سنگ‌شناسی و زئوئیتی فاتولیت فوشچی، شمال غرب ایران

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چکیده: فاتولیت فوشچی با مساحت تقریبی ۱۵۰ کیلومترمربع در شمال غرب ایران و زن سنندج- سیرجان واقع شده و به داخل سنگ‌های پرمرند نفوذ کرده است. این توده نفوذهای با سنگ‌های تندیس‌سنتی الیگو- میوسن (سارند قم) پوشیده شده است. فاتولیت فوشچی شامل پنج توده مختلف است: 
1- (گابرو- دیوریت، ب) بیوتیت- گرانیت، گ) فلدسبات گرانیت، د) سینپت، (ه) دایک‌های آبلینی. گابرو‌دیوریت‌ها قدمی ترین و اولین نفوذی در منطقه هستند که با واحد بیوتیت- گرانیت، زن‌سنندج ناشان می‌دهند. این واحد نفوذی ماهیت درون صفحه‌ای و بیونیتی دارد. گرانیت‌های قلبی، بافت گرافیتی، میکروگرانیت‌فیبری و پرینتی دارند که نشانگر جایگذاری در عمق کم و طبیعت هیپرسولوس آن هستند. از نظر زئوئیتی‌ماتی این سنگ‌ها ویژگی‌های پیامدهای بالا- متفاوت‌ترهای تا کمی بونکالن، CaO، Fe₂O₃، TiO₂، Ba، Rb، Sr، Al₂O₃ و دارای مقدار بالای SiO₂ و درون Na₂O، K₂O، Nb، Th، Y، Zr، قابل شفافیت بوده و احتمالاً با تبیور جدایی نشته‌ای باعث ماسک‌های فضاهای مشترک شده از گوشه حاصل شده‌د. ساختار کلی و آمادگی دور فاز مهم تیلوژی گروه‌های هستند. گرانیت‌های قلبی از ژیرفروکس ساختاری آشکار شده از گوشه‌های می‌شوند که یک جایگاه از گرین‌های برای آن‌ها پیشنهاد می‌شود. بیوتیت- گرانیت‌ها و سپس‌های با بالامرین بوده و خاستگاه پوسته‌ای دارند.

واژه‌های کلیدی: گرانیت‌های نوع A، سنگ‌شناسی، زئوئیتی فوشچی، زن سنندج- سیرجان، فاتولیت فوشچی.

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Petrology and geochemistry of Ghoshchi batholith, NW Iran

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Abstract: The Ghoshchi batholith, ~150 km² in size is a granitoidic pluton, which intruded the Permian country rocks, in Sanandaj-Sirjan Zone, NW Iran. This granitoidic pluton is covered by Oligocene-Miocene sedimentary rocks known as Qom Formation. The Ghoshchi batholith comprises five plutons with following compositions: (a) gabbro-diorite (b) biotite granite, (c) alkali granite, (d) syenites, and (e) aplitic dikes. Gabbro-diorites are the oldest intrusive unit and have interaction zone with biotite granites. These rocks have within-plate tholeiitic nature. Graphic, microgranophyric, and perthitic textures can be found in alkali-feldspar granites, indicate their shallow emplacement depth and hypersolvus nature. Alkali-feldspar granites geochemically are high-K alkali, metaluminous to mildly peralkaline. The alkali-feldspar granitic rocks contain lower Al₂O₃, CaO, Fe₂O₃, TiO₂, Ba, Rb, and Sr but higher SiO₂, Na₂O, K₂O, Nb, Th, Y and Zr than biotite granites samples. Alkali-feldspar A-type within-plate granites were presumably formed by high degree of fractional crystallization of mantle derived mafic magmas. Plagioclase and amphibole are two main fractionated minerals. The Alkali-feldspar granites fall into the A₁ group (mantle derived) suggesting an anorogenic tectonic setting. Biotite granites and syenites are peraluminous and have crustal source.

Keywords: A-type granites; Petrology; Geochemistry; Sanandaj-Sirjan Zone; Ghoshchi batholith.

Introduction

The Zagros orogen extends from NW to SE Iran and is formed by collision of Afro-Arabian continent and the Central Iran microcontinent in Late Cretaceous to Tertiary [1-6]. The width of this belt is about 200 km that extended 1500 km along Zagros main thrust fault (Fig. 1). Paleozoic rocks are common in the southeast of the belt, but are rare in the other parts [7], where the rocks are mainly Mesozoic in age. There are many plutons in the northern part of Sanandaj-Sirjan Zone (SSZ), NW Iran. In the Golpaygan area, the Sanandaj-Sirjan Zone can be subdivided into two parts (Fig.1) : (1) The southern part (South SSZ), which consists of rocks deformed and metamorphosed in Middle to Late Triassic; (2) The northern part (North SSZ), deformed in the Late Cretaceous, contains many composite intrusions including Alvand, Boroujerd, Arak and Malayer plutons [8]. Most of them were formed by two main phases of mafic and felsic intrusions and belong to Mesozoic to Tertiary time (Table 1). In some plutons, primary mafic and felsic rocks were intruded by third phase of alkaline granites.

