

Early Cenozoic magmatic heterogeneity in the Alborz rear-arc: Spatial variation from enriched to juvenile signatures

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Abstract

Across-arc geochemical variations in igneous rocks are common in magmatic belts that form at convergent margins, but the geological processes responsible are unclear. To investigate this, we acquired new whole-rock major and trace element data, coupled with Sr–Nd–Pb isotopic ratios, zircon Hf isotopes, and U–Pb geochronology for three intermediate and felsic intrusions in the Baghu, Chalu and Gandi regions of the Moallemen magmatic complex, NE Alborz rear-arc. These were compared to data from well-exposed Early Cenozoic Alborz rear-arc igneous rocks in northeastern and northwestern Iran. The Chalu intrusions are mainly monzonite, quartz-monzonite, whereas the Baghu and Gandi intrusions are granodiorite and granite, respectively. U–Pb zircon crystallization ages of 49.9 ± 0.74 and 46.3 ± 0.82 Ma for the Chalu intrusions indicate that they are slightly older than the Baghu granodiorite (41.2 ± 2.3 Ma) and Gandi granite (42.2 ± 0.99 Ma). The Chalu monzonite and quartz-monzonite rocks display relatively higher LILE/HFSE (Ba/Th: 60–167) but similar LILE/LREE (Ba/La: 17–21) values to those of the Baghu and Gandi intrusions (Ba/Th: 27–54; Ba/La: up to 25). All three units show the same Sr–Nd–Pb isotopic compositions, having same radiogenic Sr ($^{87}\text{Sr}/^{86}\text{Sr}$, 0.70400–0.70425) and Pb ($^{206}\text{Pb}/^{204}\text{Pb}$, 18.50–18.53; $^{207}\text{Pb}/^{204}\text{Pb}$, 15.58–15.59; $^{208}\text{Pb}/^{204}\text{Pb}$, 38.56–38.63), Nd ($^{143}\text{Nd}/^{144}\text{Nd}$, 0.51272–0.51295) and zircon Hf (+7.2 to +11.4) isotopic compositions. Modeling of Sr–Nd isotopes suggests that these magmas were generated by the interaction of mantle-derived melts with lower continental crust through a series of assimilation-fractional crystallization (AFC) processes during ascent in the NE Alborz rear-arc. Published major and trace element data, bulk rock $\epsilon\text{Nd}(t)$ and zircon $\epsilon\text{Hf}(t)$ isotope data across the Alborz rear-arc show that melts of enriched lithospheric mantle and subducted slab-derived experienced less crustal interaction in the central and NW Alborz rear-arc than in the NE Alborz rear-arc. This variation reflects differences in subduction

dynamics, crustal thickness, and mantle wedge processes along the Alborz rear-arc, indicating the utility of magmatic complexes for deciphering ancient tectonic processes. This work also settles a long-standing debate about the geodynamic evolution of the Alborz rear-arc, showing that a compressive to extensional tectonic regime existed during the Arabia–Eurasia collision.

Keywords: Slab derived melt, Assimilation-fractional crystallization, Moalleman magmatic complex Alborz rear-arc.

1. Introduction

Magmatic arcs at convergent margins commonly exhibit systematic geochemical variations from the trench towards the hinterland (Sepidbar et al., 2019). These variations are controlled by a complex interplay of factors including the composition of the mantle wedge, the degree of crustal assimilation, the depth of magma differentiation, and the nature of subducted slab inputs (e.g., fluids vs. melts). While such patterns are well-documented in intra-oceanic arcs, unravelling the dominant controls in continental arc and rear-arc settings is more challenging due to the overprinting effects of thick, heterogeneous continental crust. These complexities arise from the combined effects of source composition, assimilation and fractionation during ascent, subduction geometry, and varying crustal thickness (Annen et al., 2006). Resolving this is essential for reconstructing the interplay between magmatism, crustal recycling, and mantle dynamics during arc-continent collision.

The Tethyan orogenic belt, formed by the closure of the Neotethyan Ocean and subsequent collision between Arabia and Eurasia, provides an exceptional setting to investigate these processes during the transition from subduction to collision. The Alborz magmatic arc of northern Iran represents a critical segment of this belt, preserving a Cenozoic rear-arc magmatic record behind the main Urumieh-Dokhtar magmatic arc. This rear-arc is not a homogeneous entity, comprising distinct NW, central, and NE segments that host well-known major Eocene complexes (e.g., Zanjan-Takab, Ahar-Arasbarn, Chenask-Mobarak Abad, Kashmar, Moalleman) and exhibit contrasting crustal architectures and mantle dynamics. This spatial segmentation makes the Alborz rear-arc a natural laboratory to investigate how magmatic signatures vary across a rear-arc during continental collision and what this reveals about underlying geodynamic processes.

A key unresolved question is whether the geochemical heterogeneity observed along the strike of the Alborz rear-arc reflects primordial differences in the mantle source, varying degrees of crustal assimilation, or changes in subduction geometry and slab-derived inputs. Previous studies have offered contrasting interpretations for different domains, often based on isolated datasets (Homam et al., 2025; Natali et al., 2024; Sepidbar et al., 2019, 2021; Moghadam et al., 2015b). Resolving this requires integrated geochemical, isotopic, and geochronological data across Alborz rear-arc. To address this, we present new whole-rock geochemistry, Sr–Nd–Pb isotopes, zircon U–Pb geochronology, and zircon Hf isotope data from the poorly studied Moalleman magmatic complex in the NE Alborz rear-arc. We

integrate these new results with a comprehensive compilation of published data from the NW and central segments. Our results reveal a systematic spatial geochemical gradient: magmas in the NE exhibit stronger crustal assimilation signatures, while those in the NW retain a clearer juvenile, slab-influenced signature. We interpret this gradient to reflect along-strike variations in crustal thickness and the efficiency of assimilation-fractional crystallization (AFC) processes, ultimately controlled by the rollback of the subducting Neotethyan slab during the Eocene. This work not only clarifies the petrogenesis of the Alborz rear-arc magmas but also provides a robust model for deciphering spatial heterogeneity in collisional magmatic systems globally.

2. Paleogene volcanic–plutonic rocks in the Alborz rear-arc

The Alborz rear-arc – located between 45° E and 61° E – extends for ~1000 km in a W–E direction across north Iran (Fig. 1A), and defines a Cenozoic rear-arc magmatic zone related to the closure of the Neo-Tethys Ocean (Sepidbar et al., 2019). This magmatic belt is classically divided into three segments that lie northwest, central (proximal), and northeast (distal) from the Urumieh-Dokhtar magmatic front. The belt includes a thick (~4 km) pile of Late Cretaceous to Miocene magmatic rocks and thick (up to ~3 km) sequences of marine pyroclastic rocks associated with volcanic rocks, which are known as the Karaj Formation in the central part of the Alborz rear-arc (Ballato et al., 2011; Verdel et al., 2011). Paleogene magmatism along the rear-arc is remarkably heterogeneous with respect to the composition and petrological characteristics of exposed units. Further, rear-arc sedimentation differs between NE and central–NW domains; the former units are mostly subaerial, whereas the latter are primarily submarine. These units formed in response to numerous transgression and regression events. Plutonic rocks ranging in composition from gabbro to granite are also present.

