Original Article

Cretaceous Limestone Dolomitization and Argument of Its Mg2+ Sources: Exampling the Bekhme and Qamchuqa Formations in the Zagros Collision Belt

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Abstract: This study unveils new considerations regarding the dolomitization of the Bekhme and Qamchuqa formations (BQFs), two reefal Cretaceous units in the Iraqi Zagros collisional belt. Previous studies proposed the dolomitization of these formations due to the ascent of Mg-rich hydrothermal solutions through deep faults but lacked substantial supporting evidence. This paper present new considerations suggesting that the dolomitization of the BQFs resulted from the Cretaceous environmental conditions and basin paleogeographic setting of the platform on which these formations were deposited. To justify this consideration, seven proofs presented. First is the occurrence of dolomite as vast layers extending tens of kilometers laterally and bounded between limestone beds, which resemble a strata-bound occurrence. Second is the absence of vertical selective dolomitization such as, hydrothermal mineralization, vertical dolomite dykes, hydrothermal vents, tubes, or zones. Third is the barrenness of most of the fault surfaces and their surrounding rocks with selective dolomitization. Fourth is the sharp boundary between the dolomite and limestone layers, indicating a sudden environmental change from lagoon to reef or forereef. Fifth is the record of dolomitization in the sediments reworked by bioturbation, evident in thalassinoides burrows. Sixth is the succession of BQFs underlain by limestone and green marl devoid of dolomitization and hydrothermal upward movement. Seventh is the contradictory notion of hydrothermal dolomitization among the most recent study published in the Science journal which atributed dolomitization to normal temperate on earth surface. In the present study, the source of the Mg is argued and its presence is attributed to the warmth of the Arabian platform (plate) near the equator during the Cretaceous period. Another source is the connection of the Arabian platform with the Neo-Tethys Sea, which was the locus of Mg-rich mafic volcanism in the form of arcs and mid-oceanic ridge topography, which supplied a voluminous amount of Mg to the Arabian carbonate platform through ocean currents.

1. Introduction

The Bekhme and Qamchuqa formations (BQFs) are two Cretaceous rock units with a collective thickness of more than 1000m and composed of successions of thick dolomite and limestone beds. These formations have close stratigraphic, tectonic, geographic, chronologic, and lithologic relationships because they represent a single depositional sequence with similar lithology and geography [1, 2]. According to these studies, the Bekhme Formation (Turonian-Middle Campanian) rests on the Qamchuqa Formation (Barremian-Cenomanian) and has a sequential (gradational) boundary. Conversely, pioneering studies [3, 4] defined the boundary as unconformable due to the presence of a 20m conglomerate between the two formations, indicating the age of the Bekhme Formation as Late Campanian. Later,

another study [5] revised the boundary to a gradational one and changed its age to the Turonian-Middle Campanian by refusing the presence of the conglomerate at their boundary. Recently, Nourmohamadi *et al.* [6] did not find a conglomerate between the two formations and referred only to the occurrence of 20 cm glauconitic green marl between the two formations, rather than a conglomerate, in the Bekhal area of the Erbil Governorate.

The close relationship between the two formations validates applying the same model and conclusions about dolomitization to both. Recent studies have focused separately on each formation, whereas, Mansurbeg *et al.* [7] modeled the hydrothermal dolomitization of the Bekhme Formation. While Kareem *et al.* [8] studied the same issues in the Qamchuqa Formation and reached similar conclusions regarding the hydrothermal dolomitization of the two formations through a deep ascent of a Mg-rich solution via deep fault surfaces. Dolomitization is an old problem, and Holland *et al.* [9] discussed it in detail; however, it has remained unsolved, making the present study a contribution towards its solution

The study by Arvidson and Mackenzie [10] reported the controversial involvement of the diagenetic and depositional environments in dolomite development because of the rare detection of dolomite in modern marine environments despite its abundance in all ancient sedimentary rocks. According to Machel [11], the dolomite problem arose from poor knowledge of the chemical and hydrological conditions of its development and the challenge of proposing a single origin based on geochemical and petrographical data. The study by Kim *et al.* [12] attributed its origin to several dissolutions and precipitation of crystal layers in voluminous occurrences, explaining the occurrence of dolomitization in the natural environment with pH or salinity fluctuations. They added that the growth and ripening of the defect-free crystals were facilitated by deliberate periods of mild dissolution.

The present study aims to critically investigate and re-evaluate the previously considered hydrothermal dolomitization. Additionally, it proposes other aspects of the problem to reveal and argue the origin of dolomitization in both the Qamchuqa and Bekhme formations which applies to another stratigraphic unit of the Zagros orogenic belt. It also includes the tectonic and environmental settings of these formations during dolomitization and the main source of Mg.

The studied area includes parts of two Governorates, namely northwestern Sulaymaniyah and north of Erbil, indicated in figure 1, which consists of a parallelogram, with its four corners listed clockwise from northwest, being located at 37°03'07" N, 43°54'02" E; 35°53'30" N, 45°22'23" E; 35°38'01" N, 45°19'03" E, and 36°37'26" N, 44°04'45" E. The Bekhme Formation conformably overlies the Qamchuqa Formation in both governorates. The area comprises more than 800 square kilometers, embracing towns, such as Surdash, Dokan Gapellon, Bingird, Ranyia, Smaquly, Hiran, Shaqlawa, Harir, Khalifan, Soran, and Aqra, from southeast to northwest. Geomorphologically, the area consists of a series of high and large mountains with complementary lowlands (valleys), each compartmentalized into small mountains and deep valleys.

These features mostly coincide with the asymmetrical anticlines and synclines in the area. The carapaces (outer arc) of the anticlines are covered by either the Qamchuqa or Bekhme Formation. Where the former formation forms the carapace, the latter one is exposed either in the core or along the inner arcs of the anticlines. The documentation by another study [13] examined some of these anticlines in the study area structurally and observed a deviation (shifting) of approximately 20° northward in the axes of minor folds compared to the axes of major anticlines. They ascribed this deviation to facies changes within the study area and the effect of the Mawat Core Complex. According to Karim [2] and Karim [14], in some areas of the Sulaymaniyah Governorate, the Bekhme Formation was not deposited because of its lateral change to the Kometan Formation.

During the Early Cretaceous period, the study area was part of the northeastern passive margin of the Arabian Plate. This margin is covered by shallow water where the two formations were deposited. During the Late Cretaceous (Campanian), the platform transformed into a foreland basin due to the filling of the Neo-Tethys Sea (Sanandaj-Sirjan Zone) with Graywacke and detrital limestones [15]. Owing to this filling and collision of the Arabian and Iranian Plates, the accumulated metamorphosed sediments were uplifted, forming the Zagros hinterland, foreland, and foreland basin. During the foreland phase, many formations, such as the Shiranish and Tanjero Formations (Campanian-Maastrichtian

turbidites), in addition to ertiary Formations such as the Kolosh, Sinjar, Gercus, and Pila Spi, were deposited.

2. Materials and Methods

The present study combined petrographic investigations with field observations to achieve the present results (Figure 1). These included surveying all gorges and valleys in the study area to identify attributes concerning dolomitization in the BQFs (Figure 2). During the survey, the relationships between dolomite and limestone intervals (beds) were documented across gorges and along the anticline limbs, where the best exposures of the two formations were visible. The boundary conditions of each dolomite bed were inspected to determine the presence or absence of external addition of material *via* dykes, veins, and discolored zones. The underlying and overlying stratigraphic units were also investigated to uncover the source of Mg below and above the two formations for a hundred meters. For this purpose, 120 thin sections of the two formations were prepared and analyzed under a polarizer and stereoscopic microscopes, and the textures and structures of early- and late-stage secondary dolomites were studied. These thin sections were employed to differentiate between the hydrothermal and *in situ* sources of Mg. The hydrothermal process is commonly associated with mineralization other than dolomite and calcite. Previously published dolomitic features, such as textures and structures, were re-evaluated in the field, and new features were documented.
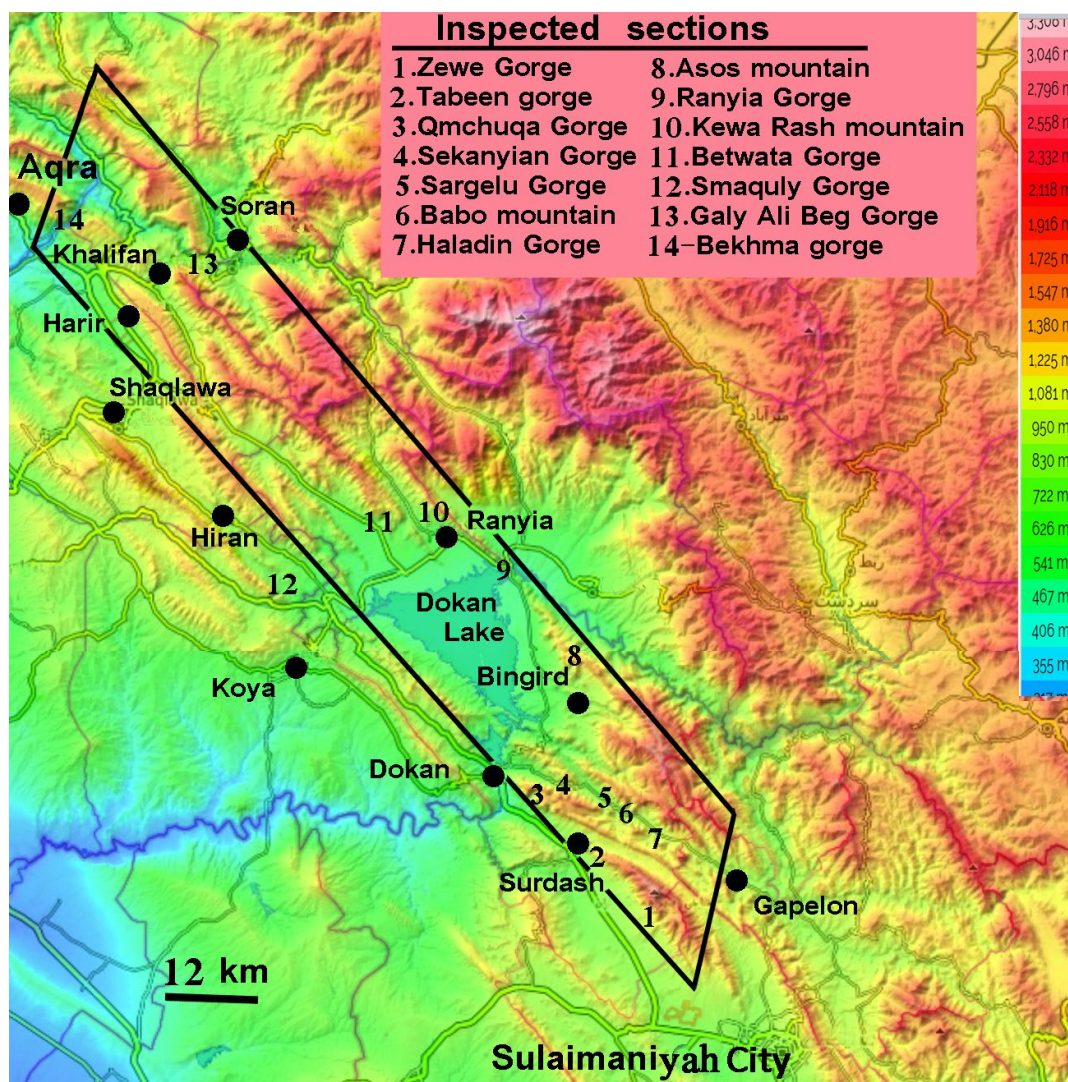