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Fig. 1. Main tectonic units of Iran (Extracting from [47]). Studied area shown by a circle.

<table>
<thead>
<tr>
<th>Pluton Name</th>
<th>Number of phase &amp; Rock composition</th>
<th>Age</th>
<th>Source</th>
<th>Tectonic setting</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Almoghalagh</td>
<td>Quartz syenite-granite &amp; gabbro diorite</td>
<td>144 ±17 Ma</td>
<td>S-type</td>
<td>Subduction related</td>
<td>[13], [14] &amp; [55]</td>
</tr>
<tr>
<td>Astane-ye Arak</td>
<td>Andalosite bearing granodiorite</td>
<td>98.9 ± 1.5 Ma</td>
<td>S-type</td>
<td>-</td>
<td>[56], [13]</td>
</tr>
<tr>
<td>Boroujerd-Malayer</td>
<td>Three phases with composition of: quartz diorite, granite, granodiorite, aplite &amp; pegmatite</td>
<td>Late Jurassic-</td>
<td>Different sources, S-type granites</td>
<td>One phase has been reported CAG type</td>
<td>[57], [58], [59]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Paleocene, 3 phases with age: 1-117-120Ma 2-99Ma 3-52-70Ma</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aligudarz-Miyandasht</td>
<td>Six plutons and minimum 3 phase include: gabbro diorite, doleritic dykes &amp; granite</td>
<td>Post-Cretaceous and Pre-Eocene</td>
<td>Basic rocks from partial melting of mantle and acidic rocks from partial melting of continental crust</td>
<td>POG type</td>
<td>[59], [60], [61]</td>
</tr>
<tr>
<td>Alvand</td>
<td>Five phases include: 1- gabbro diorite 2- tonalite 3,4- porphyric granite 5- hololeucocrate granite</td>
<td>Late Cretaceous-</td>
<td>Include: I , S and other different-type granites</td>
<td>CAG type</td>
<td>[62], [63]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Paleocene 64-70 Ma</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pichaghchi</td>
<td>Granite, granodiorite &amp; tonalite</td>
<td>72-76 Ma</td>
<td>I and H-type</td>
<td>CAG type</td>
<td>[64]</td>
</tr>
</tbody>
</table>
Obviously, in many composite plutons, mafic rocks have been generated before felsic ones. Obvious differences in rock composition indicate different sources involved in petrogenesis of each rock group [9-12]. These studies show that there are I-, S-, H-, and in a small volume A-type granites in this zone. In these studies, the source of basic to intermediate rocks and I-type granites is attributed to partial melting of mantle (primary or evolved) or underlying crust, and the source of acidic rocks (S- and A-type granites) is attributed to partial melting of continental crust (Table 1).

Many researchers [10-14] believe that Golpaygan-Urumieh plutons are generated due to subduction related magmatism and they have reported these rocks similar to active continental margin granites. In some other studies, plutonic rocks, is attributed to extentional regimes [15] (Table 1). Ghoshchi pluton is a northwestern portion of Golpaygan-Urumieh intrusions that crops out in north of Urumieh city. Similar to the other plutons, the Ghoshchi batholith includes both mafic and felsic parts, which seems that emplaced at Post-Cretaceous to Pre-Miocene time [15-16].

In this paper, we present new information about geology, petrography and geochemistry of Ghoshchi pluton. Also, we will discuss the relationship between mafic and felsic intrusions and finally we present a tectonomagmatic setting model for studied granites.

**Geological setting**

The Ghoshchi batholith is located in the northern part of Sanandaj-Sirjan Zone, NW Iran (Fig.1). The basement rocks of Ghoshechi area is metamorphic rocks with amphibolite and green schist facies attested to Late-Precambrian.

Gneiss, metahyolite, and schists are the oldest rocks. The metamorphic rocks are overlaid by Permian to Jurassic sedimentary rocks. The metamorphic rocks are intruded by plutonic rocks. Ghoshchi batholith comprises five distinct intrusive rocks including 1) gabbro-diorite, 2) biotite granite (BG), 3) alkali-feldspar granite, 4) Syenite, and 5) Aplitic to diabasic dikes.

The gabbro-diorites crop out in northern part of the batholith in the metamorphic host rocks (Fig. 2). These mafic rocks were intruded by younger granitic members and dibasic dikes. They are enclave-free. Gabbro-dioritic rocks of Ghoshchi are undeformed, fresh and with minor alteration.

Biotite granites occupy about 5-10% of the total area of batholith. Biotite granitic rocks are intruded by alkali-feldspar granite veins and dikes. They have metasedimentray and mafic enclaves. Biotite granites in contact with mafic member of batholith contain lots of mafic enclaves. In some places, e.g. along the old road of Salmas to Ghoshchi, mingling-mixing features of gabbro-diorite and biotite granite magmas can be observed (Fig. 3a).