Transgressive–regressive cycles are recorded in many Iranian rear-arc sediments deposited between the Late Cretaceous and Eocene (Ballato et al., 2011). Late Cretaceous–early Paleocene transgressions developed in response to extensional thinning of the Iranian continental crust, whereas regressions during the Middle to Late Paleocene were driven by continental emergence and led to deposition of red (subaerial) volcano-sedimentary sequences. Such sequences in NE Iran are comprised of sandstones and conglomerates intercalated with mafic to andesitic lavas and minor interbedded intermediate to felsic pyroclastic rocks. By contrast, pyroclastic rocks dominate over clastic sediments in the central–NW Alborz rear-arc (Verdel et al., 2007) (Fig. 1C). A marine transgression that began in the Early to Middle Eocene is recorded by thick (500–1000 m) piles of deep-marine Nummulitic limestones in the northwest and northeast Alborz rear-arc. Flare-up magmatism in the Alborz rear-arc domain during the Eocene was contemporaneous with this transgression, suggesting that magmatism was coeval with subsidence-related extension (Fig. 1C). Finally, all Cenozoic rear-arc magmatic rocks in north Iran were intruded into or emplaced onto Cadomian crystalline basement, which is exposed northwest of Karaj (Fig. 1A) and can be traced to the northwest into Cadomian rocks of Lahijan and Zanjan, and to the northeast to Taknar and Torud (Fig. 1A-B). Based on recently acquired

geochronological data for rear-arc early Cenozoic magmatism in this region, magmatism is thought to have occurred continuously from ~49 to 36 Ma (Early to Late Eocene). Calculated crustal Hf model ages (T_{DM}^C) for Late Paleocene to Early Oligocene (66–27 Ma) zircons with the least radiogenic Hf isotopic compositions vary between ~0.6 and 3.8 Ga, corresponding to a difference of ~3.2 Gyr in crustal residence time. This indicates that the crust underlying different parts of the Cenozoic Alborz rear-arc is strongly heterogeneous.

2. 1 Cenozoic magmatic phases in the NW-central Alborz rear-arc

The NW-central Alborz rear-arc is an uplifted plateau (Sepidbar et al, 2019; 2021) bounded to the north by the Aras fault, to the W–SW by the Tabriz fault, and to the east by the Mosha and North Tehran faults (Castro et al., 2013) (Fig. 1). In this region, Alborz rear-arc magmatism occurred from the Late Cretaceous to Pleistocene and can be traced into the Lesser Caucasus/Armenia (Fig. 1) along an arcuate belt >700 km long. Units in this region are mostly comprised of thick (500–1000 m) Paleocene to middle-Eocene sequences of marine *Nummulitic* limestones that vertically grade into fine-grained pyroclastic rocks. Eocene flare-up magmatism in the NW–central Alborz rear-arc occurred at the same time as this marine transgression, indicating significant crustal extension, given that global sea level was also falling at this time (Miller et al., 2005). Eocene magmatism is typically overlain by Late Eocene–Early-Oligocene sedimentary rocks, as well as limited pyroclastic deposits and volcanics. The late Eocene to late Oligocene regression resulted in deposition of red volcano-sedimentary sequences (Lower Red Formation). This was followed by Oligocene to Early Miocene marine transgression and deposition of limestones and marls interlayered with mafic lavas known as the Qom Formation (~1200 m) (Reuter et al., 2009) (Fig. 1C). The Qom Formation is conformably overlain by the Miocene Upper Red Formation and Pliocene to Quaternary continental sediments.

Cenozoic igneous activity in the NW-central Alborz rear-arc occurred in three magmatic pulses: (i) Late Paleocene-Eocene adakitic (Lubin-Zardeh; Zamanian et al., 2020 and Takab: Azizi et al., 2019) and non-adakitic igneous rocks (Chamlu, Rashtabad, Jizvan, Takestan and Goljeh, Shahjalm and Mianeh-ebak: Ghasemi Siani et al., 2020); (ii) early collisional late Eocene–Oligocene subduction- and early collision-related intrusions and coeval adakitic (Khoynarood; Mahmoudinia et al., 2020) and non-adakitic igneous rocks (Mendejin: Karimzadeh Somarin et al., 2005; Sungun: Hezarkhani et al., 2006 and Arasbaran: Jamali et al., 2014; Kelaybar, Bostan Abad, Hashroud (Sepidbar et al., Unpublished, Niaz and Shahjahan: Aghazadeh et al., 2011). Extension was associated with alkali-rich magmatism throughout NW Iran during middle Eocene–early Miocene time. These consist of sub-volcanic bodies of quartz monzonite to monzodiorite, normally calc-alkaline with adakitic affinity; and (iii) Late Oligocene-Miocene and Pliocene collisional adakitic intrusions associated with Cu–Au porphyry to epithermal mineralization related to crustal thickening.

2. 2 Cenozoic magmatic phases in the NE Alborz rear-arc

The NE Alborz rear-arc is a complex magmatic-sedimentary zone, nearly 600 km long, arcuate and structurally complex fault-bounded belt, with several juxtaposed blocks including the Lut block in the south, the Kopet-Dagh (Turan = Eurasia) block in the north and the Central-NW Alborz rear-arc zone in the northwest (Fig. 1). In the NE Alborz rear-arc, Eocene igneous rocks outcrop over ~8000 km² between the Sabzevar-Torbat-e-Heydarieh ophiolites, which represent remnants of an oceanic back-arc basin (Moghadam et al., 2015a) that formed during the Middle to Late Cretaceous, and are bound to the south by the Dorouned fault (Fig. 2). The Sabzevar-Torbat-e-Heydarieh ophiolites were likely emplaced during NE-dipping subduction of Neotethyan oceanic crust. The central NE Alborz rear-arc hosts an accretionary complex made up of SSE-verging thrust slices of Late Cretaceous limestone, chert and volcanoclastic rocks, dissected by post-orogenic strike-slip faults. A metamorphic complex consisting of Early Cretaceous (ca. 106–107 Ma) blueschists and amphibolites and Late Paleocene (ca. 58 Ma) adakitic granites occupies the frontal part (Moghadam et al., 2015b and references therein). This tectonic zone exposes deeper sections of the central Iran basement and may be part of a regional core complex. Cadomian igneous and metamorphic units (Taknar-Toroud complex) are widely exposed in the NE Alborz rear-arc, and record a prolonged deformation history. A previous Rb–Sr geochronological study showed that Kashmar granitoids, in the central parts of NE Alborz rear-arc formed during the Middle Eocene (ca. 42 Ma; Moghadam et al., 2015b). Previous studies suggest that the Kashmar granitoids are shallow-crustal Eocene leucogranite–granodiorite to monzogranites that formed during crustal assimilation of mantle melts associated with extension above the subducting Neotethyan oceanic slab beneath SW Eurasia.

Several undated felsic intrusions occur in the NE Alborz rear-arc, such as those of the Moalleman complex (Fig. 1A), which hosts diverse Early Cenozoic magmatic units. The lack of ages of emplacement for Moalleman units has impeded correlations between specific igneous rocks within the magmatic suite and other magmatic activity across the region, and so precludes making geodynamic links across the wider north Iranian Plateau. Here, we report new geochemistry, isotopic data, and U–Pb zircon ages for igneous rocks from the Chalu, Baghu and Gandi regions of the Moalleman magmatic complex in the NE Alborz rear-arc to examine the age and character of rear-arc magmatism. These data are used to reconstruct the geochemical evolution of the Moalleman complex, and we compare our new results with data compiled from elsewhere within the Alborz rear-arc, allowing reconstruction of the development of Eocene rear-arc magmatism in Iran.

