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ORIGINAL ARTICLE

Evidence for origin and alteration in the dolomites of salt diapirs, Larestan, Southern Iran

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Abstract Dolomites are well-known minerals; belonging to the Infra-Cambrian Hormuz Series lies within the salt domes of southern Iran. In this paper, the origin and alteration of dolomitic rocks of Paskhand and Deh-kuyeh salt diapirs in the area of Larestan (southern Iran) are investigated. Based on petrographic (size and fabric) studies, we recognize four dolomite types that consist of very fine-to-fine crystalline dolomite (D1), neomorphic dolomite (D2), fine-to-medium crystalline euhedral-to-subhedral dolomite (D3), and pore- and fracture-filling dolomite (D4). The dolomite samples with up to 26% iron can be called ferruginous dolomites. Some igneous rock patches to gehter with hydrothermal iron veins are observable in the salt domes of Larestan. Oxygen and carbon isotope values of black and white, and altered red dolomite of Paskhand and Deh-kuyeh salt domes, are equal to − 12.35 to − 18.78 for $\delta^{18}O_{PDB}$ and − 5.48 to − 8.49 for $\delta^{13}C_{PDB;}$ values enriched δ180 with low-temperature (~ 70 °C) conditions are related to D1 dolomites and values depleted δ180 with higher temperatures (~ 270 °C) are related to D3 and D4 dolomites. The most important source for secondary dolomites is deeper hydrothermal and catchment sources, which ascended through faults during the intrusion. Meteoric waters can be mentioned as less important sources for these types of dolomites. We reported sassolite $B(OH)_3$ mineral in Deh-kuyeh salt diapir for the first time in this paper. This mineral is only observed in the areas which have famous riftings Fumarol. Therefore, in this paper, the existence of sassolite in the studied area could be considered one of the most important the origin of the composing elements of Hormuz rocks from fumarols which are formed in an extensional regime.

Keywords Dolomite · Sassolite · Fumarol · Hydrothermal · Diapir · Larestan

Introduction and geologic setting

The salt diapirs are important features in the Zagros orogenic system from which some are located in the Larestan region, south of Iran (Fars province) (Fig. 1). The Hormouz complex is composed of salt, and brown and red shale, interbedded with black, white, and gray dolomites, very fine siltstones and sandstones, gypsum, pyrite, iron oxide, and igneous rocks (Rahnama-Rad et al. 2009). The emergence of dolostones is a principal part of many sedimentary rocks in the salt diapirs of Larestan region (Fig. 3). Dolostones are frequently observed as smaller interbeds in gypsum and marl sequences, and sometimes in gypsum-tuff units. Most of the dolomites of the study area are observed as black and fetid dolostones, which are often laminated with white veins of secondary carbonate that is similar to wave form, and sometimes stromatolitic structures. Faint laminations and small streaks of organic matters suggest the presence of algal mats in their genesis and indicate that they have occurred in an intertidal to supratidal setting (Bosak et al. 1998). Gypsum and halite along with dolomites are available in abundance and can be used as an indicator of evaporitic environment of deposition (Fig. 3). On the other hand, applicable dolomitization theories are the sabkha model and

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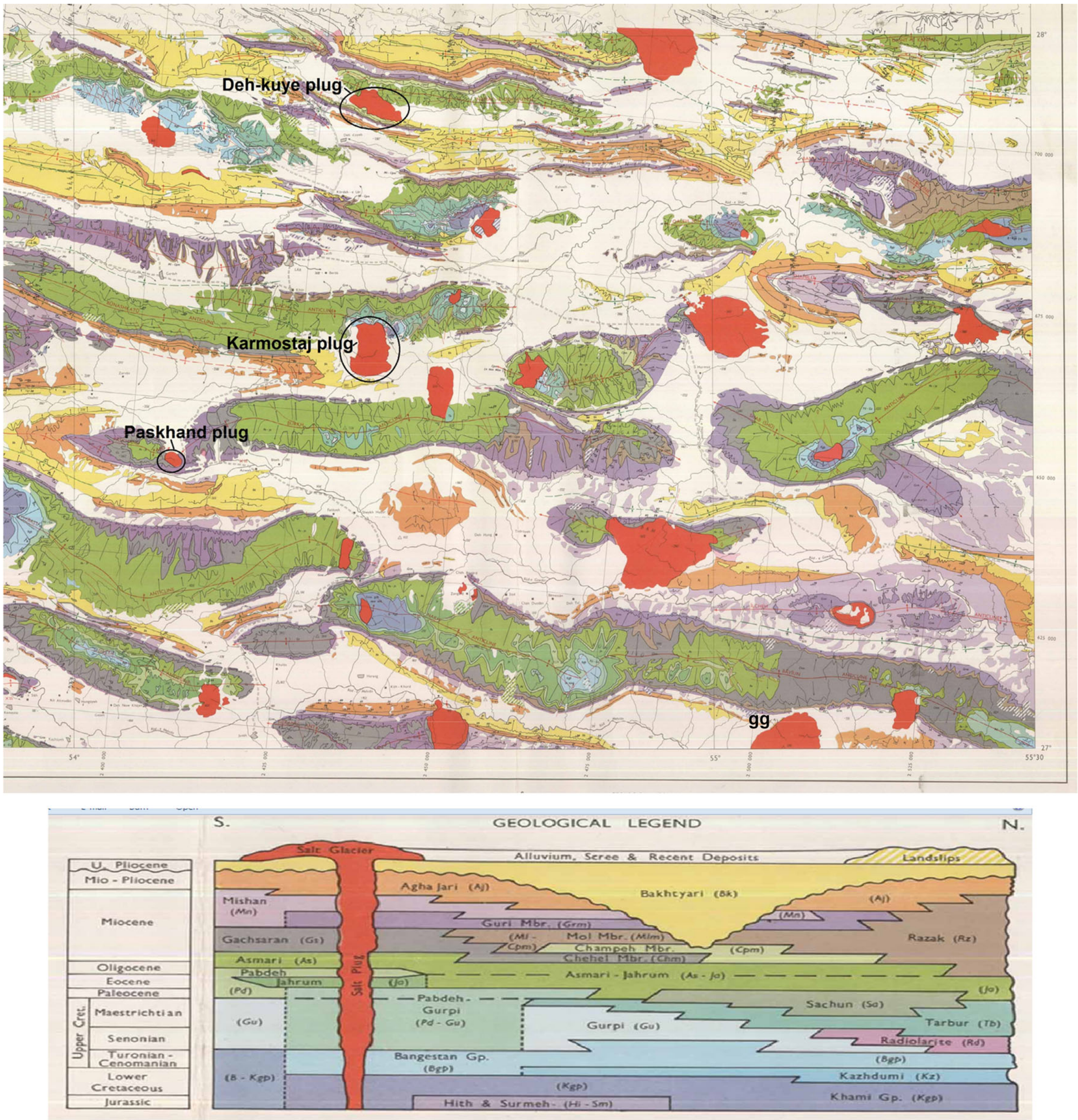


Fig. 1 **a** Geologic map of the Larestan area (scale: 1;250,000) Iranian National Oil Company (1965). **b** Geologic map of the Paskhand area with sampling locations, (scale: 1;5000) (Baharfirouzi 2010)

the brine reflux model (see Warren 2000; Machel 2004 for discussion). Few detrital quartz grains and flakes of phyllosilicate (white mica) iron oxide and some gypsum are randomly distributed all over the dolomites. In addition, dolostones outcrop with other lithotypes series that are covered by sandstones and marls. In some sections of the Deh-kuyeh plug, massive dolostone overlies rhyolite tuff and halite (Fig. 4). In the northern part of this plug, dark fetid dolostones and laminated dolostones are interbedded in gypsum-volcanic tuff-limestone sequence. The Paskhand plug which is rich in gypsum with intercalations of dark dolostones, limestone, clastics, tuff and volcanic rocks contains almost no salt minerals (Fig. 3). Due to the lack of salt, Paskhand plug can be considered as a gypsum dome. Field observations, petrographic and mineralographic investigations together with geochemical, and remote-sensing studies (Figs. 2, 3) indicate that most dolomites were affected by iron mineralization as a result of hydrothermal processes. In this research, using petrographic studies combined with geochemical, mineralogical analysis, and isotopic studies was used to recognize different types of Hormoz dolomites, origin, and the role of secondary hydrothermal solutions on the dolomites of Paskhand and Deh-kuyeh salt diapirs in Larestan area. In this reseach, geochemical, mineralogical, petrographic and isotopic investigations were used to study the occurrence and origin of the Infra-Cambrian Hormuz dolomites of the Paskhand and Deh-kuyeh diapirs in the Larestan area.

