Eocene Arc-related Magmatism within the Neotethys Subduction System in NW Iran; Geochemistry and SHRIMP zircon U-Pb Dating on Magmatic Phases in the Shahjahan Batholith

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Research Article

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Eocene arc-related magmatism within the Neotethys subduction system in NW Iran; Geochemistry and SHRIMP zircon U-Pb dating on magmatic phases in the Shahjahan Batholith

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Abstract

Granitoids of the composite Shahjahan batholith in the northernmost part of the Urmia-Dokhtar magmatic arc of Iran, and southernmost of the Lesser Caucasus (South Armenia) show SHRIMP zircon ages of 37.1±1.2 to 47.1±4.5 Ma. Dioritic rocks of the pluton with an age of 46.6 ± 4.6 to 47.1 ± 4.5 Ma are calc-alkaline to high-K calc-alkaline, metaluminous and I-type. They show arc-related affinities, characterized by LREE and LILE enrichment and HREE and HFSE depletion, especially negative Ti, Nb and Ta anomalies (TNT effect) in the normalized spider diagrams. low Ce/Pb, Nb/La and high Ba/Nb, U/Th and Hf/Zr ratios along with positive Pb, K, Th and Sr anomalies in the normalized spider diagrams for the studied samples are compatible with magma contamination with crustal materials during ascend to the lower crustal levels. Felsic dikes with granodiorite and syenite compositions and 37.1 ± 1.2 to 38.57 ± 0.41 Ma old, are characterized by high-K calc-alkaline to shoshonitic, metaluminous, and A2-type affinities which show post-collision tectonic setting geochemical features. The REE patterns for all studied samples and the composition of the trace element ratios indicate a geochemically enriched spinel-lherzolite lithospheric mantle source for the magmas, which underwent a low degree of partial melting. Dating arc-related dioritic samples and post collision felsic dikes put constrain on timing of Neotethys Ocean closure in NW Iran. Based on the present study, Middle to Upper Eocene is suggested as closure time of the Neotethys Ocean, Arabia and Central Iran plates’ collision and crustal thickening in Northwest Iran.

Keywords: Arabia-Eurasia collision, Neotethys, Subduction magmatism, Eocene magmatism

Introduction

The Alpine–Himalayan tectonic belt forms a puzzling network of suture zones and microblocks and stretches for over 12000 Km from the Alps through the Carpathians–Balkans, Turkey, Iran, Pakistan, Tibet, to Indo–China which includes sections where Neotethyan ocean lithosphere is still being subducted (e.g. the eastern Mediterranean and the Makran area in South of Iran) to
advanced continental collision (e.g. the Alps and Himalayas)\textsuperscript{51}. This complex converging system created different subduction-related magmatism and ore formation, followed by various collisions to post-orogenic magmatic and ore-forming events throughout the Cenozoic\textsuperscript{48, 54}. The Iranian plateau is a tectonically active region within the Alpine-Himalayan orogenic belt. It contains several continental fragments that have been welded together along the suture zones of oceanic character. These fragments were controlled by the opening and closure of Tethyan oceans during several successive stages\textsuperscript{16}. Based on structural trends, Stöcklin and Nabavi (1973), divided the Iranian plateau into eight geological units (Fig. 1a): Zagros fold belt, Zagros thrust belt, Sanandaj-Sirjan Zone (SSZ), Urmia-Dokhtar magmatic arc (UDMA), central Iran, Alborz–Azerbaijan magmatic belt (AAMB), Kopeh-Dagh and eastern Iran. The Shahjahan batholith with about 500 Km\textsuperscript{2} outcrop area is on the northernmost part of the Urmia-Dokhtar magmatic arc in NW Iran (Fig. 1a). The \~200 Km long and \~50 Km magmatic arc was formed by the subduction of Neo-Tethyan oceanic crust beneath the Iranian microplate, which extends to the Lesser Caucasus (South Armenia) and East Turkey\textsuperscript{31} but the time of closure and the evolutionary history of the Neotethys Ocean in the Iranian domain still is a matter of controversy\textsuperscript{1}.

