Transition from Paleogene Normal Calc-Alkaline to Neogene Adakitic-Like Plutonism and Cu-Metallogeny in the Kerman Porphyry Copper Belt: Response to Neogene Crustal Thickening

B. Shafiei, J. Shahabpour, and M. Haschke

Abstract

Tertiary magmatic activities in the Kerman porphyry copper belt (KPCB) formed two contrasting episodes of granitoids: (1) Jebal Barez-type (late Eocene-early Miocene) associated with extensive calc-alkaline/shoshonitic volcanism but without and/or with only minor Cu-mineralization, and (2) Kuh Panj-type (middle Miocene-Pliocene) associated with major porphyry copper mineralization. Neogene granitoids exhibit high Sr (406-1015 ppm) and low Y (<18 ppm) contents, moderately high REE fractionation (La/Yb=19-53) and lack of negative Eu anomalies (Eu/Eu*≤1) which is comparable with the adakitic-like magmas, when compared with Jebal Barez-type normal calc-alkaline granite (Sr=184-576 ppm; La/Yb<14.7; Eu/Eu*<1). The magmatic evolution from normal calc-alkaline in Paleogene to adakitic-like signature in Neogene which is reflected in an increase in REE fractionation can be interpreted by progressive increase in pressure and the availability of water at the lower crustal site of magma generation. These processes can be in response to crustal thickening related to excessive compressional tectonic regime during the late stages of arc development in a post-collisional tectonic setting. From the metallogenetic point of view, increasing the oxidizing conditions at the lower crustal site of melt generation due to the amphibole breakdown during Neogene crustal thickening and also declining of volcanism in this time were two critical determinants on development of porphyry copper metallogeny in Kerman region.

Keywords: Granitoids; Petrogenesis; Cu-metallogeny; Kerman; Iran

Introduction

Tertiary magmatic activities in Kerman arc segment as southeastern part of the Urumieh-Dokhtar Tertiary magmatic arc [28,61,67,68] led to the formation of two episodes of intrusions [20]: (1) Jebal Barez-type and (2)
Kuh Panj-type. Intrusive bodies in the Kerman arc segment show a linear trend from the northwestern (Dehaj area) to the southeastern (Jebal Barez area) parts (Fig. 1). Field relations [20,61] together with available radiometric data [15,46] indicated that intrusive activity in the Kerman arc segment began in the late Eocene with Jebal Barez-type intrusions; however the main development of these intrusions took place during the Oligocene in the central and southeastern parts (Table 1). Jebal Barez-type intrusions form the batholith and stock-size bodies and show a crystalline texture with a wide fractionation trend from gabbro, diorite, quartz diorite, quartz monzonite, monzonite, granodiorite to granite (Table 1). In contrast, Kuh Panj intrusions formed during the middle-late Miocene and the early Pliocene and mainly developed as stocks with porphyritic texture and restricted compositional range from diorite, quartz diorite to granodiorite, and locally quartz monzonite (Table 1). According to the geological data together with available radiometric dating (Table 1), Kuh Panj-type intrusions are associated with extensive porphyry copper mineralization; consequently is formed a porphyry copper belt on Kerman arc segment which is called Kerman porphyry copper belt (KPCB). In contrast, no porphyry copper deposits have been reported associated with Jebal Barez-type intrusions (Tables 1 and 2). In several previous regional studies in the Kerman arc segment [2,20,28,45,46,52,61,68] geochemical characteristics of these granitoids have not been addressed in detail. In present study, we used new geochemical and Sr and Nd isotope data of both granitoid episodes (Kuh Panj and Jebal Barez) to identify their geochemical characteristics, and discuss their possible magma sources. We found fundamental signatures in composition, style, etc of both granitoid types that allow us to identify how this magmatism is related in Neogene time to porphyry copper mineralization in the KPCB and introduce the discrimination diagrams to distinguish productive granitoids from non-productive granitoids.

**Geochemistry**

For present study, data was obtained from a new petrochemical database of 37 relatively unaltered samples from both granitoid suites (Jebal Barez and Kuh Panj) throughout the KPCB.

**Sampling Method and Sources of Data**

For present study four criteria were utilized to select representative samples from both granitoid types in the KPCB: (1) the specific porphyritic intrusions which were most closely related to the copper mineralization (Kuh Panj granitoids or ore-hosting porphyries) and fully crystalline intrusions which were barren (Jebal Barez granitoids), (2) samples with the same composition range from both intrusive types (diorite, quartzdiorite, granodiorite), and (3) samples with minimum effects of hydrothermal alteration and weathering. Using these criteria, drill core and outcrop sampling focused on the freshest samples of intrusive rocks and a set of 210 samples predominantly from Kuh Panj granitoids as well as Jebal Barez granitoids were collected throughout the KPCB. Petrographic observations and the loss on ignition (L.O.I. wt. %=H2O+CO2) assessment were used to select 90 the freshest samples among 210 samples with the least alteration. For present study, thirty-seven samples (15 samples from Kuh Panj granitoids and 22 samples from
Jebal Barez granitoids) mostly with ≤3% L.O.I. [47] were chosen as relatively unaltered samples and prepared for major and trace element analysis and isotope ratios measurement. Major elements analyzed by Inductively-Coupled Plasma-Atomic Emission Spectrometer (ICP-AES) method with detection limit of 0.01% and trace elements analyzed by Inductively-Coupled Plasma-Mass Spectrometer (ICP-MS) method with detection limit of 0.01 ppm, following lithium meta-borate fusions and HNO₃ total digestion, in the ALS Chemex Laboratory group Ltd, B.C., Canada. Analytical error for most elements is less than 2%. Samples description and whole-rock chemical analyses are available via senior author's e-mail.