Magmatic interaction is characterized by mafic pillow-like masses, millimeter to metric in size, in a grey-coloured granitic host rocks. The contact between the dioritic pillows and the surrounding and net-veining granite are often sharp or locally diffuse. Such features have been regarded as evidence of the coexistence of mafic and felsic magmas [10].

Main host rocks of Goshchi alkali-feldspar granites are Permian sedimentary rocks including conglomerate and limestone which are covered by Oligocene-Miocene limestones. Alkali-feldspar granites occupy about 50-60% of total outcrop of batholith about 75 to 90 square kilometer area and varies from hololeucocratic to leucocratic rocks and pink to light gray in color. This unit has miarolitic cavities indicating its shallow depth emplacement. The alkali-feldspar granite has no enclaves. Contact of alkali-feldspar granites with gabbro-diorites and biotite granites is sharp.

Syenitic group occupies about 5% of the total outcrop area. This unit is very small as apophyse that cut the biotite granites (Fig. 3b). Thickness of this unit is 2 meter.

There are some aplitic and pegmatitic dikes that cut mafic rocks. Furthermore, some quartz-feldspatic veins cut the mafic and felsic rocks in the studied area. Thickness of veins in this unit is lower than 10 cm.

Based on stratigraphical studies, Ghoshchi batholith is Post-Permian and Pre-Miocene, however [17] have attributed this pluton to Early Paleogene.
Fig. 2. schematic geological map of the Goushchi area

Fig. 3. a) Interaction (mingeled) zone between gabbro-diorites and biotite granites, b) Syenites cut the biotite granites.

**Petrography**

**Gabbro-diorites**

Modal compositions of the representative plutonic rocks are plotted in Figure 5a and representative mineral compositions are given in Table 2.

The Gabbro-dioritic rocks of Ghoshchi batholith is mainly made of olivine gabbro, gabbro, norite, diorite and quartz diorite.

Gabbro-dioritic rocks are dark grey in colour. Euhedral plagioclase (andesine to bytownite), clinopyroxene (augite), olivine, orthopyroxene (hypersthene), hornblende and biotite are the main minerals of the rock. Locally, quartz is present. Euhedral apatite, titanite, opaques and zircon form accessory minerals. Average grain size is about 1-4mm.
**Table 2- Modal composition of selected samples from Ghoshchi batholith.**

<table>
<thead>
<tr>
<th>Rock type</th>
<th>Gabbro-diorite</th>
<th>Biotite granite</th>
<th>Alkali-feldspar granite</th>
<th>Syenitic rocks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample ID</td>
<td>GD1</td>
<td>GD2</td>
<td>BG1</td>
<td>BG2</td>
</tr>
<tr>
<td>Quartz</td>
<td>0.6</td>
<td>1.9</td>
<td>25</td>
<td>23</td>
</tr>
<tr>
<td>Plagioclase</td>
<td>70</td>
<td>69</td>
<td>17.3</td>
<td>19</td>
</tr>
<tr>
<td>K-feldspar</td>
<td>0.4</td>
<td>0.5</td>
<td>42</td>
<td>40</td>
</tr>
<tr>
<td>Amphibole</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Biotite</td>
<td>2.5</td>
<td>3.7</td>
<td>14.5</td>
<td>16.5</td>
</tr>
<tr>
<td>Clinopyroxene</td>
<td>15.8</td>
<td>16</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Orthopyroxene</td>
<td>4.2</td>
<td>4.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Opaque</td>
<td>5</td>
<td>4.2</td>
<td>0.5</td>
<td>0.7</td>
</tr>
<tr>
<td>Titanite</td>
<td>0.1</td>
<td>&lt;0.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Apatite</td>
<td>1.3</td>
<td>0.5</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Zircon</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Epidote</td>
<td>0.3</td>
<td>0.5</td>
<td>0.9</td>
<td>1</td>
</tr>
<tr>
<td>Chlorite</td>
<td>0.2</td>
<td>0.2</td>
<td>0.3</td>
<td>0.5</td>
</tr>
</tbody>
</table>

**Biotite granites**

The Biotite granites straddle the fields of monzogranites to syenogranites in Figure 5a. All these granites are gray in colour; displaying a medium-grained size and an equigranular texture.

This unit consists essentially of quartz, alkali feldspar, plagioclase, biotite, and muscovite (Fig. 4c). Quartz is anhedral and generally has undulose extinction. Biotite is anhedral to subhedral with green to brown colour. Locally, biotite has been altered to muscovite as a result of to leave the Mg, Fe, and Ti (Fig. 4d). Zircon and apatite are accessory minerals. Chlorite and epidote are alteration products.