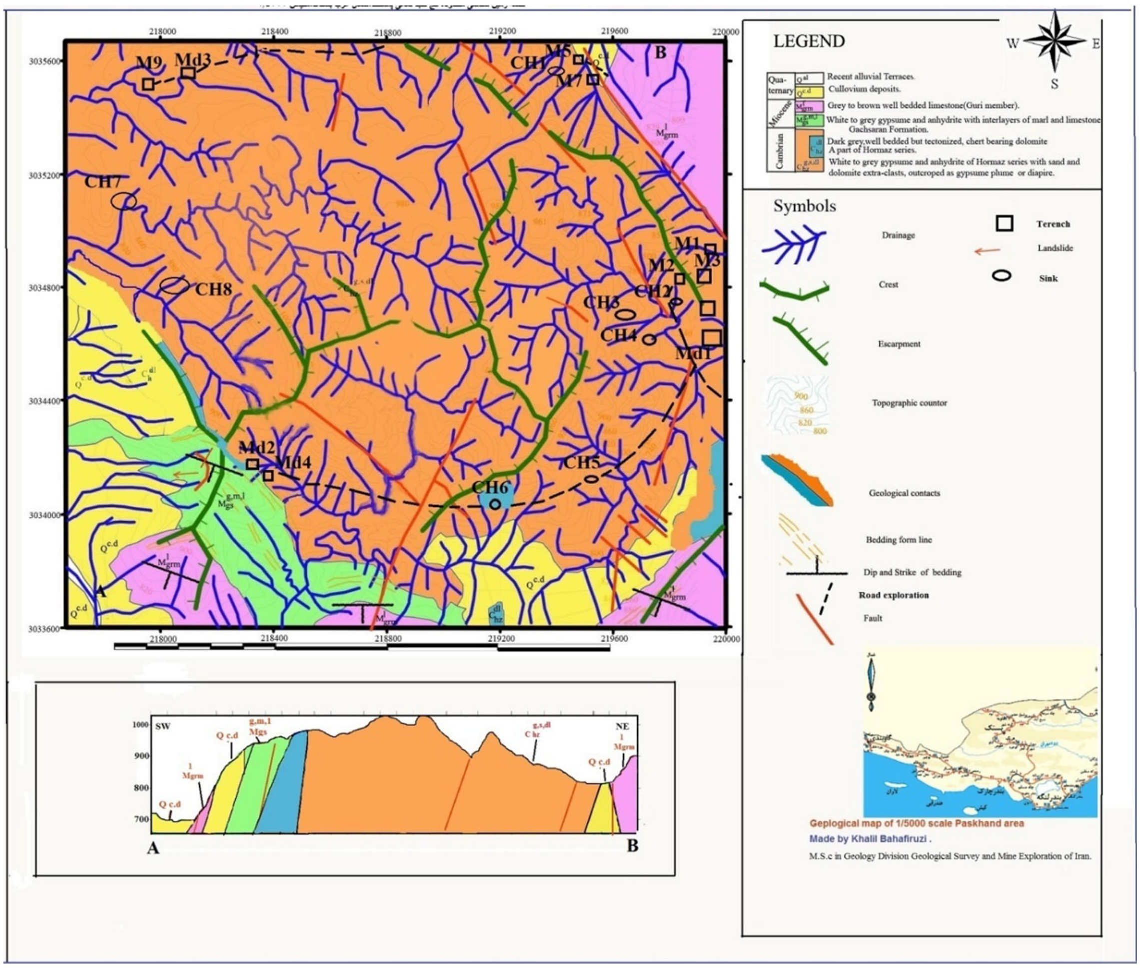


Fig. 1 continued

Method

Dolomite samples field of the Paskhand and Deh-kuyeh salt diapirs were taken from a different location. These samples were analyzed for major and trace elements by the Analytical Geochemistry Laboratories of Bureatu Veritas at the Australia Geological Survey and Kansaran Binalud Company in Iran. Approximately, 20 thin sections of dolomite samples were used to examine the petrographic and geochemical analysis. To recognize dolomites, we applied to stain Alizarin Red S and potassium ferricyanide in all of the thin sections. In this paper, we used the XRF method for determined major elements (Si, Ti, Al, Fe, Mn, Mg, Ca, Na, K, and P) and the trace elements were analyzed by the ICP-MS techniques. In addition, four dolomites samples were used to determine minerals by XRD method. The stable isotopes were measured by oxygen and carbon from four red and white altered dolomite samples and four non-altered dolomites. Dolomites are purified by the "Hand pick" method under the binocular microscope. The samples in powder form were sent to the Bureau Veritas Australia laboratory for the isotopic analysis. 15 mg of powder from each sample is placed for 24 h under the pure phosphoric acid and 25 °C, so that the CO_2 emissions is measured for the samples' mass spectrometry to prepare the powder samples of carbonate and the isotopic analysis of the oxygen–carbon. The measurement error of this method is about 0.1%. The oxygen–carbon isotopic composition of a sample is measured as δ, and expressed in terms of the amount of ppt, compared to SMOW and PDB standard.

Mineral study

Based on the XRD method, we recognized that the main mineral phases in non-altered dolomite samples of Paskhand and Deh-kuyeh plugs are frequently dolomite, with/without gypsum minerals. The altered dolomite samples have been identified quartz, dolomite, albite, microcline, and hematite as the main minerals, and muscovite and

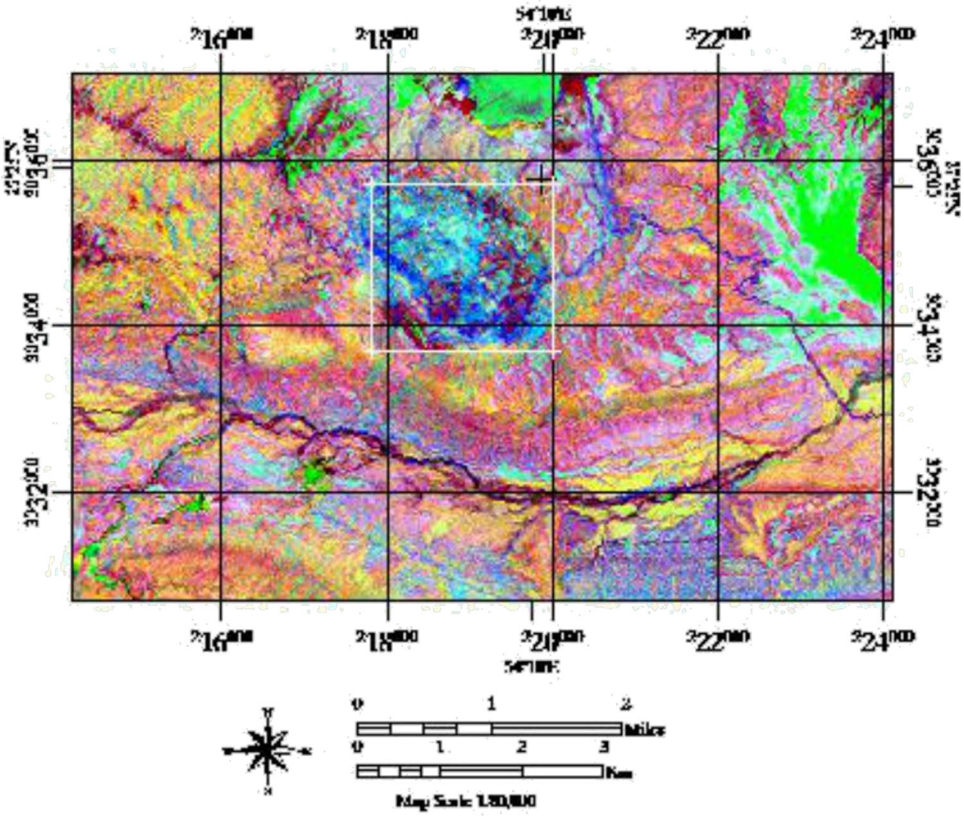


Fig. 2 Location map of Paskhand plug (shown with rectangle) in satellite images (ETM) processed by the principal components analysis (the color combinations 2, 3, and 4). Dolomite and ferruginous dolomite are shown in turquoise colors

chlorite as the minor minerals. Also in thin sections besides the dolomite, quartz, pyrite and gypsum was observed as primary minerals, and iron oxide, actinolite , chlorite and Secondary quartz as alteration minerals. The results of analyzes of the XRF method in the dolomite samples show that the amount of MgO is up to 21%. In addition, red color altered dolomite, containing abundant iron (up to 26% Fe_2O_3) (Fig. 11). The examination of these samples confirms on an effective role of hydrothermal fluids in the alteration of rocks, substitution of iron, silica, and carbonate, so that ”Ferruginous dolomites” ore has been recognized in the sampling (Figs. 5b, 11). Hydrothermal mineralization (e.g., well-crystalline hematite, galena, pyrite, and fluorite) is frequently observed in Hormuz series (Ala 1974; Salah 1996; Schroeder et al. 2003).

