

Petrology of the Plutonic Rocks at the XIV Iron-Oxide Prospect, Bafq Mining District, Central Iran

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Abstract

The XIV iron-oxide prospect in the northern part of the Bafq mining district is hosted by intrusive rocks and demonstrates similar characteristics with Kiruna mineralization. The plutonic complex of the XIV prospect is composed of two major types of intrusive rocks, including: 1) a granitic intrusive body which is itself composed of two types; a pale-pink leucogranite and a white-gray aplite, as well as 2) a gabbrodiorite intrusive body. Geochemically, these rocks are tholeiitic-calcalkaline and metaluminous in nature. Geochemical characteristics of the plutonic rocks of the study area support a non-orogenic continental setting.

Keywords

Granite, Gabbrodiorite, Geochemistry, Petrography, Bafq, Iron

1. Introduction

The Bafq mining district in Central Iran is the most important iron metallogenic province in the region and a significant district on a worldwide basis ([1]-[9]). The Bafq district, extending from Bafq to Saghand, is part of the central Iranian microplate which is now embedded within the Alpine-Himalayan orogenic system. The Central Iranian Terrane is an assemblage of several Precambrian fragments of Gondwanaland which covers an approximately 230,000 km² of moderate relief surrounded by Mesozoic-Cenozoic fold-and-thrust belts of the Alpine-Himalayan system.

The Central Iranian Terrane consists, from east to west, of three major crustal domains: the Lut Block, Tabas Block and the Yazd Block. These blocks are separated by a

series of intersecting regional-scale faults. The Tabas and Yazd blocks are separated by a more than 1000 km long and up to 80 km wide arcuate and structurally complex belt composed of variably deformed supracrustal rocks, *i.e.* the Kashmar-Kerman Tectonic Zone [7] which hosts the Bafq mining district. The Kashmar-Kerman Tectonic Zone provides remarkable exposures of the deeper sections of the Central Iranian platform strata, among which the Late Neoproterozoic and Early Paleozoic rocks are abundant [7] [8].

The XIV iron prospect (geographic coordinate: 55°28'E - 55°30'E and 32°04'N - 32°07'N) is located at 8 km north of Chah Gaz magnetite deposit (anomaly XIVA) and 60 km north of Bafq city (**Figure 1**). This prospect is divided into three ore zones (northern, central and southern orebodies). According to the data obtained from drilling cores, the main orebody (northern zone) is continued down to 300 m below surface. The magnetite consists of 62% iron and is phosphorus-poor. The northern ore zone mainly occurs in an aplite dome (caused by late differentiation of granite and called "leuco-metasomatite" in mining terminology) and is composed of the massive magnetite and hematite ore bodies together with actinolite, all of which are located in the northern and southern parts of the area. The origin of the Bafq district deposits has been the subject of longstanding debate and remains controversial. Also, the XIV iron-prospect has received little attention so far. This paper presents the outcome of the preliminary petrological investigations on the plutonic rocks of the prospect which partly hosts the mineralization. In this regard, the different rock types of the so called Zarigan granite at the prospect have been studied using petrographic and geochemical investigations and have been interpreted accordingly the tectonic setting.

2. Research Methodology

During the field observations, 120 rock samples were collected from different parts of the study area, of which 80 thin sections and 34 polished thin sections were prepared and studied using polarizing microscope. 12 samples from granite and gabbrodiorite intrusive bodies were analyzed for their geochemistry (including REEs) using ICP-MS and XRF. The petrographic and geochemical results were then interpreted for understanding the petrology of the intrusive rocks in the study area.

3. Results and Discussion

3.1. Granites

The Zarigan intrusion is the largest intrusive body exposed in the study area. This intrusion is a shallow, leucocratic body that ranges in texture and color from a typical medium-crystalline granite to a sub-volcanic granite porphyry (aplite) (**Figure 2(a)** & **Figure 3(a)**) [10]. The first type granites (Leucogranite) are pale-pink (**Figure 2(a)** & **Figure 2(b)**) and tend to be alkali granites and have a granular and peritic texture. The studied granite samples consist primarily of quartz (39%), orthoclase (35%) and plagioclase (oligoclase) (25%) in approximately equal proportions. Accessory minerals include biotite, hornblende, titanite, zircon, and opaque minerals (**Figure 2(a)**). This