3. Field geology

The Moalleman magmatic complex (Fig. 2) is a SW-NE-trending magmatic zone, approximately ~15 km wide and ~30 km long. It is located on the eastern continuations of the central Alborz rear-arc and connects the NE Alborz rear-arc to the central-NW Alborz. The oldest units of the Moalleman magmatic complex include Precambrian metamorphic rocks covered by Paleozoic epicontinental sedimentary rocks (Fig. 2). Field observations and previous studies show that magmatic activity occurred in the

Middle Eocene and possibly during the Late Eocene (Fig. 2). Two principal strike-slip faults control structural patterns: the Baghu Fault in the north and the Reshm–Pirmardan Fault in the south, which have sub-parallel NE–SW trends (Fig. 2). Based on previous kinematic analysis using fault-slip data (orientations of slip planes, slip vectors, stress ellipsoid shape, and internal friction angles), the regional stress field was determined as a left-lateral transpressional regime with a reverse component, consistent with N–NE (\sim N195°) compression driving northward lithospheric motion. These results agree with field observations of fractures, and principal mechanisms within this general shear zone.

The local stratigraphy can be subdivided into four units: (i) a sequence of Early Paleocene thinly bedded green to purple trachydacite-dacite tuffs, and a massive grey dacite-dacitic andesite tuff breccia; (ii) Late Paleocene intermediate andesite-trachyandesite lava flows; (iii) Middle Eocene grey to green andesitic-dacitic tuffs, volcanic breccias, and lava flows; and (iv) Middle to Upper Eocene subvolcanic crypto domes, hypabyssal plutons, and several dykes that intruded the overlying volcanic sequence. We collected representative samples of plutonic rocks from the Moalleman magmatic complex in the northeastern Alborz rear-arc. Plutonic rocks were sampled from the Baghu, Gandi, and Chalu in the central segment of the Moalleman complex (Fig. 2).

The Baghu intrusion is exposed over an area of \sim 10 km², occurs as an elongated body bounded by NE–SW trending faults, and is dominantly granodiorite and quartz monzonite in composition (Fig. 2). These intrusions have a clearly defined intrusive contact with Eocene volcanic rocks at their southern margin; however, they are abutted by altered host rocks and Quaternary sedimentary rocks to the north (Fig. 3A). Both the Baghu granodiorites and quartz monzonite have a medium- to fine-grained texture and contain micro-granular mafic enclaves (MMEs) (Fig. 3B). Tourmaline typically occurs as disseminations, aggregates, pods, and veins within the intrusive rocks, or as alteration envelopes and veins along pluton contacts against Eocene volcanic country rocks. Based on Ghorbani and Ghasemi (2009), tourmaline in the Baghu pluton is nearly pure schorl, although limited dravite-foitite solid solution occurs. The Gandi intrusion is exposed over \sim 5 km², is dominated by pink granite, and occurs as an elongated body bounded by NE–SW and W–E trending faults to the south and north, respectively (Fig. 2). It shows a clear and well-defined faulted contact against the surrounding Eocene volcanic rocks to the north (Fig. 3C). The Chalu body intrudes into Cretaceous carbonate units and Eocene volcanic rocks. It is mainly composed of fine- to medium-grained micromonzonite and quartz monzonite, and contains MMEs (Fig. 3D).

4. Petrography

The Baghu granodiorites have a fine-grained granular/porphyritic texture and are composed of subhedral to anhedral phenocrysts of quartz (\sim 20–25 vol. %), plagioclase (\sim 45 vol. %), alkali feldspar (\sim 15 vol. %), biotite and amphibole (\sim 10 vol. %) and clinopyroxene (1–6 vol. %) (Fig. 3E). Zircon, magnetite, sphene, tourmaline, and apatite occur as accessory minerals ($<$ 3 vol. %). Subhedral to anhedral plagioclase (0.5–2 mm) is altered to kaolinite and sericite. Both anhedral and subhedral

plagioclase is zoned, with compositions between andesine to oligoclase, and they display polysynthetic twins. Quartz forms interstitial grains between plagioclase and alkali feldspar (Fig. 3E). Quartz monzonite includes quartz (~10-15 vol. %), plagioclase (~35 vol. %), alkali feldspar (~40 vol. %), and biotite and amphibole (~10 vol. %) as main minerals and, magnetite, tourmaline, and apatite as accessory minerals (<2 vol. %) (Fig. 3F). The close association of tourmaline and turquoise is a prominent feature of this intrusion, and samples show texturally distinct microgranular and porphyritic domains with fine-grained groundmass and phenocrysts up to 2 mm long.

The Gandi granite is coarse-grained, and has hypidiomorphic granular, perthitic, graphic, and megaporphyritic textures. It mainly contains subhedral to anhedral crystals of quartz (~22 vol. %), plagioclase (~25 vol. %), alkali feldspar (~45 vol. %), and biotite and amphibole and clinopyroxene (~10 vol. %) as main minerals, and zircon, magnetite, and apatite occur as accessory minerals (<1 vol. %) (Fig. 3G). Subhedral to euhedral plagioclase (0.5–2 mm) grains are commonly altered to kaolinite and sericite, and quartz occurs as interstitial grains between plagioclase and alkali feldspar.

The Chalu micromonzonite typically contains plagioclase (35-45 vol. %), alkali feldspar (25-35 vol. %), pyroxene (10-15 vol. %), amphibole (5-10 vol. %), and minor quartz (<5 vol. %). The quartz monzonite varieties show higher quartz contents (15-25 vol. %) with plagioclase (30-40 vol. %), alkali feldspar (25-35 vol. %), and reduced mafic mineral abundances (pyroxene + amphibole = 5-10 vol. %). Accessory minerals (biotite, tourmaline, zircon, sphene, apatite) total <3 vol. % in all samples. (Fig.3H). K-feldspar occurs mainly as subhedral to anhedral crystals in all rocks, and quartz occurs as both euhedral, early-formed crystals and anhedral late-stage grains. Magnetite, zircon, apatite, and titanite are the principal accessory phases. Plagioclase is partly altered to sericite and calcite. Subhedral to anhedral amphiboles appear as fine- to medium-grained phenocrysts. The MMEs, ranging from monzonite to diorite, are similar to the host Chalu intrusion except that they have more amphibole, biotite, and plagioclase, and less quartz and K-feldspar. MEEs contain plagioclase (50–56%), K-feldspar (10–16%), hornblende (23–26%), biotite (15–20%), minor quartz, and accessory magnetite, needle-shaped apatite, titanite, and zircon. Their texture is dominantly microgranular (Fig. 3I), but occasionally fine-grained and porphyritic. Plagioclase occurs as large megacrysts that sometimes include smaller elongated plagioclase laths with complex oscillatory zoning. Minor quartz occurs either as megacrysts or as anhedral crystals that are interstitial to other minerals. Hornblende and biotite are the most abundant mafic minerals in the MMEs, occurring as subhedral to anhedral grains, or as anhedral crystals interstitial to plagioclase. Biotite shows greenish brown to reddish-brown pleochroism. Apatite, a common accessory mineral in the MMEs, occurs as acicular crystals.