The Sr and Nd isotopic compositions for mineral separates (feldspar) and whole-rock samples from selected ore-hosting porphyries and barren intrusions were determined using a GV IsoProbe-T multi-collector thermal ionization mass spectrometer at the Isotope Geology and Geochemistry Laboratory in the

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**Figure 1.** a) Inset showing the regional distribution of Cenozoic magmatic belt (Urumieh-Dokhtar arc) and location of the KPCB in simplified geologic map of Iran. b) Simplified geologic map of the KPCB and three main litho-tectonic zones and regional distribution of two granitoid groups (modified from Dimitrijevic [20], Rio Tinto Ltd. [61], and Alavi [3]).
Table 1. The summary of age relationships between two intrusive episodes and Cu-mineralization in the Kerman porphyry copper belt

<table>
<thead>
<tr>
<th>Plutonic episode</th>
<th>Location &amp; lithology of intrusions</th>
<th>Stratigraphic age (Contact relationships)</th>
<th>Absolute age (Radiometric dating)</th>
<th>Age of Cu-mineralization (Based on available radiometric dating)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kuh Panj-type</td>
<td>These plutonic bodies exposed mainly in central and northwestern parts of KPCB (e.g., Dehaj area: Jlu-Serau, Gowd Colvari, Kader bodies; Shahr Babak area: Meiduk, Sara, Abdar bodies; Sardiyeh area: Daralhe, Sarmeshk, Bondar Hanza, Surakh Mar bodies; Baft area: Kuh Shah, Lalehzar bodies; Chahar Gonbad area (Kuh Panj body; Pariz area: Sarcheshmeh, DareZar, Sarkuh bodies), which emplaced in shallow-crustal levels (sub-volcanic), Kuh-Panj granitoids have a composition range from diorite, quartzdiorite, tonalite, granodiorite, and quartzmonzonzite and their texture is porphyritic.</td>
<td>Intruded into mid to late Eocene and Oligocene volcanic rocks (Razak and Hazar complexes). Miocene volcanics are absent in these regions except in the northeastern part of Baft area.</td>
<td>3.4±1.0 Ma (40Ar/39Ar biotites from barren biotite porphyry (granodiorite) dike at Sar Cheshmeh mine). 7.3±0.3 Ma (U-He on zircons from porphyritic intrusive rocks at Abdar non-economic deposit). 7.5±0.1 Ma (U-Pb on zircons from porphyritic intrusive rocks at Abdar non-economic deposit). 8.5±0.4 Ma (K-Ar on biotites from barren granodiorite dikes at Sar Cheshmeh mine). 10.9±0.4 Ma (U-He on zircons from porphyritic intrusive rocks at Abdar non-economic deposit). 12.4±0.2 Ma (Rb-Sr on whole rocks of barren porphyry dikes from Meiduk mine). 12.5±0.1 Ma (U-Pb on zircons from porphyritic intrusive rocks at Meiduk mine). 12.5±0.5 Ma (U-Hf on zircons from porphyritic intrusive rocks at Meiduk mine). 12.5±0.5 Ma (K-Ar on biotites from the freshest samples of Sar Cheshmeh porphyry stock at Sar Cheshmeh mine). 13.3±1.1 Ma (40Ar/39Ar on hornblende biotitized andesite, at Sar Cheshmeh mine). 13.6±0.1 Ma (U-Pb on zircons from porphyritic intrusive rocks at Sar Cheshmeh mine).</td>
<td>4.9±0.4 Ma (U-He on apatites from potassic alteration zone at Abdar non-economic deposit). 8.7±0.5 Ma (40Ar/39Ar on whole rocks from potassic alteration zone, biotitized andesite, at Sar Cheshmeh mine). 9.2±0.9 Ma (40Ar/39Ar on whole rocks from potassic alteration zone, biotitized andesite, at Sar Cheshmeh mine). 10.8±0.4 Ma (40Ar/39Ar on sericite from phyllic alteration zone at Meiduk mine). 11.8±0.6 Ma (40Ar/39Ar on biotites from argillic alteration zone at Sar Cheshmeh mine). 11.2±0.5 Ma (40Ar/39Ar on k-feldspars and biotites from potassic alteration zone at Meiduk mine). 12.1±0.6 Ma (K-Ar on biotites from potassic alteration zone, biotitized andesite, at Sar Cheshmeh mine). 12.2±1.2 Ma (Rb-Sr on biotites and whole rocks from potassic alteration zones at Sar Cheshmeh mine).</td>
</tr>
<tr>
<td>Jebal Barez-type</td>
<td>These bodies developed along the entire length of the KPCB, especially in central and southeastern parts. The Jebel Barez granitoids are mainly batholite-size, which emplaced in abyssal and hypabyssal crustal level. Their texture is fully crystalline (granite and monzonite). These intrusive bodies are varies in composition from gabbro to granite.</td>
<td>With exception a few granitoid bodies (in southeastern parts of Sardiyeh and southwestern parts of Khanhe Khutan area) that intruded only to mid stratigraphic levels of Eocene volcanic-sedimentary successions (Bahr Asman and Razak complexes) and unconformable overlain by volcanioclastic units of uppermost parts of these complexes, the most of Jebel Barez granitoids intruded into Oligocene to Miocene successions (Qom marine formation).</td>
<td>18. and 24 Ma (Rb-Sr on whole rocks from Jebel Barez granitoids in southeastern part of KPCB). 16.9±0.2 Ma (40Ar/39Ar on hornblendes from barren granitoids, Chenar, in southeastern part of Shahr Babak area). 17.9±0.2 Ma (40Ar/39Ar on hornblendes from barren granitoids, Chenar, in southeastern part of Shahr Babak area). 18.1±0.7 Ma (40Ar/39Ar on k-feldspars from barren granitoids, Chenar, in southeastern part of Shahr Babak area). 18.3±0.2 Ma (40Ar/39Ar on k-feldspars from barren granitoids, Chenar, in southeastern part of Shahr Babak area). 29.0±0.2 Ma (K-Ar on hornblendes from barren granodioritic body, Archandor, in northern part of Pariz area). 29.3±0.2 Ma (U-Pb on zircons from Rigan granitoids in southeastern part of KPCB). 29.7±0.3 Ma (U-Pb on zircons from Rigan granitoids in southeastern part of KPCB).</td>
<td>1. Conrad et al. [15]; 2. Dimitrijevic [20]; 3.Ghorashi-Zadeh [22]; 4. Hassanzadeh [28]; 5. Mclnnes et al. [45,46]; 6. Rio Tinto Ltd. [61]; 7. Shafiei [67]; 8. ShahabPour [69].</td>
</tr>
</tbody>
</table>
Table 2. The inferred timing of pluton emplacement and porphyry copper mineralization in the Kerman porphyry copper belt based on available radiometric dating and stratigraphic ages [67]

<table>
<thead>
<tr>
<th>Age of pluton emplacement</th>
<th>Rock types</th>
<th>Main texture</th>
<th>Mafic minerals</th>
<th>Cu-Mineralization</th>
<th>Coeval volcanism</th>
</tr>
</thead>
<tbody>
<tr>
<td>middle Miocene-Pliocene</td>
<td>Diorite to granodiorite</td>
<td>Porphyritic</td>
<td>Hb + Bt = CPx</td>
<td>Increasingly Hb + Bt assemblies</td>
<td>Major Cu = (Mo, Au)</td>
</tr>
<tr>
<td>(Kuh Panj-type)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Eocene-Oligocene</td>
<td>Gabbro to granite, Monzodiorite to quartz-monzonite and syenite</td>
<td>Equigranular, (locally porphyritic)</td>
<td>O + CPx + Hb + Bt</td>
<td>Increasingly Hb + Bt assemblies</td>
<td>trace</td>
</tr>
<tr>
<td>(Jebal Barez-type)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3. The summary of geological evolution in the Kerman porphyry copper belt

