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Biotite and Hornblende Composition Used to Investigate the Nature and Thermobarometry of Pichagchi Pluton, Northwest Sanandaj-Sirjan Metamorphic Belt, Iran

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Abstract

Pichagchi pluton is situated in the northeastern part of the Soursat complex in Sanandaj-Sirjan metamorphic belt of Iran. The pluton with the age of 74.20 Ma is composed mainly granodiorite, diorite, and tonalite in which mafic minerals are biotite and amphibole. In this study, composition of minerals used to describe the nature of the granitic magma and estimate the pressure and temperature at which Pichagchi pluton is emplaced. Based on chemistry of biotites Pichagchi pluton formed from calc-alkaline magma. This type of magma is typically produced in subduction environments. It means that the pluton could have formed in an orogenic suit from calc-alkaline magma in subduction zone. The results obtained based on biotite chemistry compare well with the previous interpretations on the Sanandaj-Sirjan belt. Temperatures of emplacement calculated with the hornblende-plagioclase thermometer range from 615 °C to 691 °C. Aluminum-in-hornblende geobarometry indicate that the Pichagchi pluton was emplaced at pressure of 3.80-4.24 Kbar.

Keywords: Pichagchi pluton; Soursat complex; Sanandaj-Sirjan; Hornblende-plagioclase thermometer; Aluminum-in-hornblende geobarometry

Introduction

The composition of minerals provides a means of evaluating P-T conditions and the nature of magma during the emplacement of granites.

Biotite is a significant ferromagnesian mineral in most intermediate and felsic igneous rocks. Biotite compositions depend largely upon the nature of magmas from which they have crystallized [1,31,44]. Its potential to reflect both the nature and the physicochemical conditions of magmas from which it formed is high.

Igneous biotite can also be used to provide valuable petrogenetic information. Three general reviews on micas in igneous rocks are those of [16, 38 and 46]. Abdel-Rahman [1] introduces discrimination diagrams on the basis of major- element composition of biotite mineral in igneous rocks crystallized from three distinct magma types.

Amphiboles are also ideally suited for evaluation of P-T conditions for calc-alkaline intrusions emplaced within orogenic belts. Hornblende usually occurs in

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these rocks and is stable over a wide P-T range of 1-23 kbar and 400-1150 °C. It is the most useful mineral for geothermobarometry and hornblende-plagioclase thermometer and aluminum-in-hornblende geobarometry are ideally suited for calculation of exhumation and temperatures at which granites are emplaced [11,47].

Pichagchi pluton is developed within the Soursat Complex in Sanandaj-Sirjan metamorphic belt of Iran [2,9,10,33]. Estimates of emplacement depths for this pluton provide direct evidence for the ascent or descent of exposed crustal sections through time, thus providing fundamental information about tectonic processes in the area.

Pichagchi pluton has plagioclase, quartz, K-feldspar, hornblende, biotite, titanite, apatite and magnetite. This mineral assemblage is very suitable for hornblende-plagioclase thermometry and aluminum-in- hornblende barometry [4, 19, 21, 24, 43 and 47]. Biotite occurs as a major phase and it can be used to provide petrogenetic information.

In this study, we present electron microprobe data to examine the possible link existing between the chemistry of biotite and the original magma and estimate the pressure and temperature at which Pichagchi pluton is emplaced.

Materials and Methods

Geological Setting

The area NW of Takab in Sanandaj-Sirjan metamorphic belt of Iran (Fig. 1a) consists of sedimentary units and Soursat metamorphic complex. The complex is positioned above the Takab-Shahin Dezh road (Fig. 1b) and presents tectonic contact with sedimentary rocks. Two main geological units have been described for Precambrian to Paleozoic sedimentary rocks [27] : (1) upper Precambrian Kahar formation consisting of slate, sandstone and some acidic volcanic rocks those locally reveal a very low metamorphic grade, and (2) Precambrian-Cambrian and Ordovician dolomite (Bayandor and Soltaniyeh formations), sandstone, shale and dolomitic limestone (Barut, Zaigon, Lalun and Mila Formations).

The Soursat complex is composed mainly of Precambrian metamorphic rocks with younger granitic intrusion (Pichagchi pluton).