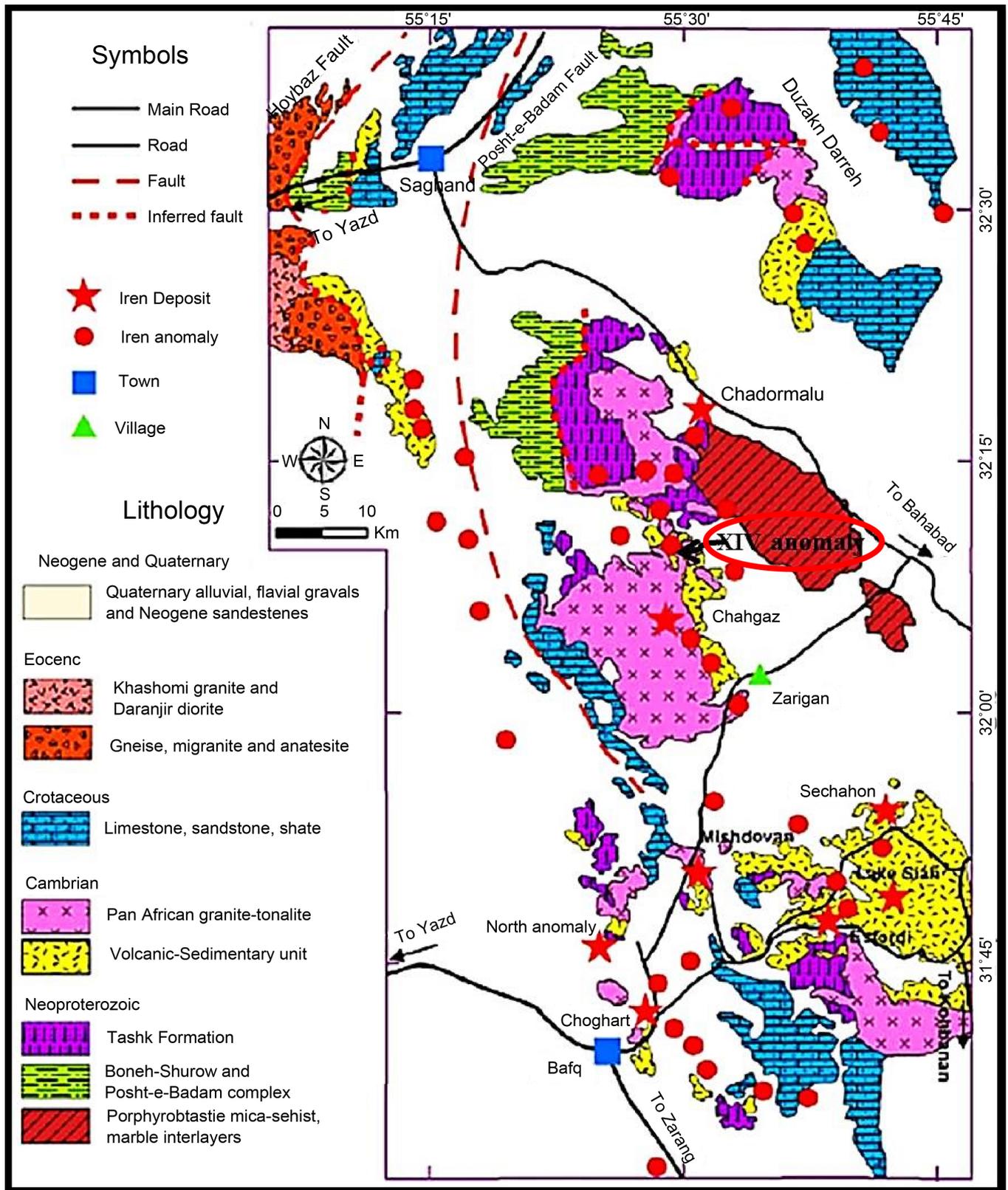


Figure 1. Simplified geological map of the Bafq mining district indicating the location of the XIV iron prospect (Modified from Hagh-pour, 1977; NISCO, 1980; Ramezani & Tucker, 2003) [9]-[15].

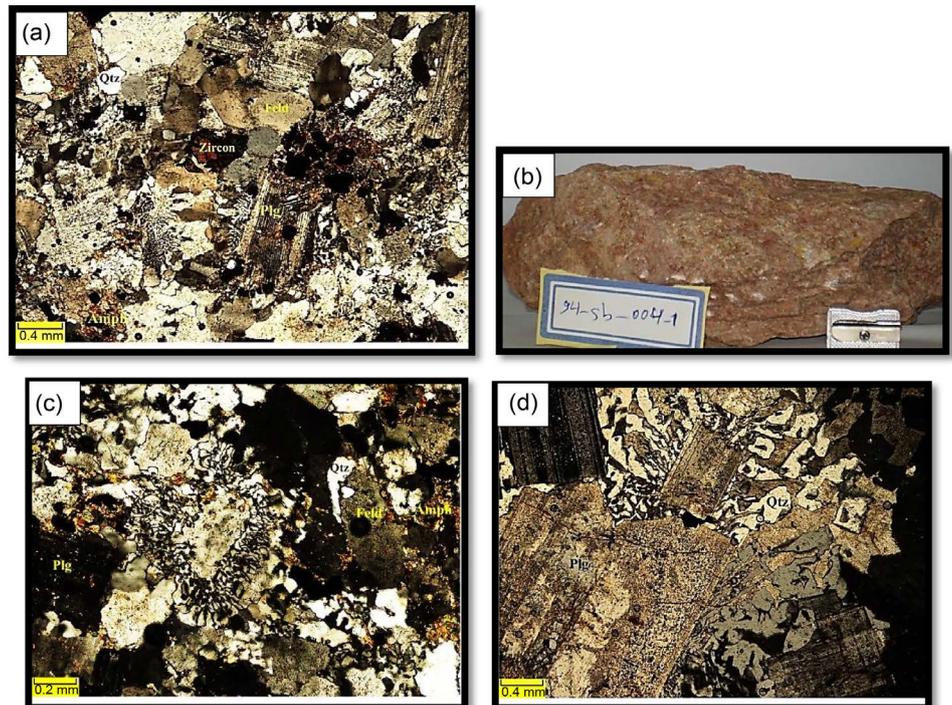


Figure 2. (a) Photomicrographs of (leuco) granite of Zarigan (XPL). (b) Hand specimen of the second type of granite. (c) and (d) Inequigranular, hypidiomorph granular, granophyric and myrmekitic textures of Leucogranite.