These uncertainties led different authors to suggest various theories for the evolution of the Neotethys basin. Berberian and King (1981) and Ghasemi and Talbot (2006) proposed a single-stage subduction scenario for the Neotethys oceanic crust beneath central Iran, whereas, Glennie (2000) advocates a double-stage subduction for the Neotethys, considering the opening of two parallel oceanic basins. The Shahjahan batholith is considered as a southern continuation of the Meghri-Ordubad granitoid complex, which extends through NW Iran, Southern Armenia, and the Eastern part of Nakhchivan\textsuperscript{54}. Several magmatic phases which include gabbro, diorite, quartz-diorite, quartz-monzodiorite, quartz-monzonite, tonalite, granodiorite, and porphyritic granite composed the main intrusions in this batholith. According to Brunet et al. (2003), the study area is located in the South Armenia-Qaradagh zone and based on Nabavi (1976) it is a part of the Alborz-Azerbaijan zone in NW Iran (Fig. 1a).
This study is based on comprehensive field geology, petrology, lithogeochemistry, and SHRIMP zircon U-Pb geochronology on plutonic rocks in the Shahjahan batholith. New major and trace elements geochemical and radiometric age data allow us to identify geochemistry and petrogenesis of magmatic phases occurred in this area and add to our knowledge on Neotethys
ocean evolution, subduction and collision time which occurred between Arabia and Eurasia continents.

**Geology of the studied area.** The Cenozoic magmatism of Iran, especially in the NW Iran, has typically been viewed in terms of widespread and voluminous Eocene–Oligocene arc-related volcanism and plutonism \(^4,6^0\). Magmatic activity in the UDMA and the AAMB started in the Late Cretaceous and continued during Eocene to the Quaternary periods \(^8\). Shahjahan composite batholith emplaced within the Upper Cretaceous to Palaeogene sedimentary, volcano-sedimentary, and igneous rocks (Fig. 1b). According to Mehrpartou et al. (1997), Upper Cretaceous successions have flysch facies composed of thick bedded and locally massive limestone, sandstone, and shale alternating with siltstone, marl, conglomerate, and submarine andesitic rocks. These units border the Shahjahan batholith to the West and South. Palaeocene sedimentary rocks are composed of shale and sandstone with intercalations of marl and limestone, overlain by submarine andesitic rocks, breccia, and acidic tuffs. Eocene to Oligocene rocks are mainly intrusive, composed of diorite, microdiorite, monzonite, granodiorite, granite, and microgranite (Fig. 2a).
Fig. 2. Representative outcrop photos of (a) studied igneous rocks (b) diorite plutons with large mafic enclave (c) sharp contact between diorite sample and metamorphic rock (amphibolite) (d) felsic dike which intruded into the metamorphic rock (amphibolite).

The scarce volcanic rocks of Oligocene age are mainly dacitic and crop out to the South of the Shahjahan batholith. Miocene sedimentary rocks consist of red conglomerate, sandstone, and marl which unconformably overlay the Upper Cretaceous successions. The Pliocene is characterized by trachytic and trachy-andesitic lava flows, volcanic domes, and acidic to intermediate pyroclastic rocks. Finally, Quaternary units include limited occurrences of andesitic to basaltic lavas outside of the Shahjahan batholith at its south and travertine, alluvial and fluvial sediments in the terraces and stream beds. The Eocene -Oligocene intrusive rocks (mainly diorite in this study) are light in color and contain large mafic enclaves with different lithological compositions (amphibolite, monzonite, and gabbro) (Fig. 2b). Metamorphic rocks (mainly amphibolite, meta volcanic rocks, and meta tuff) with NW-SE structural trend outcrop at the east of Shahjahan batholith with a sharp contact (Fig. 1b, 2c). These rocks are known as the oldest unit and continuation of metamorphic rocks in Armenia (based on relative ages reported in 1:100000 Jolfa geological map by the Geological Survey of Iran). However, petrological features and age of these rocks are not clear yet. Felsic dikes which investigated in this study mainly intruded the metamorphic rocks and have experienced high alterations (Fig. 2d).

Analytical methods

SHRIMP U-Pb zircon dating analysis. Based on a traditional water-based Wilfley table, electric, magnetic and heavy liquid separation methods, zircon minerals from one diorite (sample ZA–1D) and one felsic dike (sample ZA–3D) with granodiorite composition, were extracted from the Shahjahan batholith, and they were then handpicked and mounted in an epoxy mount together with the standard zircon FC1 (206*Pb /238U-0.8159). Before analysis, the zircon grains were photographed using both back scatter electron and Cathodoluminescence imagery, to distinguish individual patterns of zircon minerals via a scanning electron microscope (SEM, JEOL JSM-6610 LV). Zircon U-Pb isotopic dating was conducted using a SHRIMP Ile/MC instrument of the SHRIMP Center at the Korean Basic Science Institute (KBSI), South Korea. The analysis used a primary beam diameter of 23 × 23 μm. The resulting data were investigated using the program Isoplot 3.0 (Ludwig, 2003). Table 1 shows the U-Pb analyzes results for diorite pluton and granodiorite (felsic dike) samples.
### Representative age dating analyses on zircon separates from the diorite sample