<table>
<thead>
<tr>
<th>Period</th>
<th>Manifestations in the Kerman porphyry copper belt</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plio-Quaternary</td>
<td>Alkaline mafic volcanism, The youngest manifestations of volcanic activity in KPCB, related to [28,68]</td>
<td>[20,28,52,67,68,69]</td>
</tr>
<tr>
<td>Mio-Pliocene</td>
<td>Northwestward migration of magmatic arc, extensive emplacement of shallow-level intrusive bodies, remarkable regional uplift, erosion, exhumation and major phase of porphyry copper mineralization, development of two regional pediplains in northwestern parts of the KPCB, A major bi-modal (mafic to felsic) volcanic gap but extensive intermediate to felsic (silicic) volcanism and formation of some large stratovolcanos, cones, plugs and neck in central and northwestern parts of the KPCB, Inverting of ensialic fore-arc and back-arc extensional basins into retro-arc basins because of compressional regime during Neogene time,</td>
<td>[3,20,28,52,68]</td>
</tr>
<tr>
<td>Oligo-Miocene</td>
<td>Commencing of compressional tectonic regime, shortening, remarkable unconformities and deformation of older strata, Developments of arc-parallel dextral strike-slip and reverse faulting, Cessation of volcanic activities, Widespread emplacement of abyssal to hypabyssal igneous intrusions in KPCB associated with non-significant porphyry copper mineralization.</td>
<td>[3,20,52,68]</td>
</tr>
<tr>
<td>upper Eocene-Oligocene</td>
<td>Shoshonitic volcanism (Hezar complex), with 1.3 to 1.5 km thick, situated conformable over the Razak volcanic complex, exposed in the parts of the KPCB (Shahr Babak-Bardsir-Rayen regions) in extensional basins,</td>
<td>[20,28,50,61,68]</td>
</tr>
<tr>
<td>middle-upper Eocene</td>
<td>Extensive bi-modal, calc-alkaline volcanism (Razak complex), up to 2 km thick, sequences of volcanics (mafic to felsic) with intercalated sediments, unconformable and over thrust over middle Eocene sedimentary complex and ophiolite assemblages, exposed throughout most of the KPCB from the northwestern part (Anar and Dehaj area) to the southwestern parts (Sabzevaran, Jebal Barez and Hana area), Initiation of plutonic events in southeastern parts of the KPCB,</td>
<td>[2,20,28,52,68]</td>
</tr>
<tr>
<td>middle Eocene</td>
<td>Development of flysch-turbidite trough unconformable over Bahr Aseman volcanic complex (extensional basins) in central and southeastern parts of the KPCB,</td>
<td>[20,52]</td>
</tr>
<tr>
<td>lower-middle Eocene</td>
<td>Calc-alkaline (locally tholeiitic) volcanism (Bahr Aseman complex), about 7 km thick, sequences of volcanics (mafic to felsic) with intercalated sediments, unconformable and over thrust over lower Eocene complex and upper Cretaceous ophiolite assemblages, exposed in southeastern part of Kerman, in Sarduiyeh and Khaneh khatun area, in Rafsanjan region in central part of this belt and in Anar and Shah Babak region in northwestern part of the KPCB,</td>
<td>[2,20,28,68]</td>
</tr>
<tr>
<td>Lower Eocene</td>
<td>Development of inboard and outboard extensional basins in the KPCB region, Flysch trough developed in northwestern part of the KPCB region (Anar-Shahr Babak- Rafsanjan area), with possibility continuous extension to the central part of the region (Baf-Bardsir area), Unknown base, Tectonically contact with older strata (upper Cretaceous turbidites-flyschs and ophiolitic assemblages,</td>
<td>[20,52]</td>
</tr>
<tr>
<td>Paleocene</td>
<td>Deposition of Kerman Conglomerate Unconformable over upper Cretaceous (Cenomanian) flysch and/or ophiolites.</td>
<td>[20]</td>
</tr>
<tr>
<td>Upper Cretaceous</td>
<td>Deposition of upper Cretaceous turbidites -flyschs (Anar-Bardsir flysch trough) and emplacement of ophiolitic assemblages (Shahr Babak - Baf tectonized ophiolite belt), which corresponds to the north-eastern and southern parts of the KPCB, respectively.</td>
<td>[20,52,68]</td>
</tr>
</tbody>
</table>
Massachusetts Institute of Technology (MIT), Cambridge, USA. The feldspar (phenocrysts) grains of seven of the relatively unaltered samples from both Kuh Panj and Jebal Barez granitoids were separated using conventional heavy liquid (CHBr₃ MERCK; Boromoform), combined with Frantz magnetic separator as well as hand picking. Feldspar mineral fractions were used for Sr (seven samples) isotope measurements. Also, seven of the relatively unaltered whole-rock samples were measured for Nd isotopic ratio. The whole-rock and mineral Sr and Nd isotope compositions of the Kuh Panj and Jebal Barez granitoids are presented in Table 4.

### Table 4. Sr and Nd isotopic ratios of separated feldspar minerals and whole rock samples of Jebal Barez-type and Kuh Panj-type granitoids from the Kerman porphyry copper belt

<table>
<thead>
<tr>
<th>Sample</th>
<th>Sr/Sr⁰</th>
<th>Std err.(2σ%)</th>
<th>Nd/⁴⁴Nd</th>
<th>Std err.(2σ%)</th>
<th>Sample location and description</th>
</tr>
</thead>
<tbody>
<tr>
<td>SCP</td>
<td>0.704702</td>
<td>0.000008</td>
<td>0.512716</td>
<td>0.000003</td>
<td>Kuh Panj-type granitoids, Sar Cheshmeh porphyry stock, Granodiorite</td>
</tr>
<tr>
<td>MP</td>
<td>0.704550</td>
<td>0.000006</td>
<td>0.512750</td>
<td>0.000006</td>
<td>Kuh Panj-type granitoids, Meiduk porphyry stock, Granodiorite</td>
</tr>
<tr>
<td>IJP</td>
<td>0.704253</td>
<td>0.000007</td>
<td>0.512812</td>
<td>0.000005</td>
<td>Kuh Panj-type granitoids, lju porphyry stock, Quartzdiorite</td>
</tr>
<tr>
<td>KPP</td>
<td>0.704853</td>
<td>0.000008</td>
<td>0.512653</td>
<td>0.000004</td>
<td>Kuh Panj-type granitoids, Kuh Panj porphyry stock, Quartzdiorite</td>
</tr>
<tr>
<td>GGB</td>
<td>0.706810</td>
<td>0.000006</td>
<td>0.512596</td>
<td>0.000004</td>
<td>Jebal Barez-type granitoids, southwestern part of Jebal Barez map, Granodiorite</td>
</tr>
<tr>
<td>GSV</td>
<td>0.705336</td>
<td>0.000006</td>
<td>0.512667</td>
<td>0.000004</td>
<td>Jebal Barez-type granitoids, southeastern part of Sarduiyeh map, Granodiorite</td>
</tr>
<tr>
<td>GSD</td>
<td>0.706153</td>
<td>0.000005</td>
<td>0.512873</td>
<td>0.000005</td>
<td>Jebal Barez-type granitoids, southeastern part of Sarduiyeh map, Granodiorite</td>
</tr>
</tbody>
</table>