granite displays a variety of textures. The general texture of the Leucogranite is inequigranular hypidiomorph granular, poikilitic (**Figure 2(c)**) myrmekitic (**Figure 2(c)** & **Figure 2(d)**) and graphic with granophyric quartz-albite intergrowths.

Eutectic intergrowth of quartz with sodic feldspar is often of the granophyric and rarely of the micrographic type and has just been observed sporadically. In some Leucogranite samples of the XIV prospect, the granophyric texture is developed and the whole rock is composed of this type of intergrowth. Alkali feldspar in granophyres is typically of albite type that has been altered to sericite.

The second type of granite is a white to gray aplite (sub-volcanic granite porphyry or late differentiation phase of Zarigan granite which is called “leuco-metasomatite” in mining terminology) (**Figure 3(b)**). The major rock forming minerals of the aplite of the XIV prospect consist of quartz (70% - 85%) and sodic feldspar (15%), while the accessory minerals include zircon, apatite, hornblende and opaque minerals. Quartz crystals are seen as individual texture and comprise two distinct textural components: 1) a fine grained (up to few millimeters) broadly equigranular alkali feldspar and plagioclase component; 2) a fine to medium grained component (**Figure 3(c)**); sometimes intergrown with albite and rarely with perthite. These types of quartz crystals have formed simultaneously.

3.2. Gabbrodiorites

The modal mineralogical composition of representative gabbrodiorite samples (**Figure 4(a)**)

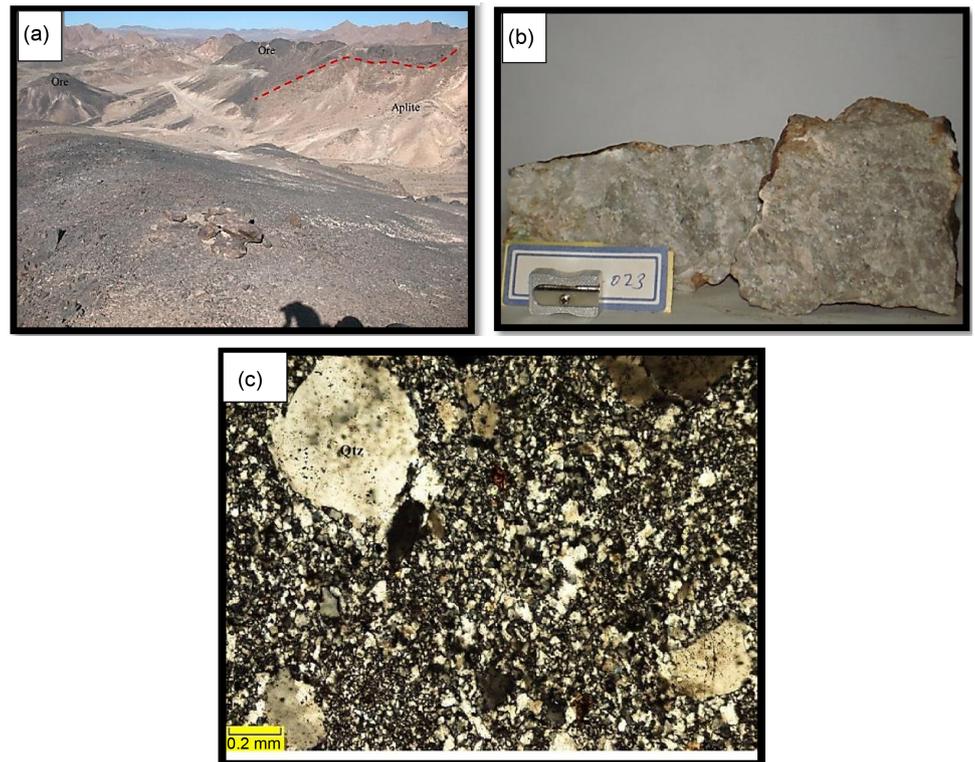


Figure 3. (a) Outcrop of the aplite dome, in north of the XIV prospect. (b) Hand specimen of the first type of granite. (c) Anhedronal to subhedral quartz crystals are seen as individual crystals with granular to cataclastic texture.

from the XIV prospect, demonstrates the major minerals of pyroxene (25% - 30%), amphibole (10% - 12%) and plagioclase (35% - 40%) (**Figure 4(b)**) together with accessory minerals of biotite, apatite, olivine, zircon and opaque minerals (**Figure 4(c)**).