The primary silica is formed from decomposed acid volcanic and volcanoclastic rocks (Nasir et al. 2008). Silicification is an abundant diagenetic and/or epigenetic process that replaces both dolomite and primary gypsum/anhydrite (veins, nodules, and impregnation) content. Silicification is often associated with ferruginization. The Mica admixture is present as sericite, chlorite, and muscovite. In addition, pyrite as larger euhedral grains or as small framboidal grains is a common admixture. In our study area, we show dolomite with gypsum as interbedded layers that indicate that the gypsum is formed by abundance Ca^+ ions. Therefore, Ca^+ ions are used in gypsum mineral. The result of this process, Mg^+ ions, increases in this surrounding that provided conditions for the deposition of the dolomites (Adabi 2004).

Petrographic study

Existing Black and white dolomites are existed in Dehkuyeh and Paskhand salt domes in four different phases: dolomicrite, dolomicrosparate, dolosparate, and horse saddle dolomite. The alteration of dolomite could be determined from the lithological evidences. Changing procedure in the transition of dolomite from dolomicrite to dolomicrosparite and coarse dolomites indicates an increase in alteration of dolomites (Adabi 2004). Hydrothermal solutions were affected on the iron oxide abundance of the four different types of dolomite. The horse saddle dolomites, which are related to iron mineralization, are exposed to most alternation. The classification of dolomite-rock texture explained by Sibley and Gregg (1987) which is based largely on the fundamental classification of Friedman (1965).

The trace element dolomite is characterized as follows.

Type 1: very fine crystalline dolomite (dolomicrite)

Dolomites of this type included unimodal textures, anhedral, and very fine crystals (Fig. 6), that are formed

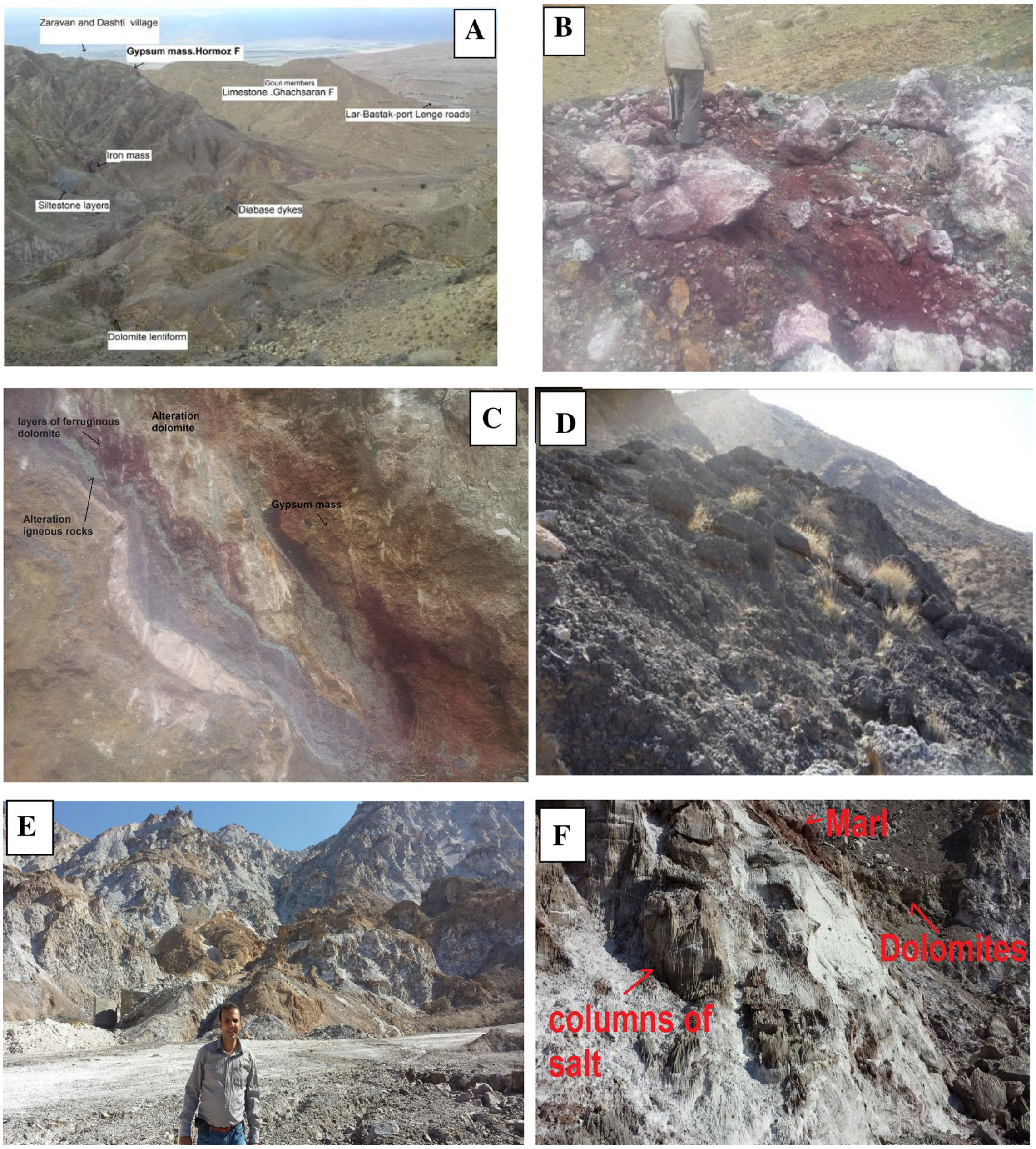


Fig. 3 **a** General view of the Paskhand plug, which shows various rocks in Hormuz Series. **b** The contact between iron veins, altered dolomites and igneous rocks in the Paskhand salt dome. **c** Dolomite shear in lens forming the Paskhand diapir. **d** The contact between alternation layers of dolomite and ferruginous dolomite, igneous rocks, and gypsum mass in the Paskhand dome. **e** General view of Deh-kuyeh plug. **f** Contact between layers of dolomite and halite in Deh-kuyeh dome. **g** Sharp contact between dolomites and halites. In addition, finally, **h** The relationship between dolomite, halite, and igneous rocks (diabase)

penecontemporaneously or by early replacement of carbonate mud, immediately after deposition, with Mg which is possibly derived from seawater. Crystal sizes of these samples range between 5 and 15 µm (average size of approximately 10 µm). Properties of these samples comprise dense and dark in color, non-porous, unfossiliferous, and preserve traces of depositional textures, such as laminations and intraclasts, and are commonly associated with scattered detrital quartz grains (Fig. 7b). Therefore, it seems that dolomite type 1 is formed in a supratidal-to-upper intertidal setting and under near surface with low-temperature (~ 78 °C) conditions. Dolomite type 1 has the most enriched δ180 values (− 2.1‰ PDB), compared to the other dolomite types. It is volumetrically significant, accounting for about 31% of all dolomite types. Type 1 dolomites are similar to xenotropic-A texture (Gregg and Sibley 1984). The crystal size of the dolomite is useful to distinguish between before and after diagenetic dolomite.

