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Mineralogy, Geochemistry and Geotectonic of Plagiogranites from Shahre-Babak Ophiolite, Zagros Zone, Iran

Fatemeh Sepidbar*[1], Hassan Mirnejad[1, 2]
1. *Department of Geology*, *University of Tehran*, *Tehran* 14155-64155, *Iran*
2. *Department of Earth and Environmental Earth Sciences*, *Miami University*, *Ohio* 45056, *USA*

ABSTRACT: Shahre-Babak ophiolite is a part of the inner Zagros ophiolite belt in Iran. Major parts of intrusive masses of Share-Babak ophiolite are gabbro and plagiogranite. The SiO_2 versus Na_2O+K_2O diagram shows that the palgiogranites are related to calk-alkaline series. Rare earth elements exhibit relatively similar pattern that indicates these rocks are syngenetic. Also, REE patterns display an enrichment of LREE compared to HREE, and are characterized by flat to slightly concave-up patterns from Gd to Yb. Such patterns contrast sharply with those of plagiogranites in more complete ophiolite sequences, such as the Semail ophiolite, Oman, or the Troodos ophiolite, Cyprus, and Neyriz, where patterns are much flatter and slightly LREE-depleted. The slightly LREE-enriched patterns of the Shahre-Babak plagiogranites support a partial melting origin for them. The low TiO_2, Nb, Ta content and high LREE concentrations of the Shahre-Babak plagiogranites indicate that the rocks were likely derived from the anatexis of amphibolites, which were related to hydrothermal alteration of gabbros in intra-oceanic back-arc basin.
KEY WORDS: plagiogranite, back-arc basin, Share-Babak ophiolite, Neo-Tethys, Iran.

0 INTRODUCTION

Plagiogranites are felsic plutonic rocks consisting of diorite, quartz diorite, tonalite, trondhjemite and albitite/anorthosite that occur in modern oceanic crust and ophiolites (Li et al., 2013; Coleman and Donato, 1979; Coleman and Peterman, 1975). Despite their minor volume, plagiogranites offer an important opportunity to examine a fundamental Earth process constraint on oceanic crust.

Crust and ophiolites (Grimes et al., 2013, 2008; Jiang et al., 2008; Tilton et al., 1981) offer a unique way to investigate oceanic basin and orogenic evolution. Three models have been proposed for the petrogenesis of plagiogranites: (1) Products of shallow differentiation of basaltic magmas in oceanic crust, representing the final stage of the oceanic crustal evolution (Jiang et al., 2008; Lippard et al., 1986; Coleman and Donato, 1979); (2) partial melting of hydrous gabbros (or basalts) (Grimes et al., 2013; Koepke et al., 2004; Gerlach et al., 1981; Malpas, 1979) or amphibolites in the shear zones at spreading centres (Flagler and Spray, 1991); (3) immiscibility products of a felsic melt and a Fe-enriched basaltic melt under anhydrous conditions (Dixon and Rutherford, 1979). Obviously, studies on the plagiogranite petrogenesis are very important for understanding the oceanic crustal evolution.

Plagiogranites from the Zagros suture zone are subdivided into two parallel belts as the outer Zagros ophiolitic belt including Neyriz, Esfandagheh and Faryab plagiogranites and the inner Zagros ophiolitic belt including Nain, Dehshir, Shahr Babak and Baft plagiogranites. Plagiogranites of Neyrizophiolite, outcropping in Fars Province, south of Iran, represents remnants of southern branch of Neo-Tethys Ocean in Iran, while plagiogranites from Shahre-Babak and Baft ophiolites, outcropping in Kerman and Yazd provinces, are located at the southwest margin of the central Iran micro-continental block (CIM) and northern branch of Neo-Tethys Ocean in Iran. Despite detailed studies on the geology, petrography, mineralogy and geochemistry of the mantle section from Zagros ophiolite belt, no detailed research has been performed on the petrogenesis of their associated plagiogranites. This paper presents data on major and trace elements of plagiogranites from Shahre-Babak, Neyriz and Baft, with the aim of constraining the source and petrogenesis of plagiogranites from the Zagros ophilitic belt.

1 GEOLOGAL SETTING

Iran is geologically composed of many structural zones identified by different characters (Figs. 1a and 1b). The Zagros thrust zone is mainly consisted of sedimentary rocks with continuous deposition until the Pliocene. The Sanandaj-Sirjan metamorphic belt is dominantly a metamorphic zone composed of Mesozoic intrusions and metamorphosed sediments (Boomeri et al., 2006). The Urumieh-Dokhtar magmatic belt is composed of plutonic and volcanic rocks of the Oligo-Miocene age. Central Iran is a complex zone of many rock types from Precambrian to present. All these zones were formed by the opening and closing of the Paleo- and Neo-Tethys oceanic

*Corresponding author: f.sepidbar@ut.ac.ir

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basins due to subduction and collision events in the south and north of Iran (Berberian and King, 1981). The north side of Iran collided with Turkmenistan or the Turan Plate (Urasia) in Late Triassic–Early Jurassic time (Mirnejad et al., 2013). In the south, Iran collided with the Arbian Plate along the Zagros suture zone, starting from Late Cretaceous (Berberian and King, 1981) and continuing to Miocene and later times (Walker and Jackson, 2002; Alavi et al., 1997).

Ophiolites from the Zagros suture zone are subdivided into the parallel belts as outer Zagros ophiolitic belt including Neyriz ophiolite and the inner Zagros ophiolitic belt including Nain, Shahre-Babak and Baft ophiolites (Figs. 1a and 1b). The Shahre-Baback ophiolite, limited to the west by the Dehshir-Baft fault and to the southwest by the Sanandaj-Sirjan metamorphic rocks, covers an area of ~400 km^2 in southwest of Shahre-Baback City (Fig. 1b). It comprises a complete ophiolite sequence dominated by highly serpentinized harzburgite. Diabasic dykes and isotropic gabbro lenses commonly intrude harzburgite (Ghazi and Hassanipak, 2000). Similar to Baft ophiolite, isotropic gabbros are common within the mantle sequence as local small masses cut by plagiogranitic veins. Plagiogranites are comprised of tonalite, trondhejemite and leucogabbro with inequigranular, hypidiomorphic and granoblastic texture.

The Baft ophiolite is located 5 km SW of Baft City as a 5–10 km wide and about 60 km long, WNW-trending belt (Fig. 1b). The ophiolite is composed of ultramafic and mafic rocks, capped by Turonian-Maastrichtian (93.5–65.5 Ma) pelagic sediments resting directly on the ophiolite (Shafaii Moghadam et al., 2013). Depleted harzburgite with abundant diabase dikes constitute the ophiolite mantle sequence. Isolated pockets of pegmatitic gabbro and lenses of isotropic gabbro occur in the upper mantle section. The plagiogranites, consisting of quartz and feldspar, are gray in colour with typical cumulus texture and occur as narrow (≤1 m thick) dykes, intruding massive gabbros. The plagiogranites occur mainly in the north within altered isotropic gabbros, and northwest as local small masses (Golestani, 2013). In some cases the injection of plagiogranites