This gabbrodiorite indicates an inter-granular and hypidiomorph granular texture with fine-grained euhedral-subhedral magnetite scattering with pyroxene and plagioclase. The petrographic investigations show that most of the amphibole has converted to tremolite and actinolite. Also undeveloped granophyric quartz-albite intergrowth is observed in the gabbrodioritic rocks which indicate mixing between granite and gabbrodioritic rocks.

3.3. Geochemistry

The result of major element analyses of granite and gabbrodiorite samples are listed in **Table 1** and **Table 2**. The alumina saturation index values [16] are plotted in **Figure 5** and show that the least altered Zarigan granites are both Al-oversaturated (peraluminous) and Al-undersaturated (metaluminous), but most samples have been plotted in the peraluminous region. The felsic plutonic rocks of the region plot in the granite and alkali granite field, while the mafic plutonic rocks plot in the gabbro field of the plutonic rock classification diagram [17] (**Figure 6**). To distinguish between calcalkaline and tholeiitic suites, the samples were plotted in an AFM diagram (**Figure 7**) which shows

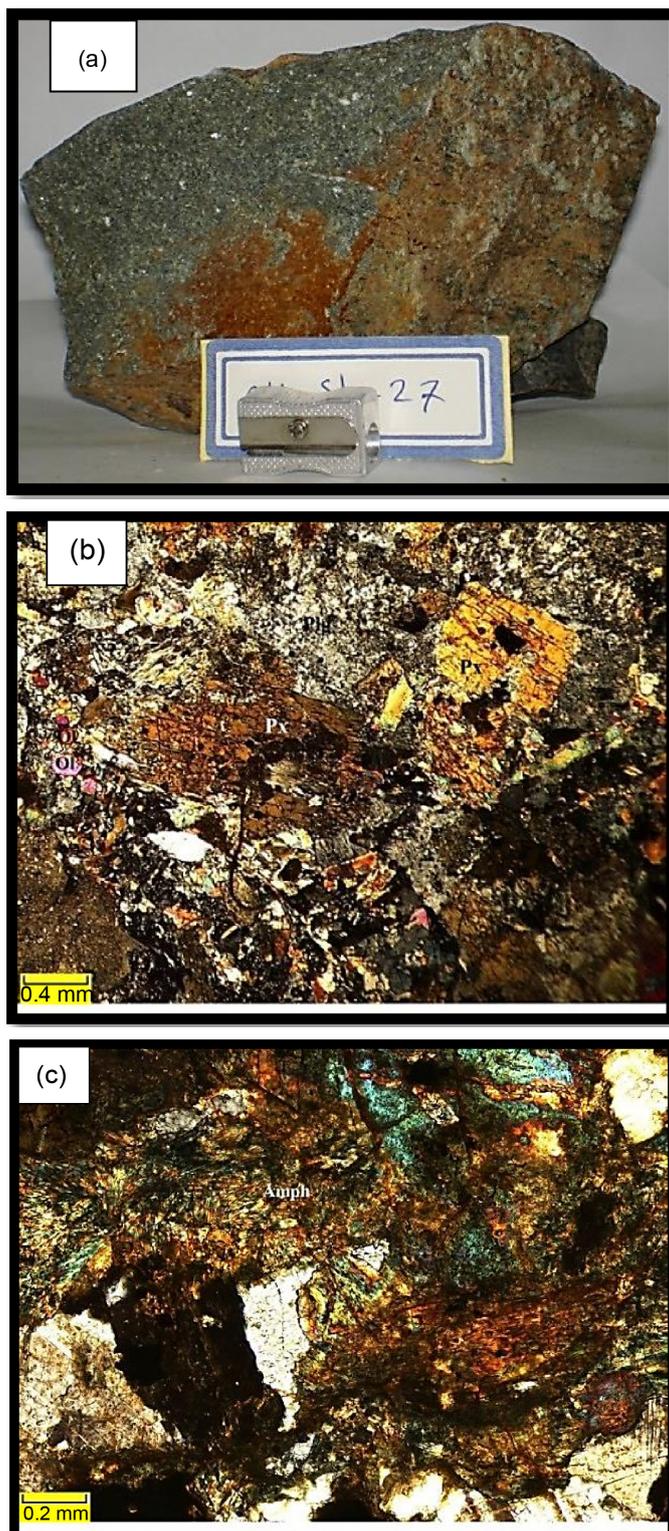


Figure 4. (a) Hand specimen of gabbrodiorite. (b) Photomicrographs of high grade alteration in pyroxene ((a), XPL and (b), PPL). (c) Photomicrographs of metasomatic amphibole filling the open spaces of highly altered plagioclase ((a), XPL and (b), PPL).

