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Geochronology of Zircon La-Icp-Ms U-Pb, Geochemistry and Evolution of Miocene Intrusive Rocks in Salafchegan Region, Central Iran

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Abstract

This paper presents new zircon LA-ICP-MS U-Pb age data, whole rock geochemistry as well as mineral chemistry analyses for the early Miocene intrusive bodies from the Salafchegan district, central Urumieh-Dokhtar magmatic arc (UDMA). The Salafchegan intrusive rocks include quartz-diorite and diorite. Zircon LA-ICP-MS U-Pb ages display a mean of 22.04+0.25 Ma and 22.38+0.23Ma for the quartz-diorite and diorite phases, respectively. The data suggest that the intrusive body was emplaced in the early Miocene. These intrusive rocks were mostly formed following the extensive submarine volcanic activities in the Eocene. Based on the Geochemical data, the Salafchegan intrusive rocks are I-type granitoids, meta-aluminous (A/CNK = 0.86-1.24), arc-related and calc-alkaline with SiO_2 contents of 59.9-65.04 wt. % and low Mg number (22.17-34.45). Moreover, these rocks are characterized by enrichment in LREEs relative to HREEs and negative Nb -Ta anomalies, a typical of arc setting. Wide ranges of Y/Nb (0.26-0.48), low Zr/Nb ratios (14.92-23.43) as well as Nb/Ta ratios (7.38-24.17) reflect mantle dominant-crust interaction during the generation of the magmas for the Salafchegan intrusive rocks.

Keywords: *Salafchegan, Intrusive rocks, zircon LA-ICP-MS U-Pb age dating, early Miocene, mantle-crust interaction*

Introduction

Concerning the widespread magmatic rocks in the continental setting, intrusive rocks are extensively studied. The intrusive rocks, with various mineralogical and geochemical signatures,

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outcrop in different geotectonic settings that shed light on deciphers the indiscernible events, e.g., mantle-crust interactions and mineralization (Gill and Shepherd, 2010; Hawkesworth and Kemp, 2006; Kemp et al., 2007; Rudnick and Fountain, 1995). Due to the difference in mineralogical and geochemical signatures of granitoids, the petrogenesis and tectonic setting classifications are controversial. Clemens and Stevens, (2012) put forwarded several geodynamic models for the generation of granitoids, e.g., mantle -and crust-derived magma mixing, fractionation of a basic melt. Some others suggested peritectic assembly, absence of restite, mixing occurrence and mix melting components, among a magma mixing phenomena (Barbarin, 2005; Collins and Sawyer, 1996; Kemp et al., 2007; Yang et al., 2007).

These complexities lead to emerge several obscurities in the crust architecture and geodynamic evolution contents, thus, it is imperative to decipher the nature and petrogenesis of granitoid rocks in different geotectonic settings. The Cenozoic volcano-plutonic complexes areas are reported from several different districts, e.g., Turkey (Keskin et al., 2008; Okay et al., 2001; Temizel and Arslan, 2009; Yiğitbaş and Yilmaz, 1996), Caucasus (Bazhenov and Burtman, 2002; Yilmaz et al., 2000) and Iran (Babazadeh et al., 2021a,b; 2019; 2017; Raeisi et al., 2020; 2021; Nouri et al., 2018). The NE-wared subduction of Neo-Tethys Ocean through early Triassic has influenced Iran (Berberian and Berberian, 1981; Alavi, 2007). Continuing the subduction of oceanic plate beneath the Iranian plateau in Cenozoic time brought about extensive magmatism through the Urumieh-Dokhtar magmatic arc (UDMA; Fig. 1) (Berberian and King, 1981; Alavi, 1994, 2007; Agard et al., 2005; Verdel et al., 2011; Chiu et al., 2013). The late Jurassic magmatic arc activities formed a linear magmatic rock that is composed of voluminous igneous rocks along the margin of Iranian plates (Stoecklin, 1968; Berberian et al., 1982; Alavi, 2007; Shafaii Moghadam and Stern, 2011). Pyroclastic layers, lava flows, tuff and ignimbrite are the