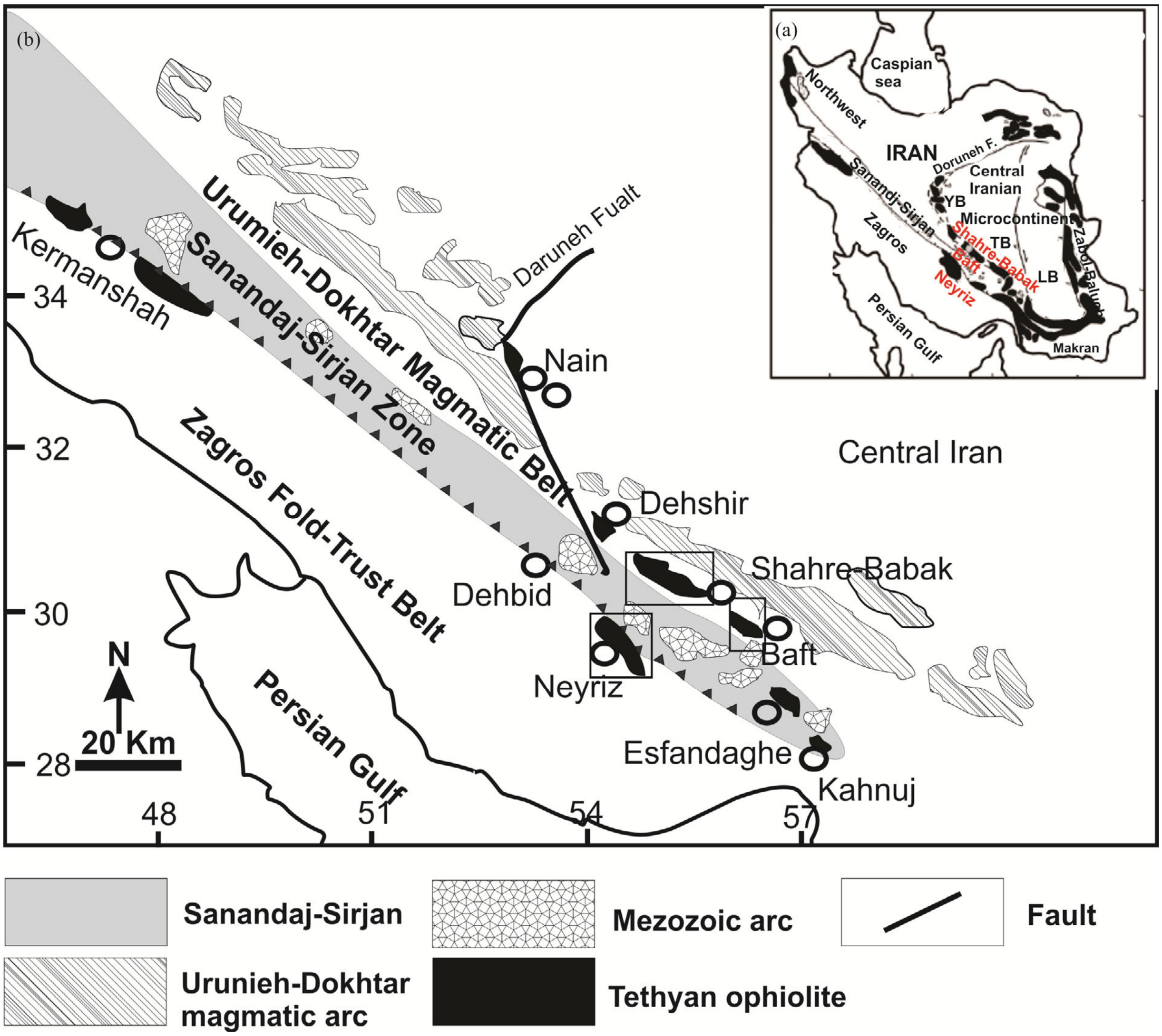

Figure 1. (a) The situation of Baft, Shahre-Babak and Neyriz ophiolite-melange in Iran. (b) Map showing the distribution of the inner (Nain-Dehshir-Baft-Shahre-Babak) and outer (Kermanshah-Neyriz-Haji-Abad) Zagros ophiolitic belts, the location of the Urumieh-Dokhtar magmatic arc (Eocene–Quaternary), and Zagros fold-thrust belt (modified after Shafaii Moghadam et al., 2009).

into gabbros and especially dolerite dykes causes the enclosing of their parts as xenoliths or expanding of plagiogranite veins within it (Golestani, 2013). Neyriz ophiolite thrusted over limestone of Bangestan Formation in Early Cretaceous along its western contact and is conformably covered by shallow-water marly limestone of Late Cretaceous along its northeastern border indicating that the emplacement of ophiolite on the Iranian microcontinent took place in the Maastrichtian (Babaie et al., 2006). The major structures in the study area are parallel to the Zagros suture zone and trend NW-SE (Rajabzadeh, 2013) (Fig. 1b). To the west and southwestern part the ophiolite, the faults overlapped the ophiolite over a widely extended colored mélange that includes pillow lava, radiolarian chert with accessory manganese deposits, globotruncana limestone (Turonian-Maastrichtien) and exotic blocs. The ophiolite in the study area is exposed in an area of 12.5 km long and 10 km wide between the Bakhtegan depression lake to the southwest and the high mountains of the Zagros thrust zone to the northeast. Plagiogranite from Neyriz ophiolite occurring in the gabbroic section of the ophiolitic sequence in the southeast of Shiraz are comprised of tonalite, trondhjemite and their contact with surrounding gabbros is either sharp or covered (Alizadeh et al., 2012).

2 PETROGRAPHY

The modal mineralogical compositions of representative plagiogranite samples from Shahre-Babak shows that they include sodic feldspar (~25%), quartz (35%–55%), and plagioclase (40%–60%) (Fig. 2a) and accessory minerals biotite, hornblende and opaque minerals. Alteration of the plagiogranite formed secondary minerals such as epidote, kaolinite, chlorite, and sericite. Plagioclase crystals show polysynthetic zoning. Sodic feldspar crystals are partly formed as the result of the influx of sodic solutions at the expense of plagioclase (Ahmadipour and Rostamizadeh, 2012). Quartz crystals are seen as individuals and intergrowth with albite. The general texture of the plagiogranites is inequigranular hypidiomorph granular, granophyric, myrmekitic (Fig. 2b) and poikilitic (Fig. 2c). In some plagiogranites of the Shahre-Babak ophiolite, the granophyric texture is developed and all rocks are composed of this intergrowth. Alkali feldspar in granophyres is typically albite type that has been changed to sericite.

Plagiogranites from Baft consist of the main minerals including plagioclase (45%–80%), quartz (35%–60%), sodic feldspar (55%) and accessory mineral including biotite, hornblende and opaque minerals. Alteration of the plagiogranite leads to the formation of secondary minerals such as epidote (epidotization), kaolinite (kaolinitization), zoisite, chlorite (chloritization), sphene, tremolite-actinolite (amphibolitization), and sericite (sericitization). Quartz crystals are seen as individuals and intergrowth with albite in these rocks. Eutectic intergrowth of quartz with sodic feldspar is often of the granophyric and rarely of the micrographic type and is just seen in some examples. Sodic feldspar in granophyres is typically of the albite type that has been changed to sericite due to moderate to extreme degree of alteration (Golestani, 2013).

