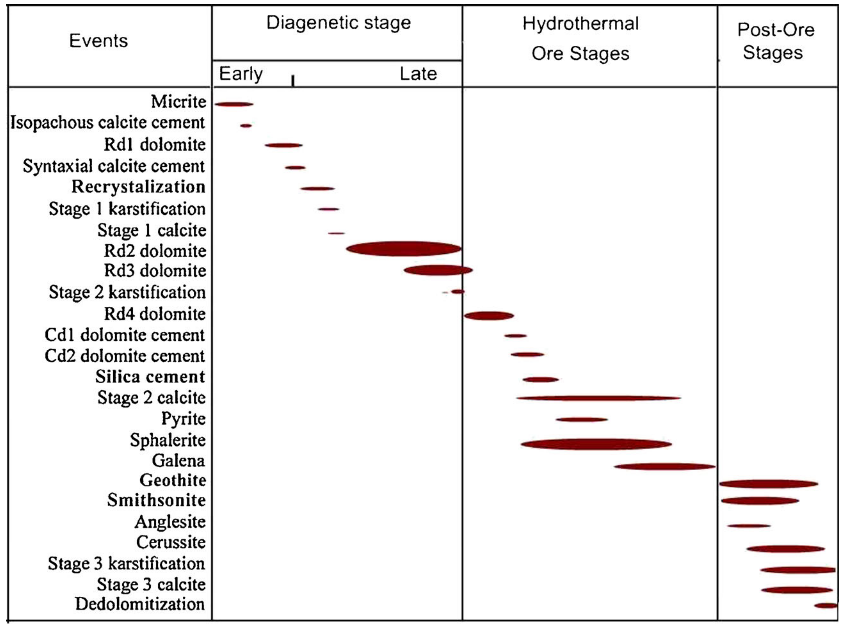


Fig. 10 Paragenetic sequence of dolomite, calcite cement, and ore deposits

Cretaceous and that second generation of karstification occurred. The next stage is characterized by a phase of shallow burial of the carbonate successions. The hydrothermal dolomites were formed during this stage. In low-temperature conditions, the crystal faces are planar and euhedral to subhedral crystals are developed. On the contrary, in the higher temperature range (50–100 °C), crystal faces are nonplanar and anhedral crystals are formed (Sibley and Gregg 1987; Gregg and Shelton 1990; Mazzullo 1992). The coarse (RD4) dolomites of the study area have changed locally from idiotopic to xenotopic, indicating an increase in temperature and salinity of the solutions.

The CD1 dolomite cement postdates RD4 dolomite because it fills vugs or fractures of the latter. CD1 is occasionally associated with silica cement and second-stage calcites (calcite 2), filling pores and spaces between the coarse crystalline dolomite. Saddle dolomite CD2 follows CD1. Generally, this dolomite type is deposited in a 60–100 °C temperature range and is associated with hydrocarbons and epigenetic base-metal mineralization (MVT) (Chen et al. 2004). This association indicates a very late diagenetic stage and possible reduction of sulfates. This type of dolomite originates from epigenetic waters with intermediate to high reducing pH (Radke and Mathis 1980). The remaining porosity of both vugs and veins is filled by calcite cements belonging to second-stage calcites (calcite 2). Continuous hydrothermal activity caused the formation of sparry calcite, locally associated with pyrite and sphalerite. The last stage of sulfide mineralization caused the precipitation of sphalerite and galena as euhedral crystals, veinlets, and host rock replacement. This mineralization stage was then followed by supergene alteration, as evidenced by the presence of oxidized pyrite grains (goethite) and by the replacement of sphalerite by smithsonite, and galena by cerussite and anglesite. A very recent karst phase is associated with the supergene alteration of sulfide ores and third generation of calcite (calcite 3). Locally, dedolomitization has been detected in relation to this phase.

Conclusion

Pb–Zn deposits which are recorded at Lefan Valley in the extremely northern part of Iraq are hosted by carbonate rocks of the Bekhme Formation (Upper Campanian). In the Lefan area, the zone of mineralization extends of about 75 m parallel to the bedding plane and exposes on the southern limb of Khamtur Mountain, about 25 km NE of Zakho (Fig. 1). The area was affected by Laramide orogeny, marked by the age of the various successions and by the presence of conglomerate intervals. This orogeny caused a local emersion of the Cretaceous succession and a karst episode in the study area. The tectonic activity, marked by thrust and other regional faults coeval with the Eocene marine transgression, may have caused an increase of the thermal gradient in the whole area and circulation of marine waters. These waters could have affected the Cretaceous succession along deep-seated faults and fractures. The relationship between major faults and dolomite distribution suggests that the fluids rose along, or more probably diffused from these tectonic lineaments, extending laterally where permeability was greater. No intensive dolomitization has been observed within the highest parts of the Bekhme Formation. The association of dolomites and Pb–Zn ores suggests that dolomitization and mineralization were temporally and genetically related. This dolomitization, recrystallization, and type of lithofacies are the main factors controlling the mineralization, while cementation and compaction have a reverse effect and dolomitization played an important role in the ground preparation for ore emplacement.

Six different dolomite textures have been recognized in the study area, including fine crystalline, planar-s (subhedral) dolomite, RD1; medium to coarse crystalline, planar-e (euhedral) to planar-s (subhedral) dolomites, RD2; medium crystalline, planar-s (subhedral) to nonplanar-a (anhedral) dolomites, RD3; coarse crystalline, planar-s (subhedral) to nonplanar-a (anhedral) dolomites, RD4; planar (subhedral) void-filling dolomite cements, CD1; and nonplanar (saddle) void-filling dolomite, CD2. The RD1, RD2, RD3 and RD4 dolomite textures are replaced in origin and are volumetrically the most important types, whereas CD1 and CD2 dolomites with sparry calcite are commonly cements that fill the open spaces. Although the dolomites of the Bekhme Formation are not macroscopically observed in the field, their different types are easily distinguished by petrographic examination and SEM. The studied Pb–Zn deposits show similarities to MVT deposits. They are epigenetic and hosted by dolostone and dolomitic limestone. Ore minerals are simple, marked by dominant sphalerite, galena, and minor pyrite.

The studied deposits formed in reefal carbonate of platform sequences typically located with thrust faults inboard of the orogenic belt, i.e., Alpine. Sedimentation took place in a foreland basin. Faults, fractures, dissolution collapse, and tectonic and karst-filling breccias control the ore locations.

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