Results

**Chemical Composition and Classification**

The processing of geochemical data of major elements from two episodes of Tertiary granitoids indicates that both granitoid types have SiO₂ and Al₂O₃ contents from ~59 to ~66, and ~14.7 to ~18 wt.%, as well as a compositional range from diorite, quartz diorite to granodiorite and quartz monzonite. Kuh Panj-type granitoids are richer in Na₂O (3.5-4.8 wt. %) relative to Jebal Barez-type granitoids (2.8-4.2 wt. %). Their K₂O/Na₂O ratio is mainly low (0.3-0.7) in comparison with Jebal Barez-type granitoids (0.1-1).

Kuh Panj-type granitoids have Mg numbers [(Mg=#100×MgO/(MgO+FeO+Fe₂O₃)] between 38 and 49, whereas Mg# of Jebal Barez-type granitoids is slightly higher (37-53). Most Kuh Panj granitoids are per-aluminous (A/ CNK=0.94-1.32), whereas Jebal Barez granitoids are mostly meta-aluminous (A/CNK=0.87-1.08) (Fig. 2a). Both granitoid types plot within calc alkaline as well as alkali calcic fields (Fig. 2b) and all belong to I-type granitoids series (Fig. 2c). From the tectonic setting point of view, Kuh Panj granitoids have been characterized as orogenic granitoids relative to Jebal Barez-type granitoids which show mantle-fractionation signature (Fig. 2d). This is consistent with their wide compositional range in comparison with restricted range of Kuh Panj intrusions. Also, Kuh Panj granitoids lie within a continental margin arc field (Fig. 2e), and mostly plot in a post-collisional field, whereas Eocene-Oligocene Jebal Barez granitoids belong to island arc setting and pre-plate collision environments (Fig. 2f). However, the post-collisional tectonic setting of Mio-Pliocene Kuh Panj granitoids is consistent with tectonic evolution history of the Urumieh-Dokhtar magmatic arc and indicates that these granitoids have been formed when the subduction was ended and the orogenic conditions had governed the magmatic arc. The Kuh Panj granitoids exhibit overall low Ni and Cr contents (Ni=12-30 ppm; Cr=20-53 ppm) compared with Jebal Barez granitoids (Ni=36-98 ppm; Cr=30-71 ppm). They have high Sr concentrations (406-1015 ppm), low Y contents (5-18 ppm), and moderately high Sr/Y ratios (33.5-115) in comparison with Jebal Barez granitoids (Sr=184-575 ppm; Y=12-29 ppm; Sr/Y ratio <32) (Fig. 3).

Cl-normalized REEs variation patterns (Fig. 4) of Tertiary granitoids show steep profiles through light-REEs (LREEs:La-Nd), middle-REEs (MREEs:Sm-Er) and heavy-REEs (HREEs) without negative Eu anomalies for Kuh Panj granitoids in comparison with Jebal Barez granitoids (steep LREEs profiles, flattening...
Transition from Paleogene Normal Calc-Alkaline to Neogene Adakitic-Like Plutonism and MREEs and HREEs profiles, negative Eu anomalies. These patterns reflect significant REE fractionation (LaCN/YbCN = 19-53), greater LREEs-MREEs enrichment (LaCN/SmCN = 6-15) and moderately high heavy-REE depletion (Yb = 0.36-1.54; SmCN/YbCN = 2-7; GdCN/YbCN = 1.82-5.42) and without negative Eu anomalies (Eu/Eu* :::: 1) of Mio-Pliocene Kuh Panj granitoids relative to Jebal Barez-type granitoids (Yb = 1.3-3.38; LaCN/SmCN = 2.33-9.73; LaCN/YbCN = 2.45-14.7; SmCN/YbCN = 1.05-2.31; GdCN/YbCN = 1.13-1.92) (Fig. 5).

Following the criteria proposed by Defant and

Drummond [17], and Martin et al. [43], with the exception of the moderately low contents of Ni and Cr, and moderate Mg#, many geochemical features of the Kuh Panj-type rocks in the KPCB such as high Sr (>406 ppm), low Y (<18 ppm), low Yb (<1.5 ppm) contents, and moderately high Sr/Y ratios (>33.5) are similar to adakitic rocks. Based on Sr/Y vs. Y discrimination diagram Kuh Panj-type granitoids plot mostly in the adakitic field, whereas Jebal Barez-type granitoid fall in normal calc-alkaline field (Fig. 6).

Figure 2. Geochemical and tectonic classification of Tertiary granitoid suits of the KPCB: a) A/NK vs. A/CNK diagram [42] (A/NK = molar Al2O3/(Na2O+K2O); A/CNK = molar Al2O3/(CaO+Na2O+K2O), b) Na2O+K2O-CaO vs. SiO2 diagram or alkali-lime index plot [21]; c) Na2O vs. K2O diagram [74], d) FeOt vs. Zr+Nb+Ce+Y diagram [73], e) Rb vs. Zr diagram [11]; f) R1 vs. R2 diagram [7] (R1=4Si-11 (Na+K)-2(Fe+Ti); R2=5Ca+2Mg+Al).
Figure 3. Plots of (a) Sr and (b) Y vs. SiO₂ of two Tertiary granitoid types from the KPCB.

Figure 4. Comparative Cl-normalized REE patterns of two Tertiary granitoid types from the KPCB. Chondrite normalizing factor from Sun and McDonough [70].
Transition from Paleogene Normal Calc-Alkaline to Neogene Adakitie-Like Plutonism and...

Figure 5. Plots of light and heavy REEs ratios variations vs. SiO$_2$ of two Tertiary granitoid types from the KPCB.