Plagiogranites from Neyriz consist of plagioclase (50%–70%), quartz (25%–35%), sodic feldspars (~3%) as major minerals and less than 10% amphibole±pyroxene, opaques and rarely titanite and zircon as minor minerals (Alizadeh et al., 2012). Alteration of the plagiogranite leads to the formation of secondary minerals such as epidote, kaolinite, chlorite, and sericite. Plagioclase shows polysynthetic, percline and rarely oscillatory zoning. Quartz crystals are seen as individuals with granular to kataclastic texture and sometime have intergrowth with albite. Eutectic intergrowth of quartz with sodic feldspar is often of the granophyric and rarely of the micrographic type (Fig. 2b). The sodic feldspar shows Karlsbad twining (Alizadeh et al., 2012).

3 GEOCHEMISTRY

The samples from Shahre-Babak plagiogranite have SiO_2 contents of 67.2 wt.%–74.3 wt.% and Al_2O_3 contents of 12.6 wt.%–14.4 wt.% (Table 1). These rocks are enriched in Na_2O (3.9 wt.%–6.6 wt.%) and depleted in K_2O (0.19 wt.%–0.47 wt.%), with the compositions plotted in the trondhjemite and tonalite fields in An-Ab-Or diagram (Fig. 3). These plagiogranites are metaluminous to peraluminous with alumina saturation index (ASI=molar $Al_2O_3/(CaO+Na_2O+K_2O)$) values up to 1.10 (Fig. 4a) and are calcic as indicated by their Rittman index values (σ=[Na_2O (wt.%)+K_2O (wt.%)]^2/[SiO_2 (wt.%)−43]) of between 0.8 and 1.4 and their position on Na_2O+K_2O-CaO vs. SiO_2 diagram (Frost et al., 2001) (Fig. 4b). There is a general decrease in Al_2O_3, FeO_t, and CaO with increasing SiO_2 (Fig. 5), while variation diagrams of SiO_2 vs. trace elements (Fig. 6) show a general decrease in Sr and an increase in Zr with increasing SiO_2. Nickel is relatively scattered against SiO_2. The

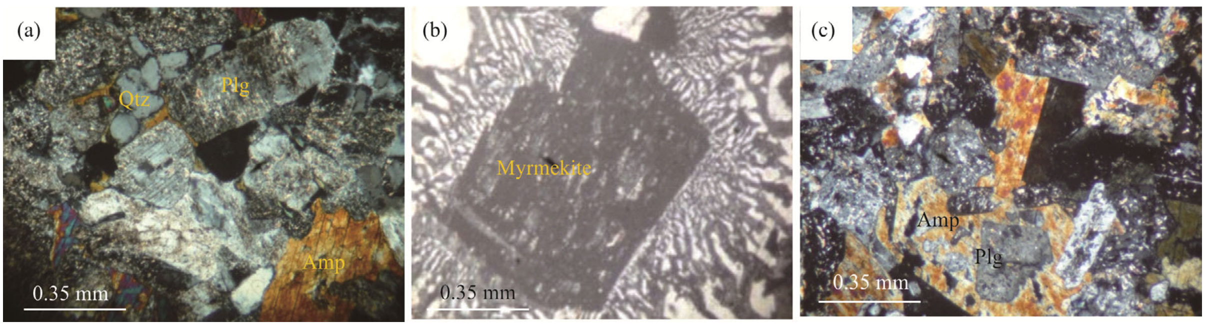

Figure 2. (a) Plagiogranite from Shahre-Babak containing sodic feldspar, quartz, plagioclase and accessory mineral biotite, hornblende. (b) Myrmekitic texture resulting from vermin form growing of quartz with sodic feldspar in plagiogranite of Shahre-Babak (light, XPL). (c) Poikilitic texture in the form of inclusion of amphibole crystals by plagioclase in plagiogranite (light, XPL). Plg. Plagioclase; Qtz. quartz; Amp. amphibole.

Table 1 Major (wt.%) and trace element (ppm) compositions of the Shahre-Babak plagiogranite

Sample	Granite	Granite	Granite	Granite	Granite	Granite	Granite	Granite	Granite	Granite
SiO_2	67.9	72.1	71.3	74.3	69.3	70.1	72.4	69.8	72.1	71.3
Al_2O_3	14.4	12.6	13.7	13.2	13.7	14.1	13.2	12.7	12.6	13.7
Fe_2O_3	4.59	3.6	2.05	2.86	4.1	2.08	3.7	3.1	3.6	2.05
CaO	4.65	2.39	3.57	2.53	3.1	2.68	4.31	3.2	2.39	3.57
MgO	1.48	0.6	0.57	0.5	0.52	0.6	0.42	0.5	0.6	0.57
Na_2O	3.9	4.3	6.6	4.9	5.7	4.7	5.7	6.1	4.3	6.6
K_2O	0.24	1.46	0.19	0.47	0.37	0.41	0.2	1.4	1.46	0.19
Cr_2O_3	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
TiO_2	0.46	0.39	0.28	0.39	0.35	0.3	0.4	0.29	0.39	0.28
MnO	0.1	0.03	0.07	0.03	0.05	0.06	0.03	0.06	0.03	0.07
P_2O_5	0.08	0.07	0.08	0.07	0.05	0.06	0.08	0.07	0.07	0.08
LOI	0.95	1.19	1.04	0.65	0.87	0.57	0.69	1.07	1.19	1.04
Ba	80	240	40	150	125.5	170.6	270	90	240	40
Ce	10.7	25.6	11.2	16.6	12.7	16.2	11.3	21.7	25.6	11.2
Co	0.9	10.5	2.6	3	3.1	2.9	0.9	3.5	10.5	2.6
Cs	0.1	<0.1	<0.1	<0.1	<0.2	<0.3	<0.4	<0.5	<0.1	<0.1
Cu	17	58	11	9	12	13	9	11	58	11
Dy	2.94	3.84	3.39	5.55	4.4	3.85	5.6	3.4	3.84	3.39
Er	2.16	2.58	2.43	3.97	2.7	3.9	2.5	4	2.58	2.43
Eu	0.77	0.92	0.96	0.98	0.97	1	0.87	0.94	0.92	0.96
Ga	13	12	12	14	13	12	15	13	12	12
Gd	2.43	3.83	3.05	4.64	4.73	3.9	2.5	2.8	3.83	3.05
Hf	3	5	4	4	4	2	3.8	0.9	5	4
Ho	0.67	0.86	0.77	1.5	1.3	0.9	1.2	0.89	0.86	0.77
La	4.9	11.8	4.9	6.6	5.6	4.3	7.2	3.5	11.8	4.9
Lu	0.32	0.31	0.47	0.61	0.5	0.4	0.6	0.5	0.31	0.47
Nb	1	3	2	2	2	1	2	2		
Nd	7.4	15.6	8.5	12.3	12.8	15.6	9.5	7.9	3	2
Pr	1.57	3.61	1.73	2.81	3.5	2.1	1.8	1.42		8.5
Rb	3	21.7	1.7	3.2	3.4	2.8	3.2	1.9	6	7
Sm	2	3.8	2.4	3.6	2.8	3.2	2.9	2.8	3.61	1.73
Sn	<1	<1	<1	<1	<1	<1	<1	<1	21.7	1.7
Sr	190	150	180	120	170	130	154	129	3.8	2.4
Ta	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<1	<1
Tb	0.43	0.62	0.54	0.7	0.5	0.8	0.4	0.6	150	180
Th	0.9	2.1	1	0.9	1.04	0.7	0.91	0.81	<0.5	<0.5
Tm	0.33	0.4	0.39	0.6	0.6	0.5	0.71	0.65	0.62	0.54
U	0.31	0.56	0.3	0.29	0.31	0.27	0.28	0.3	2.1	1
V	85	42	35	19	56	42	38	29	0.4	0.39
W	<1	<1	<1	<1	<1	<1	<1	<1	0.56	0.3
Y	18.6	24.9	22.2	36.3	19.81	20.21	29.2	8.7	42	35
Yb	2.2	2.7	2.6	2.1	2.5	2.2	2.1	2.8	<1	<1
Zr	89.4	170	139	148	158	138	170	140	24.9	22.2
Sr/Y	10.21	6.04	8.1	3.3	8.58	6.43	5.27	14.8	2.7	2.6