5. Analytical procedures

We employed a suite of analytical techniques to determine the geochemical and isotopic characteristics of samples from the Moalleman complex. Petrographic examination of over 70 samples guided the

selection of 25 fresh, representative samples for whole-rock geochemistry. Subsequently, a subset of these was chosen for isotopic analysis.

The analytical workflow consisted of five main procedures. (1) Whole-rock major and trace elements: major element compositions were determined by X-ray fluorescence (XRF) spectrometry, whereas trace element and rare earth element (REE) contents were analyzed by inductively coupled plasma-mass spectrometry (ICP-MS). (2) Zircon imaging: cathodoluminescence (CL) imaging was performed on zircon separates to identify internal structures and guide spot selection for isotopic analysis. (3) Zircon U–Pb geochronology: U–Pb dating of zircon grains was conducted using laser ablation-inductively coupled plasma-mass spectrometry (LA-ICP-MS). (4) Zircon Hf isotopes: in-situ Hf isotopic compositions of zircons were measured using multi-collector inductively coupled plasma-mass spectrometry (MC-ICP-MS). (5) Whole-rock Sr–Nd isotopes: whole-rock Sr and Nd isotopic ratios were determined by thermal ionization mass spectrometry (TIMS). A comprehensive description of the detailed analytical procedures, including instrument specifications, standard operating conditions, data acquisition parameters, and the standards used for calibration, is provided in Supplementary Appendix A.

6. Results

6.1 Whole-rock major and trace element geochemistry

Major, trace, and REE data for all 33 plutonic samples from the Moalleman magmatic complex are presented in Supplementary Table 1. The intrusive rocks of the Moalleman complex, which are distributed in Baghu, Chalu, and Gandi, range in composition from monzonite/quartz-monzonite to granodiorite and granite (Fig. 4A). Their K₂O contents increase alongside increasing SiO₂ (Fig. 4B), and their MgO contents decrease with increasing SiO₂ (Fig. 4C), whereas there is no correlation between SiO₂ and Ni, Cr, V and Co content (Supplementary Table 1).

The Chalu monzonite has restricted ranges of SiO₂ (57.0–61.1 wt. %), Al₂O₃ (15.3–16.4 wt. %), and K₂O (2.9–4.9 wt. %), whereas granodiorites from Baghu have higher SiO₂ (63.6–69.5 wt. %) and Al₂O₃ contents (14.7–20.03 wt. %), but similar K₂O contents (3.2–4.3 wt. %). The Gandi intrusions have SiO₂ = 64.0–74.1 wt. %, Al₂O₃ = 14.9–20.4 wt. %, and K₂O = 4.0–4.5 wt. %. In a K₂O-silica co-variation diagram, most of the studied plutonic rocks of Baghu and Gandi have high-K/calc-alkaline signatures whereas those of Chalu plot in the shoshonite field (Fig. 4 B).

The geochemical signatures of Sr and Y in intrusive rocks from the Moalleman magmatic complex reveal distinct magmatic characteristics between the Baghu, Chalu, and Gandi regions. Baghu units display moderate Sr enrichment (366–577.6 ppm, avg. ~480 ppm) and intermediate Y values (8.8–12.1 ppm, avg. ~10.8 ppm), characteristic of partial melting of a garnet-bearing source. Chalu units show significantly higher Sr (564–1222.9 ppm, avg. ~850 ppm) and elevated Y (13.9–20 ppm, avg. ~16 ppm), corresponding to adakitic signatures. Units from Gandi have the lowest Sr (268–365 ppm, avg. ~330 ppm) and Y concentrations (8.3–12.1 ppm, avg. ~10.5 ppm), consistent with a more typical arc-

related signature without strong adakitic influence. Baghu intrusions have moderate LREE enrichment (La(n)/Yb(n) = 4.5–8.2) and Nb–Ta troughs, Chalu units show stronger LREE enrichment (La(n)/Yb(n) = 8.3–12.7) and Nb–Ta depletion, and Gandi units display weaker LREE enrichment (La(n)/Yb(n) = 2.0–5.1) and Nb–Ta depletion in the chondrite-normalized REE and N-MORB-normalized multi-element diagrams. Rocks from all regions lack a conspicuous negative Eu anomaly ($Eu/Eu^* = 0.91–1.01$) (Fig. 5A). Geochemically, the REE and trace element patterns of the Moallemann magmatic complex units exhibit two diagnostic features characteristic of high-K calc-alkaline to shoshonitic series rocks (Peccerillo & Taylor, 1976): (i) LREE enrichment with $(La/Yb)_N = 2.04–12.70$ (Fig. 5A) and (ii) negative Nb–Ta–Ti anomalies in primitive mantle-normalized diagrams ($(Nb/La)_N = 0.21–0.52$; Fig. 5B).

6.2 Zircon U–Pb geochronology and Hf isotopes

Four samples of Baghu granite and granodiorite, Gandi granite, and Chalu monzonite were dated using LA-ICP-MS zircon U–Pb geochronology (Supplementary Table 2). From these, two samples of Baghu granodiorite and Chalu monzonite were also evaluated for Hf isotopic studies (Supplementary Table 3).

Sample Gb-4 (Baghu granite)

Eighteen zircon grains were analyzed in Baghu granite sample Gb-4. Cathodoluminescence (CL) shows that they are mostly euhedral to subhedral and prismatic in shape, ~100–250 μm long, and have length-to-width ratios of 3:1 to 1:1. Their interiors show oscillatory zoning, confirming a magmatic origin (Belousova et al., 2002). They have U and Th contents of 139–898 ppm, 84–983 ppm, respectively, and Th/U ratios of 0.6–1.1. Geochronological analyses recorded a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 42.2 ± 0.9 Ma (MSWD = 2.4) (Fig. 6A). The zircons display LREE depletion with $La(n)/Yb(n) = 0.00006–0.17$, slight negative Eu anomalies ($Eu/Eu^* = 0.06–0.15$), and positive Ce anomalies ($Ce/Ce^* = 4–959$) (Fig. 6A) (Supplementary Table 2)

Sample Gb-5 (Baghu granodiorite)

Eighteen zircons were analyzed from Baghu granodiorite sample Gb-5. All grains are prismatic with length-to-width ratios of 2:1 to 1:1 and most show oscillatory zoning, although some are unzoned. Measured U and Th contents and Th/U ratios were 164–367 ppm, 110–405 ppm, and 0.6–1.1, respectively. The analyzed zircons show a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 41.2 ± 2.3 Ma (MSWD = 2.0) (Fig. 6B) and display LREE depletion ($La(n)/Yb(n) = 0.00008–0.19$), slight negative Eu anomalies ($Eu/Eu^* = 0.07–0.19$), and positive Ce anomalies ($Ce/Ce^* = 6–941$) (Fig. 6B) (Supplementary Table 3). Their $\epsilon\text{Hf}(t)$ values are positive and vary between +8.8 and +11.4 (Fig. 7A). Two-stage model ages (T_{DM}^C) for granodiorite zircons using a $^{176}\text{Lu}/^{177}\text{Hf}$ value of 0.015 (Griffin et al., 2004) produced relatively young ages of 346–498 Ma, confirming the juvenile nature of the granodioritic magmas.