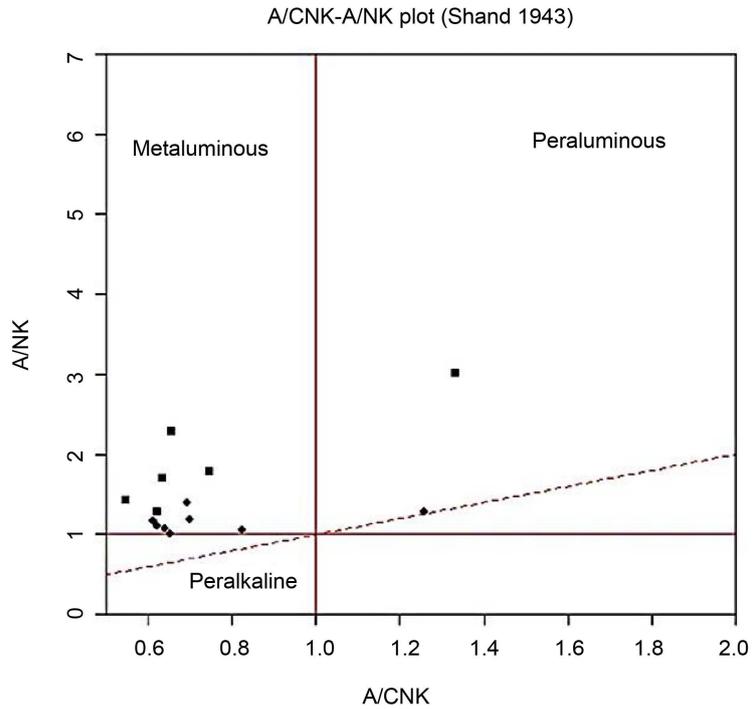


Figure 5. Al-saturation plot for granitoid rocks [16].

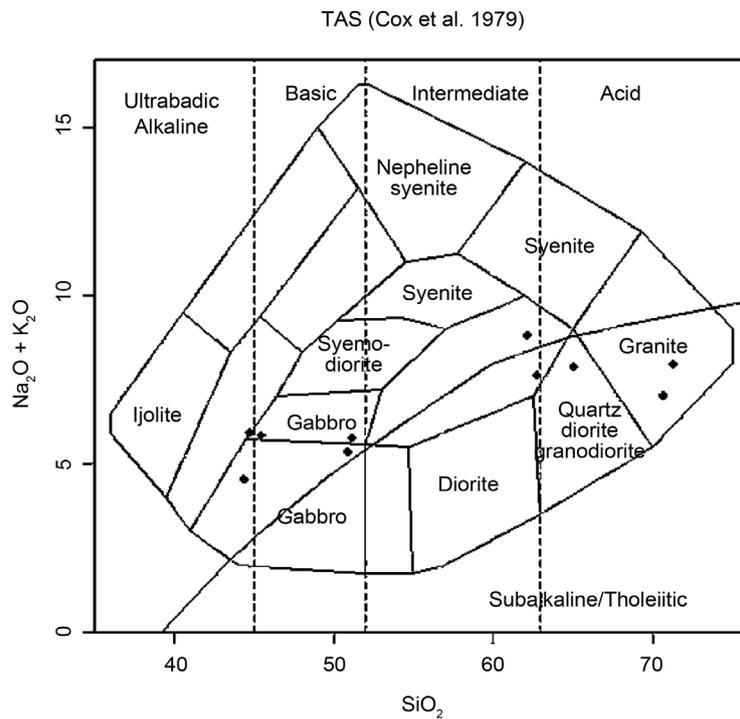


Figure 6. Classification of plutonic rocks [17].

that the samples mostly plot in contact between tholeiitic and calcalkaline field (**Figure 7**).

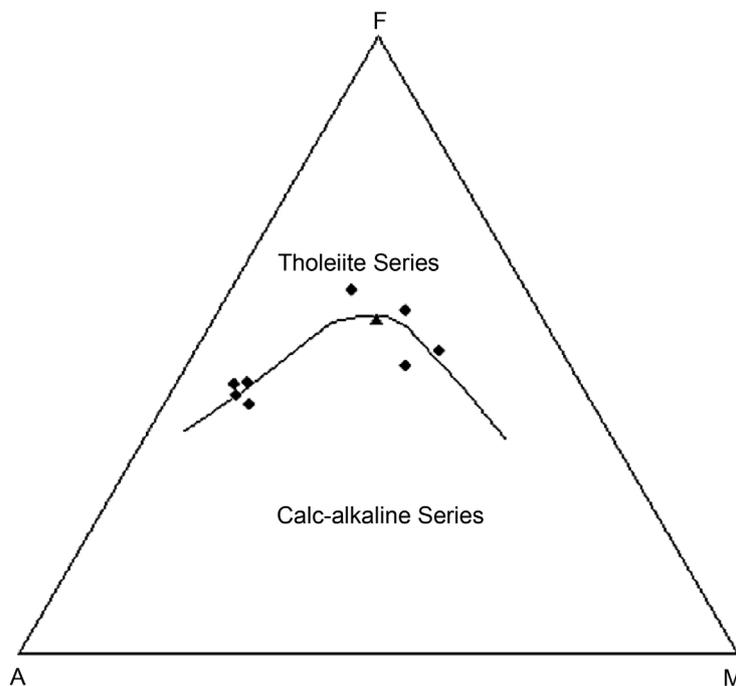


Figure 7. Discriminant diagram between tholeiitic and calcalkaline series of granitic rocks of the XIV prospect.

Table 1. Major element composition of the Zarigan granite (measured by XRF).