plagiogranites from Shahre-Babak have high Sr (120 ppm–190 ppm) and low Y (8.7 ppm–36.3 ppm) concentrations with low to high Sr/Y ratios (3.3–14.32). In comparison with ocean ridge basalts, the Shahre-Babak plagiogranites have relatively high contents of LILE such as Ba and Rb, and low HFSE contents with marked negative Nb and Ta anomalies on MORB-normalized spider diagram (Fig. 7a). The chondrite normalized REE patterns show enrichment in LREE relative to HREE ($(La/Yb)_{CN}$=0.84–2.95), with no negative Eu anomalies (Fig. 7b). Similar to plagiogranites, gabbros from Shahre-Babak are depleted in HREE and relatively enriched in LREE ($(La/Yb)_{CN}$=1.10–1.94). Such patterns contrast sharply with those of plagiogranites in more complete ophiolite sequences, such as the Semail ophiolite, Oman, or the Troodos ophiolite, Cyprus, and Neyriz, where patterns are much flatter and slightly LREE-depleted. Despite similar major and trace element compositions, there are subtle differences between the plagiogranite and gabbro from Shahre-Babak. REE concentrations in plagiogranite are higher than those in gabbros (Fig. 7b) and the plagiogranite has lower Th/U ratio (2.7–3.9) than that of the gabbro (2.0–5.8). Similar to plgiogranites of Shahre-Babak, plagiogranites from Baftophiolite are trondhjemite, tonalite and granodiorite while plagiogranites from Neyriz are trondhjemite and tonalite (Fig. 3). Plagiogranites from Baft have higher contents of SiO_2 (74.7 wt.% to 77.4 wt.%) and K_2O (0.02 wt.% to 20.36 wt.%) than those of Shahre-Babak, while the Neyriz plagiogranites have wide variation SiO_2 from 72.6 wt.% to 80.5 wt.% and less K_2O content than those of plagiogranites from Shahre-Babak and Baft ophiolites. Baft plagiogranites are metaluminous to peraluminuse and calcic, while Neyriz plagiogranite are metaluminus and calcic (Figs. 7a and 7b). Chondrite normalized REE patterns for Baft plagiogranites show wide compositional variations (Fig. 7d). They are depleted in HREE and relatively enriched in LREE with LREE/HREE ratios of 2.12 to 9.16, whereas gabbro from Baft have narrow compositional variation without Eu anomalies (Fig. 7d). In comparison to plagiogranites from Shahre-Babak and Baft, those from Neyriz are depleted in LREE and relatively enriched in LILE, HFSE and HREE with LREE/HREE ratios of 0.17 to 0.36 (Figs. 7e and 7f).

4 DISCUSSIN

4.1 Petrogenesis of the Shahre-Babak Plagiogranites

The low-Al trondhjemite and tonalite in Shahre-Babak ophiolite suite have low K_2O and Sr and high Y contents, low Sr/Y ratios, and are slightly enriched in LREE relative to HREE. These geochemical characteristics, typical of oceanic plagiogranites, are distinctly different from those of the continental high-Al tonalite-trondhjemite-granodiorite (TTG) suites that have high Sr (~400 ppm) and low Y (~20 ppm) contents, higher Sr/Y ratios and are enriched in LREE. TTG suites are suggested to be derived by low to moderate degree partial melting of hydrated basaltic crust at pressures high enough to stabilize garnet±amphibole (Jiang et al., 2008; Martin et al., 2005). It has been proposed that many oceanic plagiogranites are derived by differentiation of a tholeiitic magma (e.g., Floyd et al., 1998; Aldiss, 1981; Coleman and Peterman, 1975). Some oceanic plagiogranites are also suggested to be generated by liquid immiscibility in the deep crust (Dixon and Rutherford, 1979). However, the latter model has largely been rejected due to the lack of evidence for immiscible liquids in the rocks. Another model considers partial melting of hydrated basaltic/gabbroic rocks in oceanic shear zones as the petrogenetic process (e.g., Flagler and Spray, 1991; Pedersen and Malpas, 1984). It is therefore clear that a key question for understanding the origin of the Shahre-Babak plagiogranites is to constrain the fractionation or partial melting model and the nature of the magma source region.

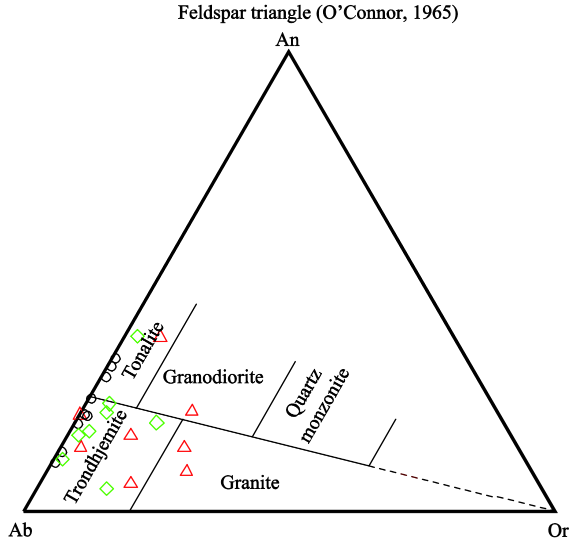

Figure 3. Plagiogranite of Shahre-Babak (diamond), Baft (triangle, Golestani, 2013) and Nyeriz (circle, Alizadeh, 2012) on the Ab-An-Or diagram (O'Connor, 1965).

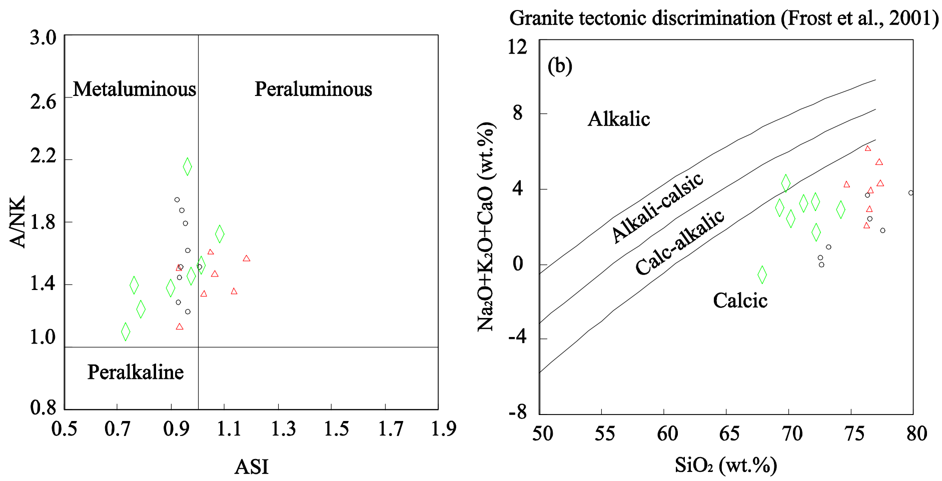

Figure 4. (a) Al_2O_3/Na_2O+K_2O (ANK) vs. aluminium saturation index (ASI) diagram (Frost et al., 2001). (b) The situation of plagiogranites from Shahre-Babak, Baft and Nyeriz on the Na_2O+K_2O+CaO vs. SiO_2 diagram (Frost et al., 2001). Symbols as in Fig. 3.