**Fig. 4.** Photos from petrographical features in felsic rocks. a) microperthitic and granular textures in alkali-feldspar granites. Crossed Nicols, b) Granophyric texture, Crossed Nicols, c) Granular texture in biotite granites. Crossed Nicolss, d) Biotite has been altered to muscovite. Crossed Nicols, e) Generation of Garnet among alkali feldspars in syenitic rocks. Plane Polarisated Nicols, Kfs= K-feldspar, Bt= Biotite, Ms= Muscovite, Grt= Garnet, Per = Perthite.
Alkali-feldspar granites
These rocks straddle the field of alkali feldspar granite in Figure 5a. The obvious textures in this unit are granular, microperthitic, porphyric, and micrographic to granophyric (Figs. 4a, b). Subhedral to euhedral grains of quartz, perthitic K-feldspar, plagioclase, and biotite make up alkali-feldspar granites. Locally amphibole (arfvedsonite-riebeckite), about 5%, exists. The perthitic nature of the K-feldspar in this unit indicates their vapor absent condition of crystallization.

Alkali feldspar minerals are anhedral including orthoclase and microcline with microgranophyric to graphic textures.

Brown to green Biotite is replaced by chlorite along cleavage planes, locally. Zircon and titanite are common accessory minerals occurring as euhedral to subhedral magmatic crystals in the matrix. Biotites has pleochroic halos around zircon inclusions.

Fig. 5. Modal and chemical classification diagrams. (a) Modal classification of igneous rocks from [50] (b) R1-R2 cationic classification of [19]. (c) Na2O+K2O vs. SiO2 from [20]. (d) Al/ (Na+K) vs. Al/ (Ca+Na+K) (mol. %): field boundaries are from [51]. (e) Agpaitic index (AI) vs. SiO2 diagram [52]. The post-collision granite (PCG) field is from [22]. (f) SiO2 vs. A/ CNK diagram. Peraluminous and metaluminous fields are after [53] and I-type and S-type fields are after [54].
Table 3. Major and trace elements of felsic and mafic rocks in Ghoshchi area.

<table>
<thead>
<tr>
<th></th>
<th>Alkali Granites</th>
<th>Biotite Granites</th>
<th>Syenites</th>
<th>Gabbro-Diorites</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Major Oxides, wt%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SiO₂</td>
<td>69 74 75 75 77 77 77 76.1</td>
<td>71 70.3 70 72 71 72</td>
<td>55.3 64.1</td>
<td>50 45 49 49 49 47.4 49</td>
</tr>
<tr>
<td>TiO₂</td>
<td>0.2 0 0.2 0.2 0.2 0.2 0.19</td>
<td>0.4 0.24 0.4 0.4 0.2 0.4</td>
<td>1.35 0.18</td>
<td>1.6 2 2 2.6 0.9 2.2</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>15 11 11 12 12 11 11.3</td>
<td>14 14.7 13 14 14 15</td>
<td>17.4 15.8</td>
<td>15 12 16 14 11.8 14</td>
</tr>
<tr>
<td>Fe₂O₃*</td>
<td>1.6 1.5 2.4 2.1 1.8 2.1 1.98</td>
<td>4.4 2.42 3 2.8 2.4 4.4</td>
<td>5.21 1.6</td>
<td>8.2 12 9.9 12 13.2 13</td>
</tr>
<tr>
<td>MnO</td>
<td>0 0 0.1 0.1 0.1 0.1 0.1 0.09</td>
<td>0 0.02 0 0 0</td>
<td>0.04 0.02</td>
<td>0.2 0.2 0.2 0.2 0.17 0.2</td>
</tr>
<tr>
<td>MgO</td>
<td>0.3 0.4 0.1 0.1 0.1 0.1 0.1 0.09</td>
<td>0.5 0.29 0.5 0.4 2.3 0.4</td>
<td>5.17 0.26</td>
<td>5.7 15 5.3 6 19.9 6.2</td>
</tr>
<tr>
<td>CaO</td>
<td>0.7 1.4 0.5 0.4 0.1 0.1 0.4 0.1</td>
<td>0.4 0.61 1.5 1.4 0.6 2.4</td>
<td>2.05 0.63</td>
<td>10 9.1 9.9 8.8 5.45 10</td>
</tr>
<tr>
<td>Na₂O</td>
<td>2.9 4.4 3.3 3.8 3.2 3.5 3.76</td>
<td>2.8 2.58 2.3 2.2 1.6 1.3</td>
<td>2.48 2.81</td>
<td>3.5 2.5 4.3 3.8 1.86 2.5</td>
</tr>
<tr>
<td>K₂O</td>
<td>7.4 5.3 5 4.9 5.4 5 4.89</td>
<td>3.6 4.82 3.6 3.4 4.7 3.1</td>
<td>5.71 6.94</td>
<td>0.9 0.5 0.6 0.6 0.67 0.8</td>
</tr>
<tr>
<td>P₂O₅</td>
<td>0.1 0 0.1 0.1 0.1 0.1 0.1 0.09</td>
<td>0.2 0.02 0.1 0.1 0.1</td>
<td>0.23 0.09</td>
<td>0.2 0.3 0.4 0.5 0.13 0.4</td>
</tr>
<tr>
<td>trace elements, ppm</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rb</td>
<td>203 196 168 173 174 182 177</td>
<td>146 261 267 176 175 191</td>
<td>81.7 83</td>
<td>19 15 12 11 17.3 10</td>
</tr>
<tr>
<td>Sr</td>
<td>20 8.3 16 16 12 11 16.3</td>
<td>73 329 390 518 527 453</td>
<td>162 171</td>
<td>238 341 311 287 105 282</td>
</tr>
<tr>
<td>Ba</td>
<td>150 37 106 115 69 132 143</td>
<td>804 777 767 818 804 822</td>
<td>1575 1535</td>
<td>267 193 439 550 86.4 238</td>
</tr>
<tr>
<td>Zr</td>
<td>206 565 514 438 407 506 410</td>
<td>187 155 134 134 142 160</td>
<td>769 777</td>
<td>160 107 163 226 101 154</td>
</tr>
<tr>
<td>Y</td>
<td>40 83 77 69 68 77 73.7</td>
<td>9 11.2 14 10 7.3 15</td>
<td>29.2 25</td>
<td>14 6 18 27 13.7 42</td>
</tr>
<tr>
<td>Nb</td>
<td>32 76 72 68 45 68 61.8</td>
<td>7.8 14 12 13 14 13</td>
<td>30.6 25</td>
<td>28 16 23 38 6.1 27</td>
</tr>
<tr>
<td>V</td>
<td>&lt;5 &lt;5 &lt;5 &lt;5 &lt;5 &lt;5</td>
<td>18 12 11 15 16 12</td>
<td>38 33</td>
<td>225 219 277 252 88 221</td>
</tr>
<tr>
<td>Cr</td>
<td>10 10 &lt;10 10 10 10 10 10</td>
<td>20 35.2 39 42 39 45</td>
<td>20 20.4</td>
<td>244 810 83 147 2250 280</td>
</tr>
<tr>
<td>Co</td>
<td>91 48 49 82 66 71 67.8</td>
<td>46 22.7 20 19 14 11</td>
<td>27.2 25.7</td>
<td>35 89 40 45 113 47</td>
</tr>
<tr>
<td>Ni</td>
<td>&lt;5 &lt;5 &lt;5 &lt;5 &lt;5 &lt;5 &lt;5 &lt;5</td>
<td>&lt;5 29.7 23 21 29 19</td>
<td>&lt;5 44.4</td>
<td>67 450 49 50 1110 64</td>
</tr>
<tr>
<td>Cu</td>
<td>&lt;5 &lt;5 &lt;5 &lt;5 &lt;5 &lt;5 6 8</td>
<td>&lt;5 &lt;5 &lt;5 &lt;5 &lt;5 &lt;5</td>
<td>&lt;5 &lt;5</td>
<td>N.A. N.A. N.A. N.A. 151 38</td>
</tr>
</tbody>
</table>