Figure 6. Y vs. Sr/Y discrimination diagram [17] for two Tertiary granitoid types from the KPCB. Samples indicated in adakites field are host intrusions related to Kerman major porphyry copper deposits include: SCP: Sar Cheshmeh porphyry stock (Sar Cheshmeh deposit); MP: Meiduk porphyry stock (Meiduk deposit); DZP: Darreh Zar porphyry stock (Darrehzar deposit); SKP: Sar Kuh porphyry stock (Sar Kuh deposit); SP: Sara porphyry stock (Sara deposit); IJP: Iju porphyry stock (Iju deposit); SNP: Serenu porphyry stock (Serenu deposit); GKP: God-e-Kolvary porphyry stock (God-e-Kolvary deposit); KDP: Kader porphyry stock (Kader deposit); NP: Now Chun porphyry stock (Now Chun deposit); DAP: Dar Alu porphyry stock (Dar Alu deposit); ABDP: Abdar porphyry stock (Abdar deposit); LZP: Lalleh Zar porphyry stock (Lalleh Zar deposit); RAMP: Razi Abad-Madin porphyry stock (Razi Abad-Madin deposit); KPP: Kuh Panj porphyry stock (Kuh Panj deposit).
Sr and Nd Isotopic Compositions

The Kuh Panj granitoids show narrow range of relatively nonradiogenic $^{87}\text{Sr}/^{86}\text{Sr}$ ratio (0.704253-0.704800) when compared with Jebal Barez granitoids ($^{87}\text{Sr}/^{86}\text{Sr}=0.705336-0.706810$). $^{143}\text{Nd}/^{144}\text{Nd}$ ratios of both granitoid types range from 0.512596 to 0.512873. The wide range and more radiogenic Sr isotopic ratios of Jebal Barez granitoids is consistent with generated magmas under crustal fractional crystallization and assimilation processes. In comparison, the relatively non-radiogenic $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of Kuh Panj granitoids show that the upper parts of crusts could not play a significant role in generating these magmas; rather, we have to look for their source in lower (deep) crust, mantle and/or oceanic crust.

Discussion

Trace element concentrations in igneous rocks provide information on the chemical compositions of the source rocks and changes in the melt source regions/or melt residue (such as, minerals fractionation), both at the site of melt-generation or in magma chambers. Among trace elements, MREEs (Sm-Er), HREEs (Tm-Yb-Lu), Y, Eu and Sr have been introduced as petrogenetic indicators [10,30,62]. It is generally accepted that MREEs are accommodated most readily in hornblende [13,30,58,62], whereas MREEs (Tm, Yb, Lu) and Y have similar behavior and preferably enter into garnet and, to a lesser degree, into amphibole; whereas, the MREEs (Sm-Er) are accommodated most readily in amphibole [30,62], Eu$^{2+}$ behaves similarly to Sr and both widely substitutes for Ca$^{2+}$ in plagioclase [30,62]. Meanwhile, REE ratios (La/Yb, Sm/Yb) serve as a guide to pressure-sensitive residual mineral assemblages at the depth that magma is generated and also melting percentages of the source [26,35]. These correlations assume that the melts are equilibrated with and reflect the source minerals of a hydrous mafic crust-mantle boundary region showing melting, assimilation, storage, and homogenization processes [31]. The higher La/Yb ratios ($>20$) indicate more HREEs (Yb) and Y retention by garnet and amphibole in the residue [26,36]. Garnet is generally thought to be stabilized in basalts at pressures of $\geq 12$ kbar (or $\geq 40$km crustal thickness) [56,64]. In contrast, lower La/Yb ratios generally indicate lower-pressure conditions. Therefore, systematic changing of REE ratios of arc magmas help to constrain the amount and timing of arc crustal thickening and magma source region [26].

Present study indicated that Neogene ore-hosting porphyries (Kuh Panj granitoids) of the KPCB show a geochemical affinity with adakites, whereas Eocene-Oligocene barren intrusions belong to normal calc-alkaline rocks. Observed change in nature of magmatism from normal calc-alkaline in the Paleogene to adakitic-like signature in the Neogene could represent a key to understanding the evolution of magma source regions of the granitoids during Tertiary times. This magmatic evolution could be related to changing the plate-tectonic configuration and crustal thickness of the Kerman arc segment during Tertiary times. Due to the significance of magma source in Cu-metallogenesis contexts, we used trace element and isotope signatures of two contrasting episodes of granitoids to constraints magma source regions and their possible genesis which is discussed below.

The Jebal Barez-type granitoids show normal calc-alkaline affinity with moderate REE fractionation ($\text{La}_{\text{CN}}/\text{Yb}_{\text{CN}} = 2.45-14.7$), negative Eu anomaly (Eu/Eu*$^*$ <1), and moderately low fractionated HREEs ($\text{Sm}_{\text{CN}}/\text{Yb}_{\text{CN}} = 1.05-2.31$; $\text{Gd}_{\text{CN}}/\text{Yb}_{\text{CN}} = 1.13-1.92$). The negative Eu anomaly and low to moderate Sr contents (<400 ppm) may reflect that some plagioclase and hornblende probably has fractionated from the melt, while the moderately HREEs fractionation preclude the retention of garnet in the residuum. In contrast, Kuh Panj granitoids exhibited some adakitic-like features such as strong REE fractionation ($\text{La}_{\text{CN}}/\text{Yb}_{\text{CN}} = 19-53$), absence of Eu anomaly (Eu/Eu*$^*$ 1), moderately high fractionated MREEs and HREEs ($\text{Sm}_{\text{CN}}/\text{Yb}_{\text{CN}} = 2-7$; $\text{Gd}_{\text{CN}}/\text{Yb}_{\text{CN}} = 1.82-5.42$) along with high Sr contents (>400 ppm). These trace element signatures show that their parent magmas were generated in an environment in which plagioclase was absent and hornblende was important as source and/or residual phases [4,59]. Also, low concentrations of Y (4.8-9 ppm), Yb (0.36-0.71 ppm) as well as strong REE fractionation ratios ($\text{La}_{\text{CN}}/\text{Yb}_{\text{CN}} = 38-53$) and high fractionated HREEs ($\text{Sm}_{\text{CN}}/\text{Yb}_{\text{CN}} = 5-7$; in SNP and AP samples, respectively) can be indicative of garnet fractionation [55,56]. Plots of LREE/MREE (La/Sm) vs. MREE/HREE (Sm/Yb) [40] show that most ore-hosting porphyries of the Kerman arc segment are LREEs and MREEs enriched relative to HREEs, two samples (SNP and AP) show strong MREEs enrichments relative to HREEs. This reflects effect of both hornblende and garnet fractionation and/or residue separation during partial melting and/or crustal AFC processes [27,35,39,58] (Fig. 7). Therefore, HREE signatures of the ore-hosting magma (Kuh Panj granitoids) record a "transitional residuum" in which garnet coexisted with hornblende (transitional residuum) [10]. As comparison, barren intrusions (Jebal Barez granitoids) are characterized by
moderate LREEs and MREEs enrichments and weak HREEs depletions, reflecting pyroxene and amphibole fractionation and/or residue separation (Fig. 7).