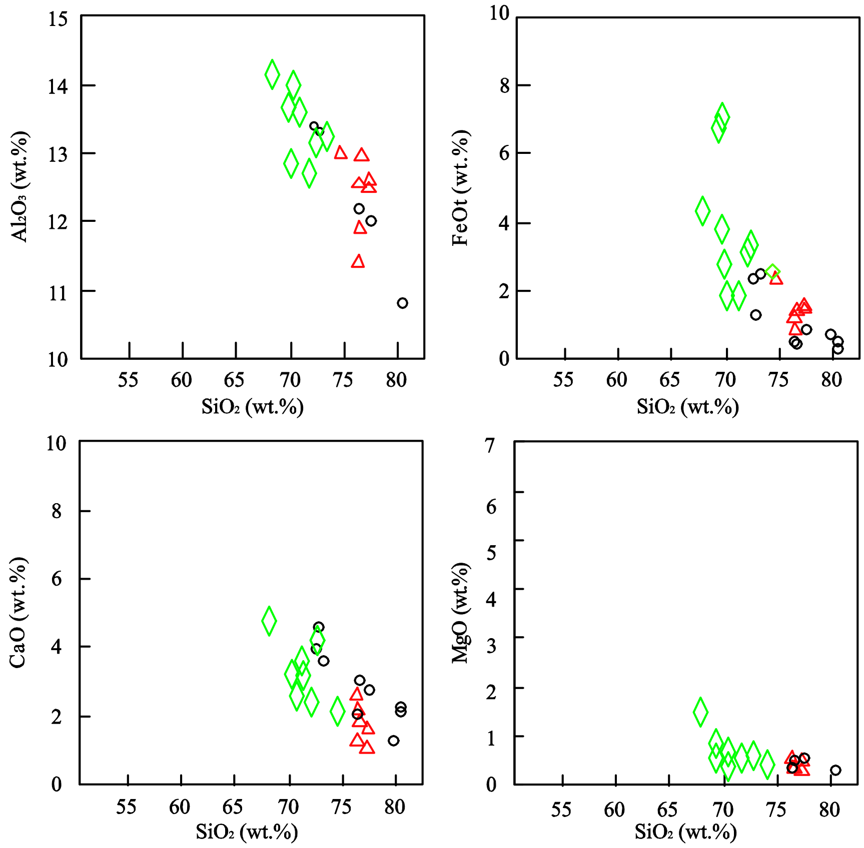

Figure 5. Selected major oxide elements vs. SiO_2 for the Shahre-Babak, Baft (Golestani, 2013) and Neyriz (Alizadeh et al., 2012) plagiogranites. Symbols as in Fig. 3.

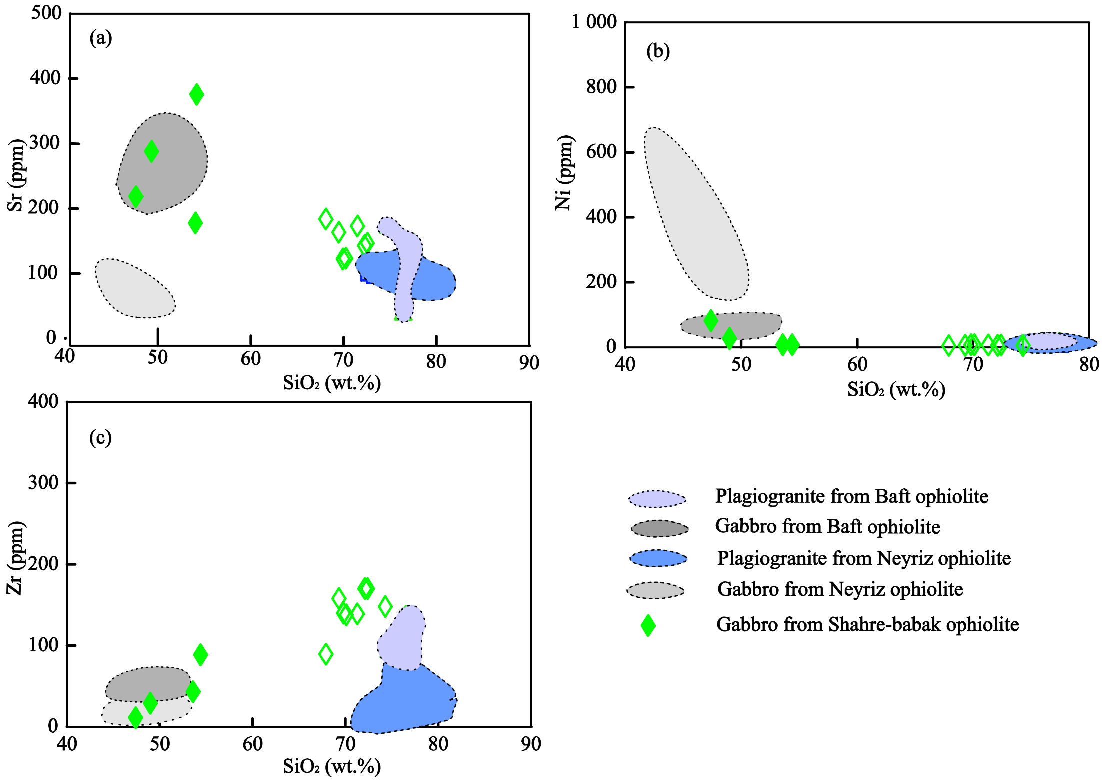

Figure 6. Selected trace elements vs. SiO_2 for the gabbros and plagiogranites from Shahre-Babak, Baft (Golestani, 2013) and Neyriz ophiolite (Alizadeh et al., 2012).