Metamorphic rocks vary from greenschist to amphibolite facies and consist of mica-schist, garnet-schist, staurolite-schist, andalusite-schist, marble, gneiss and granite-gneiss [17,18].

Pichagchi Pluton

Pichagchi pluton with NW-SE trend occurs as an elongate body exposed in a road cut along the way between Takab and Shahin Dezh and is situated in the north eastern part of the Soursat complex (Fig. 1b).

The age of Pichagchi pluton first reported in Shahin Dezh geological map (scale 1/100000). It was detected Late Cretaceous-Paleocene based on stratigraphy and field observation [27]. However, recently published K-Ar age indicates the 74.20 Ma, confirms the emplacement of the pluton during Late Cretaceous-Paleocene time corresponding to Laramide orogeny [26]. The main rock types of the pluton are tonalite, diorite, and granodiorite. The main minerals are plagioclase (30-45 vol. %), quartz (20-25 vol. %), K-feldspar (20-28 vol. %), hornblende (0-20 vol. %) and biotite (5-20 vol. %). Common accessory minerals are titanite, apatite, magnetite and secondary chlorite and epidote are also present.

Geochemical analyses of the major elements show that the pluton is cal-alkaline and metaluminous type. Genetic parameters for this pluton are compatible with Caledonian I-type granite. Pichagchi pluton formed in the orogenic area and its tectonic setting is compatible with arc related granitoids (VAG) [22,26].

Tabular Plaioclase is subhedral to euhedral. Perthite exsolutions are common and myrmekites are frequently observed at the rims adjacent to plagioclase. Kfeldspar is subhedral to anhedral. Quartz occurs in anhedral grains with highly variable size. Brown Biotite commonly occurs as eubhedral to subhedral and has few zircon and apatite inclusions. Green amphibole is prismatic and tabular in shape and they range in composition from magnesiohornblende to edenite (Fig. 4). Iron-oxides ilmenite and magnetite are commonly associated with biotite, titanite and hornblende.

Based on petrography, plagioclase and amphibole crystals are euhedral (Fig. 2), and these minerals without reaction rim are in equilibrium. That is an important prerequisite for aluminum-in-hornblende barometry [4,19,21,24,43,47,50] and hornblende-plagioclase thermometry [11,15,20,47].

Sample Selection and Analytical Methods

The Pichagchi pluton appears relatively homogeneous at outcrop scale, although microscopic and geochemical studies show that it includes mainly granodiorite and diorite with limited outcrops of tonalite.

The samples selected for present study derives from granodiorites (samples P-34 and P-36), which are more