Although Kuh Panj granitoids (ore-hosting porphyry) show a geochemical affinity with adakitic-type magmas but they cannot be explained as slab melts because of (1) the lack of a subduction zone during Neogene time beneath central Iran micro-continent [1,8,9,19,44,49,50,60], and (2) the range of lower Mg#'s of the ore-hosting porphyry magmas (Mg# 38-49) relative to the higher ones inferred for slab melts (Mg# 58-72) [55]. Our results are consistent with Richards and Kerrich [58], that these trace element signatures cannot only be recorded as an index of slab melting.

Also, adakitic-like nature of Kuh Panj granitoids (strong REE fractionation signature with La/Yb>20) cannot be explained by fractional crystallization and crustal assimilation processes. This will be supported by (1) their limited range in rock-composition (SiO2 60-65 wt. %), (2) lack of apparent coexisting mafic igneous rocks (intrusive and/or volcanic units) with these granitoids, (3) absence of crustal xenoliths, and (4) their non-radiogenic Sr isotope signatures (87Sr/86Sr = 0.704253-0.704800).

Alternatively, some of the critical characteristics of these rocks such as, their post-collisional tectonic setting, their moderate Na2O content (3.5-4.8), Mg# (38-49), moderately high Sr content (>400 ppm) and Sr/Y (≥40) together with the inferred presence of some garnet with amphibole as residual and/or source minerals make them good candidates for partial melts of the thickened lower crustal source (Mg#=27-54; Sr/Y=25-93) [5,25,56] similar to the Andean Cordillera Blanca [54], El Abra-Fortuna batholith [27], and Tibet [14,32]. Considering these and based on the limited variability in slightly radiogenic Pb-isotope ratios of the ore-hosting porphyry (67) as well as their non-radiogenic 87Sr/86Sr ratios together with moderately low HREE (Yb) and Y contents in them, we can assume a deep-crustal mafic source contribution with both amphibole and garnet as source minerals. In contrast, Jebal Barez intrusions with wide range in composition (from gabbro to granite), largely radiogenic Sr isotope signatures (87Sr/86Sr = 0.705336-0.706810), and extensive accompanying with coeval mafic igneous rocks are consistent with evolved magmas from the mantle melts during fractional crystallization process combined with progressive assimilation of continental crustal materials.

In present study, we used a geochemical batch-melting modeling to identify the source rock of the parent magma of Tertiary granitoids from the Kerman arc segment (Fig. 8). Source modeling indicates that low-degree partial melting (5-15%) of a basaltic garnet-bearing (up to 30%) amphibolite source with changing melt water fugacity [71] and the lack of plagioclase as a residual or source mineral can explain most of the moderately high La/Yb and Sr/Y ratios of the Kuh Panj-type granitoids (middle Miocene-Pliocene suites). Garnet may forms in basaltic bulk compositions by breakdown of amphibole + plagioclase under dehydration reaction: amphibole + plagioclase + quartz → garnet + clinopyroxene + new plagioclase melt at 12 and 15 kbar [63,75]. Amphibole undergoes continuous reactions (at 935-950°C) and remains stable with garnet up to at least 15 kbar [27]. Successive breakdown of amphibole is responsible for gradually raising melt water fugacity. In contrast, melting of a garnet-free amphibolite source can explain most of the moderately high La/Yb (and Sr/Y) ratios of the Kuh Panj-type granitoids (middle Miocene-Pliocene suites). Garnet may forms in basaltic bulk compositions by breakdown of amphibole + plagioclase under dehydration reaction: amphibole + plagioclase + quartz → garnet + clinopyroxene + new plagioclase melt at 12 and 15 kbar [63,75]. Amphibole undergoes continuous reactions (at 935-950°C) and remains stable with garnet up to at least 15 kbar [27]. Successive breakdown of amphibole is responsible for gradually raising melt water fugacity. In contrast, melting of a garnet-free amphibolite source can explain most of the moderately high La/Yb (and Sr/Y) ratios of the Kuh Panj-type granitoids (middle Miocene-Pliocene suites).

The moderately high La/Yb (≥20) ratios exhibited by Kuh Panj granitoids and presence of garnet as a residual and/or source mineral indicate that the mafic arc crustal base must have reached pressures of at least ~12 to 15 kbar with lower peridotite melting (10-25%) and subsequent fractional crystallization explains the low La/Yb ratios (<10) of the Jebal Barez-type granitoids (Fig. 8).
Figure 8. Plot of La/Yb vs. Yb (ppm) of two contrasting episodes of Tertiary granitoids from the KPCB. Area of solid hatch shows Jebal Barez granitoids plotting in thin crust field (30-40 km) consistent with island-arc setting. Area of dash line hatch shows Neogene Kuh Panj granitoids that overlap field of arcs with thick crust which are consistent with orogenic arc crustal thicknesses in the order of 40-50 km. Enriched-Mid Oceanic Ridge Basalt (E-MORB) source after Sun & McDonough [70]. Correlating crustal thickness from Hildreth and Moorbath [31] and H2O fugacity are from Tepper et al. [71]. For more detail see the text.

kbar or ~40 to 50 km of crustal thickness [55,56], suggesting that arc crustal thicknesses in the Miocene-Pliocene reached locally 50 km in collision time. The contrast in geochemical signatures of the arc melts suggests arc crustal thickening in the order of 10-15 km during Paleogene subduction system and the late Paleogene-Neogene collision. Therefore, our finding indicated that pre-collisional crustal thicknesses in the Kerman arc segment were ~30-35 km (at the time of Jebal Barez-type granitoids formation) that implied normal continental crustal thicknesses during the Paleogene subduction of Neo-Tethyan oceanic lithosphere beneath Central Iranian micro-continent (prior to collision). Interestingly, our geochemically derived estimate of collisional arc crustal thicknesses (at the time of Kuh Panj-type granitoids formation) is consistent - within reasonable error range - with present-day crustal thicknesses derived from gravimetric Moho depths (~45-50 km in the northwestern and central parts) [18] (Fig. 9). Meanwhile, Alavi [3] suggested an increase of about 5-10 km in the average thickness of the southern margin of the Central Iranian micro-continent at the end of magmatism related to Neo-Tethyan subduction system.