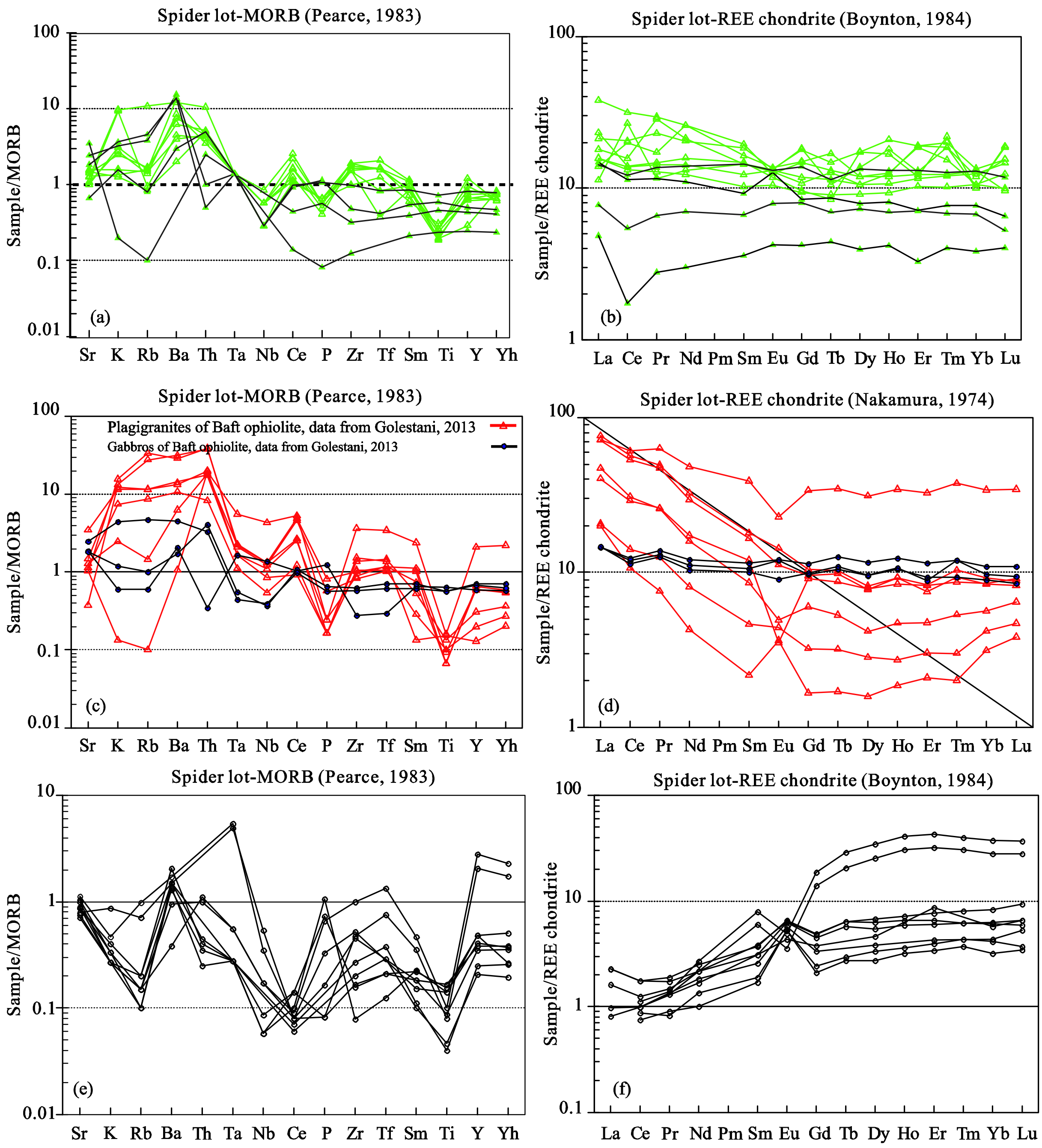

Figure 7. MORB normalized trace element patterns (left side) and Chondrite-normalized rare earth elements (right side) for the plagiogranite and gabbro from Shahre-Babak (in this study) (a)–(b), plagiogranite and gabbro from Baft (Golestani, 2013) (c)–(d), plagiogranite rocks from Neyriz (Alizadeh et al., 2012) (e)–(f).

Petrographic studies indicate that the Shahre-Babak plagiogranites and gabbro have been variably altered, and the alteration was most likely caused by interaction with seawater. During the hydrothermal alteration, transition elements (e.g., Ti, Ni and V), REE, HFSE (e.g., Nb, Ta, Zr and Y) and Th are largely immobile (e.g., Bedard, 1999; Meffre et al., 1996). Thus, these immobile elements are used in the following discussion. The compositional variations of the Shahre-Babak plagiogranites and gabbros (Fig. 5) are not linear, which rules out the possibility of mixing processes. Instead of, such compositional variations are consistent with fractionation or partial melting as the petrogenetic processes. Partial melting of hydrated basaltic/gabbroic rocks in oceanic crust could produce the magmas of plagiogranite with a residue of amphibolite (Flagler and Spray, 1991; Pedersen and Malpas, 1984) or granulite (Koepke et al., 2004). However, plagiogranites generated by such a process are characterized by a LREE-enriched signature (e.g., Flagler and Spray, 1991; Pedersen and Malpas, 1984). We have carried out detailed REE modeling of modal batch melting (in most circumstances the acid rocks are formed by a batch melting process due to their high viscosity). A tholeiitic source resembling the most mafic sample (gabbro) was selected as a source rock. The REE contents of partial melts were calculated using mineral/acid-melt partition coefficients of Arth (1976) for low to moderate degrees of partial melting (<50%) with a residue of amphibolite and granulite, respectively (Fig. 8a). The partial melts are all enriched in LREE, the REE concentrations and patterns of which are similar to those of the Shahre-Babak plagiogranites (Fig. 8a) and Baft plagiogranite (Fig. 7d), while plagiogranite from Neyriz, as a inner Zagros ophiolite belt is characterized by depletion in LREE. We have also carried out REE modeling of fractionation processes. A tholeiitic magma resembling the most mafic sample of the gabbro was selected to represent the