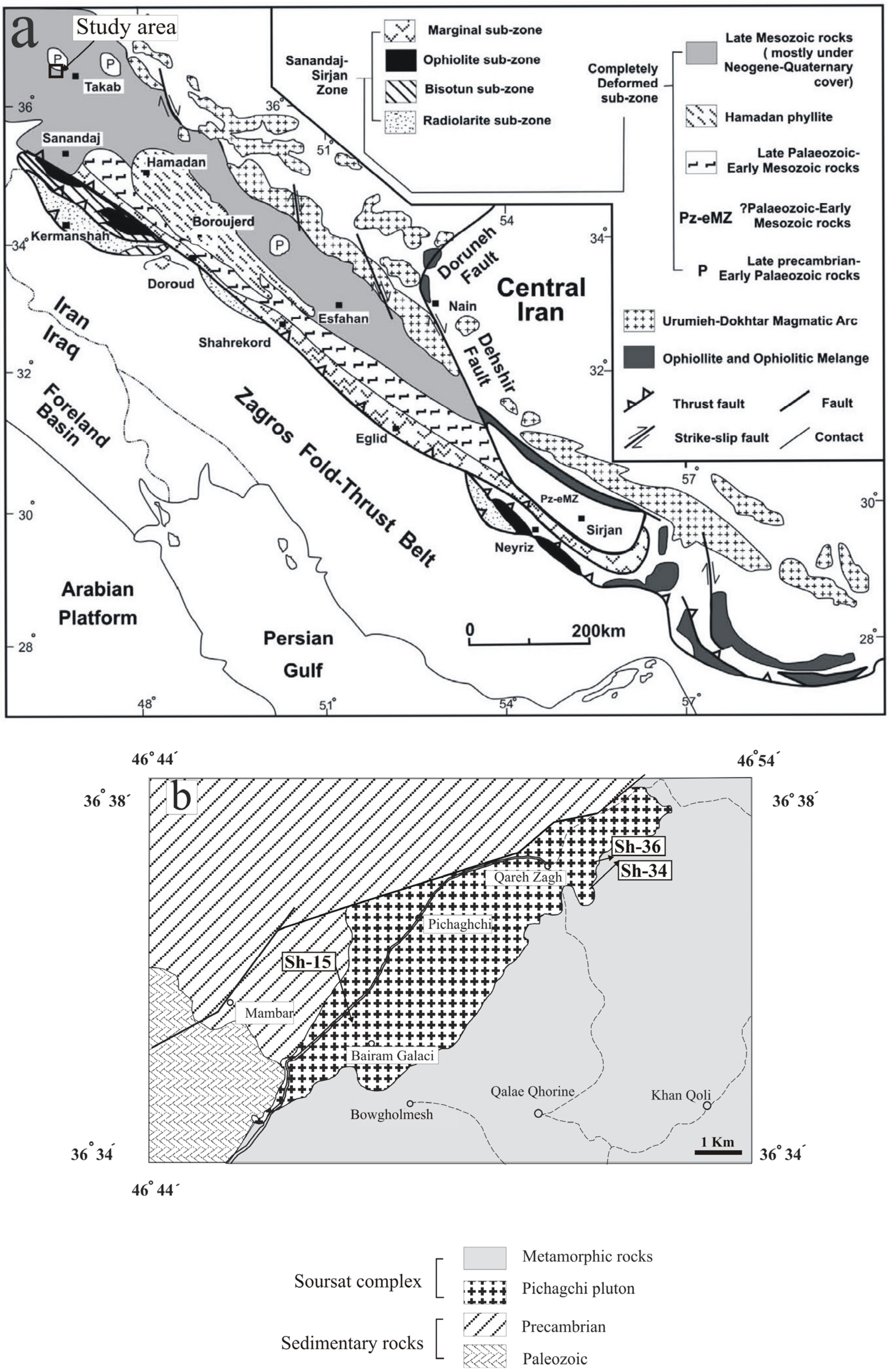

Figure 1. (a) Location of the Sanandaj-Sirjan belt in Iran (after Mohajjel & Fergusson [34]), (b) Geological sketch map of NW of Takab, simplified from Kholghi khasraghi [27], showing the location of Pichagchi pluton and analyzed samples.

Table 1. Petrography study for P-15, P-34 andP-36 samples. M:main minerals ,S: subordinate minerals, Se: secondary minerals and ×: no minerals. (Qtz: quartz; Pl: plagioclase; Kfs: K-feldspar; Bt: biotite; Am: amphibole; Zrn: zircon; Tit: titanite; Ap: apatite; Cal: calcite; Chl: chlorite; Mg: magnetite)

Samples	**Mineralogy**											**Texture**	**Rock type**
	Qtz	*Pl*	*Kfs*	*Bt*	*Am*	*Zrn*	*Tit*	*Ap*	*Cal*	*Chl*	*Mg*		
P-15	M	M	M	M	M	S	S	×	Se	×	S	Granular Myrmekite	Granodiorite
P-34	M	M	M	M	M	×	S	Se	×	Se	S	Granular	Diorite
P-36	M	M	M	M	M	S	S	×	×	Se	S	Granular Myrmekite	Granodiorite

common in the pluton and diorite (sample P-15). All selected samples have a mineral assemblage of quartz, plagioclase, hornblende, K-feldspar, biotite, titanite and magnetite. This mineral assemblage is an important prerequisite for aluminum-in-hornblende barometry [4, 19,21,24,43,47,50]. Biotite used to provide petrogenetic information. Mineralogy of studied samples is summarized in (Table 1).

Mineral analyses were collected using CamecaX100 electron microprobe at Iran Mineral Processing Research Center. The quantitative analyses of selected minerals were performed with a 15keV accelerating voltage, a 10nA beam current and a 2-5µm beam size. The counting time at each peak was 20-30s.

Biotites are rather homogeneous and their compositions are uniform throughout individual samples. Most analyses represent averages of three or more individual several spot analyses from different biotites.