Sample G-1 (Gandi granite) 332

Eighteen zircons were analyzed from Gandi granite sample G-1. Most grains are prismatic with length- 333
to-width ratios of 2:1 to 1:1, and most show oscillatory zoning. Measured U and Th contents and Th/U 334
ratios were 196–455 ppm, 138–455 ppm, and 0.6–1.1, respectively. The analyzed zircons show a 335
weighted mean $^{26}\text{Pb}/^{238}\text{U}$ age of 46.35 ± 0.82 Ma (MSWD = 2.6) (Fig. 6C) and display LREE 336
depletion ($\text{La(n)}/\text{Yb(n)} = 0.00009\text{--}0.21$), slight negative Eu anomalies ($\text{Eu}/\text{Eu}^* = 0.09\text{--}0.20$), and 337
positive Ce anomalies ($\text{Ce}/\text{Ce}^* = 5\text{--}842$) (Supplementary Table 2; Fig. 6C). 338
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Sample G-C-2 (Chalu monzonite) 340

Twelve zircons were analyzed from Chalu monzonite sample G-C-2. The zircon grains are prismatic, 341
have length-to-width ratios of 2:1 to 1:1 and show oscillatory zoning. Measured U and Th contents and 342
Th/U ratios were 155–428 ppm, 54–310 ppm, and 0.6–1.1, respectively. The analyzed zircons show a 343
weighted mean $^{26}\text{Pb}/^{238}\text{U}$ age of 49.9 ± 0.4 Ma (MSWD = 0.54) (Fig. 6D) and display LREE depletion 344
($\text{La(n)}/\text{Yb(n)} = 0.00007\text{--}0.22$), slight negative Eu anomalies ($\text{Eu}/\text{Eu}^* = 0.05\text{--}0.18$), and positive Ce 345
anomalies ($\text{Ce}/\text{Ce}^* = 9\text{--}841$) (Supplementary Table 2; Fig. 6D)). The $\epsilon\text{Hf}(t)$ values of zircons from 346
Chalu monzonite are characterized by lower values between +0.13 and +4.2 (Fig. 7A). Two-stage model 347
ages (T_{DM}^{C}) for zircons produced relatively higher ages of 613–781 Ma, suggesting the juvenile nature 348
of the monzonite. 349
350

6.3 Bulk-rock Sr–Nd–Pb isotopes 351

Six samples of Moalleman magmatic rocks were analyzed for Sr and Nd–Pb isotopes (Supplementary 352
Table 4) to decipher the melt reservoir characteristics of their source regions and give insight into 353
secondary processes that may have affected the intrusions during emplacement, such as contamination 354
or interactions with their host rocks. Both $^{87}\text{Sr}/^{86}\text{Sr}(t)$ and $^{143}\text{Nd}/^{144}\text{Nd}(t)$ ratios were calculated using an 355
age of 42 and 49 Ma for Chalu and Baghu regions, respectively. All the Moalleman plutonic rocks have 356
restricted initial $^{87}\text{Sr}/^{86}\text{Sr}(t)$ values of $\sim 0.70419\text{--}0.70428$ and $\epsilon\text{Nd}(t)$ values of -1.9 to $+2.4$ (Fig. 7A) 357
and lie near the chondritic uniform reservoir (CHUR) line on a Sr–Nd isotope diagram (Fig. 7B). They 358
also have low $^{147}\text{Sm}/^{144}\text{Nd}$ ratios ranging from 0.10083 to 0.09129. Two-stage Nd isotopic model ages 359
(T_{DM}) of the samples range from 0.8 to 1.0 Ga. While both $\epsilon\text{Hf}(t)$ and $\epsilon\text{Nd}(t)$ indicate an enriched mantle 360
source, the higher $\epsilon\text{Hf}(t)$ values relative to $\epsilon\text{Nd}(t)$ (Fig. 7A) reflect differing fractionation of Lu/Hf and 361
Sm/Nd in the source region. Zircon $\epsilon\text{Hf}(t)$ records the melt’s composition at crystallization, whereas 362
whole-rock $\epsilon\text{Nd}(t)$ may integrate post-emplacement processes or minor crustal assimilation. Such 363
decoupling is consistent with metasomatized mantle sources where Hf–Nd isotope systematics are 364
inherently fractionated (e.g., Chauvel et al., 2008; Vervoort et al., 2011). The $^{206}\text{Pb}/^{204}\text{Pb}$, $^{207}\text{Pb}/^{204}\text{Pb}$ 365
and $^{208}\text{Pb}/^{204}\text{Pb}$ values of these rocks vary from 18.503 to 18.529, 15.580 to 15.92 and 38.563 to 38.586, 366
respectively (Supplementary Table 2), and they plot above the Northern Hemisphere Reference Line 367
(NHRL) of Hart (1984), lying near to enriched mantle (EMII) (Fig. 7C). 368

7. Discussion

The Alborz rear-arc is a key segment of the Tethyan orogenic system, and exhibits a complex magmatic history influenced by the protracted subduction and subsequent collision of the Arabian and Eurasian plates (Sepidbar et al., 2019, 2021). Eocene magmatic activity in this region shows notable lithological variation from NW to NE, reflecting changes in geodynamic processes, crustal composition, and mantle sources. Here, we synthesize and compare the petrogenetic, geochemical, and tectonic characteristics of magmatic rocks across different segments of the Alborz rear-arc including Moalleman magmatic complex. By examining these variations, we can better constrain the evolution of the Alborz rear-arc and its implications for the broader Tethyan tectonic framework. We will specifically discuss the magma source and petrogenetic history of Moalleman rocks in the western parts of the NE Alborz rear-arc, and what spatial variations in the geochemistry of magmatic rocks from the Alborz rear-arc as a whole can inform about its geodynamic evolution during the Paleogene.

7.1 Magma source and petrogenesis

The geochemical and isotopic signatures of the Moalleman igneous rocks provide critical insights into the relative contributions of mantle and crustal sources to magma genesis. The magnesium number ($Mg\# = 100 \times Mg/(Mg+Fe^{2+})$) is a robust proxy for assessing mantle-derived inputs, as primitive magmas typically exhibit high $Mg\#$ (>60–70), reflecting equilibration with mantle peridotite (e.g., Tatsumi, 2005). However, Moalleman igneous rocks have very low $Mg\#$ (<40; 16-35; Supplementary Table 1) suggesting significant fractional crystallization and/or crustal assimilation of mafic phases (e.g., olivine, pyroxene) occurred during magma ascent. The low Ni (<50 ppm) and Cr (<15 ppm) contents of all samples indicates also that these samples are not primary mantle-derived magmas, further supporting significant modification during ascent via fractional crystallization (FC), crustal assimilation (AFC), and/or magma mixing.