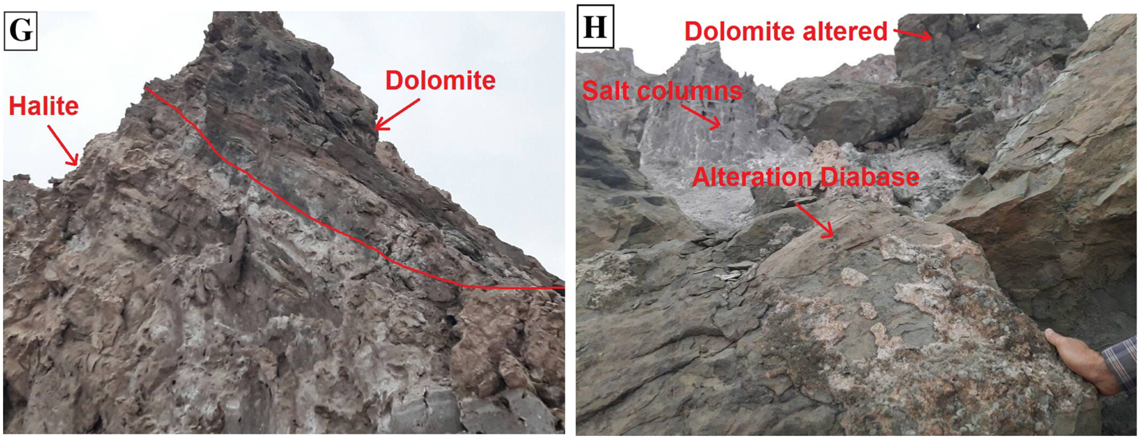


Fig. 3 continued

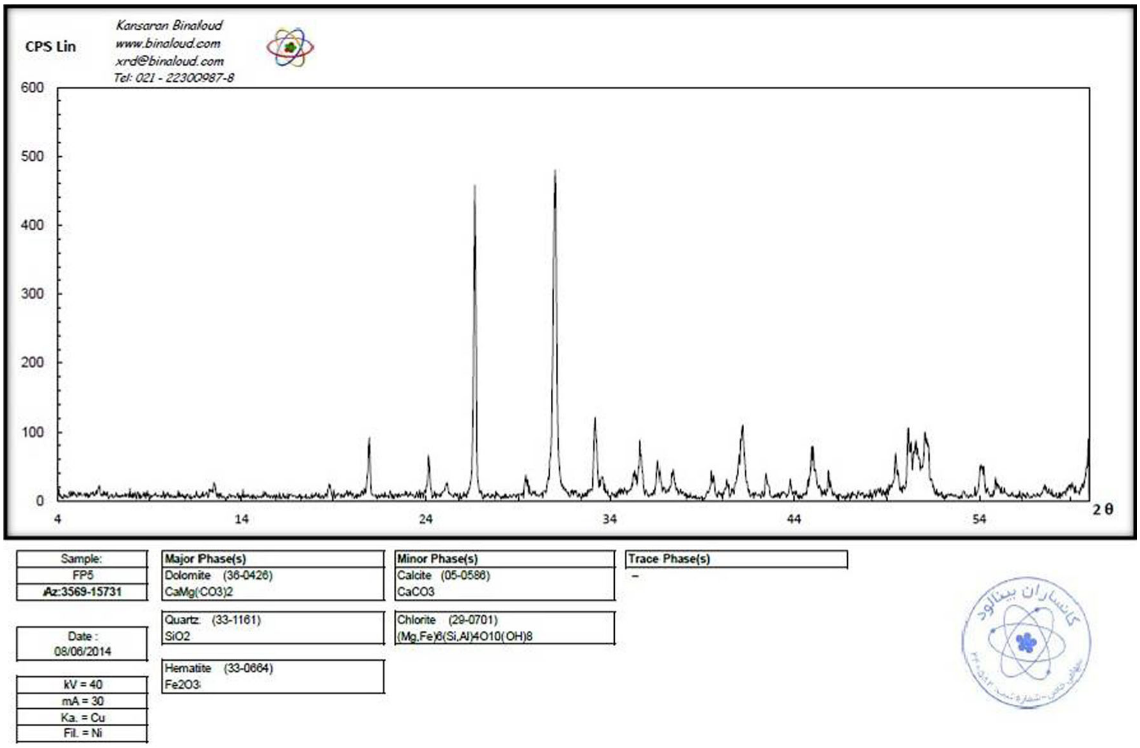


Fig. 4 X-ray diffraction diagram for a representative ferruginous dolomite sample

Type 2: fine crystalline dolomite (dolomicrosparite)

Dolomite Type 2 is composed mainly of dense unimodal textures of subhedral-to-anhedral planar-s crystals (Fig. 7c). This type of dolomite is referred to as idiotopic-S by Gregg and Sibley (1984) and as planar-s texture by Mazzullo (2000). The crystal size is about 16–62 µm, with an average size of 45 µm. Fine crystalline dolomite is volumetrically the most dominant form of dolomite within the study area considering with 49% of all the dolomite phases. Intercrystalline porosity in dolomicrosparite is more than other dolomite types. Therefore, dolomite texture type 2 is considered to represent a diagenetic replacement of pre-existing limestone and/or recrystallization of dolomicite is possibly occurred during early shallow burial, below critical roughening temperature (Shabafrooz et al. 2010) and also Mg is probably formed by dissolution of high-Mg calcite. (Mazzullo 2000). This process might be incomplete (Fig. 7d) or complete (Fig. 7c) with dolomite type 2, evaporative, quartz and

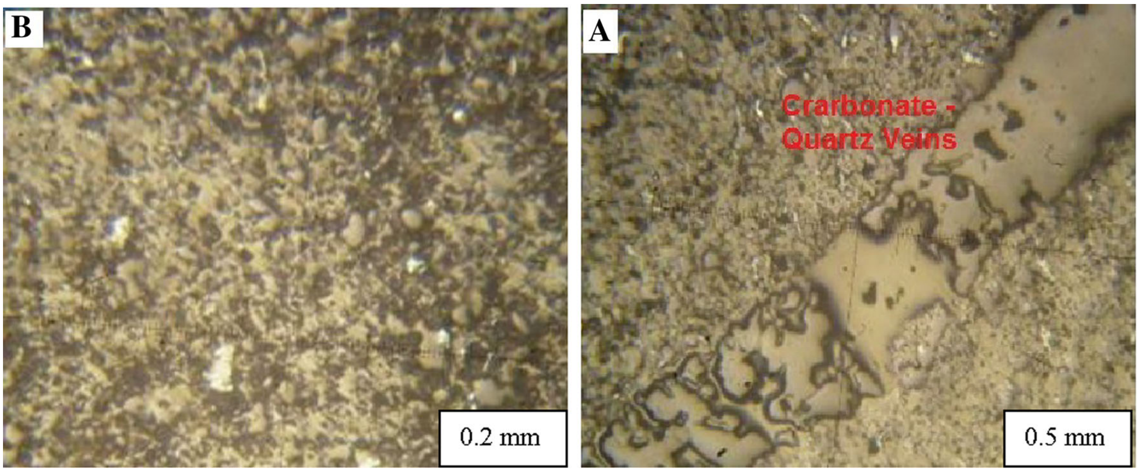


Fig. 5 **a** Polished section of FP5 sample: quartz-carbonate-hematite veins (texture of progressive resistant Islands. **b** Distribution of metal minerals (secondary hematite) and quartz grains in red color dolomitic rock samples. This sample contains abundant iron (up to 26% Fe_2O_3 by XRF method)

Fig. 6 Hand sample of fine crystalline dolomite in Paskhand plug

opaque minerals filling cavities, fractures, and replacement (Fig. 7c).

Type 3: medium crystalline dolomite (dolosparite)

The properties of dolomite type 3 included polymodal, dense, closely packed textures of medium (62–250 µm, with an average of 150 µm), nonplanar-A (anhedral) crystals often characterized by nonmimically replaced allochems (Figs. 8, 9a, b). The dolomite crystals had irregular intercrystalline boundaries that consist of nonplanar-a texture (Mazzullo 2000). We show increment in the degree of alteration because the fabric of dolomites is variated between dolomicrite to dolomicrosparite and dolosparite. These samples, apparently opaque crystals are relicts of pyrite. This type of dolomite spreads about 10% of the total dolomite of the study area. Dolosparite is texturally destructive and has largely modified or obliterates before diagenetic features. Dolomite type 3 represents a diagenetic replacement of pre-existing limestone and/or recrystallization of an early formed dolomite, possibly after some burial.

Type 4: coarse crystalline planar-c (cement) dolomite

This type included clear, coarsely crystalline, planar-C (cement), anhedral dolomite crystals, lining voids, vugs, and fractures. In the studied area, these fractures are filled with minerals such as quartz, actinolite, chlorite, and iron oxide (Fig. 10c, d). This type of dolomite is characterized as forming at the latest diagenetic stage and at elevated temperature, ranging from 94 to ~ 110 °C. In addition, they involved polymodal dolomite, with crystal sizes ranging from 200 to 1100 µm. Some crystals in this dolomite type are comparable to saddle dolomite fabrics. They have been identified by curved crystal faces, sweeping extinction, and an abundance of small two-phase fluid inclusions. Dolomite type 4 estimated about 10% of the total dolomite by volume. Iron mineralization is occurred with saddle dolomite. Dolomites type 4 with the highest temperatures of formation is possibly formed during the late stage diagenesis in a deeper burial environment into Hormuz Formation with maximum hydrothermal activities between Paleocene and Eocene periods. Most likely, the Zebra rocks were formed during this event as suggested from a number of indications for a hydrothermal origin, whereby basement-rooted faults permitted the passage of hot fluids.