Figure 1: Location of the study area on a digital elevation map of northeastern Iraq.
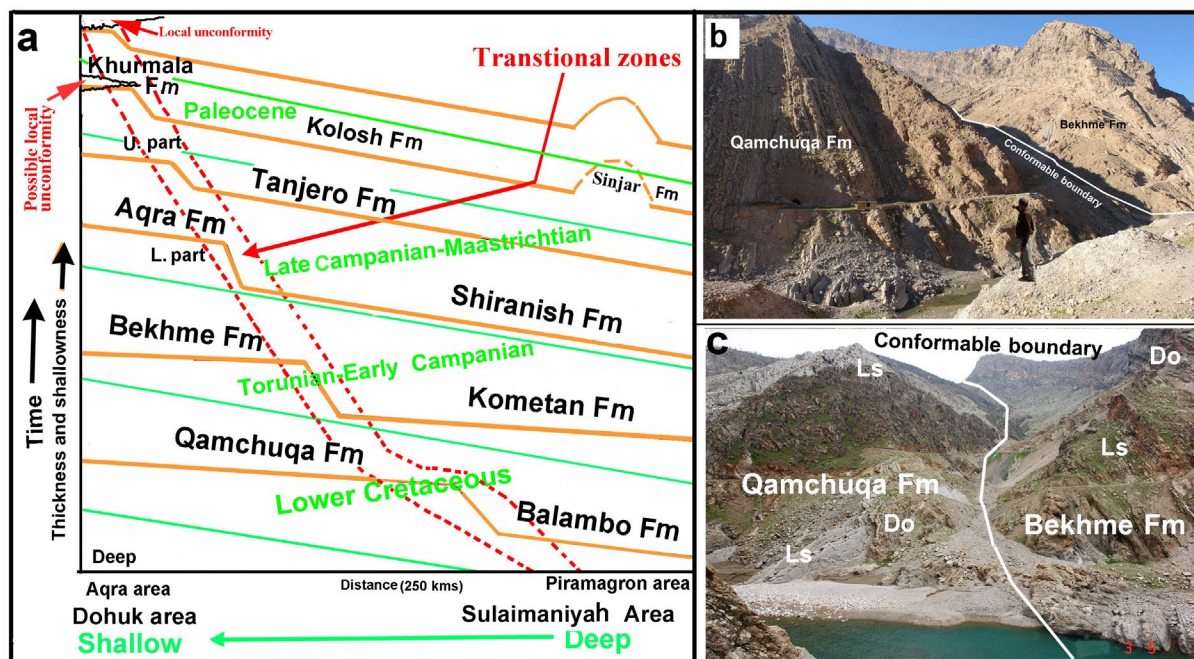
Figure 2: (**a**) Field and depositional environment relations between several Cretaceous and Tertiary formations applying to the studied area [2]. The deep marine carbonate formations are barren of dolomite while their shallow ones are mostly dolomitic. (**b, c**) Two photos of the Bekhme Gorge show the boundary and stratification of the BQFs.

3. Results

3.1. Large and Small-scale Mutual Stratifications of Dolomite and Limestone in the Two Formations

The BQFs have pervasive stratification at both large and small scales. On a large scale, these formations are characterized by well-developed beds (layers), each numbering several hundred (Figures 1, 2b, and 2c). These layers extend for approximately 100 kilometers in the study area, between the Erbil and Sulaymaniyah Governorates. The alternation of dolomite and limestone beds as a thick succession is observable in the two formations in the field as well as on a large scale across the study area. The predominant dolomite texture in both formations is idiotopic, with cloudy centers (Figure 3a).