The presence of MMEs in two plutons provides direct evidence for magma mingling and mixing. This necessitates consideration of interaction between compositionally distinct magmas as a fundamental process. The isotopic data further constrain the nature of these end-members and their interactions. The rocks exhibit consistently high positive $\epsilon Hf(t)$ values (+8.8 to +11.1; Supplementary Table 4), indicating a dominant juvenile mantle component in the system. In contrast, $\epsilon Nd(t)$ values are variable, ranging from slightly negative to positive (-1.9 to +2.4; Supplementary Table 3) indicating the role of crustal melts in their genesis. As mentioned before, while both $\epsilon Hf(t)$ and $\epsilon Nd(t)$ indicate an enriched mantle source, the higher $\epsilon Hf(t)$ values relative to $\epsilon Nd(t)$ (Fig. 7A) reflect different degrees of fractionation between Lu/Hf and Sm/Nd in the source region. Zircon $\epsilon Hf(t)$ records the melt's composition at crystallization, whereas whole-rock $\epsilon Nd(t)$ may integrate post-emplacement processes or minor crustal assimilation. Such decoupling is consistent with metasomatized mantle sources where Hf–Nd isotope systematics are inherently fractionated (e.g., Chauvel et al., 2008; Vervoort et al., 2011).

A mantle source component for Eocene granitic rocks in the NE Alborz rear-arc was also proposed by Moghadam et al. (2015b) based on juvenile isotopic signatures (high $\epsilon\text{Nd}(t)$, low $\text{Sr}(i)$) and primitive geochemical features (e.g., high $\text{Mg}\#$) observed in their least evolved samples. The formation of arc/rear-arc-related magmatism is often related to partial melting of hydrated mantle, which may contain phlogopite and/or amphibole (Holwell et al., 2019). Low-degree partial melting of phlogopite-bearing source rocks controls the K, Ba, Nb, and Rb concentrations or partial melts, and forms magmas that have the same Rb/Sr (>0.1) and Ba/Rb (<20) ratios as those from the phlogopite-bearing source (e.g. Furman and Graham 1999) (Supplementary Table 1). Most of the Moalleman magmatic rocks exhibit Rb/Sr and Ba/Rb ratios of 0.1–0.3 and 3.8–11.2 (Supplementary Table 1). These values align with the diagnostic ratios for phlogopite-derived melts, suggesting phlogopite was a significant residual phase during mantle melting beneath the Alborz. Enrichment in U, Th, Rb, Ba, Pb, and Sr further indicates that micas (e.g., biotite, muscovite) crystallized and stabilized in the deep crust (>15 – 20 km depth; Villemant et al., 1981). Under these high-pressure conditions, micas act as dominant hosts for these large-ion lithophile elements (LILEs), reflecting fluid-present melting or metasomatism of deep-crustal sources.

The Moalleman intrusives were emplaced over ~ 8 – 9 Myr (i.e. Chalu monzonite at 49 Ma and Baghu granite at 41 Ma) (Fig. 6), and have intermediate (SiO_2 : 55.4–61.1 wt. %) to felsic (SiO_2 : 63.9–74.1 wt. %) compositions in the Chalu and Baghu-Gandi regions, respectively. Most samples track along a liquid line of descent and show decreasing CaO, MgO, TiO_2 , FeO, P_2O_5 and La/Nb and increasing alkalis, (i.e. units with low SiO_2 have higher CaO, MgO, TiO_2 , FeO, P_2O_5 ; Supplementary Table 1). As CaO, MgO, TiO_2 , and FeO are compatible and will be removed from the magma in early-crystallizing minerals in magmatic systems, a decrease in CaO, MgO and FeO and increase in SiO_2 acts as a proxy for clinopyroxene and plagioclase fractionation among the Moalleman samples. In addition, Nb/Ta and Dy/Yb vs. SiO_2 plots (Figs. 8A-B) show that the magmatic rocks from the study region have similar Nb/Ta and Dy/Yb ratios, which reflects a clinopyroxene and plagioclase fractionation trend, as titanite strongly incorporates Ti, its fractionation will decrease TiO_2 while SiO_2 increases (Tiepolo et al., 2002).

The Moalleman igneous rocks are enriched in LILE and LREE but depleted in HFSE (Fig. 7C). These signatures in arc magmas are classically attributed to derivation from a mantle source metasomatized by subduction-related melts/fluids (e.g. where HFSE depletion may reflect melting of a depleted mantle wedge or slab-derived fluid transfer; Duggen et al., 2007), although they may also indicate (i) crustal assimilation during magma ascent, (ii) magma mixing processes (cf. MMEs within these rocks; Section 3), or (iii) a combination of subduction metasomatism and crustal interaction. Thus, while subduction-related mantle metasomatism remains a viable contributor to the observed trace element patterns, crustal assimilation and hybridization processes documented in this study must also be considered as potential drivers of LILE/LREE enrichment and HFSE. Slab-derived fluids that affect magmatism are characterized by high Ba/Th >1000 , low $(\text{La}/\text{Sm})_N$ values (~ 1), as well as radiogenic Sr

isotope ratios (Elliott, 2003). In contrast, crustal dominated melts derived from slab or continental crust are generally characterized by lower Ba/Th and higher La/Sm ratios and trace element contents (Elliott 2003). Moalleman intrusive rocks share some geochemical similarities with crustal dominated melts, being characterized by low Ba/Th (27–167; mean at 58) and high $(La/Sm)_N = 3.2–7.9$. The mantle derived melts influenced by crustal-derived inputs also show lower LILE/HFSE, LILE/LREE, and LILE/Th ratios than those affected by fluid released from the down-going oceanic slab (e.g. Woodhead et al., 2001). Except for some samples from Baghu region, most Moalleman intrusive rocks show enrichment in Th (~2 times) over Ba in NMORB normalized patterns (Fig. 5b), supporting sediment/crustal contributions rather than fluids.

The nature of depletion and enrichment of the mantle source, as well as the involvement of the slab components in the mantle wedge (i.e., mantle vs. the subducted slab components), can be deduced using plots of Th/Yb and La/Yb vs. Nb/Yb (Pearce and Peate, 1995), as neither Nb nor Yb is added to the mantle wedge by subduction-related fluid fluxes. Variable addition of Th-enriched components from subducted slab or continental crust to a mantle with a homogenous composition should result in Th/Yb values that differ from those defined by “mantle array compositions”. The degree to which Th/Yb diverges from the mantle array depends on the amount of subduction-related inputs or crustal assimilation, coupled with the degree of initial enrichment or depletion of the mantle wedge (Pearce and Peate, 1995). The Moalleman samples plot above the mantle array (i.e., have high Th/Yb (Fig. 8C) and La/Yb), showing a contribution of subducted sediment components/crustal assimilation in the mantle wedge, which is the probable source of the Moalleman magmatic rocks. They are also characterized with higher Sr/Y (29.5–66.4), La/Yb (14.8–36.2), and Th/Yb (5.3–18) ratios when compared with those of depleted mantle (<15; <5; <0.1; respectively; Drummond et al., 1996). This indicates the voluminous addition of crustal components to the magma. The plots of Pb isotopic results (Fig. 7B-C) also suggest modification of the mantle, as our samples lie above the NHRL, suggesting incorporation of recycled crustal/sediment components.