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main products of the magmatism in the UDMA (Alavi, 2007; Berberian and Berberian, 1981; Stoecklin, 1968). The plutonic bodies of the UDMA span wide ranges of mineralogy and geochemistry compositions; predominantly granitic, and to lesser extent, quartz diorite, granodiorite, and gabbro (Babazadeh et al., 2017; 2022; Raeisi et al., 2020; 2021; Nouri et al., 2018). Although the commencement of Neotethys subduction has been chronologically attributed to Triassic period (Alavi, 2007; Berberian and Berberian, 1981), several other periods including upper Cretaceous (Alavi, 1994; Berberian and King, 1981), the late Paleocene-Early Eocene (Mazhari et al., 2009), Eocene-Oligocene (Agard et al., 2009; Dargahi et al., 2010; Horton et al., 2008) to Miocene-Pliocene (Aftabi and Atapour, 2000; Axen et al., 2001; Azizi and Moinevaziri, 2009; Berberian and Berberian, 1981; Guest et al., 2006; Mcquarrie et al., 2003; Okay et al., 2010; Stoecklin, 1968) are controversial. Studies on the UDMA have dominantly been focused on volcanic belts, and the origin of plutonic rocks is poorly defined. In this scenario, the petrological, whole rock geochemical and zircon LA-ICP-MS data of the Spid and Mushakiye bodies located at northwest of Salafchegan area, central UDMA, are investigated. The results discuss the crystallization age, source of magma, and tectonic implications for the UDMA.

Geological setting

The main magmatic activity of the UDMA dates back to 55-36 million years ago that produced thick volcanic sequences with acidic compositions (Agard et al., 2009) and was followed by the emplacement of intrusive bodies through Oligo-Miocene similar to the outcrops in Spid and Mushakiye bodies. Intrusive and sub-intrusive bodies in these areas are parallel to the general NW-SE trending of the UDMA, and show sharp to gradual contact with the Eocene volcanic

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counterparts (Fig. 2). The maximum activity of magmatism is related to eruptions of trachybasalt, andesite, dacite, ignimbrite and tuff during Eocene (Hajian, 1977; Nogole-Sadate, 1978). Verdel et al. (2011) reported LA-ICP-MS age data from some volcanic sections of the study area as 54.7–44.3 Ma which are in line with early Eocene (Ypresian–Lutetian) and the Late Eocene (Priabonian) reported fossils (Hajian, 1977). The same authors show significant discrepancy with the previously reported ages of the volcanic units (i.e., 26.0 ± 1.6 Ma; Ghorbani and Bezenjani 2011) through K-Ar isotopic method. Raeisi et al. (2019) and Babazadeh et al. (2022) recorded 24-19 Ma for the gabbroic to granodioritic, and ~ 17.5 Ma for gabbroic dikes crop out at 60 km north of the study area. The investigated region, from the bottom to the top the host units are composed of conglomerate, marl and sandstone (unit E1), ignimbrite, tuff, and sandy limestone that contain nummulite (unit E2), combination of green rhyolitic to dacitic tuff with marl, shale, sandstone and limestone (unit E3), red to dark brown tuff and dark lava (unit E4), green tuff, sedimentary strata and rhyolite (unit E5) and basalt, andesite and dark tuff interlayered with nummulitic limestone (unit E6) (Mirnejad et al., 2019).

Field observations and petrography

Spid and Mushakiye plutons are shallow and affected by tectonically reverse and dextral fault movements which resulted in the thrusting of the Eocene volcano-sedimentary series over the Oligocene Qom formation and/or the Pliocene conglomerate (Figs. 3a to d).

Based on the field and petrographic observations, intrusive rocks are classified into three groups: diorite, quartz diorite and to lesser extent, quartz monzo-diorite (Figs. 4a and b). The Spid area is composed of Eocene volcanic units that are surrounded by intrusive rocks (Hajian, 1977). The extrusive rocks such as tuff and lavas include dacitic to andesitic compositions. Quaternary

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alluvial deposits cover the southern and western sections of the intrusive rocks. Iron mineralization in the form of oxide ores (hematite and oligiste) and iron hydroxides (limonite and goethite) are found at the contact between the Miocene plutonic rocks and the Eocene volcanic rocks. Field studies and structural interpretations in the Spid area indicate that most faults have NW-SE and E-W trends and revealed direct relationship with the mineralization and alteration processes.