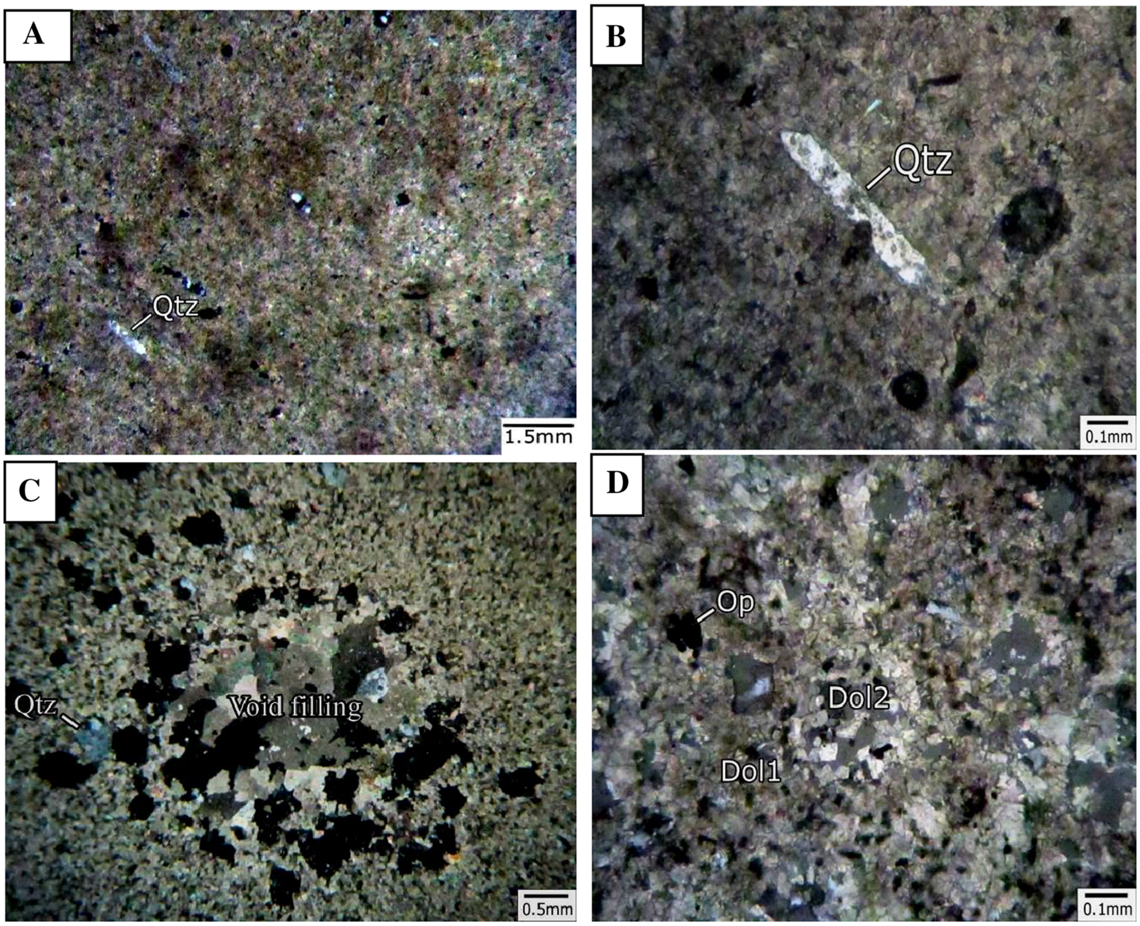


Fig. 7 **a** Very fine crystalline dolomite (type I) accompanied by euhedral coarse crystalline quartz that can form at very early stage of diagenesis, XPL. **b** Close-up of euhedral's coarse crystalline quartz at the same thin section. **c** Coarse crystalline dolomite (type 2) filling the fracture, XPL. Corners of the dolomite near the cavity is filled with cement (**d**) neomorphic dolomite (hypidiomorphic type II or D2) with dolomite (type I), and opaque minerals (main iron oxides), XPL

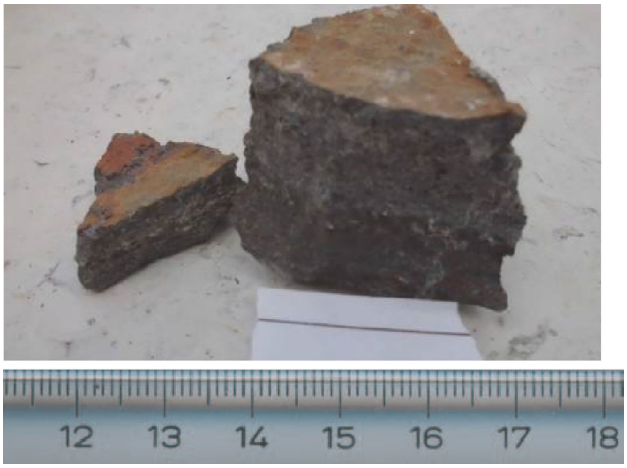


Fig. 8 Hand sample of coarse crystalline dolomite (type 3) in Dehkuyeh plug

Dolomite geochemistry study

Dolomicrites contain higher amounts of sodium (max 562 ppm), strontium (max 162 ppm) and lower amounts of iron (min 384 ppm), manganese (mean 74 ppm), and magnesium (12%) (Fig. 4 and Table 1). The relatively high levels of sodium and strontium and low concentration of magnesium in this type of minerals is a sign of non-stoichiometry state. These features testify that the first type of dolomite is formed in a near-surface environment such as high tidal zone (Sabkha) because of the leakage and return processes (mixing of marine and atmospheric waters). In the second type of dolomite, the concentration of magnesium (14%), sodium (average 362 ppm), strontium (average 120 ppm), iron (average 600 ppm), and manganese (average 94 ppm) can be attributed to the shallow environment. The presence of inter-granular waters and the

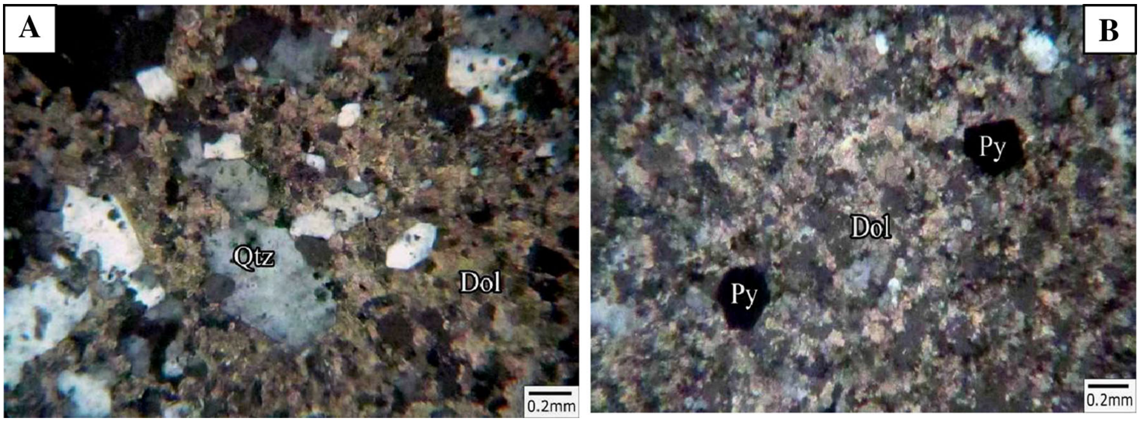


Fig. 9 **a** Coarse crystalline, anhedral replacement dolomite along with quartz coarse crystalline (type 3), XPL. **b** Pictures of Euhedral's opaque crystals relict of pyrite in the dolomites, XPL