Petrogenetic Model

According to geodynamic considerations on Urumieh-Dokhtar magmatic arc, it is generally accepted that the middle-late Mesozoic subduction of the Tethyan oceanic lithosphere underneath the central Iranian micro-continent continued to the late Oligocene-early Miocene and then the Alpine continental tectonic regime is superimposed on Tertiary Andean-type arc magmatism, and the collision of the plates resulted in thickening and shortening of the continental crust by folding, thrusting, and uplift of the Iranian plateau [1,8,9,19,44,49,50,60].

Figure 9. a) The simplified present-day Moho-depth map of Iran derived from gravimetric data by Dehghani and Makris [18]. b) Contour map of crustal thicknesses throughout the KPCB (simplified from gravimetric Moho-depth map of Iran by Dehghani and Makris [18]) and regional distribution of major porphyry copper deposits from Nedimovic [52].
From the petrogenetic point of view, we envisaged a model in which some mantle-derived basaltic melts in Paleogene subduction zone are under-plated at the arc crustal base. Under-plating and crystallization of the metasomatized mantle melts will yield hydrous lower crustal gabbro which will gradually be metamorphosed into mafic amphibolite under crustal thickening.

Subsequent mantle melts will encounter and partially (re) melt the lower crustal amphibolite. As melting of hydrous amphibolite produces SiO₂-rich melts [64,66], the resulting melts will be more silicic (granitoid) than the initial mafic intrusions (gabbros). This process together with assimilation and fractional crystallization of mantle melts can be formed Jebal Barez-type granitoids with normal calc-alkaline affinity during Paleogene active subduction zone (Fig. 10a). After the end of subduction of the Tethyan oceanic lithosphere underneath the central Iranian micro-continent and prevailing of a collisional tectonic regime during Miocene-Pliocene time [1,8,9,19,44,49,50,60], the thickness of crust increased due to the increasing of the compressional stress regime and tectonic shortening. This crustal thickening has been accompanied by an increase in temperature and pressure of the lower crustal rocks which could change the residual mineralogy of lower crustal source rocks from garnet-free amphibolite in Paleogene to garnet-bearing amphibolite during Neogene. In the absence of invasion of mantle-derived hydrous melts and also influx of slab-derived supercritical fluids into the lower crust in a post-collisional tectonic setting. Partial melting of eroded and/or delaminated eclogite lower continental crust [38,76] in asthenospheric mantle source and dehydration melting (amphibole breakdown) lower crustal garnet amphibolite are two the possible sources for genesis of adakites. The explanation for delamination is that tectonically eroded mafic forearc crust and/or lower mafic arc crust reached pressure and temperature conditions favorable to the formation of eclogite. These eclogitic materials were denser than the mantle rocks and could sink into the mantle wedge, i.e., delaminate [38,76]; consequently crustal thickening [23,48]. Under such circumstances, hot asthenospheric material rises and replaces the cold lithospheric mantle, inducing dehydration melting and the generation of adakitic magma. As these melts rise, they pass through the mantle while assimilating and equilibrating with mantle peridotite, consequently elevating their MgO and Mg# values due to extensive mantle-lower crust eclogite material interaction [38,76]. Geochemical batch-melting modeling (Fig. 9) showed that the crustal thickness reached 45-50 km at the time of the generation of Kuh Panj-type granitoids and has never reached eclogite facies to be affected by the crustal delamination mechanism. Moreover, lower Mg# values (38-49) of adakitic-like magmas and garnet-bearing (up to 10%) amphibolitic source relative to delaminated lower crustal-derived melts (Mg# 40-60) and their eclogitic source are in contrast with adakitic melts generated by partial melting of delaminated lower crust in hot-asthenospheric mantle. Furthermore, arc crustal thickening during the time of adakitic magmatism and copper mineralization in the KPCB are inconsistent with crustal thickening under lower crustal delamination process. Alternatively, dehydration melting of the lower crustal garnet amphibolite is the best mechanism to explain the adakitic-like magma genesis in a post-collisional tectonic setting. Collision-related processes such as upwelling hot-asthenospheric mantle (due to slab-break off) [16], rift-related decompressional melting of older collision-modified lithospheric mantle [25] would generate hot lithospheric mantle melts (Fig. 10b), which may be underplated at or near the crust-mantle boundary. Mafic underplating generates heat and water flux into lower crustal garnet amphibolitic rocks. The significant addition of heat at the base of thickened arc crust due to both intrusion of the hot mantle melts therein and crustal thickening permits breakdown of amphibole [35,63,75]. This built-up of heat, combined with the increasing of the availability of water at the site of melt generation by intrusion of hot lithospheric mantle-derived hydrous melts as well as breakdown of
amphibole provides the conditions for partial melting of lower arc crust (garnet amphibolite) in temperatures lower than 1000°C (according to the lowest temperature gradient 20°C/km) [5] and the pressure of 12-15 kbar or ~45 to 50 km of crustal thickness [55,56,64,66] and forms a region of melting in mantle-lowermost crust boundary (MASH zone) (Fig. 10b). Consequently, partial melting of thickened mafic lower arc crust and their interaction with mantle-derived mafic melts continues to produce a successively more hydrous and intermediate-composition hybrid melt with up to tens of percent of the deep mafic crust contributions [31].

**Metallogenetic Implications**

During the last decade, there has been growing interest in adakitic magmatism and its relation to porphyry copper mineralization throughout the world [10,33,51,53,57,65,72,77]. According to geochemical characteristics and petrogenetic model proposed here (Fig. 10), the Kuh Panj granitoids as ore-hosting porphyries in the KPCB exhibited some adakitic-like features such as high Sr (>400 ppm), low Y (<18 ppm), low Yb (0.36-1.5 ppm), high Sr/Y (>40), high La/Yb (19-53) and generated by dehydration and partial melting of the lower crustal garnet amphibolite rocks in a thickened arc crust (>40km). Increasing the thickness of arc crust in the KPCB from Paleogene to late Neogene as well as from southeastern (30-35 km) toward central and northwestern parts (~45-50 km) (Fig. 9) which is associated with Neogene adakitic-like granitoids (Kuh Panj-type) and major porphyry copper mineralization (Sar Cheshmeh, Meiduk, Dareh Zar, Iju, Now Chun, ...) in this part may reflect the relationship between crustal thickening and porphyry copper mineralization. This is supported by localization of abundant occurrences of major and minor porphyry copper deposits and prospects with Neogene adakitic-like granitoids in thickened parts of Kerman arc crust (Fig. 9).