Syenites
The syenites plot in the fields of alkali feldspar syenite and syenite in Figure 5a. The rocks have granular texture with fine to medium grain size and consists essentially of perthitic alkali feldspar, plagioclase, garnet, clinopyroxene, quartz, riebeckite, biotite, sphe, and opaque minerals. Alkali feldspar as anahedral to subhedral minerals forms the main volume of the rock. Orthoclase, with orlassbad twin and microperthite with striped pattern are two different kinds of alkali feldspar. After alkali feldspar, plagioclase is the main mineral in syenites.

Garnet is the product of late stage of crystallization in syenitic rocks and it fills spaces between alkali feldspars (Fig. 4e). Fe-rich biotites together with riebeckite have been formed in spaces between alkali feldspars. Allanite is accessory mineral in these rocks. Aplitic and diabasic dikes Plagioclase (andesine), amphibole (hornblende), biotite, and chlorite are main minerals in the diabasic dikes. Opaque minerals and very small titanite are accessory minerals. Many aplitic dikes intruded Ghoshchi batholith. They are hololeucocratic with white colour and equi-granular texture. This rock is consisted of quartz, alkali feldspar, plagioclase, biotite and chlorite. Frequently, quartz is anhedral and has fine to medium grain size. Alkali feldspar is anhedral and includes orthoclase and microcline. Plagioclase is subhedral and it has polysynthetic twinning.

Geochemistry
Analytical method
In order to study the geochemistry of the Ghoshchi batholith, 21 representative rock samples with minimal alteration were chosen for chemical analysis. Selected whole rock samples were analyzed for major elements using XRF at GSI (Geological Survey of Iran) laboratory. Samples were analysed for trace and rare earth elements by ICP-Mass Spectrometry at ALS CHEMEX Ltd., Canada. The results of the XRF and ICP-MS analyses are presented in Table 3.
### Rock classification

Using the cationic classification [19] (Fig. 5b), mafic samples plot in gabbro and gabбро-norite fields. A few straddle the boundary between the gabбро and gabбро-diorite fields. The alkali granitic rocks occupy the alkali granite field, whereas the syenites and biotite granitic rocks fall mainly in the syenite to monzonite and granite fields respectively.