<table>
<thead>
<tr>
<th>Spot Name</th>
<th>U (ppm)</th>
<th>Th (ppm)</th>
<th>U238/Pb206</th>
<th>Error</th>
<th>Pb207/Pb206</th>
<th>Error</th>
<th>Pb207/U235</th>
<th>Error</th>
<th>Pb206/U238</th>
<th>Error</th>
<th>Error Corr</th>
<th>Age (Mya) 204cor</th>
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<td>ZA1D-5</td>
<td>82</td>
<td>53</td>
<td>150</td>
<td>2.1</td>
<td>0.053</td>
<td>8.4</td>
<td>0.022</td>
<td>87</td>
<td>0.0064</td>
<td>3.3</td>
<td>0.04</td>
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<td>ZA1D-8</td>
<td>195</td>
<td>125</td>
<td>140</td>
<td>2.9</td>
<td>0.045</td>
<td>4.9</td>
<td>0.050</td>
<td>11</td>
<td>0.0072</td>
<td>2.9</td>
<td>0.26</td>
<td>46.2</td>
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<td>ZA1D-9</td>
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<td>288</td>
<td>129</td>
<td>1.9</td>
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<td>3.3</td>
<td>0.032</td>
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<td>0.0076</td>
<td>2.1</td>
<td>0.10</td>
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<td>ZA1D-12</td>
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<td>3.1</td>
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<td>0.048</td>
<td>8.1</td>
<td>0.062</td>
<td>15</td>
<td>0.0070</td>
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<td>0.19</td>
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<td>140</td>
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<td>0.047</td>
<td>3.7</td>
<td>0.038</td>
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<td>0.16</td>
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<td>142</td>
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<td>5.2</td>
<td>0.029</td>
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<td>0.0064</td>
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<td>0.25</td>
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<td>0.06</td>
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<td>46</td>
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<td>7.2</td>
<td>0.060</td>
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<td>ZA1D-23</td>
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<td>323</td>
<td>135</td>
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<td>0.049</td>
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<td>0.033</td>
<td>24</td>
<td>0.0072</td>
<td>3.3</td>
<td>0.14</td>
<td>46.6</td>
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<td>ZA1D-29</td>
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<td>139</td>
<td>144</td>
<td>2.0</td>
<td>0.043</td>
<td>6.2</td>
<td>0.027</td>
<td>38</td>
<td>0.0068</td>
<td>2.4</td>
<td>0.06</td>
<td>43.7</td>
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<td>ZA1D-32</td>
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<td>291</td>
<td>134</td>
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<td>0.068</td>
<td>10.3</td>
<td>0.015</td>
<td>92</td>
<td>0.0070</td>
<td>3.0</td>
<td>0.03</td>
<td>45.0</td>
</tr>
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</table>

### Age dating analyses on zircon separates from the granodiorite sample (felsic dike)

| ZA3D-54 | 290 | 324 | 165 | 2.0 | 0.044 | 4.8 | 0.046 | 13 | 0.006 | 2.1 | 0.17 | 39.5 |
| ZA3D-56 | 111 | 81 | 169 | 2.9 | 0.053 | 7.5 | 0.055 | 19 | 0.006 | 3.3 | 0.17 | 38.7 |
| ZA3D-30 | 273 | 253 | 168 | 2.6 | 0.043 | 5.9 | 0.099 | 16 | 0.006 | 3.5 | 0.22 | 41.7 |
| ZA3D-44 | 306 | 293 | 167 | 3.2 | 0.048 | 4.6 | 0.014 | 78 | 0.005 | 3.6 | 0.05 | 37.0 |
| ZA3D-49 | 260 | 233 | 166 | 2.4 | 0.047 | 4.7 | 0.022 | 40 | 0.005 | 2.7 | 0.07 | 37.8 |
| ZA3D-73 | 103 | 83 | 160 | 5.0 | 0.047 | 7.9 | 0.008 | 209 | 0.005 | 6.1 | 0.03 | 37.4 |
### Table 1. Age dating analyses on zircon separates from the diorite and granodiorite samples