For each sample, rims of several (usually 2, sometimes 3 or 5) pairs of co-existing hornblende and plagioclase were measured. All measured rims of hornblende are in contact with quartz or K-feldspar, which is an important requirement for application of aluminum-in-hornblende barometry [47]. Representative analytical data are listed in (Tables 2, 3 & 4). BSE images of analyzed minerals are shown in (Fig. 2).

Mineral Chemistry

Using the Minpet 2.02 program designed by Richard [40], structural formulae of biotite were calculated on the basis of 24 (O, OH, Cl, F) and 8 cations. According to the nomenclature of Speer [45] and Deer [14], the biotite of the Pichagchi pluton is classified as biotite (Annite- siderophyllitic) (Fig. 3).

Using the same program, structural formulae of plagioclase were calculated on the basis of 8 oxygens and 5 cations. Anorthite content ranges between 23.9 and 28.4% (Table 2).

Structural formulae for hornblende were calculated on the basis of 23 oxygens following the method outlined in Holland & Blundy [20]. Based on the nomenclature of Leake et al. [29], the hornblende of Pichagchi pluton is classified as magnesiohornblende and edenite (Fig. 4).

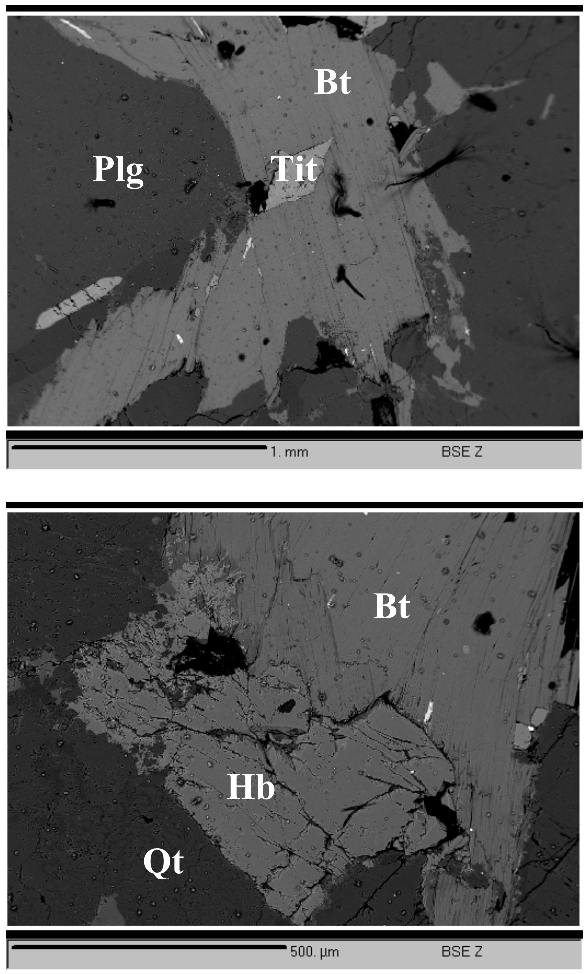

Figure 2. BSE of mineral assemblages in analyzed sample (P-35). Bt= Biotite, Hbl= Hornblende, Plg= Plagioclase Qtz= Quartz, Tit= Titanite.

Table 2. Representative analyses of biotite from Pichagchi pluton

Lithology	Granodiorite		Diorite		Granodiorite	
Sample	*P-15-1*	*P-15-2*	*P-34-1*	*P-34-2*	*P-36-1*	*P-36-2*
Wt.%						
SiO2	36.97	38.26	37.48	37.82	37.02	37.24
TiO2	2.08	2.54	2.24	2.33	2.32	2.31
Al2O3	14.47	15.25	14.43	14.77	14.21	14.71
FeO	14.35	13.83	14.17	14.49	13.94	13.49
Fe2O3	2.87	2.77	2.83	2.90	2.79	2.70
MnO	0.28	0.28	0.28	0.27	0.25	0.20
MgO	12.46	12.37	12.47	12.67	13.01	12.20
CaO	0.01	0.07	0.06	0.09	0.05	0.03
Na2O	0.43	0.12	0.27	0.08	0.08	0.26
K2O	10.12	10.08	10.03	9.68	10.04	9.68
F	0.6	0.00	0.00	0.00	0.41	0.00
FeO*	16.93	16.32	16.72	17.09	16.45	15.92