On the total alkali silica (TAS) diagram (Fig. 5c), as defined by [20] the Ghoshchi felsic rocks plot in the granite and syenite fields and Ghoshchi mafic rocks fall into the gabбро-diorite field. According to the K₂O vs. SiO₂ diagram of [21] Ghoshchi felsic rocks display medium-K to high-K characters (Fig. 7), while the Ghoshchi mafic rocks plot in the low-K field. On the other hand, Ghoshchi mafic rocks have alumina saturation indices (ASI), defined as the molar A/CKN=Al₂O₃/(CaO+Na₂O+K₂O), of less than 1.1, indicating their metaluminous character, whereas, Ghoshchi felsic rocks have two distinct characters: alkali-feldspar granites are mainly metaluminous (except for one sample which shows peraluminous character) and, biotite granites and syenites are peraluminous (Fig. 5d). The aphaitic index (AI) of the felsic to mafic rocks of Ghoshchi complex, calculated as molar (Na+K)/Al, suggesting an alkali metaluminous character for alkali-felspar granitic rocks (Fig. 5e). In this diagram, the alkali granites occupy the field given by [22] for the Pan-African post-collision granites.

Biotite granites and syenites have peraluminous and S-type characteristics (Fig. 5f).

The alkali-felspar granitic rocks exhibit anhydrous and hypersolvus characteristic of A-type magmas. In a series of diagrams designed by [23] to discriminate A-type granites (Figs. 6a-d) the alkali-felspar granitic rocks plot in the A-type granite or close to the boundary of the A-type granite field, typical of metaluminous A-type granites [24] Whereas, the biotite granites and syenites plot in the field of I-, S- and M-type granitoids.

| Element | Zn | Ga | Cs | La | Ce | Pr | Nd | Sm | Eu | Gd | Tb | Ho | Er | Tm | Yb | Lu | Hf | Ta | Th | U | Pb |
|---------|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| Value   | 29 | 30 | 3.6 | 90 | 168 | 18 | 59 | 10 | 0.5 | 9.9 | 8.1 | 1.6 | 4.7 | 0.7 | 4.6 | 0.6 | 7 | 2.6 | 36 | 4.4 | 16 |
| N.A.    | 141 | 28 | 0.2 | 68 | 123 | 19 | 63 | 14 | 0.7 | 15 | 14 | 3.3 | 9.7 | 1.4 | 9.4 | 1.3 | 7 | 5.2 | 24 | 9.5 | 15 |
| Value   | 74 | 28 | 2.3 | 87 | 170 | 18 | 71 | 14 | 0.7 | 16 | 14 | 2.8 | 8.3 | 1.2 | 7.7 | 1.1 | 8 | 4.7 | 34 | 14 | 1.4 |
| N.A.    | 51 | 28 | 2.5 | 82 | 150 | 19 | 54 | 12 | 0.7 | 6.1 | 14 | 2.6 | 7.4 | 1.1 | 8.9 | 1.1 | 8 | 3.1 | 5 | 12 |
| Value   | 42 | 28 | 2.5 | 55 | 103 | 14 | 88 | 14 | 0.7 | 6.7 | 14 | 2.8 | 8.7 | 1.2 | 8.3 | 1.1 | 8 | 6.6 | 28 | 1.3 | 18 |
| N.A.    | 53 | 28 | 2.7 | 96 | 158 | 19 | 71 | 14 | 0.7 | 3.3 | 14 | 2.8 | 8.9 | 1.3 | 8.8 | 1.1 | 8 | 7.1 | 56 | 1.3 | 18 |
| Value   | 65 | 30 | 3.0 | 81.5 | 95 | 19 | 79 | 14 | 0.7 | 3.3 | 14 | 2.8 | 8.9 | 1.3 | 8.8 | 1.1 | 8 | 7.1 | 56 | 1.3 | 18 |
| N.A.    | 65 | 30 | 3.0 | 81.5 | 95 | 19 | 79 | 14 | 0.7 | 3.3 | 14 | 2.8 | 8.9 | 1.3 | 8.8 | 1.1 | 8 | 7.1 | 56 | 1.3 | 18 |
| Value   | 71 | 28 | 3.0 | 81.5 | 95 | 19 | 79 | 14 | 0.7 | 3.3 | 14 | 2.8 | 8.9 | 1.3 | 8.8 | 1.1 | 8 | 7.1 | 56 | 1.3 | 18 |
| N.A.    | 65 | 30 | 3.0 | 81.5 | 95 | 19 | 79 | 14 | 0.7 | 3.3 | 14 | 2.8 | 8.9 | 1.3 | 8.8 | 1.1 | 8 | 7.1 | 56 | 1.3 | 18 |
| Value   | 71 | 28 | 3.0 | 81.5 | 95 | 19 | 79 | 14 | 0.7 | 3.3 | 14 | 2.8 | 8.9 | 1.3 | 8.8 | 1.1 | 8 | 7.1 | 56 | 1.3 | 18 |

N.A. = Not Analysed
Elements and oxide variations

Major and trace element variations were evaluated using selected Harker variation diagrams (Figs. 7 and 8). Compared to the biotite granites, alkali granites are characterized by rather high abundances of SiO₂, K₂O, Na₂O, Nb, Th, Y, Mn, and Zr with lower abundances of Al₂O₃, CaO, Fe₂O₃, TiO₂, Ba, Rb, and Sr (Fig. 8). The MnO abundances of alkali-feldspar granitic rocks are about 2-3 times lower than the average A-type granites (0.06%, see [23]). The gabbro-dioritic rocks have low abundances of K₂O, Rb, Y, and Zr. Na₂O content of these rocks is ranging from 1.86 to 4.26 (Fig. 7). The major and trace element compositions of the biotite granites tend to cluster or spread more or less vertically parallel to y-axis of the diagrams, partly as a function of the small range of silica values.