The composition of Spid is mainly granular quartz diorite to diorite (Figs. 4c and d) and includes plagioclase (55-60 vol.%), quartz (0-5 vol.%), alkali feldspar (10-15 vol.%) and amphibole (10-15 vol.%) (Fig. 4a). Accessory minerals are apatite, Fe-Ti oxide and opaque. Orthoclase is experiential as euhedral to anhedral crystals (1.16-0.2 mm) and has partly been altered to sericite. Quartz forms intergranular fine-grained to amorphous crystals (0.6–0.1mm) and fill the spaces between other coarse-grained minerals. Plagioclase is mostly idiomorphic to hypidiomorphic and elongated (4.12–0.13 mm) and shows a textural zone. Sieve texture is observed in some plagioclase crystals. Hornblende is euhedral to subhedral with different grain sizes (3.6 - 0.2 mm) that is altered to chlorite.

Moushakiye pluton with an area of 16 km^2 along NW-SE trending shows homogenous petrologic characteristics. This area includes Eocene volcanic-pyroclastic rocks, tuff and lavas with dacitic to andesitic compositions (Fig 2). These rocks involve plagioclase (45-50 vol.%), K-feldspar (30-35 vol.%), quartz (0-5 vol.%) and hornblende (5-10 vol.%). Accessory minerals are opaque minerals (2-3%), zircon and titanite (Fig. 4). Plagioclases are euhedral to subhedral and tabular crystals (2.6 to 0.3 mm) in shape and shows normal zoning. Quartz minerals make up 0-5 vol.% of the mineral composition and normally occur as small size (0.1 to 0.64 mm) filling the spaces between coarser minerals. K-feldspar ranges from 0.4 to 2.2 mm in size. Idiomorphic and

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pseudomorphic amphibole, as the dominant ferromagnesian mineral, with small to medium size (0.1 to 1.2 mm) and bright green to dim green pleochroism in colour is scattered in a matrix composed of feldspar and quartz. Biotite, as the second ferromagnesian mineral, shows different degrees of chloritization.

Analytical techniques

The fieldwork was conducted in the study area through geological data and sample collection from different rock types. Fifty samples of intrusive rocks were collected for petrographic purposes. In order to carry out laser ablation-inductively coupled plasma-mass spectrometry (LA-ICP-MS) and U–Pb chronologic dating, first, the separation of zircon grains carried out using magnetic separation and conventional heavy liquid methods at the Department of Geology, University of Tabriz. Hand-picking of the zircon done using a binocular microscope, mounted, and polished down to expose the internal structures for LA-ICP-MS analyses at the Key Laboratory of Hefei (China). Concordia diagrams (U–Pb age) and weighted mean computing were carried out using Isoplot/Ex_ver3 software program (Ludwig, 2003). Detailed operating conditions for the laser ablation system and the ICP-MS instrument and data reduction are the same as description by Hou et al. (2009). Laser sampling was performed using an ESI NWR 193 nm laser ablation system. An AnlyitikJena PQMS Elite ICP-MS instrument was used to acquire ion-signal intensities. Helium was applied as a carrier gas. Argon was used as the make-up gas and mixed with the carrier gas via a T-connector before entering the inductively coupled plasma. Each analysis incorporated a background acquisition of approximately 15 s (gas blank) followed by 45 s data acquisition from the sample. Off-line raw data selection and

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integration of background and analyte signals and time-drift correction and quantitative calibration for U–Pb dating were performed by ICPMSDataCal (Liu et al., 2010).

Zircon GJ1 was used as external standard for U–Pb dating and was analyzed twice every 5–10 analyses. Time-dependent drifts of U–Th–Pb isotopic ratios were corrected using a linear interpolation (with time) for every 5–10 analyses according to the variations of GJ1 (i.e., 2 zircon GJ1 + 5–10 samples +2 zircon GJ1; Liu et al., 2010). Uncertainty of preferred values (0.5%) for the external standard GJ1 was propagated to the ultimate results of the samples. In all analyzed zircon grains, the common Pb correction was not necessarily due to the low signal of common ^{204}Pb and high $^{206}Pb/^{204}Pb$. U, Th, and Pb concentrations were calibrated by NIST 610. Concordia diagrams and weighted mean calculations were made using Isoplot/Ex ver3. The zircon Plesovice is dated as unknown samples and yielded weighted mean $^{206}Pb/^{238}U$ age of 337 ± 2 Ma (2SD, n = 12), which is in good agreement with the recommended $^{206}Pb/^{238}U$ age of 337.13 ± 0.37 Ma (2SD; Sláma et al., 2008).