Table 3. Representative analyses of plagioclase from Pichagchi pluton

Lithology	Granodiorite		Diorite		Granodiorite	
Sample	*P-15-1*	*P-15-2*	*P-34-1*	*P-34-2*	*P-36-1*	*P-36-2*
Wt.%						
SiO2	61.83	61.24	62.99	61.4	62.32	61.87
TiO2	0.01	0.00	0.00	0.00	0.00	0.00
Al2O3	23.26	24.2	22.69	23.25	23.61	23.03
FeO	0.15	0.03	0.01	0.01	0.07	0.16
CaO	5.21	5.98	4.58	5.31	5.1	4.93
Na2O	9.09	8.15	9.26	8.84	8.6	8.56
K2O	0.28	0.24	0.17	0.23	0.25	0.15
Total	99.83	99.84	99.7	99.04	99.95	98.7
Number of ions on the basis of 8 oxygens						
Si	2.757	2.72	2.798	2.754	2.762	2.776
Al	1.222	1.276	1.187	1.229	1.234	1.217
Ti	0.00	0.00	0.00	0.00	0.00	0.00
Fe	0.006	0.001	0.00	0.00	0.003	0.006
Ca	0.249	0.285	0.218	0.255	0.243	0.237
Na	0.778	0.703	0.798	0.77	0.742	0.746
K	0.016	0.014	0.01	0.013	0.015	0.009
Total	5.028	4.999	5.011	5.021	4.999	4.991
Mol.%						
Ab	74.6	70.2	77.8	74.2	74.2	75.2
An	23.9	28.4	21.2	24.6	24.3	23.9
Or	1.5	1.4	1	1.3	1.5	0.9

Table 4. Representative hornblende compositions of the investigated granitoid

Lithology	Granodiorite		Diorite		Granodiorite	
Sample	*P-15-1*	*P-15-2*	*P-34-1*	*P-34-2*	*P-36-1*	*P-36-2*
Wt.%						
SiO2	46.39	45.62	46.44	46.06	46.01	46.52
TiO2	0.70	0.49	0.67	1.00	0.79	0.77
Al2O3	8.19	8.82	8.24	8.33	8.50	8.11
FeO	15.18	15.74	14.78	14.61	14.76	15.13
MgO	12.14	11.35	12.17	11.80	11.98	12.05
MnO	0.46	0.41	0.46	0.36	0.43	0.49
CaO	11.46	11.99	12.04	11.60	11.58	11.85
Na2O	1.28	2.26	1.16	2.43	1.60	1.40
K2O	0.82	0.87	0.90	0.74	1.02	0.93
Total	96.62	96.10	96.87	96.93	96.66	97.24
Formulae per Holland and Bundy (1994)						
T-sites						
Si	6.885	6.805	6.888	6.871	6.853	6.891
Al (IV)	1.115	1.195	1.112	1.129	1.147	1.109
Sum T	8.00	8.00	8.00	8.00	8.00	8.00
M1-3 sites						
Al (VI)	0.318	0.356	0.329	0.336	0.345	0.307
Ti	0.078	0.055	0.075	0.112	0.089	0.086
Fe	0.428	0.178	0.329	0.138	0.303	0.314
Mg	2.686	2.524	2.691	2.622	2.659	2.661
Mn	0.058	0.052	0.058	0.045	0.055	0.061
Fe	1.433	1.785	1.505	1.685	1.536	1.561
Ca	0.000	0.050	0.013	0.061	0.014	0.011
Sum M1-3	5.000	5.000	5.000	5.000	5.000	5.000
M4 sites						
Fe	0.022	0.000	0.000	0.000	0.000	0.000
Ca	1.822	1.866	1.900	1.793	1.833	1.870
Na	0.155	0.134	0.100	0.207	0.167	0.130
Sum M4	2.000	2.000	2.000	2.000	2.000	2.000
A sites						
Na	0.214	0.518	0.235	0.496	0.294	0.271
K	0.155	0.166	0.169	0.141	0.194	0.176
Sum A	0.369	0.685	0.404	0.637	0.488	0.447
Sum-cat	15.369	15.685	15.404	15.637	15.488	15.447
Al (total)	1.433	1.551	1.441	1.465	1.492	1.415

Results and Discussion

Discussion will deal first with the significance of biotites chemistry in Pichagchi pluton in order to propose an interpretation of magma type and their tectonic setting. We will then calculate the P-T conditions of generations of granites based on their magmatic nature.