In the metallogenetic context, porphyry copper deposits are generally derived from S-rich, and oxidized magmatic systems [12,34]. The principle problem concerning the origin of the porphyry copper deposits as products from melting lower crustal source is how these ore deposits have formed and we need to explain how fundamental determinants in ore genesis were provided and the site of magma generation, such as increasing availability of H2O, oxidizing conditions, and necessary metals and sulfur.

From the metallogenetic point of view, we suggest two critical metallogenetic determinants in porphyry Cu mineralization associated with Neogene adakitic-like granitoids in the KPCB. First, crustal thickening, and second, increasing the oxidizing conditions at the site of melt generation (mafic lower crust). The gradual increase in thickness of arc crust continues the attachment of mantle-derived mafic melts at the base of arc crust during long-lived Paleogene subduction system (magmatic thickening) as well as tectonic shortening during an excessive compressive stress regime in late Paleogene-early collision (collision time) can form a thickened mafic lower crust. Since mafic rocks are normally assumed to provide much of Cu and sulfur in porphyry copper deposits [10,29], the partial melting of the thickened mafic lower crust by dehydration reactions (amphibole breakdown) can produce hydrous magmas enriched in Cu. Also, increase in oxidizing conditions (Eu/Eu*≥1) is a response to the dehydration reactions (amphibole breakdown) and removal of plagioclase at the site of melt generation.

According to our model, the rising of collisional-hot asthenospheric mantle melts through the cold, and hydrous lithospheric mantle not only increased heat flux and water therein, but also removed the sulfur and chalcophile elements (e.g. Cu) from the melted source rocks and melt pathways during magma ascent [72]. This process formed a hot and hydrous mafic melt enriched in metal and sulfur at the base of thickened arc crust. Subsequently, mantle-derived hydrous magmas provide large quantities of heat [12] and water that facilitates partial melting and assimilation of lowermost crustal rocks, which can induce amphibole breakdown due to increasing pressure at the lower crust during crustal thickening [35]. Addition of water in the MASH zone generates intermediate and oxidizing melts with about 3 wt.% water [12]. These hydrous, intermediate, and oxidizing magmas intrude at shallow crustal levels (2-3 km) [12]. The oxidizing conditions in the resulting magma (up to two log fO2 units above the fayalite-magnetite-quartz buffer; prevent the separation of Cu-sulfide melts therein [24], which ultimately results in Cu-enrichment of post-collisional arc magmas.

Some of geochemical data of Kerman arc granitoids especially trace and rare earth elements concentrations and ratios such as Y, Sr/Y, Yb, La/Yb, and Eu/Eu” not only have metallogenetic significance but also can be used as exploration tools for regional prospecting in the porphyry copper belts. Based on these criteria, the Kuh Panj granitoids as Cu-hosting suites have low Y (<18 ppm), high Sr/Y (>33.5), high La/Yb (≥20), and Eu/Eu’≥1 relative to Jebal Barez-type non-productive suites (Y=12-29; Sr/Y=33; La/Yb<15; Eu/Eu’<1) (Fig. 11). This fundamentally reflects the hydrous and oxidized nature of productive suites (Kuh Panj-type granitoids) in comparison with non-productive suites (Jebal Barez-type granitoids).
Transition from Paleogene Normal Calc-Alkaline to Neogene Adakitic-Like Plutonism and...

Figure 11. Plots of (a) Y vs. MnO [6], and (b) Eu/Eu* [59] (c) Yb, (d) Sr/Y, (e) Sm/Yb vs. SiO₂ for discrimination of between productive and non-productive Tertiary granitoid suites from the KPCB. Positive Eu/Eu* (Eu/Eu* = En/Sm+Gd), higher Sr/Y and Sm/Yb ratios of Neogene granitoids are consistent with hydrous and oxidized nature of their magmas.

Considering these, and taking into account the petrogenetic and geodynamic considerations, we believed that major hydrothermal activities and porphyry copper mineralization in the KPCB was coincident with a change towards increased HREE fractionation (from Paleogene granitoids to Neogene granitoids), reflecting the replacement of amphibole by small quantities of garnet as minor residual phase in the lower crustal source (garnet amphibolite) during crustal thickening. We suggest this occurred in late stages of arc development during Paleogene-Neogene excessive compressional tectonic regime. This will be supported by record a transitional residuum (some garnet coexisted with amphibole) for Kerman Neogene adakitic-like magmas. The amphibole breakdown at the site of melt generation (thickened mafic lower crust) can be assumed to provide much of the fluid necessary for the hydrothermal alteration and mineralization.

Conclusions

Observed change in nature of magmatism from normal calc-alkaline in Paleogene to adakitic-like signature in Neogene is not an isolated phenomenon, and that it could represent a key to understanding the evolution of granitoids magma source regions in the light of the particular crustal geodynamic evolution in the KPCB during Tertiary times. The present study indicated that observed magmatic evolution in the KPCB can be interpreted by changing the plate-tectonic configuration and thickness of Kerman arc crust during Tertiary times.

We believed that Jebal Barez-type granitoid with arc-type, normal calc-alkaline signature formed partly from fractional crystallization of mantle-derived melts, also partial melting and subsequent MASH-type processes of under-plated basaltic sub-arc crust in a normal crustal thickness (30-35 km) under extensional tectonic regime over a normal subduction system during Paleogene times. In contrast, Kuh Panj-type granitoids with adakitic-like geochemical affinities can be accommodated by hydrated melting in a thickened garnet-bearing amphibolitic sub-arc crust (~ 45-50 km thickness of crust) in a compressional tectonic regime during Neogene times. Moderate Mg#, moderately high Na₂O, and moderately low Ni and Cr contents indicate magma derivation from a thickened lower crustal mafic melt rather than slab melt.

From the metallogenic point of view, some of the geochemical characteristics of Kerman adakite-like productive granitoids, in particular, the high Sr/Y, La/Yb, and Eu/Eu* ≥ 1, probably reflect their hydrous
nature. Cu-related granitoids inferred to have been derived from melts generated in the mafic lower crust, in which the thickness of crust was 45-50 km at the time, leaving a residuum in which both amphibole and garnet survived. This was coincident with a critical change toward increasing heavy-REE fractionation and consequently increasing availability of water at the site of Neogene adakitic-like magma generation. This evolutionary trend can indicate increasing oxidation states necessary for formation of productive magmas, leading to the generation of hydrothermal systems and copper mineralization. We believed that the occurrence of porphyry copper mineralization in the KPCB was coincident with the cessation of extensive volcanism, and also crustal thickening related to the prevailing of compressional tectonic regime during Neogene time.

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