Associations of Nb/Ta with either conservative and non-conservative element ratios or abundances can show whether the observed Nb/Ta fractionation was inherited from the mantle wedge or whether it reflects slab processes. Geochemically paired HFSE elements (e.g., Nb–Ta and Zr–Hf) typically show consistent behavior during mantle melting, and thus mantle-derived magmas usually preserve chondritic Nb/Ta ratios of ~17.6 (Sun and McDonough, 1989); however, the Moalleman plutonic intermediate to felsic rocks have Nb/Ta ratios of 5.7–17.0, with a mean value of 11.2, making them sub-chondritic. The Nb/Ta ratios in the studied Moalleman rocks also evidently preclude the addition of felsic sediment melts from subducted slab into the mantle wedge, which melt-source regions would otherwise recognize with high Nb/Ta values (>33) (Stolz et al., 1996). Negative correlations between Nb/Ta values and Th/Yb in the Moalleman magmatic rocks further imply modification of their Nb/Ta ratio by crustal assimilation; specifically, by contamination with continental crustal material that had a low Nb/Ta value (Munker, 1998) (Fig. 8A). A $(^{143}Nd/^{144}Nd)_i$ vs. $(^{87}Sr/^{86}Sr)_i$ plot for the studied

Moalleman magmatic rocks reveals a mixing trend between a sub-continental lithospheric mantle (SCLM) melt and lower continental crust. The mixing of continental crust is also demonstrated by (i) the presence of MMEs within the plutonic rocks (Fig. 3B, D), (ii) the variations in zircon $\epsilon_{\text{Hf}}(t)$ data, and (iii) higher Th/Yb ratios (Fig. 7C; Supplementary Table 1) in felsic rocks. Therefore, we propose that the Moalleman intrusions formed via a complex series of magmatic processes involving pyroxene, amphibole, plagioclase and titanite fractionation from mafic melts, combined with contamination and assimilation of continental crust. Supporting this interpretation, Moghadam et al. (2015b) also reported that the Kashmar granite, located in the eastern Moalleman magmatic complex, was enriched in LILE and LREE but depleted in HFSE and HREE, intruded at ~ 40 Ma (U–Pb zircon), and had $\epsilon_{\text{Nd}} = -0.43$ to -2.3 and zircon ϵ_{Hf} values of -1.9 to $+7.2$, indicating derivation from an evolved mantle melt that was later affected by FC processes and crustal assimilation.

7.2. *Spatial changes Iranian Alborz rear-arc: Enriched vs. Juvenile signatures*

A key question regarding the evolution and genesis of the Eocene Moalleman magmatic complex is how these units are linked to igneous rocks of similar ages in the Alborz rear-arc. We compiled bulk-rock major and trace element data, and isotopic and trace element analyses of zircon from Paleogene igneous rocks across the Alborz rear-arc to assess spatial variations in these characteristics from northwest to northeast. Our compilation suggests that mafic and felsic rocks have similar relative abundances at the level of exposure in the northwestern, central, and northeastern segments; however, the northeastern Alborz rear-arc shows more compositional variation relative to central and northwestern sections (Fig. 9A). The Paleogene igneous rocks from northeast of Alborz tend to contain more variable K_2O contents than those in the central and northwestern domains (Figs. 9B), including low-K, high-K, and shoshonitic signatures. This suggests that AFC processes had a more variable influence on the genesis of the northeastern Alborz rear-arc rocks than those in the central and northwestern domains. The Nb/Ta ratios in the NE Alborz rear-arc rocks also evidently preclude the addition of felsic sediment melts from subducted slab into the mantle wedge, which melt-source regions would otherwise reveal with high Nb/Ta values (>33) (Stolz et al., 1996) (Fig. 9D). In contrast, central-NW Alborz rear-arc rocks are characterized by higher mean Nb/Ta ratios of 19, implying more modification of their Nb/Ta ratio by melts derived by subducted sediments (Munker, 1998) (Fig. 9D). The NE Alborz magmatic units exhibit enriched isotopic signatures (low $\epsilon_{\text{Nd}}(t)$, high $^{87}\text{Sr}/^{86}\text{Sr}(i)$) and a range of adakitic features—from strong (e.g., Chalu) to weak (e.g., Gandi), consistent with substantial crustal interaction (Figs. 4D, 7, 9D-E).

Magmatic rocks in the central-NW Alborz rear-arc display more juvenile isotopic signatures (higher $\epsilon_{\text{Nd}}(t)$, $\epsilon_{\text{Hf}}(t)$; Fig. 9E-F) and include lithologies with adakitic affinities (higher Sr/Y; Fig. 4D), indicating a stronger contribution from mantle sources metasomatized by subducted sediment melts with less subsequent crustal modification. This interpretation is supported by geochemical and isotopic studies of NW Alborz rear-arc igneous rocks, which document elevated La/Nb, and Pb isotope ratios

characteristic of sediment melt input into the mantle wedge (Homam et al., 2025; Moghadam et al., 2022; Natali et al., 2024). The bulk-rock $\epsilon\text{Nd}(t)$ and zircon $\epsilon\text{Hf}(t)$ values are also more variable for the northeastern Alborz rear-arc (Fig. 9E-F). Such isotopic variability seems to be mainly controlled by more influence of crustal material.

To further examine along-arc variations in crustal architecture and evolution, whole-rock geochemistry was used to calculate crustal thicknesses (Moho depth) and the temperature of zircon saturation (T_{Zircsat}) of the magmas (Siégel et al., 2017) from which they were formed. The following equation (1) was used to calculate crustal thicknesses from the Late Cretaceous to the Late Eocene in the northeast, central, and northwest Alborz:

$$\text{Sr/Y} = (0.9 \times \text{dm}) - 7.25, \text{ or } \text{dm} = (1.11 \times \text{Sr/Y}) + 8.05 \quad (\text{Eq. 1})$$

where Sr/Y is whole rock average ratios, and dm = crustal thickness (depth to the Moho). This produced values of ~9–90 km (mean of ~39.2 km), ~11–66 km (mean of ~30 km), and ~18–68 km (mean of ~32 km) for the NE, central and NW Alborz rear-arc, respectively.

Calculated T_{Zircsat} for Late Cretaceous to Late Eocene magmas in the northeast, central, and northwest Alborz rear-arc were calculated using equation 2:

$$T_{\text{Zircsat}} (\text{°C}) = (12900/\ln(497600/\text{Zr}(\text{ppm}))) + 3.8 + 0.85 (M-1) - 273 \quad (\text{Eq. 2})$$

where M is the cationic ratio $(\text{Na} + \text{K} + 2\text{Ca})/(\text{Al} + \text{Si})$, and Zr (ppm) is the concentration of Zr measured in the rock. This produced values of ~700–1083 °C (mean of ~869 °C), 792–1080 °C (mean of ~894 °C), and 907–1102 °C (mean of ~1002 °C), respectively (Supplementary Table 5).

These data indicate somewhat higher crustal thicknesses in the northeast Alborz rear-arc, whereas temperatures are more variable. A thicker arc crust affects the trace and significant elemental chemistry of magmatic products that form within it (e.g., Palin et al., 2016) and can affect the degree of crustal assimilation by an ascending (Haschke et al., 2002). Most zircons in Eocene magmatic rocks from the NW Alborz rear-arc record low Hf/Y (up to ~18), Eu/Eu*(n) (< ~0.3), and Yb/Gd (< ~30) ratios, which imply fractionation of amphibole (\pm titanite) from the magmas during cooling and ascent (e.g., Lu et al., 2016). By contrast, zircons in Eocene magmatic rocks toward the NE Alborz rear-arc show similar low Hf/Y (up to ~20) and Yb/Gd (< ~30) ratios, but higher Eu/Eu*(n) (< ~0.25–0.61) ratios, which records the fractionation of amphibole (\pm titanite) and plagioclase from host magmas (e.g., Lu et al., 2016). Finally, zircon Eu/Eu*(n) ratios in Paleogene igneous rocks increase from the NW to the NE in the Alborz rear-arc, consistent with the trend of variable Sr/Y ratios and calculated crustal thicknesses (Deng et al., 2018; Tang et al., 2020).