Biotite Composition and Magma Type

Biotite composition has been used to describe the nature of granitic magma [1,8,13,16,25,31,36,37,38,42,44,45].

Abdel-Rahman[1] suggested discrimination diagrams on the basis of major - elements (FeO, MgO, Al2O3) of biotites in igneous rocks crystallized from A, P and C magma types. Based on his classification; biotites in anorogenic alkaline suites (field A) are mostly iron-rich, siliceous biotites (near annite), with an average FeO*/MgO ratio of 7.04; those in peraluminous (including S- type) suites (field P) are siderophyllitic in composition and have an average FeO*/MgO ratio of 3.48; whereas biotites in calc-alkaline orogenic suites (field C) are moderately enriched in Mg; with an average FeO*/MgO ratio of 1.76. It should be noted that the average FeO*/MgO ratio in biotite doubles from calc-alkaline through peraluminous to alkaline suites (FeO*= total Fe).

The investigated biotites are found in field C (Fig. 5). It means that based on chemistry of biotites Pichagchi pluton formed from calc-alkaline magma. In such magma, dissociation of H2O and the release of H would enrich the system in oxygen at an early stage. The availability of oxygen leads to early crystallization of iron-rich amphibole and iron oxides (typically magnetite), which in turn precludes the build-up of iron in calc-alkaline melts from which a moderately Mg-rich biotite crystallizes [1,28,44].

On the basis of whole rock analyses, calc-alkaline magma has been taken as source magma for Pichagchi pluton [22, 26] that is in line with conclusion obtained based on biotite chemistry.

Hornblende-Plagioclase Thermometry

Hornblende and plagioclase are commonly co-existing minerals in calc-alkaline igneous rocks, so they are usually used for thermometry [11, 15, 20 and 47]. Based on hornblende solid-solution models and well constrained natural and experimental systems, two hornblende-plagioclase geothermometers (thermometer A and B) were calculated by Holland & Blundy [20].

Thermometer A is based on the edenite-tremolite reaction (edenite+4 quartz → tremolite + albite), which is applicable to quartz-bearing igneous rocks: and thermometer B is based on the edenite-richterite reaction (edenite + albite → richterite + anorthite), which is applicable not only to quartz-bearing but also quartz-free igneous rocks [20,47]. According to Anderson [5] thermometer B (edenite-richterite) is preferable based on comparison to other igneous thermometers. We have chosen thermometer B to calculate the temperatures and pressures of emplacement for Pichagchi pluton. However, the temperatures calculated by thermometer A are also listed for comparison (Table 3).

Equilibration temperatures for hornblende-plagioclase assemblages were calculated based on iteration using Anderson & Smith [4] pressure at various thermometers. The calculated temperatures (edenite-richterite thermometers) for Pichagchi pluton are in the range of 615 to 691°C (Table 3).

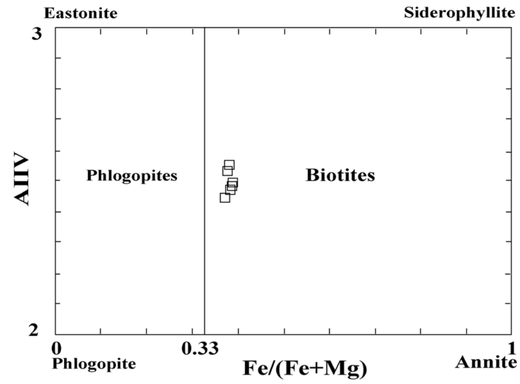

Figure 3. Diagrams showing the classification of biotite according to the nomenclature of Speer [45] and Deer [14].

Calcic group, (Na+K)A>0.5; Ti<0.50: Fe<Alvi

Calcic group, (Na+K)A<0.5; Ti<0.50.