Ten least-altered samples were selected for the whole rock geochemical analyses using ICP–OES and ICP–MS at the Department of Geology and Environmental Earth Sciences, Miami University, Ohio. Major elements were detected with an analytical precision greater than ±2–5%. For earth and trace elements, errors were estimated to be lower than 2% and the precision was higher than 10% (Table 2).

Zircon geochronology

Two samples from the intrusive rocks located in the north-western Salafchegan region were selected for zircon U-Pb geochronology (see U-Pb data in Table 1). The location of the analyzed samples is observed in Fig. 2. Zircons separated from the plutonic rocks in the Salafchegan

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arregion are euhedral to short prismatic crystals, medium size grains (50 - 150 μm long) and exhibit oscillatory zoning and lack of inherited cores (Fig. 5). Some zircons show CL-bright bands that cross-cut oscillatory zoning, but are not terminated at the contact. Zircons have low to relatively high contents of U (67.5 –2231 ppm) and Th (0.23 –1554 ppm) and Th/U ratios are from 0.02 to 29.71. Samples of intrusive rocks in Spid and Moushakiye samples yield the weighted mean ages of 22.70+0.55 Ma (MSWD=2.5, n=9) and 22.38+0.23 Ma (MSWD=2.2, n=14), respectively (Figs. 5a and b).

Geochemistry

Chemical analyses of samples from intrusive rocks in Salafchegan region are represented in Table 2. The samples have moderate to high SiO_2 (59.95–64.04 wt.%) and Al_2O_3 (15.03-16.99 wt.%) concentrations and low to moderate contents of CaO (3.10-6.29 wt.%), Fe_2O_3 (5.80-7.59 wt.%) and MgO (2.3-4.85 wt.%). The samples also have a wide range of Cr (3.60- 25.17 ppm) and V (92.26-186.92 ppm). Based on chemical criteria represented in the alkali-silica discrimination diagram of (Cox and Hawkesworth, 1985), the intrusive rocks are mainly classified into quartz diorite to diorite (Fig. 6a). All samples plot in metaluminous and peraluminous filed with the ASI [=molar Al_2O_3/ (CaO + K_2O+Na_2O)] values of less than 1.24 (i.e., ASI=0.86 to 1.24). On AFM diagram (Irvine and Baragar 1971; Fig. 6b), the data plot in calc-alkaline field. On the SiO_2 vs. FeO_T/(FeO+MgO) (Frost et al., 2001) and Zr+Nb+Ce+Y vs. FeO_T/MgO (Whalen et al., 2006) diagrams, the study samples plot within the fields of unfractionated and I-type granitoids, respectively (Figs. 6c and d).

The chondrite-normalized REE patterns (Sun and Mcdonough, 1989), the study samples are characterized by enrichment in LREE and relatively flat HREE patterns, $(La/Yb)_N$ ratios ranging from 3 to 5.15, $(Sm/Yb)_N$ ratios from 1.59 to 2.22 and lack of Eu anomaly (Eu/Eu*= 0.91-1.18

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(Fig. 7a). Further, negative Nb-Ti-Ta and P together with enrichment in LREE and LILE (e.g., Cs, Rb, and K), and positive Pb anomaly are evident on the primitive mantle-normalized patterns (Fig. 7b). The Rb/Nb ratio is between 2.86 and 6.82 that imply a subduction zone setting (Pearce, 1984).