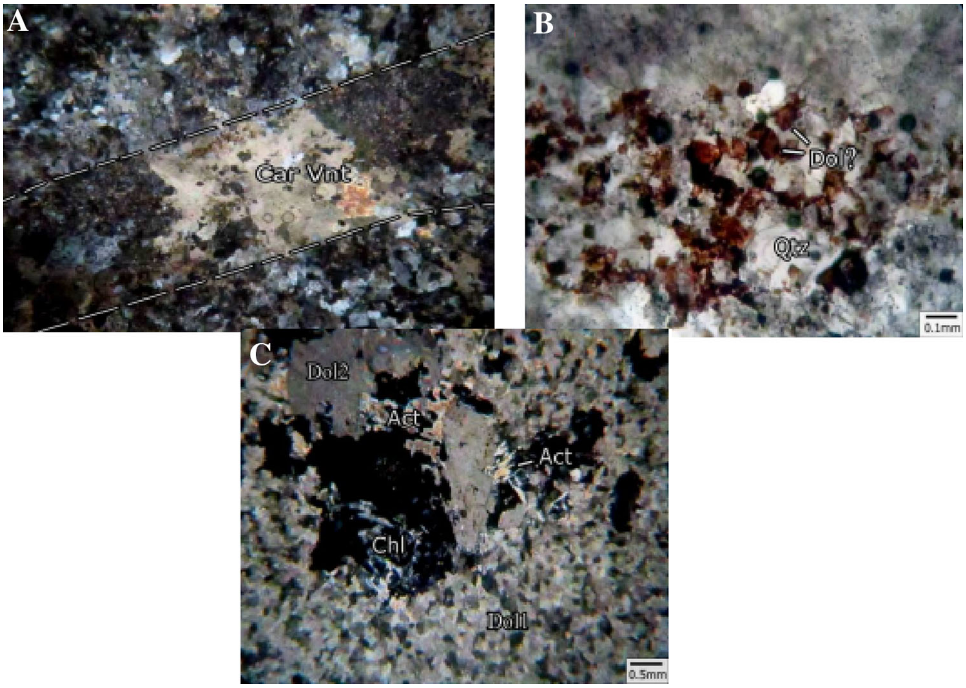


Fig. 10 **a** Coarse crystalline planar-C dolomite (type 4) filling the fracture. Some of crystals are similar to saddle dolomite fabrics, XPL. **b** Fracture-filling dolomite with autogenic quartz minerals and iron oxides the resulting hydrothermal solutions PPL. **c** Fracture-filling dolomite (Dol2) with chlorite and actinolite. Pay attention to the corners of the dolomite near the cavity filled with cement XPL

replacement of calcite with high magnesium are testified as a source of magnesium for this type of dolomite (Mukhopadhyay et al. 1996). The coarse-grained dolomite (third type) has less contents of sodium (average 200 ppm), strontium (mean 80 ppm), and higher concentrations of iron (average 1200 ppm), manganese (average 120 ppm), and magnesium (18%). These characteristics illustrate a medium-to-deep burial environment for this type of dolomite. Geochemical data show that in these type of dolomites the isotopic ratio, magnesium, sodium and strontium amounts decreased, but the amount of iron and magnesium increased. This shows decreasing the calciumin in dolomites and the difference in the dispersion coefficient and element geochemical behavior (Land and Hoops 1973; Pingitore 1978).

Strontium element

The Sr concentration in very fine crystalline dolomite alteration to dolomite ferruginous non-alteration ranges from 101 to 162 ppm (mean 116 ppm).

Due to the smaller Sr element partitioning coefficient in dolomite, we show the lower Sr element concentration in dolomite relative to the limestone samples (Land 1986; Veizer 1983).The low levels of strontium in dolomites in comparison to limestone are mainly due to the lower distribution of strontium in dolomites (Veizer 1983). The amount of strontium in dolomite is less than calcite. Strontium concentrations in dolomite types 1 are relatively higher than those in dolomite types 2, 3, and 4. The plot of strontium against Mg element shows that Sr element

Table 1 Results of elemental analysis in the Larestan salt dome dolomites

Type of dolomite	Sample no.	Ca (%)	Mg (%)	Sr (ppm)	Mn (ppm)	Fe (ppm)	Na (ppm)
Xenotopic A	D300	31.68	9.84	121	0. 074	3100	20,000
	A122 a	33.8	9.22	80	560	3200	24,230
	A122 b	33.53	8.72	90	580	3770	23,470
	A134 b	35.69	7.37	160	177	3450	13,990
Idiotopic-S(M)	A29	32.14	12.15	60	240	2080	22,700
	A36	32.38	11.1	90	180	2040	26,890
	LM6-013	31.71	12.7	60	300	11,000	23,650
	A14	30.66	14.08	124	858	1420	562
	A62	32.78	10.93	80	150	1090	22,610
	A63	32.43	11.86	80	190	2110	17,970
	A72	31.64	11.96	70	140	1020	35,650
	A91	31.43	13.38	50	170	1960	21,610
Idiotopic-S(L)	LB21-4	30.51	15.59	50	6100	12,460	1392
	FP5	16.05	10.68	177.1	7852	95,671	1120
	LM11-039	34.99	11.99	50	1480	7840	2365
	LM11-039	33.42	14.28	56	2748	9875	1250

concentration increases with increasing Mg % (Fig. 11). The total amount of strontium in the dolomites of our study area is higher (average 130 ppm) than the average standard dolomite (50 ppm).

Na element

Na has been used in many instances as an indicator of paleosalinity and determines the origin and the destination of the dolomite (Veizer 1983; Land 1986). The Na concentration in the dolomites of the salt diapirs ranges from 200 to 562 ppm (mean 328 ppm). The average Na concentrations of different dolomite types are much higher than those of dolomite that is formed in a normal marine environment, which typically has 110–160 ppm Na (Veizer 1983). The plot of Na versus Mg % shows that Na concentration increases with increasing Mg % (Fig. 12). There is a strong correlation between sodium and the degree of salinity of the fluids. The highest concentration of Na values in hormoz dolomites (D1) is because of the high salinity of dolomitic fluids in early formation environment of the salt domes (Al-Assam and Pakard 2000). An exceptional value of sodium (5900 ppm) in the samples of completely altered K4 shows the action of highly salty solutions.

Mn and Fe elements

The Mn and Fe concentrations in the Hormoz dolomites range from 384 to 14,932 ppm (mean 5150 ppm), and dolomite alteration reach between 1180 and 33,466 ppm (mean 12,079 ppm), respectively (Fig. 13). Mg element in dolomite is generally substituted by Mn and Fe elements. Therefore, a higher Mn and Fe concentrations in dolomite are due to a higher concentration of Mg in dolomite rather than limestone. The higher concentrations of these

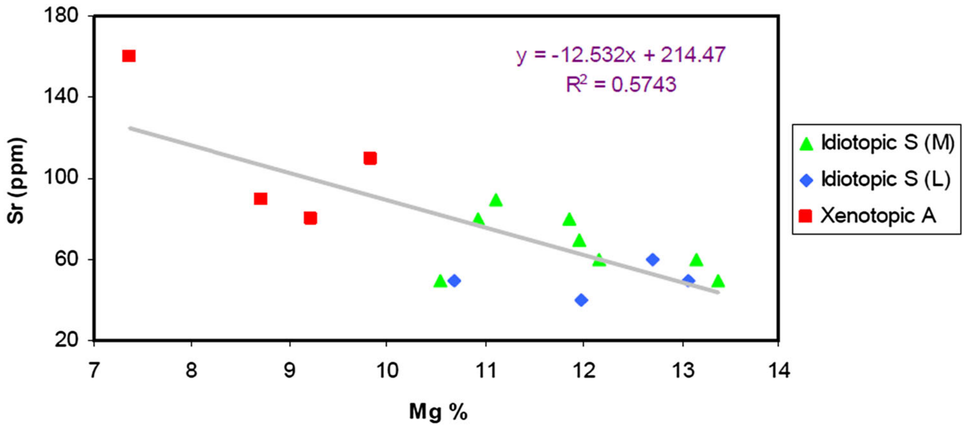
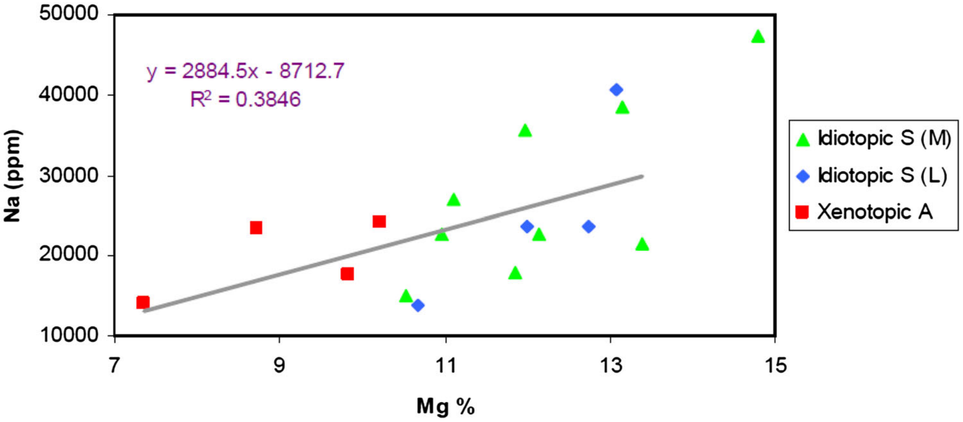