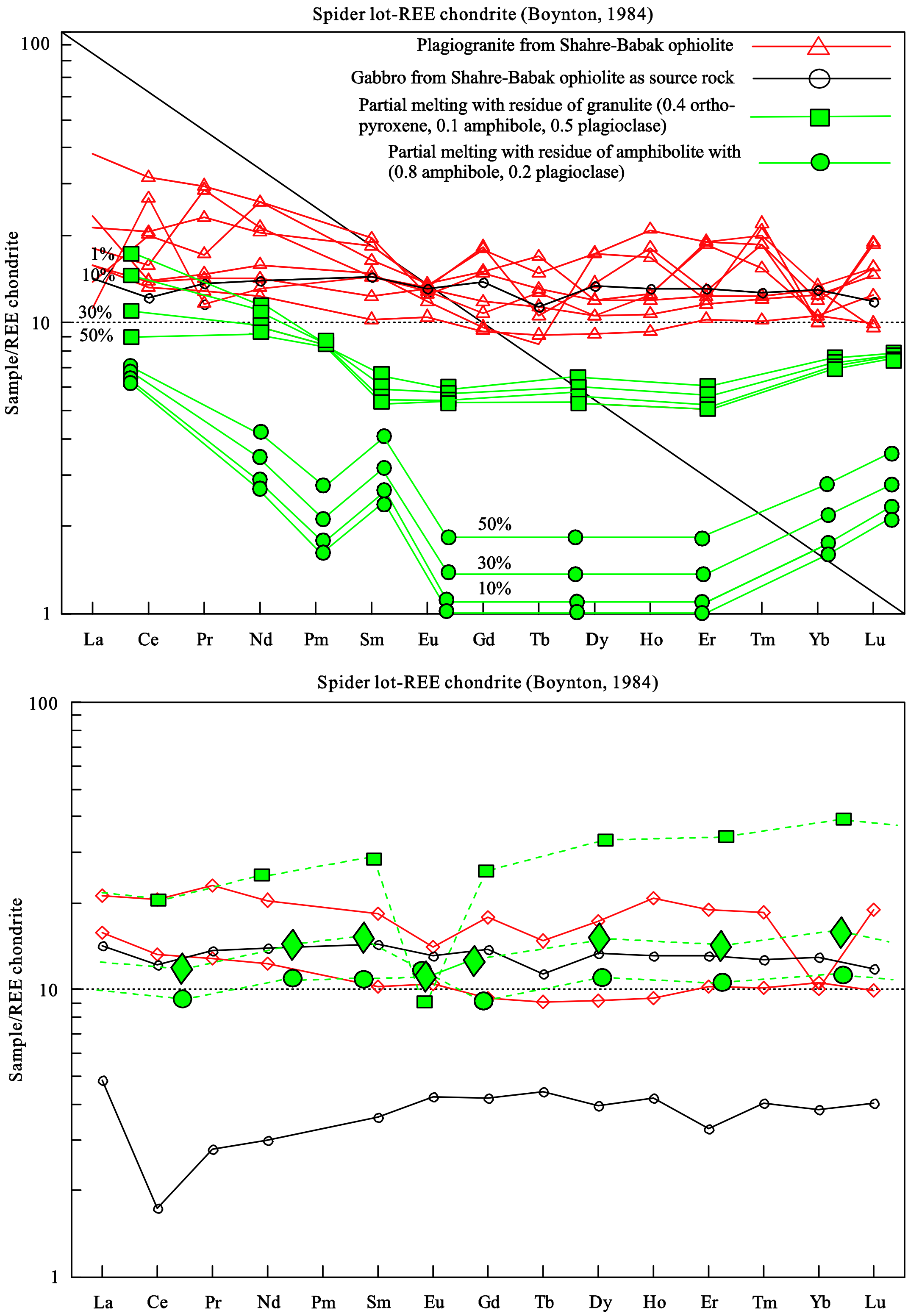

Figure 8. (a) Chondrite-normalized (Boynton,1984) REE patterns of 1%–50% batch modal melts of a tholeiitic source resembling the most mafic sample of the gabbros with residue of amphibolite and granulite, respectively, (b) and of 40%–85% fractional crystallization of a tholeiitic parental magma, the REE contents of which resemble the sample gabbros.

parental magma. The results show flat to slightly LREE-depleted patterns for fractional crystallization of a tholeiitic magma, such as gabbro, while plagiogranite show slightly LREE-enriched patterns (Fig. 8b). In summary, the slightly LREE-enriched patterns of the Shahre-Babak and Baft plagiogranites support a partial melting origin. This is also satisfied by the position of data on La against La/Sm diagrams (Allègre and Minster, 1978) (Fig. 9).

Three models have been proposed for the origin of oceanic plagiogranites: (1) differentiation of basaltic magmas (Jiang et al., 2008; Lippard et al., 1986; Coleman and Donato, 1979), (2) partial melting of metasomatised gabbros or amphibolites (Grimes et al., 2013; Koepke et al., 2004; Flagler and Spray, 1991; Gerlach et al., 1981; Malpas, 1979), (3) liquid immiscibility in deeper crust (Dixon and Rutherford, 1979). However, the third model has largely been discarded due to the lacking of evidence for immiscible liquids in oceanic magmatic systems. The two widely accepted genetic types for plagiogranites are namely Karmoy-style (or the anatectic-type) derived from partial melting of amphibolites or amphibolite-metamorphosed gabbros and Visnes-style (or the differentiated type) related to the differentiation of basaltic magmas (Pedersen and Malpas, 1984). The Zr and Y are incompatible elements that have great effect on the partial melting process (Hanson, 1978). So the Visnes-style plagiogranites have higher contents of Zr, Y, and Zr/Y ratios than those of the Karmoy-style plagiogranites (Zeng et al., 2015) (Fig. 10). The Shahre-Babak plagiogranites have low contents of Zr, Y, and Zr/Y ratios, which are consistent with the Karmoy-style plagiogranites. The Shahre-Babak plagiogranites geochemistry shifts away from the Raleigh fractionation trend and is close to the anatectic plagiogranite region (Fig. 10a), which implies that the plagiogranites may have been generated by gabbro anatexis rather than by the basaltic magma fractionation. As mentioned above, intrusions within the Shahre-Babak ophiolite suite are composed of low-Al trondhjemite and tonalite. The rocks from Share-Babak as well as Baft plagiogranites have low K_2O and Y and high Sr contents with High Sr/Y ratios, and are enriched in LREE relative to HREE. These geochemical characteristics are typical of oceanic plagiogranites and apparently similar to the continental high-Al tonalite-trondhjemite-granodiorite (TTG) suites that have high Sr and low Y contents with much higher Sr/Y ratios and are enriched in LREE. TTG suites are suggested to be derived by low to moderate degree partial melting of hydrated basaltic (low-K) crust at pressures high enough to stabilize garnet±amphibole (Martin et al., 2005) (Table 1) whereas the plagiogranites of the Neyriz ophiolite differ from those from Shahre-Babak and Baft. These results are suggested that fractional crystallization can be roled in genesis of plagiogranites from Neyriz. TiO_2 contents in tholeiitic melts are dependent on the oxygen fugacity (e.g., Berndt et al., 2005; Toplis and Carroll, 1995; Snyder and Dunning, 1993). A high f_{O2}(~15) enhances the stability of Ti oxides resulting in generation of the melts with relatively low contents of TiO_2. Since MORB differentiation occurs under much more reducing conditions (Bézos and Hunler, 2005; Christie et al., 1986). Koepke et al. (2007) performed experiments under oxidizing conditions which were used for constructing a line delimiting the minimum amount of TiO_2 expected in evolved melt generated from differentiation in tholeiitic liquids. Koepke et al. (2007) proposed that TiO_2 was higher in the melts generated by MORB differentiation or liquid immiscibility and lower in the melts generated by gabbro anatexis. TiO_2 contents of the Shahre-Babak plagiogranites are substantially lower than the melts derived from MORB differentiation or immiscibility, which further support the anatexis hypothesis (Fig. 10b). The paradox of LREE enrichment in the plagiogranites has drawn the attention of many geoscientists. Ludden and Thompson (1979) and Humphris (1984) proposed that under certain conditions, especially in alteration zones, seawater can selectively mobilize LREEs. Hydrothermal alteration not only changes the geochemistry of oceanic crust, but also lowers the melting point of the rocks. The Shahre-Babak plagiogranites have low LOI (less than 1.3 wt.%). The enrichment of LREE of the rocks indicates that the Shahre-Babak plagiogranites were most likely the products of amphibolite/amphibolitised gabbro anatexis.