Discussion

Subduction zones can buffer partial melting to various degrees (Hirose, 1997; Pearce et al., 1994), hence, the variation in LREEs is affected by the source, as observe in the study samples. The lack of negative Eu anomalies on the patterns of Figure 7b and the presence of hydrous ferromagnesian minerals (i.e., amphibole) can be interpreted as the presence of the water content in the magma source that prevents the crystallization of plagioclase feldspar until late stages of fractionation, and also visualize an oxidizing condition in the mantle source. The oxidization state can also be corroborated by the presence of magnetite in the studied samples. The rather flat and unfractionated patterns of M-HREE (Fig. 7a) imply amphibole fractionation (excluding garnet) from a hydrous melt, a signature of arc settings. As shown on rock/primitive mantle diagram, The Salafchegan samples are signified by enrichment in Rb, Th, K, Sr, Pb, and Hf, and depletion in P and Ti, the geochemical signatures that in line with the contribution of continental crustal components in their petrogenesis (Griffin et al., 2002; Zhou et al., 2008) or the enrichment of mantle through subduction and recycling of crustal materials (Fig. 10). On the Nb vs. Y, and Rb vs. Y+Nb diagrams which widely apply to the tectonic classification (Pearce, 1984), the Salafchegan data lie in the arc-related field (Figs. 8a and b).

The arc signature of the study samples can also be confirmed by high Th/Yb (1.97 - 3.21) and La/Yb (4.5 - 7.72) as proposed by Condie (1989), and plotting data on arc field of Th/Yb vs.

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Ta/Yb diagram (Pearce and Peate, 1995; Fig. 10a). The immature signature of continental arc in Salafchehan area during Miocene diagram is shown by plotting the data on of Rb/Zr ratio vs. Nb diagram (Fig. 10).

Two main processes are attributed to the generation of I-type magmas in arc settings including fractional crystallization of primary magma within the crustal chambers (Grove et al., 2003; Wu et al., 2012), and partial melting of a hybrid magma (i.e., sub-continental lithospheric mantle and lower crustal melt) ponded at the base of the continental crust (Hildreth and Moorbath, 1988). Additionally, crustal components can be involved in the melt-derived mantle during ascent or in a magma chamber (Depaolo, 1981; Tepley Iii et al., 2000; Gao et al., 2014).

Some trace element ratios such as Rb/Sr (avg. 0.06), Th/Ta (avg. 18.09), Nb/La (avg. 0.45), Nb/Ce (avg. 0.21) and La/Sm (avg. 3.78) could be very useful to identify settings. The Rb/Sr ratio is criteria for discrimination of mantle–and crust-derived melts since mantle melt signifies by low Rb/Sr ratios (i.e., 0.01-0.1; Hofmann, 1988; Taylor and Mclennan, 1985), whereas, higher Rb/Sr ratios is attributed to the melt-derived crust (i.e., Rb/Sr = 0.12) (Rudnick and Fountain, 1995; Wedepohl, 1995). The Rb/Sr ratios for granitoids in the Salafchegan region range between 0.04 and 0.09. In addition, mantle products are characterized by Nb/La, Nb/Ce, and $(La/Sm)_N$ ratios of 1.01, 0.39 and 1, respectively (Sun and Mcdonough, 1989), whereas they are 0.46, 0.23, and 4.25 in the crustal products (Weaver and Tarney, 1984). Nb/La, Nb/Ce, and $(La/Sm)_N$ ratios for the study intrusive rocks range from 0.34-0.73, 0.17-0.3, and 1.66-3.1, respectively. Judging from our data, the interaction between mantle and crust materials is proposed for the generation of the intrusive rocks, which is a common feature of continental arc granitoids (Pearce, 1996). The mineralogical signatures of the Salafchegan granitoids such as the presence of hydrous ferromagnesian minerals (e.g., amphibole and biotite) together with zircon,

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apatite, and Fe-Ti oxides as accessory minerals, the absence of vestige of metamorphic minerals (e.g., garnet, andalusite, sillimanite and cordierite) and in part, the presence of mafic microgranular enclaves invoke the arc setting that magma went through a minor crustal mixing during ascent to the shallower levels (Barbarin, 1999). Using Sr/Y vs. Y diagram to discriminate between adakitic and non-adakitic nature (i.e., normal calc-alkaline), the igneous rocks lie within the classical volcanic arc field, and away from that of adakite (Fig. 9).