Sample	SiO ₂	Al ₂ O ₃	CaO	MgO	Fe ₂ O ₃	P ₂ O ₅	TiO ₂	Na ₂ O	K ₂ O	FeO	LOI
Sb2	65.11	13.02	1.92	1.52	3.51	0.41	0.85	6.78	1.07	3.59	1.08
Sb4	70.77	12.29	4.72	0.1	1.29	0.27	0.05	6.45	0.55	1.28	2.26
Sb4a	71.71	10.83	4.63	0.1	0.97		0.05	0.05	8.5	0.77	2.15
Sb8	71.37	12.63	0.1	3.48	0.91	0.05	0.05	2.19	5.77	1.16	1.81
Sb10	70.35	12.15	3.88	0.1	0.99	0.05	0.05	0.05	9.46	0.71	2.39
Sb17	67.81	12.22	4.91	0.1	1.9	0.05		0.05	8	1.69	3.12
Sb31	71.13	16.41	0.35	1.53	0.99		0.05	0.06	0.07	1.16	2.49

Table 2. Major element composition of the gabbrodiorite (measured by XRF).

Sample	SiO ₂	Al ₂ O ₃	CaO	MgO	Fe ₂ O ₃	P ₂ O ₅	TiO ₂	Na ₂ O	K ₂ O	FeO	LOI
Sb6	45.48	13.94	5.96	5.66	5.16	0.75	2.94	2.73	3.1	8.79	4.63
Sb7	44.45	14.74	8.82	6.45	4.83	0.87	2.05	2.71	1.83	9.39	2.66
Sb24	51.78	15.52	7	2.07	3.65	0.96	1.09	5.85	2.38	3.66	3.54
Sb27	48.42	15.72	3.61	9.47	4.69	0.64	1.8	3.14	0.05	8.33	3.36
Sb37	51.22	11.9	7.38	4.06	6.3	0.74	1.41	3.75	2	8.33	1.22

The samples of the XIV granite have SiO₂ contents of 62.8 wt% - 72 wt% and Al₂O₃ contents of 11.99 wt% - 16.41 wt% (**Table 1**) and are enriched in Na₂O (2.19 wt% - 6.78 wt%) and K₂O (0.5 wt% - 10.74 wt%), as it is demonstrated in the TAS diagram (**Figure 6**). These granites are metaluminous with alumina saturation index values (ASI = molar

$\text{Al}_2\text{O}_3/(\text{CaO} + \text{Na}_2\text{O} + \text{K}_2\text{O})$) up to 1.10 (Figure 5) and are calcic as indicated by the Rittman index values between 0.8 and 1.4 ($\sigma = [\text{Na}_2\text{O} (\text{wt}\%) + \text{K}_2\text{O} (\text{wt}\%)] / 2 / [\text{SiO}_2 (\text{wt}\%) - 43]$) and their position on $\text{Na}_2\text{O} + \text{K}_2\text{O}$ vs. SiO_2 diagram [18]. There is a general decrease in Al_2O_3 , FeO and CaO with increasing SiO_2 (Table 1).

The XIV granites have relatively high contents of LILE such as Ba and Rb, and low HFSE contents with marked negative Nb, Sr and Ti anomalies on MORB normalized spider diagram (Figure 8(b)). The chondrite normalized REE patterns show an enrichment in LREE relative to HREE ((La/Yb) CN = 0.84 - 2.95), with negative Eu anomalies (Figure 8(a)). Similar to granites, the gabbrodiorites of the XIV prospect are depleted in HREE and relatively enriched in LREE ((La/Yb) CN = 3.2 - 23.5). Such patterns contrast sharply with those of granites in other sequences. Despite similar major and trace element compositions, there are subtle differences between the granite