#### Whole-rock major and trace-element analysis.

To understand chemical composition of studied plutons, seven samples were collected from fresh and less weathered outcrops and were analyzed by X-Ray fluorescence Spectroscopy (XRF) for major oxides and Inductively Coupled Plasma Mass Spectrometry (ICP-MS) for trace and rare earth elements at Actlabs research Laboratories, Canada (4-litho-Research analytical package). About 1 Kg of each sample was crushed by steel-jaw mill and was pulverized to 200 mesh. A known amount of sample was mixed with lithium metaborate and fused on a gas heater. The resulting glass discs were used for XRF analyses of major oxides. After digestion in acid and dilution they were used for minor and trace elements analyses using an ICP-MS. International standards were used for calibrations. Detection limits for all oxides were about 0.01%. The analytical results are illustrated as geochemical diagrams using the GCD kit software. The results of chemical analyses are shown in Tables 2 and 3.

### Table 2. Whole rock analyzes for the studied samples in the Shahjahan batholith (Wt %)

<table>
<thead>
<tr>
<th>Sample</th>
<th>Rock</th>
<th>SiO$_2$</th>
<th>Al$_2$O$_3$</th>
<th>TiO$_2$</th>
<th>FeO</th>
<th>Fe$_2$O$_3$</th>
<th>MnO</th>
<th>MgO</th>
<th>CaO</th>
<th>Na$_2$O</th>
<th>K$_2$O</th>
<th>P$_2$O$_5$</th>
<th>L.O.I</th>
<th>Total</th>
</tr>
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<td>ZAJ-15</td>
<td>Diorite</td>
<td>58.23</td>
<td>16.62</td>
<td>0.713</td>
<td>5.4</td>
<td>1.6</td>
<td>0.152</td>
<td>2.81</td>
<td>6.37</td>
<td>3.29</td>
<td>2.19</td>
<td>0.16</td>
<td>1.42</td>
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<tr>
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<td>Diorite</td>
<td>57.68</td>
<td>17.97</td>
<td>0.61</td>
<td>4.5</td>
<td>2.37</td>
<td>0.148</td>
<td>3.23</td>
<td>7.53</td>
<td>3.39</td>
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<td>1.81</td>
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<td>3.1</td>
<td>0.159</td>
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**Table 3.** Trace elements analyzes for the studied samples in the Shahjahan batholith (ppm)

**Conscious approval.** All authors confirm the consent for publication of identifying information/images in an online open-access publication.
Results

Petrography

Diorite Samples. Diorite to monzodiorite plutons form dominant lithology in the study area which mainly composed of plagioclase (~50 modal %), amphibole (~20 modal %), and biotite (~15 modal %) with subordinate amounts of quartz (~4 modal %), K-feldspar (~4 modal %), clinopyroxene (~3 modal %), and opaque minerals (magnetite), which display granular texture (Fig. 3a, b). Accessory minerals are titanite and zircon. The rock samples show disequilibrium texture evidence (i.e. subhedral pyroxene grain surrounded by secondary amphibole rim as shown in Fig. 3c, 3d, 3f) which display alteration effects on these plutons. Under plane-polarized light, the quartz is colorless, while plagioclase and K-feldspar grains are euhedral to subhedral and cloudy due to variable degrees of alteration. Amphibole (length/width ratio of 3:1) is fresh and displays typical pleochroism. Also, under cross-polarized light, polysynthetic twinning developed within plagioclase grains. Brown titanite is characterized by strong relief and high-order interference colors.

![Fig. 3. Photomicrograph of the intrusive rocks in the Shahjahan batholith. (a and b) Coarse-grained granular texture and sub-hedral biotite and plagioclase in the diorite. (c and d) Changing of pyroxene (core) to amphibole (around) with anhedral quartz minerals in the diorite sample. (e and f) Coarse-grain and sub-hedral amphibole along with altered plagioclase in the felsic dike (granodiorite sample). Mineral name abbreviations are from Whitney and Evans (2010).](image-url)
**Felsic Dikes.** The felsic dikes which intruded into the metamorphic rocks (amphibolite) are composed of granodiorite to tonalite and syenite. Granodiorite to tonalite (sample ZA–J1) is composed of plagioclase (~50 modal %), quartz (~35 modal %), and biotite (~10 modal %) with subordinate amounts of amphibole, and K-feldspar which display granular texture. Quartz grains are anhedral and colorless, plagioclase grains show weak polysynthetic twinning, and K-feldspar grains are highly altered and become cloudy (Fig. 3e). The syenite (sample ZA–J34) is mainly composed of K-feldspar (~55 modal %) and amphibole (~20 modal %) with subordinate amounts of quartz (~5 modal %), plagioclase (~5 modal %) and opaque minerals. K-feldspar and plagioclase grains are subhedral and cloudy due to alteration. Amphibole is subhedral with weak pleochroism.