Amphibole and phlogopite are the most common volatile-bearing minerals and are also the major repositories for LILE in the lithospheric mantle. Trace elements can also give us information on the influence of hydrous mineral phases in the melting process, as elements such as Ba and Rb are compatible with phlogopite, whereas Ba, Sr and Rb are only moderately compatible with amphibole. Melts in equilibrium with phlogopite exhibit higher Rb/Sr (>0.1) and lower Ba/Rb (<20) ratios than those from amphibole-bearing sources (Furman and Graham, 1999). In this scenario, the whole-rock data show Rb/Sr ratio less than 0.1 (i.e., 0.04-0.09), and Ba/Rb ratio range between 11 to 32 which are indicate the presence of both amphibole and phlogopite in the mantle source region. However, the most basic samples suggest the presence of amphibole only in their source region.

Implications for the Arabian-Eurasian continental collision

The UDMA was constructed by a sequence of events as follows: (1) the initial phase was signified by the subduction of Neotethys Ocean beneath the Iran (Alavi, 1994; Berberian and King, 1981; Kananian et al., 2014; Mohajjel et al., 2003; Verdel et al., 2011; Babazadeh et al., 2021a; b; 2022) or an island-type arc (Ghorbani, 2006; Ghorbani and Bezenjani, 2011; Shahabpour, 2007) during Triassic-Tertiary (Alavi, 2007; Bagheri and Stampfli, 2008; Berberian

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and King, 1981; Wilmsen et al., 2009); (2) collision of Arabian and Iranian continental plates in Miocene (McQuarrie et al., 2003); and (3) post collision high-K magmatism during mid-Miocene to the present (Chiu et al., 2013; Dargahi et al., 2010; Babazadeh et al., 2019). There appears to be no direct way to date the Arabia-Eurasia collision along Zagros and Bitlis suture zones along the Iran and Turkey, respectively, since late Cretaceous to Pliocene is proposed as an approximate collision time (Berberian and King, 1981; Alavi, 1994; Mohajjel and Fergusson, 2000; McQuarrie et al., 2003; McQuarrie and van Hinsbergen, 2013; Pirouz et al., 2017). Shahabpour (2007) attributed the formation of different Cenozoic sedimentary basins in Central Iran to a change in subduction angle during the subduction of Neo-Tethys oceanic crust beneath Iranian microplate. It was concluded that subduction has been shallow in Oligocene, steep in Oligo-Miocene and then back to shallow in Miocene (Shahabpour, 2007). Moreover, steep subduction led to back-arc extension and the formation of immature arc system in Central Iran during Oligo-Miocene time.

Richards and Şengör (2017) proposed Miocene as the closure time by spreading diachronous from early Miocene in the northwest to late Miocene in the southeast of Iran. Omrani et al. (2008) believes that the Arabian-Eurasia collision occurred in Oligocene (30±5 Ma). The magmatic quiescence of UDMA during the Oligocene - upper Miocene as well as the low magmatic activity due to the slab break-off during Upper Miocene to Plio-Quaternary is the geodynamic model suggested for UDMA by Omrani et al. (2008). Mohajjel et al. (2003) assumed Miocene as the collision time regarding the imbrication and development of blind thrusting and folding in Zagros orogeny belt. Agard et al. (2011) believed that shift arc magmatism from SSZ to UDMA occurred in late Paleocene-Eocene and increased magmatic activity as a result of an oceanic slab subduction below the Iranian plate. The collision between

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Arabian and Eurasia plates was related to Oligocene period followed by a second slab break-off, leading to the formation of adakites in the Central Iran during Mid- to- Late Miocene. Based on this study, the Salafchegan intrusive rocks (ca. 22 Ma) represent a subduction by which a magmatic system is generated in an arc setting before collision between the Arabian and Eurasia plates. Accordingly, a straightforward interpretation of magmas in Salafchegan region is that the cold and rigid down-going slab could have essentially dehydrated yielding water to the overlying mantle wedge. Descending slab migrating backwards in the mantle (rollback) resulted in strong upwelling of the hot juvenile mantle to a relatively shallow level (<80 km). This prompted heating and erosion of the uppermost, and particularly the metasomatized mantle wedge which was dragged along in the upwelling limb of the flow and fostered adiabatic decompression melting. It is logical that the magma production in the continental arc settings is a result of rapid passage through a relatively thin overlying lithospheric sequence. With the continuous supply of hot mantle-derived magmas, the basic melts have interacted moderately with the overlying crustal component enroute to the surface, experiencing limited AFC processes to form the Salafchegan plutonic rocks.