Both formations are bounded from the base and top by marl and limestone, respectively, and their underlying formations are green marl and marly limestone of the Sarmord Formation (Figure 3b) While the overlying formation is the Shiranish Formation. On a small scale, such as within a meter or less, these formations often exhibit laminations in addition to the alternation of limestone and dolomite beds, together with sharp boundaries in the vertical succession (Figure 4). Despite surveying hundreds of kilometers of the outcrops of the two formations in the present study, no invation of the hydrothermal signals were detected at either the large or small scale. Hydrothermal solutions ascend through vents and channels [16] and are associated with different types of mineralization. Their invasion of carbonate rocks manifests as clear discoloration, vein mineralization, and textural modifications. These features must appear in outcrops as frequent discordances (dykes) across parts or entire stratification of the two formations. However, in the stratification of the BQFs, these passages of hydrothermal solution flow were not observed either as vertical, oblique, or horizontal conduits; mineralization veins; or dolomite tubes (Figure 5). A thin-section study revealed the barrenness of the two formations from quartz which is one of the main mineralization of the hydrothermal solution. The only silica phases observed in the BQFs are chert nodules, which are not rare in these two formations and are common in other Cretaceous stratigraphic units, such as the Sarmord and Kometan Formations. In the BQFs and other units, the chert nodules are aligned along the bedding plane (Figure 5), and have sedimentary origins according to Laschet [17].
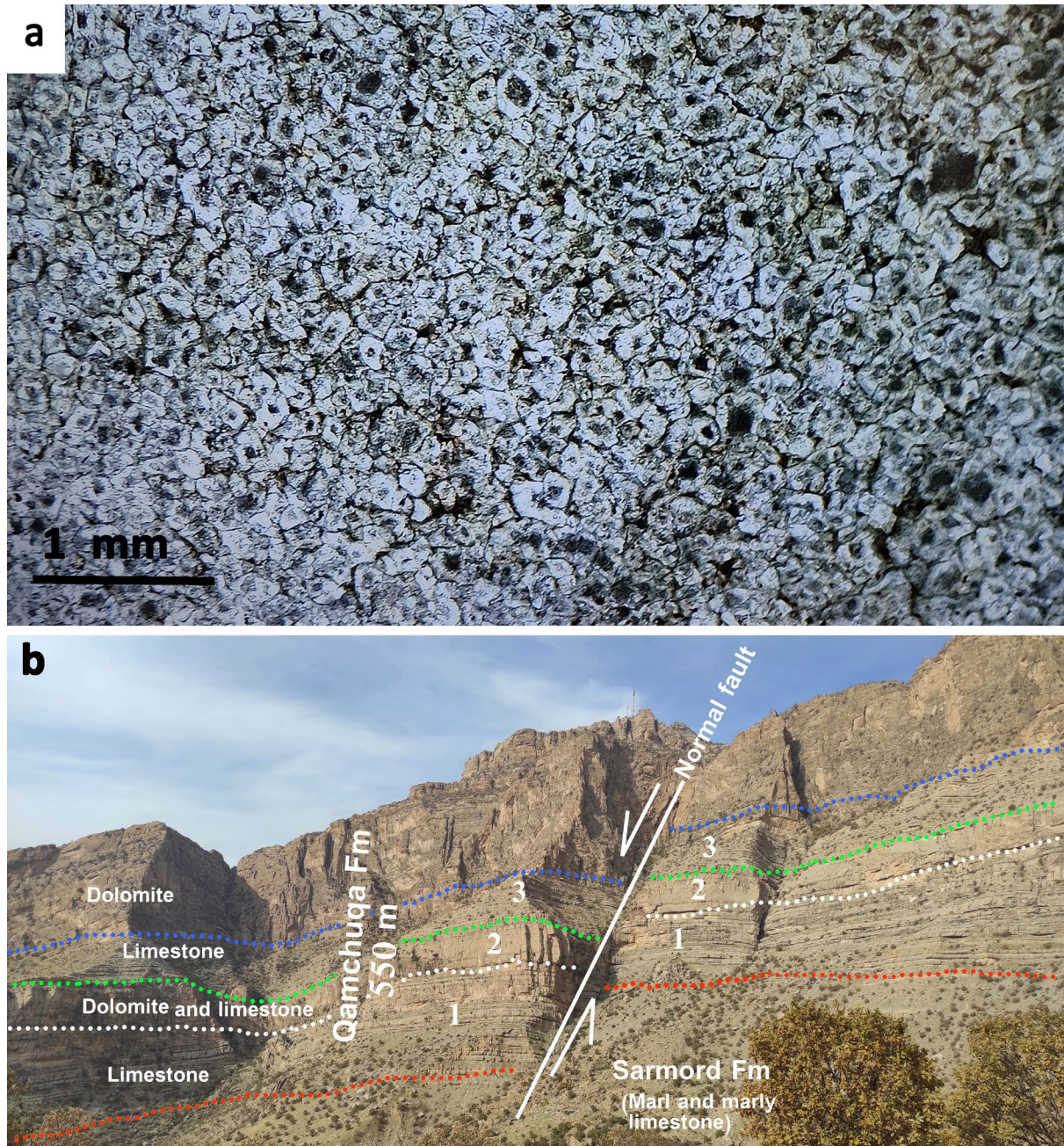
Figure 3: (a) The most common dolomite texture in the two formations is *idiotopic* with cloudy centers. **(b)** Stratified alternation of limestone and dolomite in the Qamchuqa Formation, directly at the western boundary of Sarmord Village in the Dokan area, with no selective dolomitization around or along the normal fault surface.
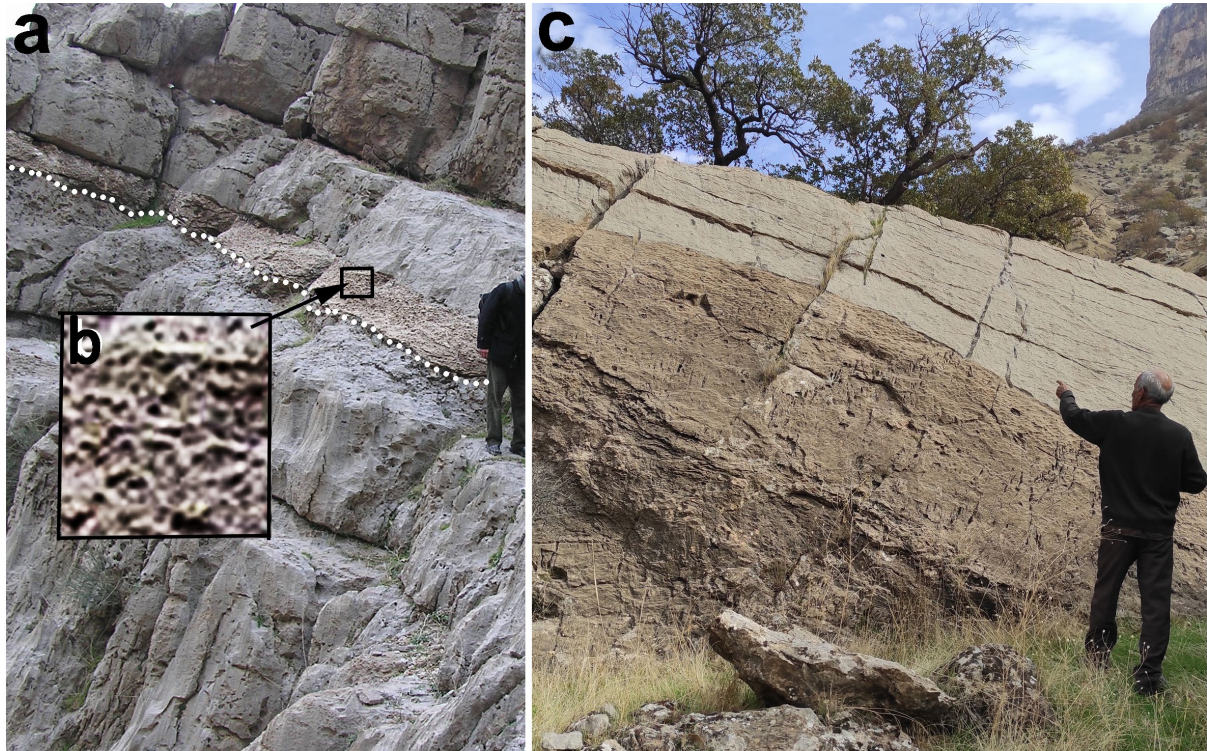
Figure 4: (**a**) Stratiform dolomite bed (light brown) sandwiched between limestone beds (light gray) on the Kewa Rash Mountain 2 km north of Ranyia town at 36°15'54.93"N, 44°54'19.00"E. (**b**) Close-up view of a part of the bed shows a thalassinoid burrow. (**c**) Planar and sharp contact between dolomite (light brown) and limestone (milky) beds in the Qamchuqa Gorge, 400 m southwest of Sarmord village, suggesting that dolomitization is not related to the hydrothermal invasion.

Figure 5: Eleven chert nodule horizons aligned parallel to the bedding plane on the Kewa Rash Mountain at the lower part of the Qamchuqa Formation at 36°16'24.90"N, 44°53'19.57"E. There is no vertical or inclined chert mineralization.

The pervasive dolomitization of the BQFs covers hundreds of square kilometers aerially and several tens of meters vertically, therefore, it requires high-frequency hydrothermal passages and huge volumes of related fluid migration for dolomitization, which are not present in the study area. Figures 2, 3, and 6 clearly show the strata-bound (stratiform) dolomite confined between the limestone layers. All the dolomites are restricted to certain strata or successions and have sharp contacts with the overlying and underlying limestone beds. The stacking pattern of dolomite-limestone alternations is barren from signs of the external sources of Mg, introduced through passages because there are no cross-cutting veins, mineralization dykes, or tubes. The fault plane in Figure 3 has no role in dolomitization, which is contradictory to previous studies [7, 8, 18].
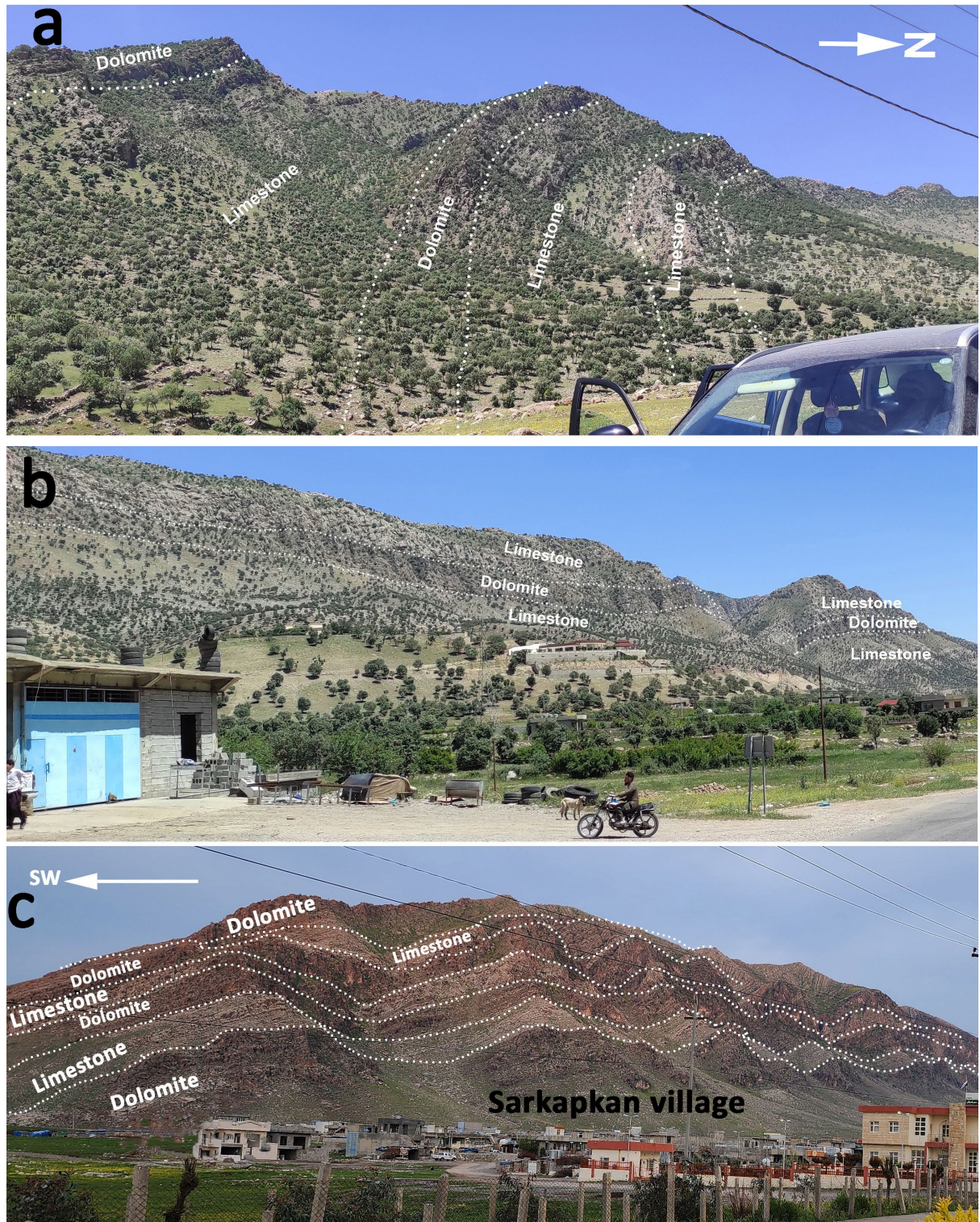
Figure 6: Stratified dolomite between limestone beds at three different locations of the Qamchuqa Formation: (**a**) on the Sardol Mountain, the photo was taken from the Nwawa village, (**b**) The same stratification on the Ware Mountain near the Balisan village, (**c**) The same stratification along the northeastern side of Makok Mountain, the photo was taken from Sarkapkan village.