**U-Pb SHRIMP zircon ages.** Zircon separated from the diorite (sample ZA–1D) and granodiorite (sample ZA3-D) are euhedral to subhedral; they are short, prismatic, colorless to honey yellow with length/width ratios ranging from 2:1 to 3:1. The Cathodoluminescence images show a core – rim texture in both samples. The dark-gray zircon cores are in an irregular shape and have oscillatory zoning whereas light zircon rims are relatively wide and show no or weak zoning color (Fig. 4). Seven spot analyses of zircon cores in diorite sample give U concentrations of 90 to 446 ppm and Th concentrations of 46 to 378 ppm, with Th/U ratios of 0.51 to 0.95, and yield $^{207}\text{Pb}/^{206}\text{Pb}$ ages of $46.6 \pm 4.6$ Ma ($^{204}\text{Pb}$ corrected, 2σ; Fig. 5a). In contrast, five- spot analyses on zircon rims give U and Th concentrations of 82–291 and 53–279 ppm, respectively, with Th/U ratios of 0.54 – 0.95, and yield $^{207}\text{Pb}/^{206}\text{Pb}$ ages of $47.1 \pm 4.5$ Ma ($^{204}\text{Pb}$ corrected, 2σ; Fig. 5b). In granodiorite sample, eleven spot analyses of zircon cores give U concentrations of 103 to 782 ppm, and Th concentrations of 83 to 1636 ppm, with Th/U ratios of 0.80 to 2.0, and yield $^{207}\text{Pb}/^{206}\text{Pb}$ ages of $38.57 \pm 0.41$ Ma ($^{204}\text{Pb}$ corrected; 2σ; Fig. 5c). Also, three spot analyses on zircon rims give U and Th concentrations of 111–181 and 81–131 ppm, respectively, with Th/U ratios of 0.72–0.74, and yield $^{207}\text{Pb}/^{206}\text{Pb}$ ages of $37.1 \pm 1.2$ Ma ($^{204}\text{Pb}$ corrected, 2σ; Fig. 5d).
Fig. 4. Cathodoluminescence image of representative zircons (a) from the diorite sample (Sample ZA-1D) (b) from the granodiorite sample (felsic dike). The representative analyses spots are shown with $^{207}\text{Pb}/^{206}\text{Pb}$ ages.
Whole-Rock Geochemistry. SiO$_2$ contents range from 57.25 to 66.62 Wt. % in the studied samples. They have 0.84 to 3.13 Wt. % K$_2$O, 3.21–5.89 Wt. % Na$_2$O, 16.31–18.76 Wt. % Al$_2$O$_3$, 1.75–3.23 Wt. % MgO, 0.16–0.32 Wt. % P$_2$O$_5$, 4.91–7.53 Wt. % CaO and 1.19 to 3.12 Wt. % LOI. According to the R1-R2 classification diagram of De la Roche et al. (1980), most of the studied samples fall into the diorite, tonalite to syeno-diorite (felsic dikes) fields (Fig. 6a). According to Co-Th contents, diorite samples are related to calc-alkaline to high-K calc-alkaline magmatic series, however, granodiorite and syenite (felsic dikes) show high-K calc-
alkaline and shoshonitic affinities (Fig. 6b). Al/Ca+Na+K (A/CNK) vs. Al/Na+K (A/NK) ratios for the studied samples (Shand, 1943), (Fig. 6c) show that all of them have metaluminous affinity (i.e. ASI<1). According to the granitoid classification of Barbari (1999), and their origin, the studied granitoids classify as amphibole-rich calc-alkaline granitoid (ACG).