Conclusion

The intrusive rocks located in the Salafchegan region are composed of quartz diorite to diorite. Zircon LA-ICP-MS U-Pb ages display a mean of 22.04+0.25 Ma and 22.38+0.23 Ma for the quartz-diorite and diorite phases, respectively. All magmatic phases that form the intrusive rocks are metaluminous to slightly peraluminous, and characteristic of I-type granites. These rocks are classified into magnesian series with calc-alkaline affinity which are in line with oxidized I-type volcanic arc granitoids. The study rocks are characterized by LREE enrichment patterns and high LREE/HREE ratios, negative Nb-P- Ti, and lack of negative Eu anomalies. Field observations,

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mineral composition and geochemical studies demonstrate that all intrusive rocks are co-magmatic. It is important to note that the intrusive rocks outcropped in the Salafchegan region do not show any affinities for adakitic magmas but have characteristics similar to that of normal arc magmas. Based on petrography and geochemical analysis, it can be concluded that the Salafchegan region is developed from the interaction between magmas derived from the partial melting of the lower crust and the lithospheric mantle, respectively. New LA-ICP-MS U-Pb zircon dating confirms that granitoids are formed in the NW of the Salafchegan region and show a pre-collision stage of an orogenic cycle.

Figures

Fig. 1. Salafchegan intrusive locality on the Urumieh-Dokhtar magmatic arc - Simplified geological map of Iran after (Nabavi, 1976; Stoecklin, 1968).

Fig. 2. Local Geology map of the Salafchegan intrusive rocks.

Fig.3. Field relationships in the Spid and Mushakiye granitoids. (a-b) The emplacement of a plutonic body and volcanic units due to reverse and dextral fault movements (c-d) Close-up view of the plutonic body and the hand specimen.

Fig.4. Petrographic characteristics of different rock types of the Spid and Mushakiye granitoids.(a-b) sub-granular diorite with mainly plagioclase minerals (Pl), less quartz (Qz), K-feldspar (Kfs), and mafic mineral; biotite (Bt) and hornblende (Hbl) minerals, Mushakiyestock. (c) Sub-granular to granular quartz-diorite containing plagioclase, hornblende and opaque minerals (Opq),Spid stock. (d). (Mineral abbreviations after (Whitney and Evans, 2010).

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Fig. 5. Zircon concordia diagrams, intrusive rocks in Spid area yield the age of 22.70+0.55 Ma (MSWD=2.5) and Moushakiye plutonic rocks return to the ages of 22.38+0.23 Ma (MSWD=2.2).

Fig. 6. The classification diagrams for the Salafchegan intrusive bodies (a) SiO_2 vs. K_2O+Na_2O diagram (Cox and Hawkesworth, 1985), the studied samples ranges plot in diorite to granodiorite fields; (b) AFM ($A=Na_2O+ K_2O$, $F=FeO_t$, M= MgO) diagram. The differentiation lines adopted from Irvine and Barager (1971). The Salafchegan samples show a calc-alkaline affinity. (c and d) $FeO_t/(FeO_t+MgO)$ vs. SiO_2 and FeO_t vs. Zr+Nb+Ce+Y discrimination diagrams for I-, S- and A-type granitoids (Whalen et al., 2006).

Fig. 7. (a) Chondrite-normalized REE patterns (Nakamura et al., 1974), (b) Primitive mantle normalized patterns (McDonough and Sun, 1995).

Fig. 8. Geotectonic discrimination plots; showing the arc tectonic setting of the Salafchegan intrusions (After Pearce, 1982).

Fig. 9. (a). Sr/Y vs. Y (ppm) diagram (Defant and Drummond, 1990); the study samples lie in the classical (normal) arc or calc-alkaline field. (b). La/Sm vs. Sm/Yb diagram.

Fig. 10. (a). Ta/Yb vs. Th/Yb diagram (Pearce 1983). (Sho: shoshonite; Tho: tholeiite; Calc-alk: Calc-alkalin). (b) Arc maturity model (Brown, 2013) in Rb/Zr vs. Nb diagrams.

Fig. 11. The Nb-Y-Ga ternary diagram (Eby, 1992); the Salafchegan magmatic rocks formed as a result of mantle–crust interference.

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