3.2. Stratigraphic Positions and Boundary Conditions of the BQFs

The boundary conditions of the BQFs were investigated across a scale ranging from meters to several tens of kilometers within the study area. This investigation revealed that the Sarmord Formation (Hauterivian-Barremain) underlies the BQFs. According to Buday [3], this formation primarily consists of marl and marly limestones, with neritic limestones in its upper part below the Qamchuqa Formation. Our observations revealed barrenness of dolomitization in all marl, marly limestone, and neritic

limestone outcrops. Therefore, if the hydrothermal invasion were to occur, it would be expressed in the Sarmord Formation through discoloration, dolomitization dykes, sills, dolomite tubes, and mineralization zones because this unit is the main privilege direction for the invasion of dolomitization fluids below BQFs. The overlying stratigraphic units of the BQFs also lack dolomites because they vary according to the location. In the Sulaymaniyah Governorate, they are overlain by the Kometan Formation (pelagic limestone) or Shiranish Formation (Campanian marl). In Erbil city, it is overlaid by the Shiranish Formation or Aqra Formation. Therefore, according to the boundary condition study, the hydrothermal dolomitization of the BQFs was excluded because there were no signs of Mg introduction from the surroundings. Not only do vertical and stratigraphic boundary conditions refuse hydrothermal dolomitization, but so do the lateral (spatial) boundary conditions. This is because each of the BQFs has its time-equivalent basinal units. In this context, the Qamchuqa Formation changes laterally into the deep basinal Balambo Formation (mainly detrital and pelagic limestone [19, 20]. The former article concluded that the Balambo Formation mainly consisted of the erosion products of the Qamchuqa Formation, transported to the deep basin of the former formation by turbidity currents and deposited as calciturbidites (Figures 2 and 7) during the Early Cretaceous period. According to Karim [2] and Karim [14], the reefal Bekhme Formation is equivalent in time to the Kometan Formation and shares the same basin (Figure 2). Neither the Balambo nor the Kometan Formation contains dolomite, contradicting the claims of [7, 8, 18] regarding the migration of Mg^{2+} from a deep basinal source *via* fault passages. According to their model (Figure 8), the source of Mg^{2+} was the Thrust Zone, which is hundreds of kilometers away from the study area. If this source were true, dolomitization would be extensive in the latter two formations because they are located in a basinal environment and higher tectonic settings resulting from their proximity to the Thrust Zone compared with that to the BQFs. The field boundary condition contradicts these claims (Figures 8b) because there are no observable dolomite dykes, veins, or discoloration on any outcrops.
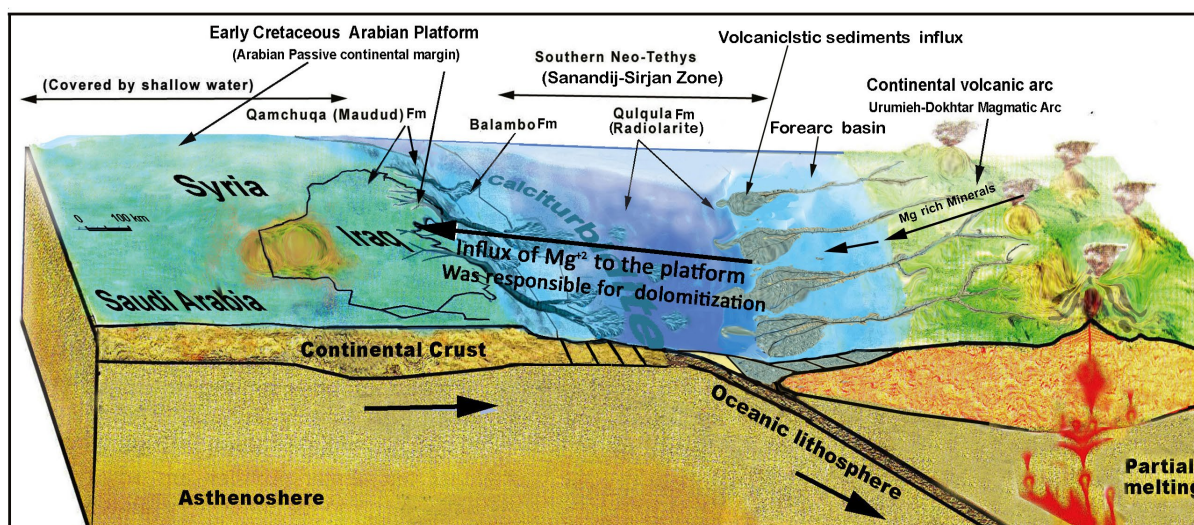
Figure 7: Neo-Tethys Sea (present Sanandaj-Sirjan Zone) during the Early Cretaceous in which the Qamchuqa and Balambo formations were deposited on its western passive continental (platform) margin (modified from [19]). There was an influx of the mafic volcanogenic sediment (graywackes) from the active margin (Urumieh-Dokhtor Magmatic Arc), supplying the basin with a sufficient amount of Mg2+ by currents for pervasive dolomitization.
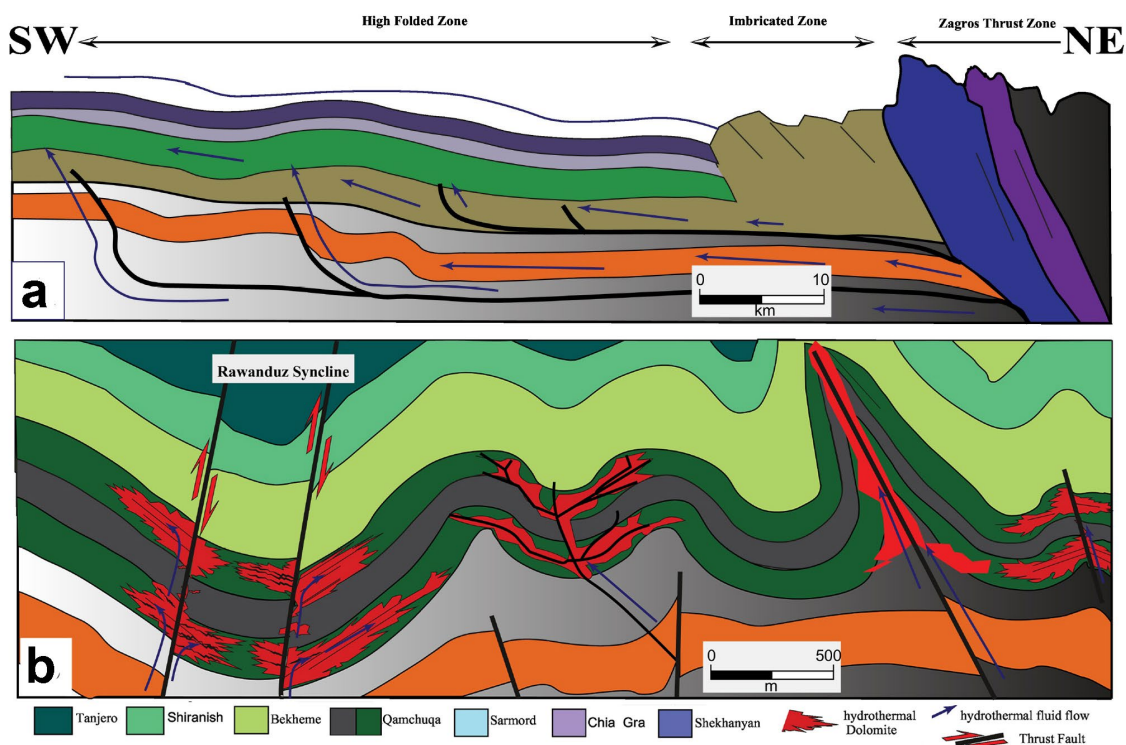
Figure 8: Geological cross-section and conceptual fluid flow model of the dolomitization of the Qamchuqa Formation by [8]. (**a**) Non-focused regional hydrothermal fluid flow and dolomitization. (**b**) A sketch shows the occurrence of focused hydrothermal fluid fluxes, saddle dolomite replacement and cementation.

3.3. Re-assessment of the Dolomitization of the BQFs

The Qamchuqa Formation comprises thick dolostone and limestone successions with a total thickness of more than 600m [3, 5]. According to these authors, the lithology of the formation can be divided into four or six units (according to geographic location), half of which are limestone and half are dolostone units. The limestone units are rich in fossils, such as pelecypods, rudists, corals, and stromatolites in the reefal and forereef facies, whereas the lagoonal facies contain algae, rotalids, and miliolid orbitoids. The formation has different stacking configurations; the beds of the lagoonal facies are relatively thin (10–50cm) and mostly laminated, whereas those of the reef and forereef are thicker or massive and show only faint laminations. The geographic distribution of the formation outcrops includes some of the parts of the Erbil, Duhok, and western Sulaymaniyah Governorates. In these areas, the formation is exposed along both the crests and inner arcs of the anticlines, forming high cliffs and tight gorges. Overall, the dolomitization of the two formations is stratified (multilayered) and sandwiched between limestone beds. Field evidence does not reveal the external addition of any ingredients to the sandwiched layers, either vertically or laterally.