**Fig. 6.** Chemical classification of studied rocks (a) R1-R2 diagram from De la Roche et al, 1980 (b) Co versus diagram from Hastie et al, 2007 which shows the magmatic series for studied samples (c) Al/Ca+Na+K (A/CNK) versus Al/Na+K (A/NK) diagram (Shand, 1943) which shows the metaluminous affinity for all of the studied samples.
**Trace elements geochemistry.** All of the diorite and felsic dike (granodiorite-tonalite and syenite) samples in the primitive mantle \(^{33}\), EMORB \(^{58}\) and chondrite normalized diagrams \(^{59}\) display significant enrichment of large ionic lithophile elements (LILE) which include Rb, Ba, Th, U, K. LREE are enriched relative to the high field strength elements (HFSE) like Ta, Nb, Ti, Zr, Hf, Y and heavy rare earth elements (HREE) (Fig. 7). The negative anomalies of HFSE (Ti, Nb and Ta, known as TNT effect) are characteristic of arc environments \(^{40}\). The samples show positive U, Th, Pb, Ba, Sr and K anomalies in the normalized spider diagrams also, approximately flat HREE pattern in the REE chondrite normalized diagram\(^{39}\) (Fig. 7c and 7d). The Eu/Eu* (Eu\(_N\)/√(Sm)\(_N\)*/(Gd)\(_N\)) ratio varies from 0.71 to 0.99 and (La/Sm)\(_N\) varies from 2.2 to 2.7 in diorite samples. Eu/Eu* (Eu\(_N\)/√(Sm)\(_N\)*/(Gd)\(_N\)) ratio is about 0.93 in granodiorite and syenite samples.
Fig. 7. Spider diagrams for studied samples. (a) Primitive mantle normalized spider diagram (b) E-MORM normalized spider diagram (c) Chondrite normalized spider diagram (Thompson, 1982) (d) REE-Chondrite normalized spider diagram.

Discussion

Petrogenesis, magmatic evolutions and tectonic implications. The studied rocks have Nb/U ratios ranging from 2.4 to 6.09, which are significantly lower than the MORB and OIB (Nb/U=47±7; Hofmann et al., 1986) and the lower crust (Nb/U ≈ 25). High Nb and Ta have been used to indicate an Oceanic Island Basalt (OIB) component in magmatic rocks. The studied samples show negative Nb and Ta anomalies in the E-MORB and primitive mantle normalized spider diagrams which show their source is not related to the oceanic islands. Such pattern is characteristic of arc magmatism in the subduction zones and can be found in magmas sourced from a subducted oceanic crust and the overlying metasomatized mantle wedge, which has undergone partial crystallization, assimilation and contamination with crustal materials. The lack of negative Sr, Ba and Eu anomalies show that the studied plutonic samples are not originated from continental crust materials. Also, the absence of normative corundum in the CIPW norms calculations of the studied samples (not shown) confirms the non-continental origin for the studied rocks. LREE enrichment on all of the normalized spider diagrams can be attributed to the low degree of partial melting and/or magma contamination by crustal materials, though it may also be resulted from magma contamination with crustal materials during ascend to the lower levels and emplacement above the Benioff zone. Uranium enrichment in the E-MORB normalized spider diagrams can indicate the source enrichment by slab-derived fluids. Approximately flat HREE pattern in the REE chondrite normalized diagram, indicates the lack of garnet as residual phase in the mantle source. Pearce and Gale (1977) suggested that Zr/Y ratio can separate the continental volcanic arc from oceanic arcs, such that, Zr/Y>3 in the continental arcs but Zr/Y< in oceanic arcs. This ratio ranges from 6.26 to 13.26 for the studied samples, a continental arc tectonic setting can be considered for the studied rocks.

The high ratios of Ba/Nb, Ba/Zr, U/Th, and the low ratio of Nb/La (<1.3) show the crustal contamination. Nb/La ratio is <1 in the studied samples along with high ratios of Ba/Nb (84.83-150.25 in diorite samples), Ba/Zr (3.53-7.80 in diorite samples) and U/Th (0.24-0.29 in diorite samples). The positive Th, Pb, Ba, Sr and K anomalies in the normalized spider diagrams show probable crustal contamination (Fig. 7a, b).

Most of the previous studies confirm the UDMA as a magmatic arc which generated by Neotethys subduction beneath the central Iran microplate and different plutonic intrusions generated in an active continental margin tectonic setting, however, authors such as Amidi et al. (1984) and Dargahi et al. (2010) proposed post-collision affinity for some intrusions in the UDMA. To understand tectonic setting of the studied samples, Rb vs. Y+Nb diagram is used which shows volcanic arc and post collision tectonic settings for diorite and granodiorite- syenite (felsic dike) samples respectively (Fig. 8a). All diorite samples in the Ce vs. 10000*Ga/Al diagram from Whalen et al. (1987), plot in the I-type field but granodiorite and syenite (felsic dikes) plot.
in the A-type field (Fig. 8b). Also, based on Nb-Y-Ce triangle diagram (Eby, 1992), granodiorite and syenite samples (felsic dikes) show A2 type (post-collision) affinity (Fig. 8c). The Th/Yb versus Ta/Yb diagram \(^{41}\) is used to investigate the role of source enrichment for the studied rocks (Fig. 8d). Based on this diagram, the studied samples plot outside and parallel to the mantle array. Also, their high Th/Yb ratio shows source enrichment by subduction processes which can be confirmed by U enrichment in the E-MORB normalized spider diagrams.