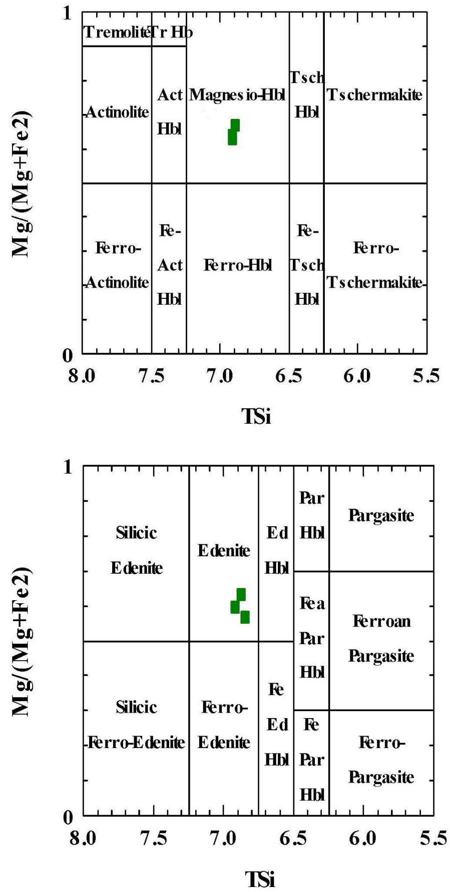

Figure 4. Diagrams showing the classification of hornblendes according to the nomenclature of Leake et al. [29].

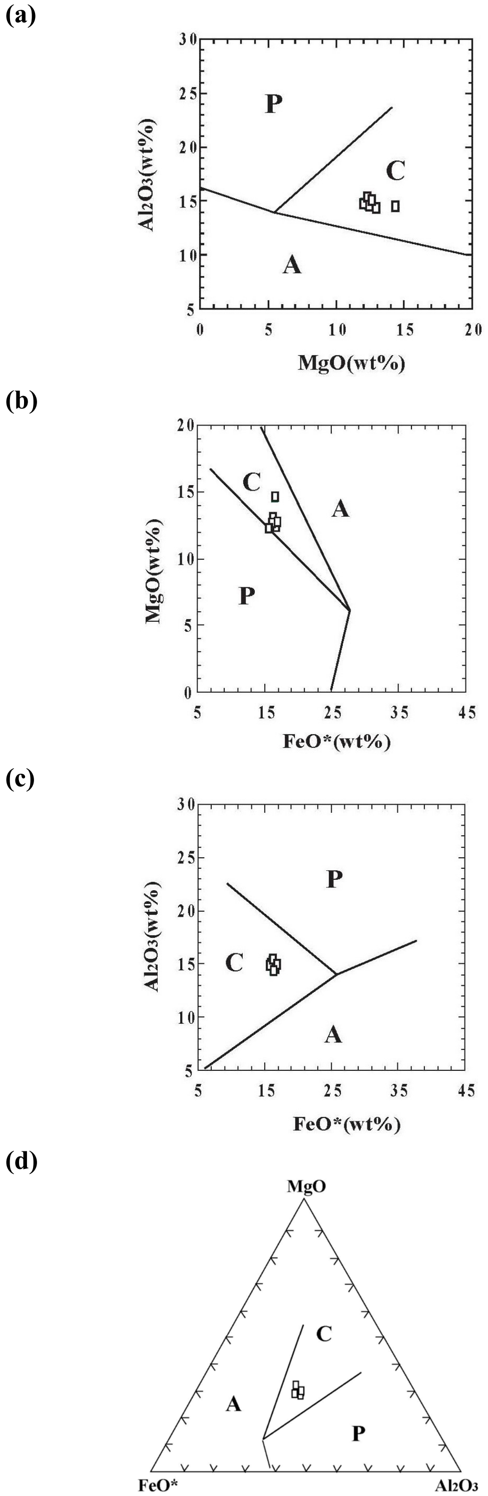

Figure 5. Diagrams showing the classification of magmas after Abdel-Rahman [1], (a) Al2O3-MgO biotite discrimination diagram, (b) MgO-FeO* biotite discrimination diagram, (c) Al2O3-FeO* biotite discrimination diagram, (d) MgO-FeO*-Al2O3 biotite discrimination diagram. All studied samples are in field C (calc-alkaline).