3.4. Environmental Control of Mg²⁺ Versus Hydrothermal Pumping

In the previous sections, the mutual stratification of dolomite and limestone is manifested in addition to the absence of dolomite dyke, hydrothermal vents, vertical or inclined tubes of solution migration and mineralizations. It is well known that the Cretaceous was the period of carbonate deposition (limestone and dolomite), as its name indicates (creta, Latin for chalk). Therefore, the deposition of the dolomite and concentration of high rate of Ca^{2+} and Mg^{2+} in its basin is logical, since the two formations are deposited on the Arabian Platform and according to some studies [21-23] located near the Equator during the Cretaceous, therefore a warm climate is not excluded during their deposition (Figure 9).

The submarine weathering of the mafic-rich sediments and rocks [see 16] of the Oceanic and Sanadaji-Sirjan Zone supplied sufficient Mg ions to the Neo-Tethys Ocean water which reached the platform by currents and concentration there by evaporation in the shallow and warm environment milieu. This is documented by Breislin [24] who mentioned that post-depositional alteration of basalts

by CO_2-rich fluids could lead to the alteration of olivine and release of magnesium to the seawater by which the Mg/Ca ratio was increased.

The study of Kareem *et al.* [8] modeled many selective dolomitizations around the faults on the graphical figure (Figure 8), however, this claim was unaided by any pieces of evidence. On the contrary, fieldwork of the present study, recorded several large and tens of small faults that cut strata of either Qamchuqa or Bekhme formations, however, none of them shows selective dolomitization on their two walls or their direct neighboring rocks. These faults are observable in the Zewe, Qamchuqa, upper Dokan, Smaquly, and, Bekhma gorges in addition to those present on the Qarasard, Kosrat, Asos and Perse anticlines (Table 1) and (Figure 10).
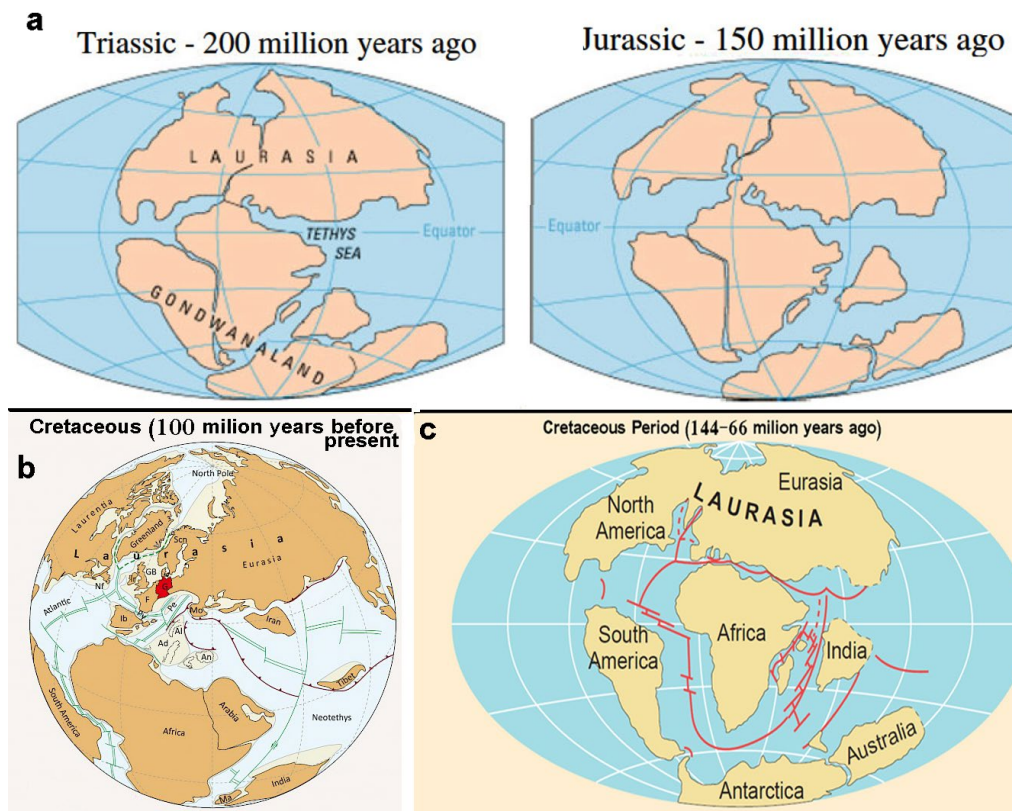

Figure 9: Location of the Arabian Platform (Plate) and Qamchuqa Formation relative to the Equator during the Cretaceous according to the following authors: (**a**) by [22], (**b**) by [23], [25], (**c**) by [24].

Table 1: Location of the main faults in the study area, where no selective dolomitization was found on their walls and surrounding rocks.

Fault location	GPS coordinate	Type of fault	Displacement	Figure.
Zewe gorge	35° 44' 14.21" N 44°15' 14.21" " E	3 Reverse faults	12 m	9a
Qamchuqa gorge	35° 54' 43.74" N 45° 01' 40.11" E	Normal fault	30m	3
Qamchuqa gorge	35° 54' 01.36" N 45° 01' 14.80" E	Strike-slip fault	60 m	
Qamchuqa anticline	35° 53' 53.19" N 45° 01' 59.15" E	3 Reverse faults	40 m	9b
Qarasard anticline	35° 58' 05.71" N 45° 02' 41.34" E	Reverse fault	15 m	9c
Qarasard anticline	35° 58' 05.71" N N 45° 02' 41.34" E	Reverse fault	15 m	
Qarangwe	35° 55' 19.28" N 45° 06' 02.41" E	Reverse fault	8 m	
Kosrat anticline	36°02'30.12" N 44° 51' 52.83 E	Reverse fault	15 m	9d
Smaqully galy	36° 10'20.70 N 44° 35' 15.51" E	Normal fault	40m	9e
Bekhma gorge	36° 42' 03.27"N 44° 16' 09.03" E	Reverse fault	20 m	
Perse anticline	36°48' 40.43" N 43° 59' 29.58 E	Reverse fault	18 m	9f
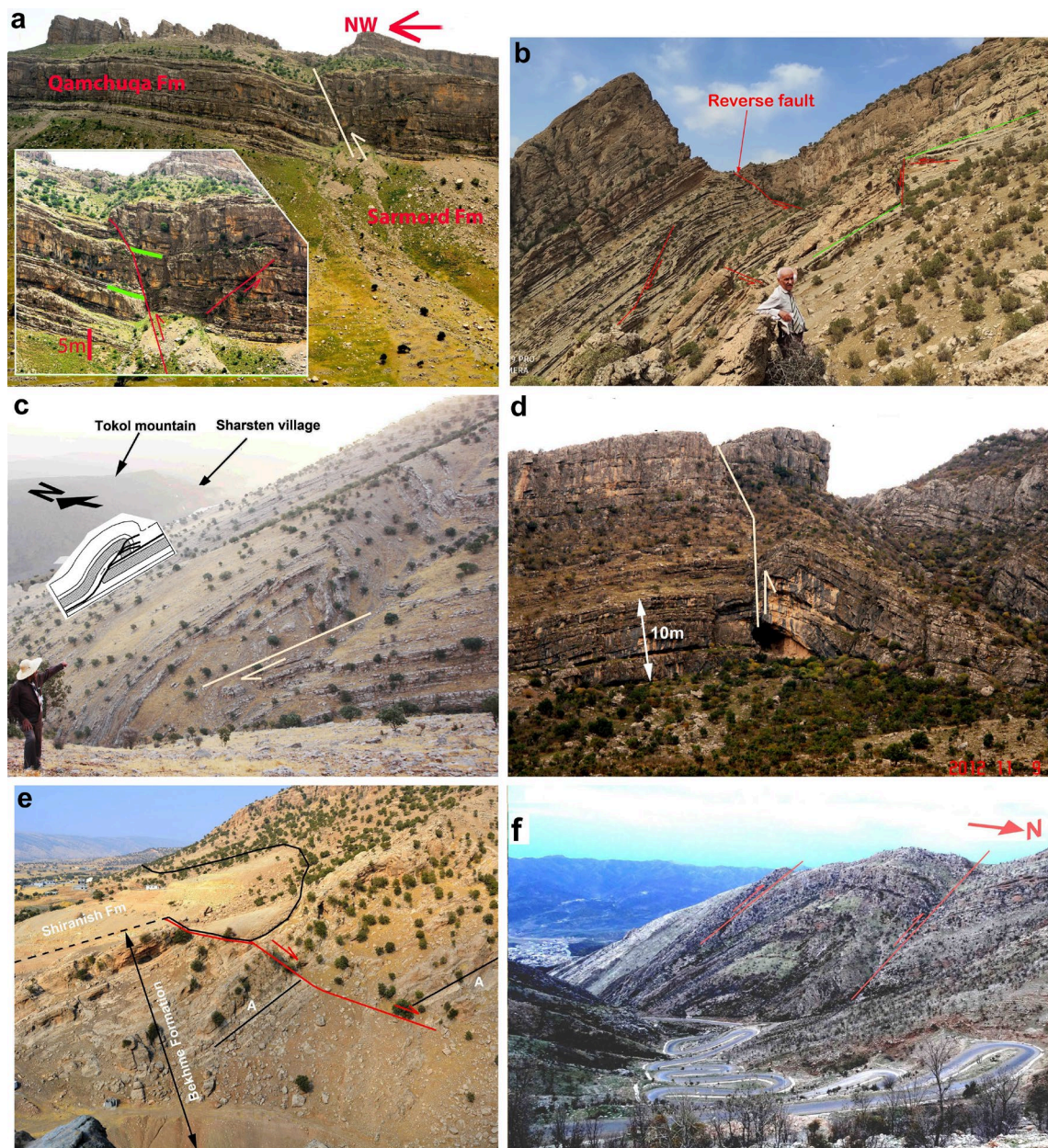
Figure 10: Field photos of the reverse and normal faults inside the Bekhme and Qamchuqa Formations, (**a**) in the Zewe Gorge, (**b**) in the Qamchuqa Gorge, (**c**) on the northeastern limb of the Qaraserd anticline, (**d**) on the southeastern limb of the Kosrat anticline, (**e**) in the Smaquly Gorge, and (**f**) on the northeastern limb of the Perse anticline (see Table 1 for their locations).