4.2 Geodynamic of Shahre-Babak Plagiogranites

The Shahre-Babak plagiogranites have pronounced negative anomalies of Nb, Ta, Ti (Fig. 7a), and relatively high LREE/HREE ratio (Fig. 7b), which are diagnostic features of intra-oceanic subduction melts (Hawkesworth et al., 1993). Rajabzadeh et al. (2013) proposed that the Shahre-Babak ophiolite was derived from back arc basin. The suprasubduction-zone oceanic backarc basin ophiolites are generated by decompression melting of the as the nospheric mantle as a result of seafloor spreading (Dilek and Furnes, 2011; Xu et al., 2003) (Fig. 11a). The Shahre-Babak ophiolites were emplaced during the spreading in the Nain-Baft backarc basin from the upwelling as the nospheric mantle. We propose that during the spreading, any resistance of moving the oceanic plate may manifest as low-angle shearings near the base of the crust (Fig. 11b). The addition of LREE-enriched hydrothermal solutions (the seawater from the shearing zones) made the gabbro evolve to amphibolite which lowered the melting points. The amphibolite was subsequently heated up by as the nospheric heating, probably with additional heat from shearings during plate motion, which facilitated the anatexis of amphibolite forming magma chamber, and then formed tonalite and trondhjemites through fractional

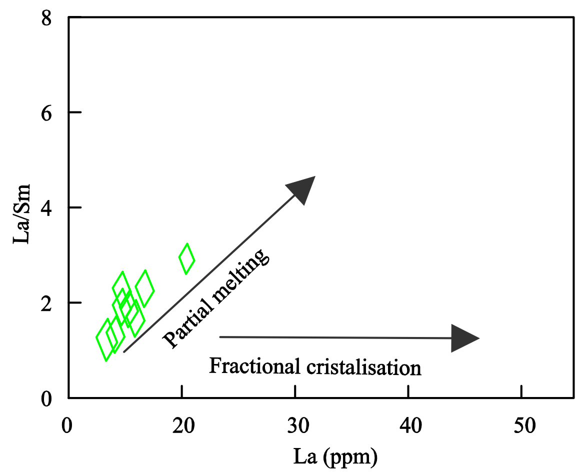

Figure 9. Plots of La versus La/Sm for the Shahre-Babak plagiogranites (Allègre and Minster, 1978).

crystallization.

5 CONCLUSION

Most of intrusive masses in Share-Babak ophiolite include gabbro and plagiogranite. Rare earth elements exhibit relatively similar pattern that indicates these rocks are syngenetic. REE patterns display an enrichment of LREE compared to HREE, and are characterized by flat to slightly concave-up patterns from Gd to Yb. Such patterns contrast sharply with those of plagiogranites in more complete ophiolite sequences, such as the Semail ophiolite, Oman, or the Troodos ophiolite, Cyprus, and Neyriz. The slightly LREE-enriched patterns of the Shahre-Babak plagiogranites support a partial melting origin for them.

The low TiO_2, Nb, Ta content, LREE enrichment values of the Shahre-Babak plagiogranites indicate that the rocks were likely derived from the anatexis of amphibolites, which were related to hydrothermal alteration of gabbros in intra-oceanic back-arc basin.

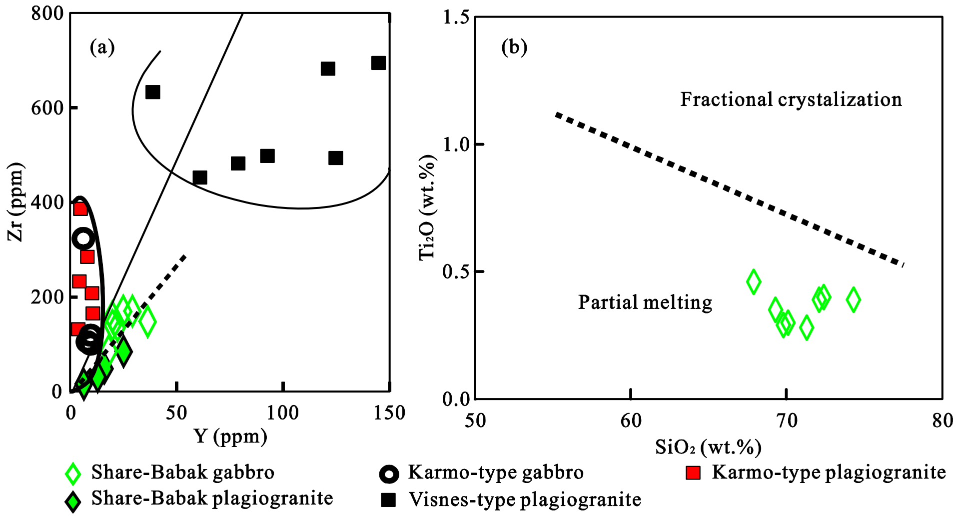

Figure 10. (a) Plot of Y versus Zr for the Shahre-Babak plagiogranites compared with the Karmoy ophiolite (Pedersen and Malpas, 1984). Partition coefficients for Zr and Y are from Watson and Harrison (1983) and Pearce and Norry (1979), respectively. (b) SiO_2 versus TiO_2 (Koepke et al., 2007). Symbols as in Fig. 4.

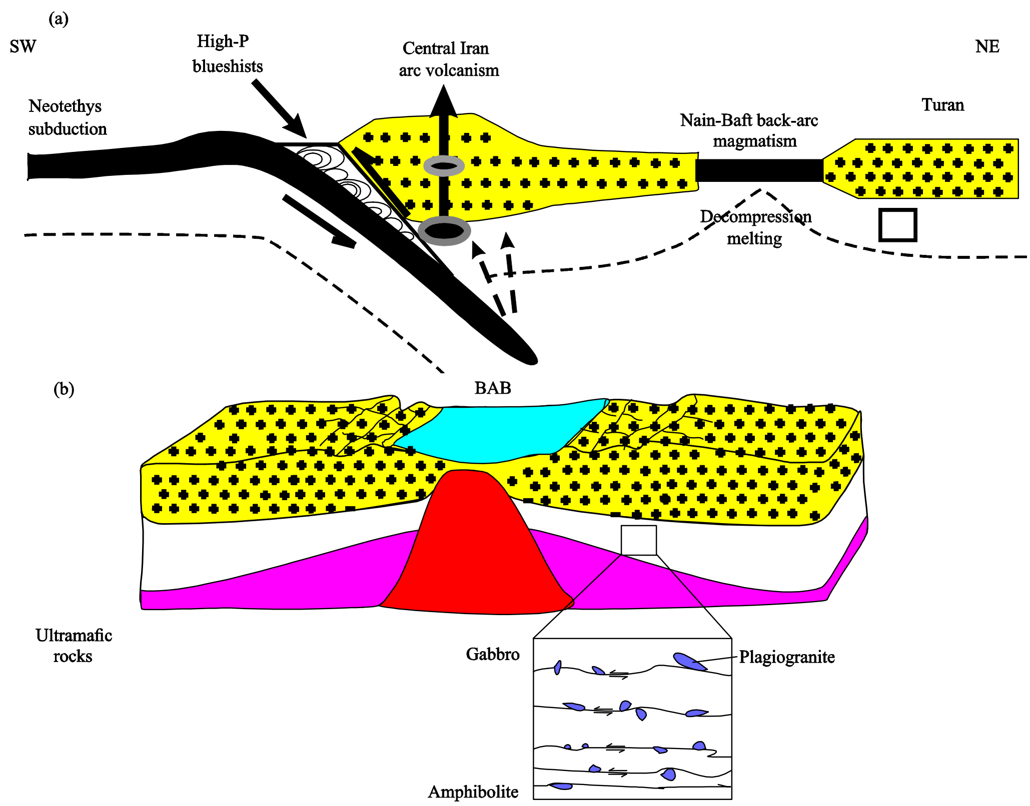

Figure 11. Schematic tectonic model for the formation of the Shahre-Babak plagiogranites. (a) Backarc basin ophiolite and (b) Shahre-Babak plagiogranites formation. BAB. back-arc basin.

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