![Geotectonic classification of the studied samples](image)

**Fig. 8.** Geotectonic classification of the studied samples (a) Rb versus Y+Nb diagram \(^{43}\) (b) Ce versus 1000*Ga/Al diagram from Whalen et al. (1987) (c) Nb-Y-Ce triangle diagram \(^{12}\) (d) Th/Yb versus Ta/Yb diagram \(^{41}\) (e) (La/Sm) \(_N\) versus (Tb/Yb) \(_N\) diagram \(^{41}\) (f) Sm/Yb versus La/Yb diagram showing the melt curves obtained from fractional and batch melting equations of Shaw (1970).

To work out the mineralogy and partial melting rate of a primary source (mantle), we used La and Sm as incompatible trace elements not affected by mantle mineralogy (i.e. spinel or garnet) whereas, Yb is extremely sensitive to presence or absence of garnet in the source. The (La/Sm) \(_N\)
versus (Tb/Yb) N diagram suggests a spinel lherzolite source for the studied rocks (Fig. 8e). Therefore, the primary magma, which generated the studied samples, derived from 5% partial melting of the lithospheric mantle with spinel lherzolite composition by the subduction process (Fig. 8f).

Age constraints and its importance. The Shahjahan batholith at the northern part of the Urmia-Dokhtar magmatic arc, contains numerous plutons of varying ages and compositions. The magmatic arc hosting the pluton, formed by Neotethys subduction beneath the central Iran microplate but the time of closure of the Neotethys Ocean in the Iranian domain is highly debated. Various timing are proposed for closure of the Neotethys basin which are from Late Cretaceous - Early Paleocene to Middle to Late Miocene.

The Shahjahan batholith is a key area to find closure time of the Neotethys ocean and collision time between the Arabian plate and central Iran microplate. Most of the previous studies were mainly focused on different mineralization occurred in the different parts of this batholith. Based on Re-Os molybdenite dating, Simonds et al. (2017), reported 22.9±0.2 Ma and 21.7±0.2 Ma mineralization ages in the Sungun porphyry copper deposits in the central part of the Shahjahan batholith. Also, Simmonds et al., 2019 reported U-Pb zircon dating (32.7±0.4 Ma to 30.9±0.4 Ma) and Re-Os age dating (29.1±0.2 to 28.1±0.2 Ma) for the Siah-Kamar porphyry molybdenite deposit in this batholith. However, Jamshidibadr and Hassanpour (2015), reported 40.52 ±0.44 and 46.4 ± 2.6 Ma intrusive ages for granodiorite and granite plutons respectively, based on Ar-Ar age dating on biotite minerals.

Zircon minerals separated from diorite and granodiorite samples in the current study, exhibit oscillatory and sector zoning patterns and, their Th/U ratio is higher than 0.7, suggesting their magmatic origin. Our new U-Pb zircon data shows 46.6 ± 4.6 to 47.1 ± 4.5 Ma and 37.1 ± 1.2 to 38.57 ± 0.41 Ma for diorite sample with volcanic arc tectonic setting and granodiorite sample (felsic dike) with post- collision tectonic setting respectively (Fig. 5). These data are consistent with the range of major igneous activity at the Eocene epoch in North West of Iran and suggest the collision happened in Eocene. Our findings are in agreement with ages reported by Jamshidibadr and Hassanpour (2015) for some of the plutons in the Shahjahan batholith.

Relationship between studied samples, Meghri-Ordubad plutonic complex and Eastern Pontides magmatic rocks, NE Turkey. Northward subduction of the Neotethys oceanic lithosphere and Eurasia-Arabia collision resulted in the formation of a complex suture zone and magmatic arc along a 2500 km-long curved fold-and-thrust belt known as the Bitlis-Zagros Belt which extended from south west Iran toward Nakhchivan and Turkey. Different magmatic rocks along the Urmieh-Dokhtar magmatic arc (e.g. Shahjahan batholith), South Armenia (e.g. Meghri-Ordubad plutons) and North east Turkey (e.g. Eastern Pontide magmatic rocks) show similar intrusive ages and lithological compositions which suggest North west Iran, North east turkey and south Armenia experienced a similar geotectonic event during a special time. The composite Meghri-Ordubad pluten of the Zangezur-Ordubad region in the southernmost Lesser Caucasus,
Armenia consists of successive Eocene to Pliocene magmatic pulses with diorite, granodiorite, tonalite, quartz monzonite, gabbro and granite compositions. These plutons constitute the northern extension of the Iranian Alborz and Urmieh-Dokhtar magmatic and metallogenic belts.