3.5. Problem of White Secondary Dolomite (*Zebra dolomite*)

According to [25], Zebra dolomite consists of alternating and periodic, dark and light bands of dolomite. They attributed the development of these bands to factors, such as stress and host rock permeability, common in many rocks. There are many theories about the origins of the Zebra dolomite, such as the lengthwise precipitation of dolomite through a horizontal set of microfractures [26], opening of bedding or cleavage planes by focused fluid flow [27], vein growth by pressure solution of the calcite host and its replacement by dolomite [28], and replacement of sedimentary partings (laminations) by hydrothermal fluid [29].

In the context of BQFs, Zebra dolomite is rare because its aerial and volume occurrences on outcrops are less than one per thousand. One can walk several kilometers on the outcrops of the two formations without finding any Zebra dolomite. In rare cases, when it is found, it is typically limited to a few meters in both the lateral extent and thickness (Figure 11). Zebra dolomite in the BQFs consists of

alternating white and dark gray bands (laminae). The white bands consist of clear spray dolomite crystals, whereas the dark gray consists of cloudy and inclusion-rich crystals.

The present study   considers the white bands are horizontal or inclined fractures filled with secondary spray dolomite, hence called secondary dolomite veins. Zebra dolomite in the BQFs sometimes shows shearing and brecciation, with a spotty appearance or vitiligo-like appearance, Figure 11a). It (in the BQFs) is associated with small faults of the Upper Miocene-Pliocene epoch but not with deep-seated faults of the Cretaceous, as reported by Kareem *et al.* [8]. This small fault possibly aided and amplified local differential unloading in a few places.

The works of Kareem *et al.* [8] and Ghafur *et al.* [18] attributed their development to hydrothermal solution influx through deep-seated faults, mainly along the anticline axial planes. The field observations of the present study contradict the hydrothermal origin of the Zebra dolomite based on five points. First is the absence of connection with the surrounding host rocks, which is present in the field where the Zebra dolomite is not connected to the underlying strata by veins or conduits to supply hydrothermal fluid for dolomitization. Second is the horizontal orientation of the white band in most occurrences of the Zebra dolomite; whereas, only rare occurrences are slightly inclined. This horizontal orientation is manifested by the parallelism of bands to the bedding interface. Presently, most of them appear tilted because of tectonic folding, indicating their generation by unloading (release of pressure) during the uplift of deep-buried BQFs before folding during the Upper Miocene-Pliocene epoch, when they sheared (faulted during folding). In the thin section, the Zebra dolomite shows several stages of parallel fracturing (Figure 11b).

The overlying stratigraphy (thickness of the sedimentary rocks) of the two formations indicates a burial depth of more than 8 km during the Middle Eocene-Oligocene epoch. This depth corresponds to temperatures around 160 C^{o} considering the geothermal gradient of 20 °C/km [30]. Therefore, the buried connate water of the formations reached such temperatures at the aforementioned depth. The recorded temperature of Kareem *et al.* [8] hrough geochemical analysis is resulted from this burial (depth of 7 km) but they assumed it as evidence of deep-seated geothermal fluid raised through faults from the thrust zone. Third is the occurrence of crenulated limestone in the Kometan Formation near Said Sadiq Town and other locations. The texture (structure) of this limestone is similar to that of the Zebra dolomites because it comprises more than 60 m of alternation of two types of thin bands on a scale of several millimeters. One type of lamina consists of milky fine-grained limestone, while the other is thinner gray calcite. Transparent secondary calcite in the outcrop appears as gray, not white like secondary dolomite. This alternation was studied by Ghafor *et al.* [31], both in the field and under the microscope, attributing its development to the release of stress by unloading (Figure 12). Fourth is the failure of our inspection of tens of axial planes (axial zones) of the anticlines to detect signals of hydrothermal incursion in these two formations. The study of Kareem *et al.* [8] suggested the role of hydrothermal invasion through anticlines *via* their axial planes and dolomitization of the Qamchuqa Formation; however, they failed to provide any evidence for their claims. Their depiction of a syncline trough instead of an anticline further supports our field observations regarding the lack of evidence for hydrothermal dolomitization.

The fifth point is the demonstration of a thin section and hand specimen of the reverse fault breccia, indicating that the BQFs underwent pervasive dolomitization before faulting. This is evident from dolomite clasts fragmented by reverse faults to form breccias in the Bekhme Formation in the Bakhma Gorge (Figure 13c). The dolomite contains many small and large veins (fractures filled with secondary dolomite), which cut early dolomite, indicating that the pervasive dolomitization predates tectonic deformation, while secondary dolomite formation is synchronous with or postdates the deformation (Figure 13c). The final point is the record of common saddle dolomite as a constituent of the Zebra dolomite in the Qamchuqa Formation [8]. Although they described its occurrence in detail, there was no strong evidence. They presented two photographs of curved dolomite in thin sections without stereoscopic microscopy. Moreover, the SEM image presented by Kareem [32] failed to show a clear image of the saddle dolomite.

Our inspection of the Zebra dolomite failed to record saddle dolomite. Instead, it suggests that the curved dolomite crystals (in thin sections) are deformed crystals showing the effects of stress as wavy extinctions under polarized microscopes (Figures 13d and 13e). These types of crystals are common throughout the carbonates of the Zagros collisional belt. they are found also in less tectonic areas of Iraq, whereas, Karim *et al.* [33] found curved calcite crystals in the Low-Folded Zone of Iraq near Koya Town within the Upper Oligocene Anah Formation. They attributed the calcite curvature to the tectonic stress of the Miocene epoch.
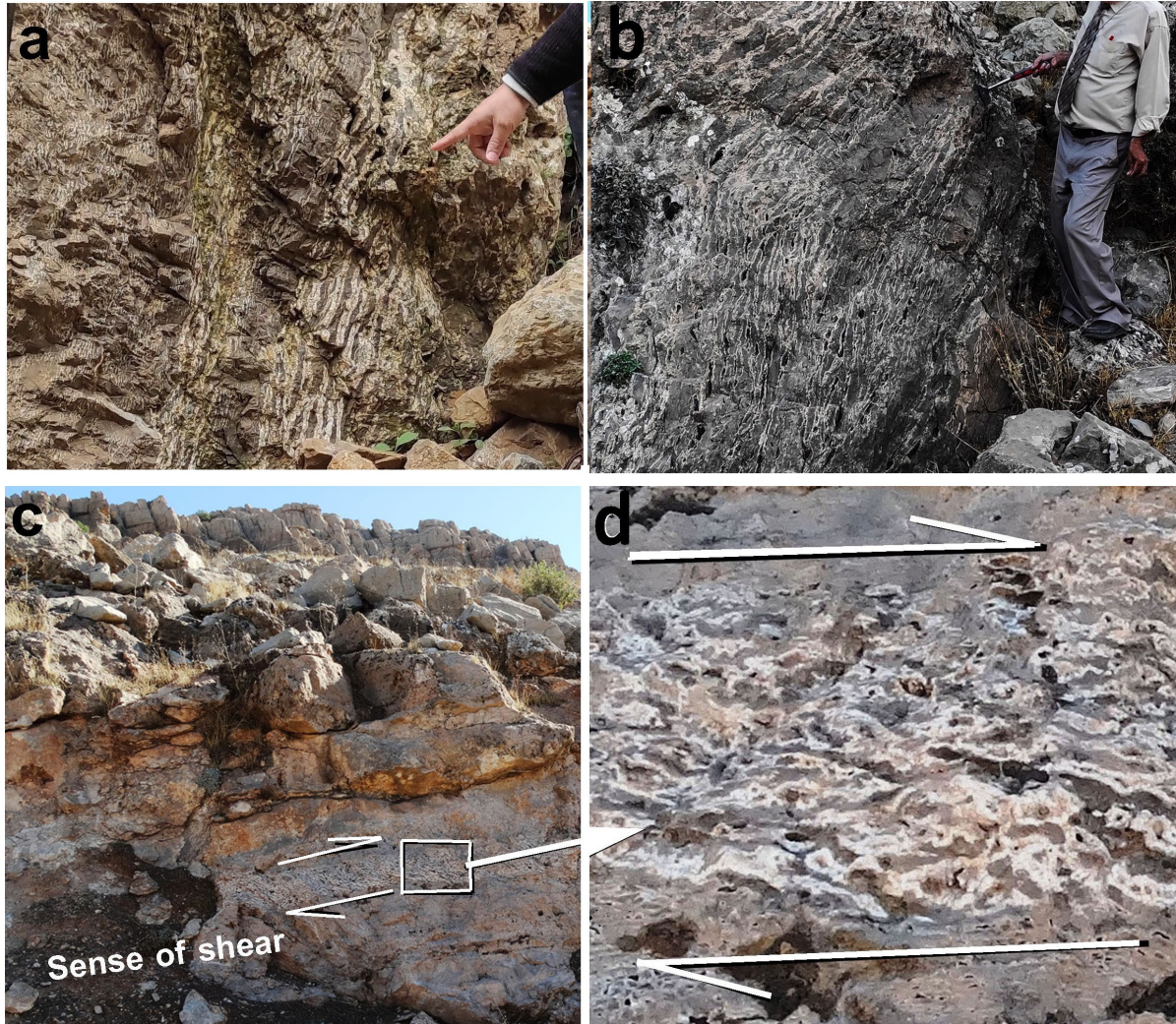