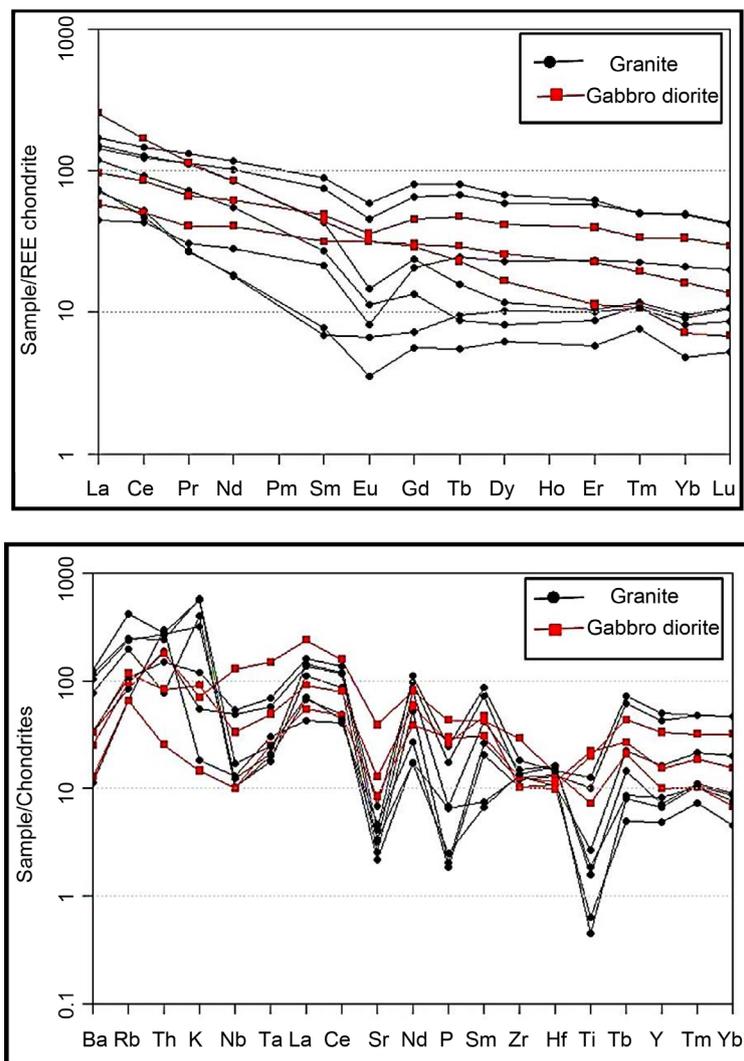


Figure 8. MORB normalized trace element patterns (down) and Chondrite-normalized rare earth elements (up) for the granite and gabbrodiorite of the XIV prospect.

and gabbrodiorite of the XIV prospect. REE concentrations in the granite are higher than those in gabbrodiorites (Figure 8(a)) and the granite has a higher Th/U ratio (2.5 - 7.4) than that of the gabbrodiorite (0.7 - 3.52). The gabbrodiorite of the XIV prospect have lower contents of SiO₂ (44.45 to 51.22 wt%) and K₂O (0.05 to 3.1 wt%) rather than those of granite. Chondrite normalized REE patterns for the XIV gabbrodiorite show wide compositional variations (Figure 8(a)). They are depleted in HREE and relatively enriched in LREE with LREE/HREE ratios of 4.3 to 42, and have narrow compositional variation with negative Eu anomalies (Figure 8(a)).

3.4. Tectonic Setting: Anorogenic or Post-Orogenic?

The host rocks of the XIV prospect area, according to this study and the study conducted by Ramezani and Tucker [13], vary from granite to gabbrodiorite, indicating an alkaline-sub-alkaline or a bimodal composition. The tectonic setting diagrams (Figure 9) illustrate volcanic arc granites.

Boron is an interesting trace element, as it is strongly enriched in seawater and marine sediments compared with its concentration in most crust and mantle rock types [19]. Therefore, boron can be used as a tracer to indicate the presence of subducted sediment or altered oceanic crust in magma's source regions. Boron concentration gener-

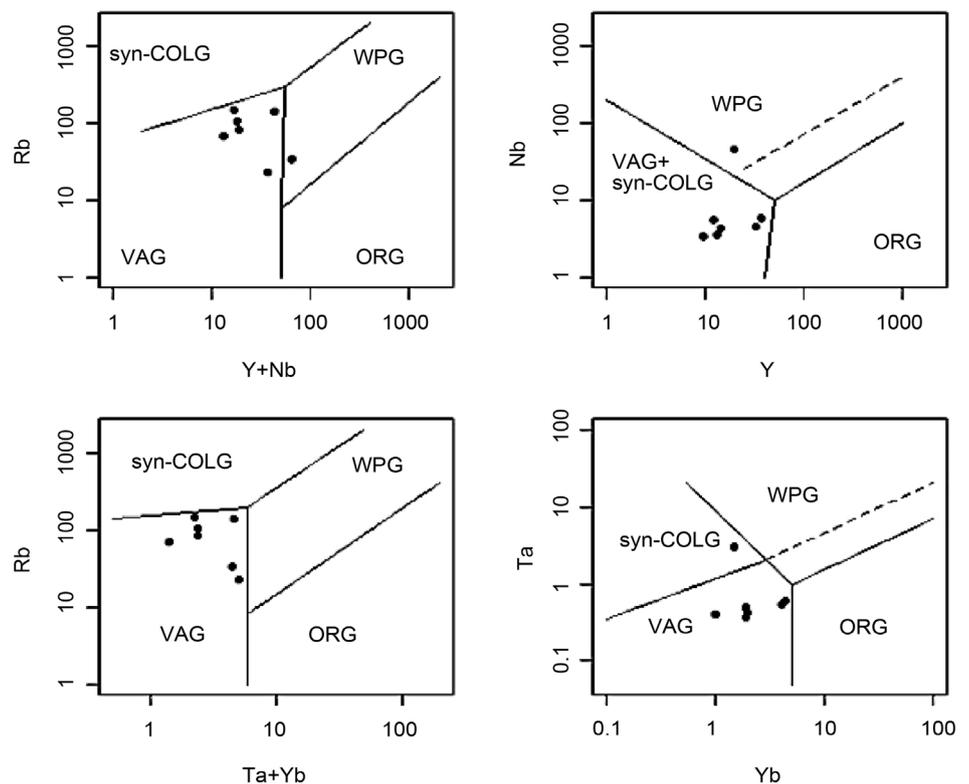


Figure 9. Plot of granitoid rocks from the XIV prospect on the Y + Nb vs. Rb & Y vs. Nb & Tb + Yb vs. Rb & Yb vs. Ta discrimination diagram of Pearce *et al.* [20]. Abbreviations of fields: VAG: volcanic arc granites; WPG: within plate granites; Syn-COLG: Syn-collisional granites; ORG: ocean ridge granites; Post-COLG: post-collision granites.

ally varies from 1 to 2 ppm in mid-ocean ridges and ocean island basalts, but, frequently reaches to more than 10 ppm in volcanic arc basalts and andesites. No boron was detected in this study or those conducted by Ramezani and Tucker [13] and Isfahani and Sharifi [21] probably indicating an orogenic continental rift setting for the Bafq region.