In the REE diagrams (Figs. 9a, b) each rock type show different patterns. The data are normalized to chondrite [25] and invariably show relative enrichment of light rare earth elements (LREE). Alkali-feldspar granites and biotite granites show clear negative Eu anomaly and gabbro-diorites show small negative anomaly, whereas syenites do not show this characters.

ORG-normalized spider diagrams [26] for alkali-feldspar granites and biotite granites indicate increasing trend from Yb to Rb. For alkali-feldspar granites Ba has intense negative anomaly and Rb and Th are considerably enriched compare to Nb and Ta. Ce, and Sm are enriched compared to adjacent elements (Fig. 9c). These selected enrichment (Ce and Sm), can be attributed to crustal interference or contamination. For biotite granites, Ba shows negative anomaly and Ce and Sm show positive anomalies.

In the (ocean ridge granite) ORG-normalized diagram (Fig. 9c), the alkali-feldspar granites are significantly enriched in Rb and Th relative to Nb and Ta and Ce and Sm are enriched relative to their adjacent elements on the diagram.

Primitive Mantle-normalized spider diagrams [27] for the investigated plutonic rocks (Fig. 9d) show enrichment in large ion lithophile elements (LILE) relative to high field strength elements (HFSE). The alkali-feldspar granites show Sr, Ba, Nb, and intense Ti negative anomalies, which are typical of subduction related magmas [26]. Gabbro-diorites have convex pattern in Primitive Mantle-Normalized diagram (Fig. 9d), as it has maximum content of Pb. The biotite granites show negative anomalies for Nb, La, and P and positive anomaly for Pb (Fig. 9e). Also, the syenitic rocks have positive anomalies in Rb, K, PB, and Zr (Fig. 9d).
Fig. 7. Harker variation diagrams of selected major element oxides. Fields in K$_2$O vs. SiO$_2$ after [21]. Symbols as in Fig. 5.

Fig. 8. Harker variation diagrams of selected trace elements. Symbols as in Fig. 5.
**Discussion and conclusions**

**Tectonic setting**

Using the tectonic discrimination diagrams of [26], the alkali-feldspar granites (Fig. 10) have characteristics of intra plate (WPG) and post-collision. Post-collision character of alkali-feldspar granites is confirmed by Al vs. SiO<sub>2</sub> diagram (Fig. 5d). Nevertheless, biotite granites have mainly VAG or syn-collision characteristics (I-type). Syenitic rocks show intra plate and VAG characteristics.

Gabbro-diorites show a tholeiitic trend using the classification diagrams of [28-29], also these rocks show continental basalts and within-plate character (Figs. 11c and d) using the classification diagrams of [30-31].

A-type granites can be formed in both post-orogenic and anorogenic settings [23-32]. [32] subdivided the A-type granites into A<sub>1</sub> and A<sub>2</sub> groups. The A<sub>1</sub> group is mantle-derived and are emplaced in an anorogenic setting such as continental rifts or other intraplate environments. The A<sub>2</sub> group comprises crustal derived magmas of
a post-orogenic setting. Using the Rb/Nb vs. Y/Nb (Fig. 12) and Y-Nb-3×Ga (not shown) discrimination diagrams of [32] the alkali-feldspar granites fall into the A₁ group (except one sample) suggesting an anorogenic tectonic setting. Some samples of alkali-feldspar granites fall in boundary of A₁ and A₂ or in A₂ field.

![Fig. 10. Tectonic discrimination diagrams. (a) Rb vs. Y + Nb (b) Nb vs. Y (c) Rb vs. Ta + Yb and (d) Ta vs. Yb [26]. VAG: volcanic-arc granite; Syn-COLG: syn-collision granite; ORG: ocean ridge granite. The field labeled PCG as in Fig. 5d. Symbols as in Fig. 5.](image)

![Fig 11. Tectonic discrimination plots showing within-plate tholeiite nature of the gabbros from Ghoshchi area, after (a) [29], (b) [29], (c) [30], (d) [31]. Symbols as in Fig. 5.](image)
Petrogenesis
Two main models have been presented for the origin of A-type granites: (1) extensive fractional crystallization of mantle-derived parental mafic magmas [33-34], and (2) partial melting of pre-existing crustal rocks [35-38]. However, the existence of both mantle- and crustal-derived A-type granites has also been advocated [32].

Considering the coexistence of mafic and felsic rocks (alkali-feldspar granites) in the studied area, it can be conclude that the petrogenesis of these two types of rocks is connected to each other. However, geochemical evidences indicate obvious differences between biotite granites and alkali-feldspar granites. Biotite granites have crustal source but alkali-feldspar granites have mantle source.