Figure 11: Layers parallel zebra dolomites (bands of early and vein-filling late (secondary) dolomites), (**a**) In the Qamchuqa Gorge, where the bands dip 45° southeast, (**b**) The Zewe gorge with similar dips, (**c**) Sheared bands on the Asos anticline, and (**d**) Close-up of the Zebra dolomite zone with a sense of shear.
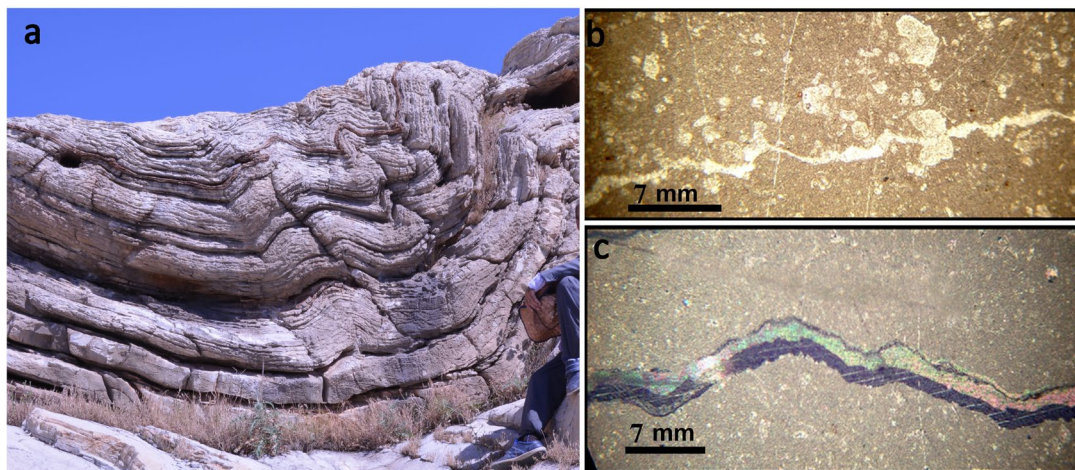
Figure 12: (**a**) Outcrop section of the Kometan Formation at the northern boundary of the Sharazoor plain on the Ashbulagh Hill, 300 m west of Said Sadiq Town, at 35°21'27.07" N, 45°51'25.03" E. The photo shows bedding (on a scale of 5–20 cm) and crenulation (Zebra limestone) (on a scale of 2–20 mm) in the Zebra limestone. (**b**) and (**c**) Limestone of the same outcrop under normal and cross-polar lights of a polarized microscope showing a bedding parallel vein developed by unloading and pressure of crystallization.
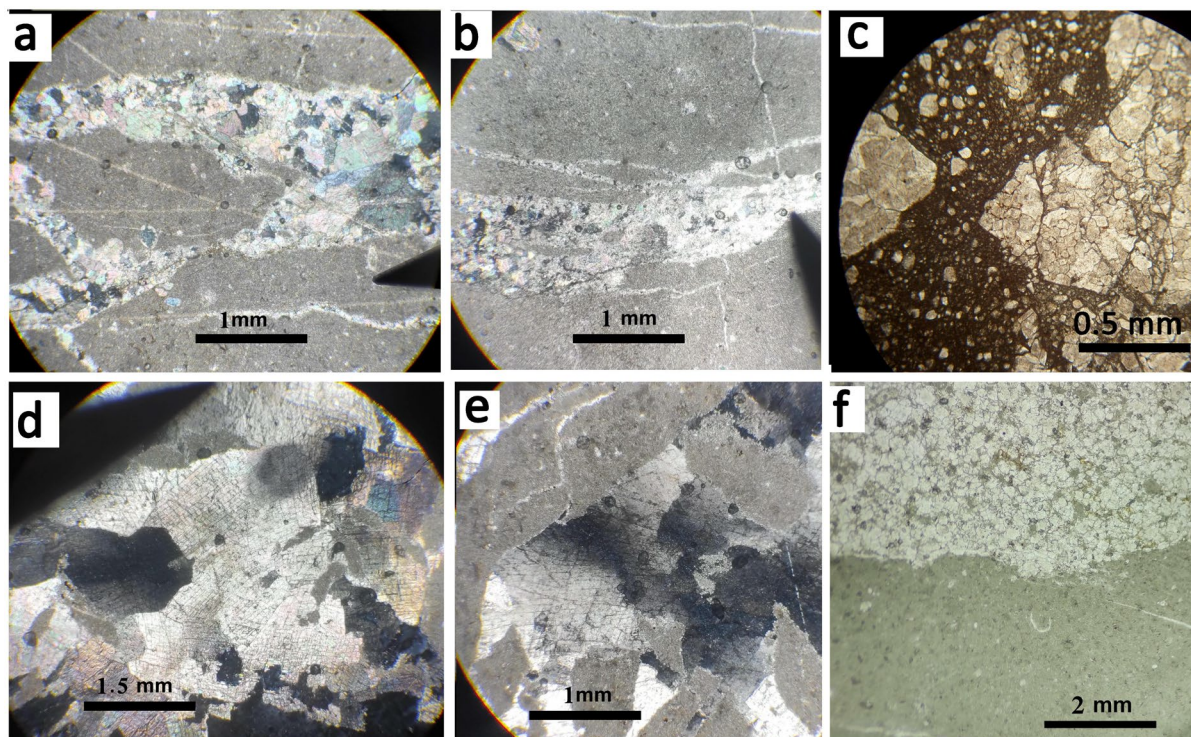
Figure 13. Microphotographs of some aspects of dolomitization in the BQFs: (**a**) A brecciated dolomite (gray) and late (white) diagenetic dolomite filling of the fracture, XP light, S.n. Q10. (**b**) Zebra dolomite consists of parallelly fractured dolomite of the Qamchuqa Formation and filling of the fracture by secondary dolomite, XP light, S.n. Q12. (**c**) Fault breccia of the large reverse fault within the Bekhme Formation in the Bekhma Gorge, not associated with secondary dolomite but the fracture filled with fine matrix (dark gray) PPL light, S.n. B10. (**d, e**) Wavy extinction, curved, and sutured crystals of dolomite due to shearing stress, XP light, S.n. Q6. (**f**) The sharp boundary between a thalassinoide trace (white) and hosting limestone (gray) on the Asos mountain, Normal light, S.n. A15.

3.6. 4.6. Dolomitization by Reworking

The BQFs are rich in pelecypods, gastropod shells, and their bioclasts which are observable in most limestone beds, whereas rare in dolomite beds because of their destruction by recrystallization (Figures 14a and b). The living activities of these molluscs are widespread in the two formations, especially in the Qamchuqa Formation. In the field, these activities are manifested by thalassiniode trace fossils. These traces consist of horizontal, inclined, or vertical burrows with irregular outlines in the exposed

sections. They are either branching or non-branching, and the range of their diameters is 1–4cm and lengths is 4–12cm. The frequency of the burrows changes from one bed to another; some are sparsely burrowed, while others are intensely burrowed (Figures 4a, 15c, and 15d). Rarely, they change to omission surfaces and hard ground (Figure 14). In some places, such as the Sekanyian Gorge and Asos Mountain, an entire interval (approximately 5–20 m thick) is intensely bioturbated and some horizons are dolomitized and transformed into hardground (Figure 4a). These bioturbated intervals, located in the lower part of the Qamchuqa Formation, were studied by [34] while studying unconformity in the latter formation (Figure 14). The bedding and lamination are due to differential bioturbation, including the effect of current erosion and deposition. Despite bioturbation and current reworking, the remains of the traces can be observed, and their sizes agree with those of the molluscs in the BQFs (Figures 14c and 15). Under polarized microscopes, the boundary between the host and traces of sediments appears sharp, represented as coarse crystalline dolomitic limestone (or dolomite) and fine-grained limestone (Figure 12f).

The sediment fills of these burrows have positive relief on outcrop exposures and are more dolomitic and darker in color than the host limestone rock (Figures 14 and 15). The dolomitization of this burrow is attributed solely to sediment reworking by molluscs, exposing the sediment to Mg-rich seawater for a longer duration than the host rocks during deposition or soon afterward. Therefore, the dolomitization of these traces refutes the hydrothermal dolomitization previously recorded in the BQFs by Kareem *et al.* [8]. In a similar context, Chatalov [35] recorded dolomitized sediments of burrows in limestone, calling this type of dolomitization as "Fabric-selective dolomitization" of the burrows and attributed Mg to a local source in a near-surface setting from non-evaporitic solutions with a low Mg/Ca ratio. The data of Burgess [36] manifested two types of dolomites controlled by organic (biological) and depositional factors. He observed a patchy appearance on the former type, developed by dolomitization of burrow sediments.