Aluminum-in-Hornblende Barometry

Empirical studies by Hammarstrom [19] and Hollister et al. [21] suggest that, in the presence of an appropriate buffer assemblage, the Al content of calcic amphibole may exhibit an approximate linear relationship to the pressure during pluton crystallization. Subsequent experimental studies [24,41,43,48] provided general confirmation of crystallization, and to constrain the emplacement depths of batholiths or vertical displacements of crust [15,30,32,47]. There are several calibrations for aluminum-in-hornblende barometry, including:

$P\ (\pm 3\ \text{kbar}) = -3.92 + 5.03\ \text{Al total},\ r^2 = 0.80$ [19];

$P\ (\pm 1\ \text{kbar}) = -4.76 + 5.64\ \text{Al total},\ r^2 = 0.97$ [21];

$P\ (\pm 0.5\ \text{kbar}) = -3.46 + 4.23\ \text{Al total},\ r^2 = 0.99$ [24];

$P\ (\pm 0.6\ \text{kbar}) = -3.01 + 4.76\ \text{Al total},\ r^2 = 0.99$ [43].

The last two calibrations have been more commonly used because of their experimental derivation. Anderson & Smith [4] developed a temperature-corrected Al-in-hornblende barometer calibrated using the experiments by Schmidt [43] at approximately 675 and those of [24] at approximately 760.

The new calibration of [4] is as follows:

$$P\ (\pm 0.6\ \text{kbar}) = 4.76\ \text{Al total} - 3.01 - \{[T\ (°C) - 675]/85\} \times \{0.530\ \text{Al total} + 0.005294\ [T\ (°C) - 675]\},\ r^2 = 0.99$$

Because the influence of temperature (and oxygen fugacity) on the pressure calculation has to be considered, we have chosen of the calibration of [4] to calculate the crystallization pressures of the investigated plutons. Temperature was calculated based on co-existing hornblende and plagioclase using the thermometry of Holland & Blundy [20]. Pressures were also calculated by the methods of Johnson & Rutherford [24] and Schmidt [43] and were compared with results obtained from the Anderson & Smith [4] calibration. Calculated pressures from aluminum-in-hornblende barometry are listed in (Table 5). The temperature-corrected pressures calculated using Anderson & Smith [4] of the pichagchi pluton is 3.80 - 4.24 kbar.

Local Implications

Pichagchi pluton with biotite and hornblende mafic minerals is part of Soursat metamorphic complex in Sanandaj-Sirjan metamorphic belt of Iran.

Biotite compositions clearly define the nature of magmas from which they have crystallized. Based on chemistry of biotites Pichagchi pluton formed from

Table 5. Results of geothermobarometry, Plag Ab- the atomic ratio [Na/(Na+Ca+K)]; Amph Al (Total)- the number of Al cations calculated in the structural formula of hornblende(Table3); P-Sch-pressure calculated using Schmidt [43]; T(ed-tr) temperature calculated using plagioclase-hornblende geothermometer A(edenite-tremolite) of Holland & Blundy [20]; T(ed-ri)-temperature calculated using plagioclase-hornblende geothermometer B (edenite-richterite) of Holland & Blundy [20]; P-A&S- the temperature-corrected pressure, calculated using Anderson & Smith [4], T=T(ed-ri)

Sample	Spots	Plag Ab	Amph Al (Total)	T(ed-tr) (°C)	T(ed-ri) (°C)	P-Sch (Kbar)	*P-J&R* (Kbar)	*P-A&S* (Kbar)
P-15-1	1	0.74	1.433	668	**654**	3.81	2.60	**3.97**
P-15-2	2	0.70	1.551	681	**687**	4.37	3.46	**4.24**
P-34-1	1	0.77	1.441	658	**615**	3.85	2.63	**4.16**
P-34-2	2	0.74	1.465	666	**691**	3.96	2.73	**3.80**
P-36-1	1	0.74	1.492	666	**662**	4.09	2.85	**4.20**
P-36-2	2	0.75	1.415	672	**649**	3.72	2.52	**3.91**

calc-alkaline magma which could produced in subduction environments [12,52,39,51,23,7,6,3].

Temperatures of emplacement calculated with the hornblende-plagioclase thermometer range from 615 °C to 691 °C. Aluminum-in- hornblende geobarometry for this calc-alkaline pluton indicates that granite emplaced at pressure of 3.80-4.24 Kbar.

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