The plutonic rocks of the Bafq region are diverse and range from granite to gabbrodiorites (bimodal composition). Many are identified as syenites and/or red granite (e.g. Sorkh granite in the vicinity of Chadormalu paleocrater) (Figure 1). These rocks generally display either potassic or sodic alteration and are pervasively replaced by hydrothermal hematite and magnetite. Extensive sodic, potassic, sericitic and silicic alterations are present at the XIV iron-oxide prospect and its associated iron deposits.

A conceptual conclusion by Hitzman *et al.* [22] (on the basis of Forster & Knittle's data, 1979), suggests an extensional environment for the Bafq region. According to Aghanabati [23], Upper Precambrian-Lower Cambrian volcanic rocks in the Bafq region are alkaline and reflect a continental drift. In the absence of distinguishable contact between Late-Precambrian volcanicevaporite deposits and Early-Cambrian formations, Aghanabati [23] suggests a Late-Precambrian to Early-Cambrian age, extending into Middle Cambrian. Samani [24] proposed an intra-continental rift facies (Saghand Formation), comprising five members with different lithologies and bimodal volcanism. According to Momenzadeh [25] and Feiznia [26], a volcanic activity introduced ions and volatile components in an early rift basin and evaporate deposition occurred during an early to intermediate rifting stage. Moore and Modabberi [27] also proposed bimodal volcanism and immature nonmarine clastic sediments in an anorogenic continental drift.

Emami [28] proposed a within plate magmasim at the Chadormalu-Saghand area, again, a non-orogenic continental rift environment associated with tholeiitic, alkaline-subalkaline or undersaturated-saturated or bimodal volcanism; and LREE enrichment [27] [29] [30]. According to Hall [31] and Raymond [32], in those island arcs that are not underlain by continental crust, andesites are associated with abundant basalts (e.g. shoshonitic basalts) and scarce dacites and rhyolite, but, in volcanic regions underlain by continental crust, they are associated with less abundant basalts and voluminous dacites and rhyolites; in other words, unlike orogenic belts, where intermediate igneous rocks are commonplace, the anorogenic continental areas are characterized by a bimodal association of rhyolite and basalt, or granite and gabbrodiorite; that is, continental rift basalts typically are accompanied by more siliceous volcanic rocks ranging from andesite to rhyolite in composition, but the volcanic rock suites are commonly bimodal consisting mainly of two basalt and rhyolite types. Sillitoe [33] proposed that, in arc environments (e.g. IOCG deposits), shoshonitic basalt, basalt, basaltic andesite and high K calc-alkaline series are dominant, while dacite and rhyolite are rare. In other words, there is a tholeiitic-calc-alkaline bimodal composition which is dominant at these environments. In contrary, alkaline-sub alkaline bimodal suites occur in anorogenic continental rift settings [27] [29] [30] [31] [32] [34].

The collected evidence in this study shows that the host rocks (bimodal series) con-

tain voluminous intermediate-felsic intrusive and extrusive rocks (andesite-dacite-rhyolite) with lesser mafic igneous rocks, *i.e.* non-orogenic environment (B-type), as suggested by Hitzman [35].

4. Conclusions

The Zarigan granite is one of the most important plutonic rocks in the study area. This intrusion is a shallow, leucocratic body that ranges in texture and colors from a typical medium-crystalline granite to sub-volcanic granite porphyry (aplite). Mineral assemblage in these rocks is quartz, K-feldspar, plagioclases, biotite, chlorite and opaque minerals. The alumina saturation index values [19] show that Zarigan granites are Al-undersaturated (metaluminous), while these felsic plutonic rocks of the region plot in the granite and alkali granite field of the plutonic rock classification diagram [18].

Other important group is gabbrodiorite which contains pyroxene (25% - 30%), amphibole (10% - 12%) and plagioclase (35% - 40%), and some accessory minerals like biotite, apatite, olivine, zircon and opaque minerals. Also, Gabbrodiorite shows an inter-granular and hypidiomorph granular texture with fine-grained euhedral-subhedral magnetite scattering with pyroxene and plagioclase.

Plutonic rocks from the XIV prospect are similar in their REE patterns. They are depleted in HREE and relatively enriched in LREE with LREE/HREE ratios of 4.3 to 42, and have narrow compositional variation with negative Eu anomalies.

The collected evidence in this study shows that the host rocks (bimodal series) contain voluminous intermediate-felsic intrusive bodies which have occurred in a non-orogenic environment.

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