Reworking and erosion (either biological, physical, or chemical) are important because Kim et al. [12] recently concluded that erosion (dissolution on the crystal scale) plays a significant role in accelerating dolomitization. These erosions and reworking events have been widely recorded in the Qamchuqa Formation in the form of erosional surfaces, unconformities, and paleokarsts by Karim [20] and Karim [34].

Figure 14: (**a**) Outcrop of part of the Qamchuqa Formation on the Asos mountain shows approximately 20m of extensively bioturbated and selectively dolomitized carbonate at 36°04'44.19" N, 45°04'36.62" E. (**b, c**) Close-up of the same outcrop.

Figure 15: (a and b) Field photos of two different types of gastropods inside the Qamchuqa Formation. (c and d) Intensely and scantily bioturbated limestones inside the Qamchuqa Formation, the sediments inside traces are reworked dolomitizations by gastropods and pelecypods. All photos belong to the Qamchuqa Gorge (its locality type).

4. Discussion

We believe that the claim of the hydrothermal dolomitization of the Bekhme Formation (upper beds) by Mansurbeg *et al.* [7] if true was not need to repeat same processe in an article by Kareem *et al.* [8] on the Qamchuqa Formation which is located below the Bekhme Formation. This is because they referred to the ascend of Mg rich soultion from deep subsurface beow former formation. If the upper formation is dolomitized by deep hydrothermal solution, the lower one surely suffered from same process and even predate the upper one.

According to Al-Sadooni [37], dolomitization is the main feature of the Qamchuqa rocks, both in the subsurface sections and outcrops; forming more than 60% of the formation. In these outcrops, he referred to the regular distribution and general massiveness of the Qamchuqa dolomite. The study of Al Shdidi *et al.* [38] attributed this dolomitization to burial dolomitization before tectonic deformation. They cited the obliqueness of the best reservoir facies to the anticlinal axis and credited it to pre-tectonic dolomitization. These studies do not support hydrothermal dolomitization because fluid migration mostly occurs along the anticlinal axis, with the prevalence of dolomite facies.

The articles Kareem *et al.* [8] and Ghafur [18] claimed that the dolomitization of the two formations resulted from the introduction of Mg^{2+} from the deep-seated hydrothermal solution sources in the Thrust Zone during the Late Cretaceous to Oligocene. This study has other considerations about this deep Mg-rich hydrothermal, because, according to Buday [3] in the thrust Zone, the sources of Mg (mafic Igneous rocks) are not located in the deep subsurface but rested on the surface by obduction on the carbonate rocks of the Arabian Platform of the Early Cretaceous and Jurassic Periods. According to the latter authors, these mafic rocks are transported from remote distances by thrusting and have no relation with the platform on which the BQFs are deposited. The only siliciclastic that may occur in the deep subsurface near the present studied area is the Khabour Quarzite Formation [3, 39] which is poor in Mg and rich in silica.

Another challenge to the present study is the record of 170 °C by the latter authors by geochemistry, we respond to this record and justify if by considering it as a burial temperature of the strata of the BQFs. We estimated that their burial in their area reached more than 8km during the Middle Eocene-Oligocene when the overlying stratigraphy (thickness of the sedimentary rocks) over the two formations was calculated. This calculation includes the thickness of the formations such as Shiranish, Aqra, Kolosh, Khurmala, Gercus, Pila Spi, Lower Fars, Upper Fars and Bakhtiari formations. Therefore, the burial of BQFs reached more than 8km and this depth corresponds to temperatures around 160 °C considering the geothermal gradient of 20 °C /km [30]. Therefore, the buried connate water of the formations reached such temperatures at the aforementioned depth.

Another factor that aids the result of the present study is occurrence of Lagoons during Cretaceous which is the main locus of dolomitization) [40] and well described in previous studies in the stratigraphy of northern Iraq previous studies [41,42] who modeled and discussed reef environments, including vast lagoons, and showed penecontemporaneous dolomitization in a backreef and lagoon (Figure 16). Another environmental factor contributing to the Mg2+ richness of the basins of the two formations is the abundance of mafic clastic sediments (volcaniclastic sandstones) and mid-oceanic ridges. According to other studies [16, 43, 44], these sediments were deposited in the Neo-Tethys ocean (present Sanandaj-Sirjan Zone) during the Jurassic and Cretaceous periods. They added that these sediments were sourced from the Urumieh-Dokhtor Magmatic Arc and deposited in the latter ocean which was connected to the Arabian Platform through a passive margin. The works of other two studies [16, 20] elucidated the transport of voluminous quantities of calciturbite and volcaniclastic (graywacke) sediments across the margins to the deep basin of the Neo-Tethys ocean (Figure 7). In addition to the volcaniclastic sediments, Latif *et al.* [45] discussed the influx of Mg, Mn, and Fe from the mid-oceanic ridge to the waters of the Neo-Theys Ocean.

The newly published articles aid the result of the present study because Karim *et al.* [13] published their article in the Journal of Science and their result proved that dolomitization occurs in normal temperatures. Their study pointed out that dolomitization increased sevenfold through cycles of precipitation in a supersaturated medium and dissolution of crystal surfaces at ambient temperature in an undersaturated solution. This mechanism explains, by the latter authors, why the prevalence of modern dolomite is primarily found in natural environments with pH or salinity fluctuations and reveals that the growth and ripening of defect-free crystals can be facilitated by deliberate periods of mild dissolution.

Another problem of deep-seated hydrothermal invasion of Kareem *et al.* [8] and Ghafur [18] is the high oil content of the dolomite of the two formations in the many localities of Iraq such as Kirkuk and Mosul oil fields. The porosity and permeability of the dolomite are studied in several tens of articles and reports as some of them cited Aqrawi *et al.* [46] but, as the present authors were aware, no one of them referred to the effect of deep hydrothermal invasion on the properties of dolomite of the two formations and its oil content. No one of these studies found abnormal mineralization such as quartz, sulfur, and volatile gases that normally can associate deep innovation of hydrothermal solution. Another criticism against Kareem *et al.* [8] and Ghafur [18] is the absence of hydrothermal solution seepage on the surface of the present days Iraqi Kurdistan Region which indicated its absence in the past because the present is the key to the past. Therefore, the results of the present study are criticisms-free and supported by facts that are observable in the field and agree with the nature of the area.
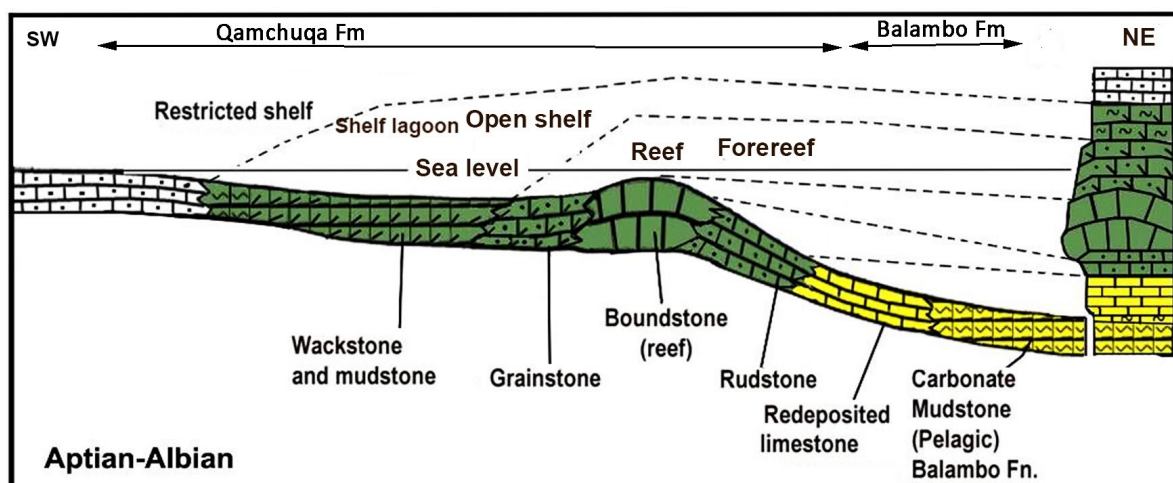
Figure 16: Paleographic and environmental setting of the Early Cretaceous Arabian Platform (Qamchuqa Formation) with plotted facies [42], manifesting a restricted wide lagoon environment that enhanced Mg concentration and dolomitization.

5. Conclusions

The results of the present study contradict the previous considerations and indicate that the dolomitization of the BQFs occurred in a Cretaceous shallow reefal platform basin. In this basin, significant amounts of dolomitization Mg were concentrated as a proximal source, by evaporation in the shelf lagoons. The primary source was an influx from the weathering of basaltic rocks in the Neo-Tethys Basin. To justify this new consideration, we documented seven pieces of evidence. First is the occurrence of dolomite as vast layers extending tens of kilometers laterally and bounded between limestone beds indicating a stratabound pattern. Second, is the absence of vertical selective dolomitization, such as vertical dolomite dikes, tubes, or zones. Third is the barrenness of all fault surfaces and their surrounding rocks of selective dolomitization. Fourth is the sharp boundary between the dolomite and limestone layers, indicating a sudden environmental change from lagoon to reef or forereef. Fifth is the record of dolomitization by sediment bio-reworking, which appears in the thalassinoide burrows. Sixth is the succession of the two formations underlain by limestone and green marl, which are barren of dolomitization and any signs of hydrothermal transit. Finally, a contradiction between previous studies and the most recent ones that attribute dolomitization to cycles of precipitation and dissolution of the dolomite substrate at ambient temperature.

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