Fig. 11 Sr versus variations Mg (%). Note that the increasing trend in both diagrams represents non-stoichiometric fabric in dolomites in Salt domes Paskhand and Deh-kuyeh dolomites

Fig. 12 Na versus Mg variations (%). Note that the increasing trend in both diagrams represents non-stoichiometric fabric in dolomites in Salt domes Paskhand and Deh-kuyeh dolomites



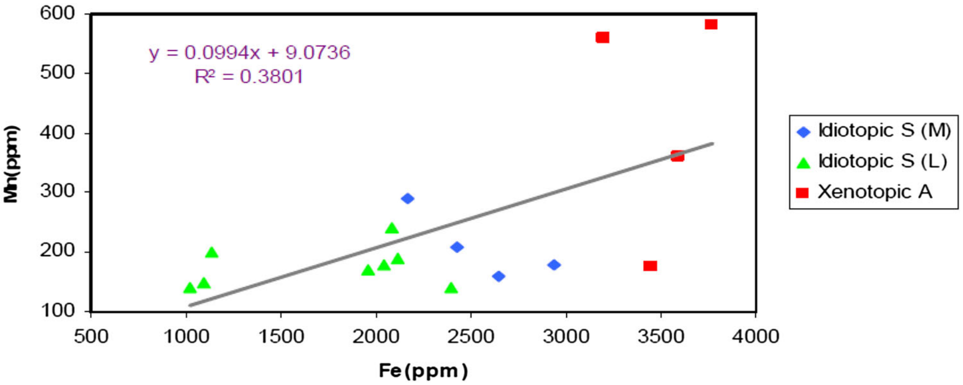
elements in dolomites may show reducing conditions (Land 1986), so that sometimes, dolomites have secondary iron up to 20% and they can be named iron dolomite (example FP5). The field observations, thin section studies, and the geochemical and mineralogical analyzes present intense altered by the influx of fluids rich in iron and silica. In general, in this area, the igneous rocks can be seen in the dolomites, and we showed the hydrothermal veins of iron concentration (Fig. 3b).

Origin of magnesium in primary dolomites and stable isotopes of oxygen and carbon

In Deh-kuyeh salt diapir, we recognize sassolite $B(OH)_3$ mineral that is only reported in the areas of the world which has famous rifting. These minerals were reported in Hormoz series for the first time. It can be a possibility to accept a source of magnesium in primary dolomitization (D1). In other words, a source of the primary dolomitization is forming in the fomaruls. Therefore, we assume that significant amounts of Infra-Cambrian Evaporates were created by magmatism. Furthermore, dolomites of the Deh-kuyeh and Paskhand precipitated in the reducing depositional environment, because oxygen content of Late Neo-Proterozoic–Early Cambrian oceans is considered low compared to the Phanerozoic (Hurtgen 2003). Small streaks of organic matter proved this idea. The Infra-Cambrian age and the presence of organic materials in the studied rocks suggest that organogenic dolomitization could be considered as an alternative dolomitization model (Nasir et al. 2008). The compression of Shale deposits and the conversion of clay minerals, such as conversion of smectite to illite (Magara 1976), compressive dissolution (McHargue and price, 1982), condensation, and evaporation of evaporative minerals like gypsum anhydrite (Cantrell and Hagerty 1999), are the most important sources of supplying magnesium that is applied in deep burial model (saddle and cement). Basaltic magmas and their hydrothermal activities fill fractures between dolomites of Hormuz with crystals such as hematite, sanidine, and quartz. According to the 1000 Sr/Ca ratio (Fig. 14), dolomite samples are located in an open system.

Isotopic studies are a useful method for understanding the past and present depositional environments and diagenetic (Morse and Mackenzie 1990; Hudson 1977; James 1983). One the applications of oxygen isotopes in carbonates is using it as a thermometer (Morse and Mackenzie

Fig. 13 Variations of Mn versus Fe (ppm) in Salt domes Paskhand and Deh-kuyeh dolomites



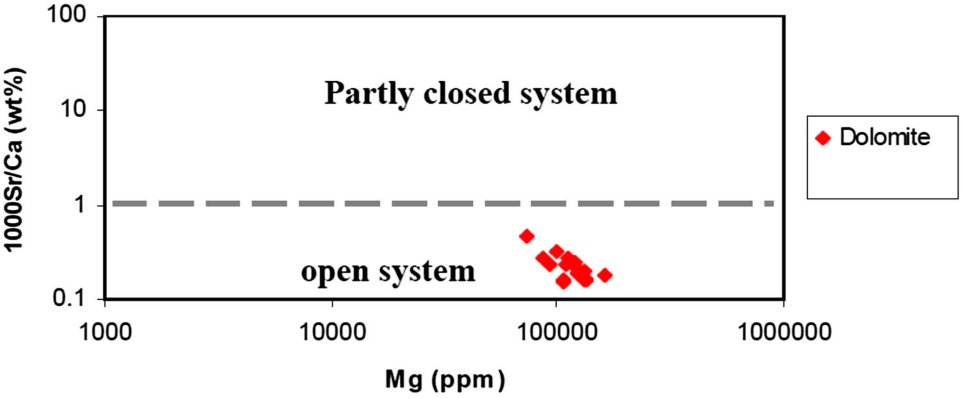


Fig. 14 1000 Sr/Ca versus Mg

1990). Compared to the other dolomites, dolomicrites have heavier isotope composition, which illustrate low environmental temperature, forming this type of dolomite (Allan and Wiggins 1993). Coarse-grained dolomite is also lighter than isotopes compared to other studied dolomites. Allan and Wiggins (1993) suggest that dolostones with a magnitude of δ^{18}O, because of their deep buried model, are negative (smaller) (− 6.5‰) at high temperatures.

This issue is also true in the dolomites and the formation temperature calculation is one of the most important topics in the dolomite studies. In this research, the Land equation was used to determine the temperature formation of dolomite (Land 1985):

$$T(^{\circ}\mathrm{C}) = 16.4 - 4.3\left(\left[\delta^{18}\mathrm{O\ dol}\ -3.8\right] - \delta\mathrm{water}\right) + 0.14\left(\left[\delta^{18}\mathrm{O\ dol}{-}3.8\right] - \delta\mathrm{water}\right)2.$$

In the Land equation, the oxygen isotope of dolomite rocks and fluids is, respectively, shown with δ^{18}O dol and water. In the above equation, the oxygen isotope Permian seawater is equivalent to − 2.8% and instead of δwater. Typically, for determining the depositional environments and the diagenetic, temperature is, respectively, used for the heaviest and the lightest isotopes δ^{18}O respectively (Adabi 1996). Originally, dolomites are formed in near-surface environments (such as super-tidal environments) that have lower temperatures, whereas, delayed diagenetics are formed in deeper environments which lead to higher temperature dolomites (Rao 1996). On this basis, the average temperature of black dolomite in the Paskhand and Deh-kuyeh is 270 °C (Al-Aasm and Abdallah 2006). If the lightest (equival to − 18/78 PDB ‰) and heaviest (equival to the PDB ‰ − 12/35) isotopes δ^{18}O in the secondary dolomites have lodged in the Land equation, the maximum (diagenetic temperature) and the minimum (temperature depositional environment) dolomite formation temperature is, respectively, estimated at about 270 and 132 °C (Fig. 15). Quot; Source many differences in the oxygen isotope content of Precambrian seawater, and the isotopic variations of seawater δ^{18}O have been considered between − 11 and 0 (the mean of this range is estimated about − 4