The petrology and geodynamic of the Meghri-Ordubad plutons are well studied by Mederer et al. (2013), Moritz et al. (2016) and Rezeau et al. (2017, 2019). They reported three main magmatic phases with different geochemical features from the Middle Eocene to Early Miocene, coeval with the closure of the Neotethyan Ocean and the regional Arabia-Eurasia continental collision. A 44.03 ± 0.02 Ma-old granite and 48.99 ± 0.07 Ma-old granodiorite belong to an initial Eocene magmatic pulse which show calc-alkaline to high-K calc-alkaline composition and normal arc affinity, subsequent Oligocene magmatic pulse which show calc-alkaline to high-K calc-alkaline composition and normal arc affinity, subsequent Oligocene magmatic pulse was constrained by U-Pb zircon ages at 31.82 ± 0.02 Ma and 33.49 ± 0.02 Ma for a monzonite and a gabbro, with high-K calc-alkaline to shoshonitic composition and a late Miocene porphyritic granodioritic and granitic pulse yielded ages between 22.46 ± 0.02 Ma and 22.22 ± 0.01 Ma, respectively, with adakitic and calc-alkaline to high-K calc-alkaline compositions.

Eastern Pontides plutonic complex, NE Turkey, composed of different plutons such as Kozluk, Kılıçkaya, Peliti, Aydıntepe, Kemerlikdağ, Dölek and Sarıçücek intrusions which studied by Kaygusuz and Öztürk (2015), Kaygusuz et al. (2020) and Karslı et al. (2007). Aydıntepe, Kemerlikdağ and Peliti plutons range from gabbro, diorite, tonalite, monzogranite and have I-type, medium to high-K calc-alkaline and metaluminous characteristics. U-Pb SHRIMP zircon dating yielded 45.10 ± 0.44 and 45.87 ± 0.43 Ma crystallization age for diorite and granodiorite samples from the Kemerlikdağ pluton respectively, also 45.23 ± 0.29 and 45.81 ± 0.48 Ma crystallization age for gabbro/diorite and tonalite samples from the Aydıntepe and Peliti plutons respectively. Kaygusuz and Öztürk (2015) reported 46.9±0.6 and 46.7±0.7 Ma for diorite and tonalite samples from the Kozluk and Kılıçkaya intrusions respectively. Our new U-Pb SHRIMP zircon dating and geochemical data for studied samples are in agreement with geochemical and geochronological data from Meghri-Ordubad and Eastern Pontides plutons and show their generation at a same time and same geotectonic event.

Conclusion

The above data set and interpretations provide detailed geochemical and tectonic constraints also age dating on magmatic phases in the Shahjahan batholith, NW Iran. In this study diorite plutons, which mainly are outcropped in the northern part of the Shahjahan batholith also granodiorite and syenite dikes which intruded into metamorphic rocks (mainly amphibolites) were investigated from geochemistry and age dating view-points. Based on this study, we infer that the diorite plutons with calc-alkaline and met-aluminous affinities are formed in an active continental margin tectonic setting by Neotethys subduction beneath the central Iran microplate during Mid-Eocene. The primary magma which generated studied samples originated from spinel-lherzolite source and affected by crustal contamination. Felsic dikes with upper Eocene age and granodiorite-syenite compositions show shoshonitic and A2 type affinities which are formed in the post-collision tectonic setting. According to geochronological data and tectonic settings, we propose
the possibility collision time between the Arabian and central Iran microplates occurred between middle to upper Eocene and caused crustal thickening in the NW Iran. These data are in an agreement with different studies which done on plutons from the South Armenia and East Turkey.

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**Author contributions**

Z. Ahmadi performed the experiment and wrote the paper, A. Jahangiri and M. Moazzen reviewed the collected data and edited the paper. Ch. Whan oh conceived the idea. A. Jahangiri was responsible for editing, original data and text preparation. All authors took responsibility for the integrity of the data that is present in this study.

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**Competing interests**

The authors declare no competing interests.

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The authors declare that all relevant institutional, national, and international guidelines and legislation were respected.