The source of basic rocks in the studied area, is attributed to mantle doming process [15] which caused rifting. Partial melting of upper mantle and generation of basaltic magma and ascend to lower crust, caused melting of crust then generation of granitic magmas.

Gabbro-diorites show a tholeiitic trend. Also, this group have $\text{Al}_2\text{O}_3<17\%$ and quartz and hypersthene in the normative composition, that confirms their tholeiitic character.

Mafic members of Ghoshchi batholith are a suitable source to test the hypothesis of fractional crystallization for the origin of the A-type granites. Modeling of Rayleigh fractionation vectors, which shows the effects of crystallization of a range of selected phase combinations from magmas of different compositions, was performed using the FC-Modeler program of [39]. We have taken the Rb and Y contents of the protolith (Rb$=14$ ppm and Y$=17$ ppm) from the data on the studied mafic rocks. The vectors show the effect of 85% crystallization of the range of phase combination given in the inset in Fig. 13. Positive trend shown by the plotted alkali-feldspar granites and syenitic rocks supports this idea that the alkali-feldspar granites and syenitic rocks were derived from a parent mafic magma by extensive fractional crystallization (up to ~85%). Contrary, the flat to negative trend displayed by the biotite granites indicates that it should be a separate magma not linked with mafic units through fractional crystallization.

Also, depletion in many elements (Fig. 9) suggests that plagioclase (Ca and Sr) and amphibole (CaO, Fe$_2$O$_3$, MgO, TiO$_2$ and Y) were the dominant fractionating phases during the evolution of the alkali-feldspar granitic magmas. Intense negative Eu anomaly in REE pattern of alkali-feldspar granites (Fig. 9a), confirms the plagioclase fractionation.

Moreover, the P and Ti negative anomalies shown in the multi-element abundances diagram (Fig. 9c) indicate minor fractionation of apatite and Fe-Ti oxide, respectively.

The alkali-feldspar granites show depletion in Al$_2$O$_3$, CaO, MgO, Fe$_2$O$_3$, TiO$_2$, P$_2$O$_5$, Sr and Ba (Figs. 7 and 8), implying their evolution by extensive fractional crystallization from a less fractionated magma.
It has been proposed that A-type granites are originated from the partial melting of LILE-depleted granulitic residue in the lower crust, from which the granitoids melts were previously extracted [35-37]. But the geochemical characteristics of the alkali-feldspar granites, especially their enrichments in LILE (Figs. 9c and e), contradicts sharply with this model.

[16] Believes that A-type granites in NW of Iran are generated due to metasomatism of mafic rocks. The great volume of A-type granite relative to mafic rocks and shortage of petrographic evidence for metasomatism does not confirm this idea. However, there are some evidences that indicate effects of metasomatism in this area in small scale.

Accordingly, we favor the derivation of the Ghoshchi A-type granites from mantle-derived magmas in a post-collision setting with extensive fractional crystallization. Also, the melts are affected by continental crust.

**Geodynamic implications**

Existence of mafic rocks in the Ghoshchi batholith, suggests the presence of the mantle-derived mafic magmas in the source area of the granites. The alkali-feldspar granites fall into the A1 group (mantle derived characteristics) which suggests an anorogenic tectonic setting, but some evidences show that the alkali-feldspar granites are generated in a post-collision extensional regim. Also, gabbro-diorites have within-plate and tholeiitic character. Terefore, it can be conclude that these rocks are generated in an extensional setting.

Deformation in Zagros Basin and opening of Neo-Tethys Ocean commenced during Permian [40-45]. This was a phase of rifting, which flanked the Sanandaj-Sirjan Zone and was associated in the Upper Permian with basic (basalt, diabase, and some intermediate rocks) volcanic activity. There is general agreement that subduction started during the Middle Jurassic, but the time of the continental collision is controversial, Late-Cretaceous [1-2] to Eocene [46-47] or even Miocene [3-48].

It is certain that, the studied granites are formed in an extensional regime eather an anorogenic setting; or a post-orogenic setting. With the available data, it is not possible to distinguish these two, but using field geology data and similar studies in the neighboring area [49], the post-orogenic setting seems reasonable for the studied granites.

If we accept the Cretaceous time for collision, consequently, alkali-feldspar granites will have post-Cretaceous emplacement age.

Accordingly, we favor that the studied alkali-feldspar granites are generated in an extensional regime (post-collision extentions of Neo-Tethys Ocean closure) and then extensive fractional crystallization of mafic tholeiitic rocks.

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**Fig. 13.** Y vs. Rb diagram showing Rayleigh fractionation vectors for 85% crystallization. Tick marks along each vector refer to 10% crystallization intervals. Inset shows phase combinations for each vector. A, I, and B = acidic, intermediate and basic melt compositions, respectively. Symbols as in Fig. 5.
Biotite granites are generated as a result of partial melting of continental crust due to intruding mafic magmas.

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