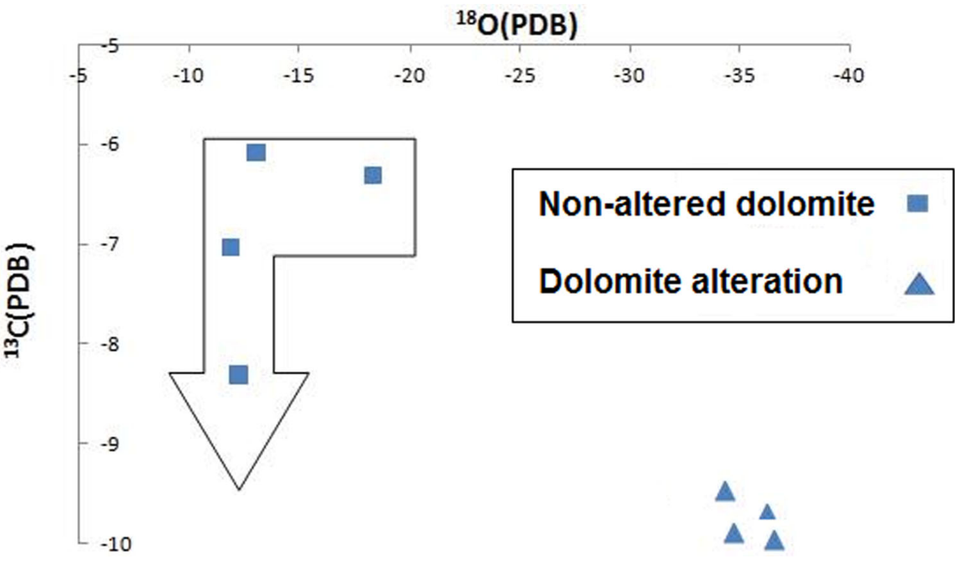


Fig. 15 Changes for δ^{18}O PDB versus δ^{13}C PDB in the dolomites of the Paskhand and Deh-kuyeh salt domes

by scientists). By placing the number − 4 in the Land equation, the formation temperature of primary black dolomites of the studied salt domes will be counted at about 270 °C. The existence of light carbon and oxygen isotopes in the vein cements shows the organic carbon assimilation and influence of increased temperature/meteoric water (Al-Aasm and Abdallah 2006). Furthermore, lower δ^{18}O values could be attributed to dedolomitisation of salt dome carbonates during cap rock formation. Negative carbon isotopes in the salt dome samples are probably attributed to the negative^{TM} $_{13}$C excursion at the Precambrian/Cambrian boundary (Reuninga et al. 2007). The differences in the size and isotopic composition of the studied dolomites have been shown as two fluids with different origins. The low variation of oxygen isotopes in carbonate minerals of dolomite Type 1 (D1) reflects the constant temperature in the carbonate formation and the unique source of fluids (Gilg et al. 2008). The different formation temperatures and the fluids with more than a source were concluded by the large difference for oxygen in the primary and altered dolomites. Negative changes of δ^{13}C (from – 5.8 to – 8.94‰ VPDB) in the studied dolomites of Paskhand and Deh-kuyeh salt domes have showed the organic and volcanic origin of carbon (Holland and Malinin 1979). XRD analysis proved the presence of dolomite beside sassolite. The fairly extensive and negative values of δ^{18}O and δ^{13}C in carbonate samples have demonstrated the burial diagenetic processes (Al-Asam and Veizer 1986; Choquette and James 1987; Nelson and Smith 1996). The meteoric diagenesis in carbonate rocks can be identified from the varied range of the oxygen and carbon, which is called the Returned-J (Lohmann 1988). Based on Fig. 3, the values of δ^{18}O in front of δ^{13}C in dolomites of the study are small; therefore, the variability in dolomites of the study (dolomicrites dolomicrosparite, dolosparite, and saddle dolomite) has shown the diagenesis, meteoric, and burial origin. Due to the oxygen and hydrogen isotopes, the mentioned dolomites have been affected by at least two different fluids such as the hydrothermal brine of salt dome's penetration and the waters of the primary volcanic basins (Fig. 12). Black dolomites formation is probably a result of the magnesium ions release from the volcanic sources and the iron deposits with the altered dolomites of the saline salt dome. The brine along the porous and permeable conduit systems (due to tectonic pressures resulting from the gradual movement of salts) was removed and altered the dolomite and other rocks, and finally, mineralization of the hydrothermal iron has occurred. In a different study, Ghazban and al-Aasm (2010), at Hormoz Island, salt diapir in the eastern Persian Gulf showed that δ^{13}C of black dolomite range from – 0.8 to – 1.94‰ VPDB that was obtained from sea water that provided carbon for the dolomite precipitation. δ^{13}C of white and gray dolomites range from – 18.66 to – 29.31‰ VPDB with the depleted δ^{13}C indicating hydrocarbon oxidation (Bahremandi et al. 2013). Based on δ^{18}O of these dolomites (− 15.94 to − 17.21‰ VPDB), fluid inclusion shows temperatures (215 °C). The calculated δ^{18}O water in equilibrium ($4 < \delta^{18}$O fluid < 6.5‰) shows the involvement of sedimentary formation waters. Black dolomites are formed at shallower depths. Pyrites and native sulfur are formed in a reducing environment, where the source of sulfur was H2S from evaporites. Heavy δ^{34}S for evaporites (ranging from 21 to 33‰) and sulfides (ranging from 17.2 to 23.4‰) preclude sulfur contribution from magmatic sources or early Cambrian shale. The sulfate appears to be the likely source of high δ^{34}S with H_2S produced by the thermochemical reduction. The sulfate appears to be the likely source of high δ^{34}S with H_2S produced by the thermochemical reduction. Pyrites and dolomites are formed at depth within the migration plume; hence, it is envisaged that hydrocarbon leaked along the flanks of the dome creates a reducing environment that promotes the formation of diagenetic mineral. The temperature of the formation of black dolomite in Jahani salt diapir is 250 °C (Taghipour and Eskandari 1995), and in addition, δ^{18}O changes of black dolomite in Jahani salt diapir are negative and can be attributed to an increase in temperature or a change in composition (Al-Aasm and Abdallah 2006).

Conclusion

In this paper, for the first time, sassolite $B(OH)_3$ mineral is observed in Deh-kuyeh salt diapir. This mineral is only reported in the areas of the world which has famous rifting. Therefore, the origin of magnesium in primary dolomitization in the Hurmuz formation is probably fumarols. These dolomites are formed in a marine environment, in a reducing depositional. Researchers believe that dolomitization is related to a sabkha setting and brine reflux.

The Infra-Cambrian age and existence of organic materials in the studied rocks suggest that organogenic dolomitization could be recognized as an alternative dolomitization model. Furthermore, compactions of shale basinal brines and conversion of evaporite minerals are possible sources of magnesium for burial dolomitization (dolomite types 2 and 3) and for burial dolomite cementation (dolomite type 4) that is affected by hydrothermal activity.

We suggest that widespread changes and alteration impacts on rocks of southern Iranian salt diapirs have been caused by the extensive activities of hot secondary solutions.

Moreover, the impressions of these secondary hydrothermal activities made clearly are substantiated by the alteration, redistributions of elements, iron ore veins, solidification in the host rocks to ore veins, and some parts of the salt diapir. Furthermore, the impressions of these secondary hydrothermal activities on rocks have been shown by alteration, redistributions of elements, iron ore veins, and solidification in the host rocks to ore veins in part of salt diapir (Nokhbatolfoghahaie 2014). The secondary fluids are the result of the repeated activities of the magmatism and salt movement. These secondary fluids leached metals from mafic–ultramafic rocks and precipitated them along deep shear zones as well as shallower faults and fractures. Sometimes of the dolomites sampling, we recognized about 20% secondary irons that are called Ferruginous dolomites, and therefore, surrounding between dolomite and igneous rocks, we show the maximum concentration of Fe in this salt diapir that is keyed for discovery of Iron. In general, in this area, the igneous rocks can be seen in the dolomites, and we showed the hydrothermal veins of iron concentration that could be considered as an exploration key of hydrothermal iron salt domes in southern Iran. Based on the isotopic studies, the difference in size and isotopic composition of Paskhand and Deh-kuyeh salt dome's dolomites can be reflected as the two fluids with different origins. Large differences in the amount of oxygen isotopes in different types of dolomites in Paskhand and Deh-kuyeh salt domes suggest the different formation temperature and more than one source for fluids. Dolomite type 1 (D1) is formed at lower temperatures (70 °C), and dolomite types 3 and 4 (D3 and D4) are formed at higher temperatures (183–270 °C), which is probably related to effect of hydrothermal waters. The studied dolomites have suffered two types of meteoric diagenesis and burial and the required magnesium ion for the secondary altered dolomites formation is provided from the brine of the salt dome. It seems that the hot brine in effect of the tectonic pressures through the regional deep faults as a result of the salt mobility which makes the metal, especially iron with altered dolomite from the surrounding rock to leach. This proces lead to concentrate dolomites in the areas with suitable conditions close to the surface. Furthermore, the Infra-Cambrian age and existence of organic materials in the studied rocks suggest that organogenic dolomitization could be recognized as an alternative dolomitization model.

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