Previous studies indicate that the thicker Eocene crust in the NE Alborz rear-arc promoted deeper magma stagnation, prolonged fractional crystallization, and enhanced assimilation of crustal material,

producing evolved melts with elevated $^{87}\text{Sr}/^{86}\text{Sr}$, low ϵNd (crustal isotope signatures), high SiO_2 , K_2O , Rb, and Th/U. In contrast, the thinner crust of the central-NW segments facilitated faster ascent of mantle-derived magmas and less effective AFC processes, preserving more juvenile signatures. The proximity of the central-NW to the NE segment may have also allowed for greater contamination from sediment-derived melts/fluids.

Zircon is a crucial mineral for tracing magmatic processes, such as AFC (Hawkesworth and Kemp, 2006). As it has a very low initial Lu/Hf ratio of ~ 0.005 and high Hf content, it is also a useful isotopic tracer of Hf. Both depleted mantle (T_{DM}) and crustal model ages (T_{DM}^{C}) were calculated based on a mantle source comparable to depleted MORB mantle (DMM) with a present-day $^{176}\text{Hf}/^{177}\text{Hf}$ ratio of 0.28328 (Salters and Stracke, 2004) and $^{176}\text{Lu}/^{177}\text{Hf}$ ratio of 0.0384 (Griffin et al., 2000), and by projecting the initial zircon values of $^{176}\text{Hf}/^{177}\text{Hf}$ to the depleted mantle growth curve by considering a $^{176}\text{Lu}/^{177}\text{Hf}$ value of 0.015 (Griffin et al., 2002). The compiled Hf isotope values and source model ages for all NW, central, and NE rear-arc early Cenozoic rocks are presented in Fig. 10A–D. The Hf isotopic compositions of zircon from Early Cenozoic magmatic rocks in the NE Alborz rear-arc span an overall $\epsilon\text{Hf}(t)$ range of $^{176}\text{Hf}/^{177}\text{Hf} = 0.28270$ to 0.28291 ; zircons from the central Alborz rear-arc are more juvenile, with $^{176}\text{Hf}/^{177}\text{Hf} = 0.282796$ – 0.283026 ; and zircon from the NW Alborz rear-arc has a more restricted range of $^{176}\text{Hf}/^{177}\text{Hf} = 0.282528$ – 0.282926 (Fig. 10A). Thus, these data support other lines of evidence for AFC processes having been relatively more important in magma evolution in the NE Alborz rear-arc. In contrast, the central-NW Alborz rear-arc preserves magmas that are more juvenile. This temporal evolution of magmatism from calc-alkaline to high-K calc-alkaline/shoshonitic to alkaline and adakitic compositions has been described in southern Armenia (Rezeau et al. 2017, 2016).

Hf crustal model ages (T_{DM}^{C}) of zircons from Eocene magmatic rocks in the NE, central, and NW Alborz rear-arc were used to constrain the timing of extraction from a presumed depleted-mantle source (cf. Griffin et al., 2002). These data show no significant differences in ages along the Alborz rear-arc. As a result, we compiled measured Hf isotopic compositions of magmatic zircons in this study and other intrusions from the northeastern Alborz rear-arc together with Eocene–Oligocene magmatic zircon from the central and northwestern Alborz rear-arc. The calculated T_{DM}^{C} ages of all zircons from these domains are shown on histograms in Fig. 10B–D. The combined T_{DM}^{C} age histogram of magmatic zircons from northeastern Alborz rear-arc zircons, which have the least radiogenic Hf isotopic compositions, vary between ~ 0.8 to 1.5 Ga (Fig. 10B), with a significant peak at ~ 0.7 Ga. In contrast, those from the central Alborz rear-arc dominantly range from 0.4 to 0.8 Ga, with a substantial peak at ~ 0.6 Ga, reflecting heterogeneity in the underlying crustal sources. Zircons from northwestern Alborz rocks yield T_{DM}^{C} values of 0.7 – 1.1 Ga, peaking at 0.9 Ga. These model ages represent the mean crustal residence time and indicate that the magmas incorporated material derived from Neoproterozoic crust, as these ages significantly predate the host rock formation and crust older than the Ediacaran has not been identified in Iran.

7.3 Tectonic Framework

The Cenozoic Iranian arc likely resembled an Andean-type convergent margin, where the subduction of oceanic crust and associated dewatering caused mantle melting, and the ascending melts interacted with the overlying arc continental crust to generate a magmatic front and rear-arc (Sepidbar et al., 2019; Moghadam et al., 2021) (Fig. 11A). However, unlike the modern-day Andean continental arc, subduction initiation during the Late Cretaceous (Fig. 11A) was followed by Paleogene slab roll-back and extension above the subduction zone (Sepidbar et al., 2019) (Fig. 11B). The change in the slab dip from Late Cretaceous-Paleocene to Eocene in close association with other causes such as rifting due to the extreme extension controlled the features and extent of the magmatic rocks across the rear-arc Alborz rear-arc during the Cenozoic. The transgressive–regressive cycles conserved in Paleogene extensional basins and crustal thicknesses show that the Paleogene tectonic evolution of Iran was complex (Supplementary Fig. 1). Several main factors to explain these variations have been proposed in previous studies, including: (i) crustal thickness and composition (Farmer and Lee, 2017); (ii) subduction geometry and slab inputs (Peng and Liu, 2023); (iii) mantle wedge heterogeneity (Turner et al., 2017) and (iv) tectonic stress regimes (Tatsumi, 2005). Crustal thicknesses and composition (adakitic vs. non-adakitic) of the Cenozoic Alborz rear-arc can be reconstructed by using Sr/Y elemental ratios of intermediate rocks (55–68 wt% SiO₂) (Chapman et al., 2015). Our compiled data for the intermediate SiO₂ composition of the Paleogene rocks show that the crustal thickness or Moho depth varied in different segments of Iran Alborz rear-arc; *av.* 30 km in N–NW Iran (Alborz) and 39.2 km in NE Iran (see Section 6.3). These crustal thickness variations show that lithospheric extension was more important for the central–NW Alborz rear-arc, as it is located in the proximal zone relative to Neo-Tethys subduction zone. Most Eocene magmatic rocks in NE Alborz rear-arc show adakitic and non-adakitic (low to high Sr/Y, no strong Eu anomalies), intermediate-felsic (andesitic-dacitic/granite) compositions with enriched Sr-Nd isotopic signatures. In contrast, the central-NW Alborz rear-arc is characterized by both adakite- and non-adakite signatures (low and high Sr/Y, low HREE) and strong slab-mobile element enrichments (e.g., Th, Pb and Sr), indicating a higher degree of slab sediment contributions during magmatism.

In this framework, since Neo-Tethyan subduction was active beneath Iran from Late Cretaceous to the Eocene (Fig. 11), the subducting sediments continued to melt more in the central-NW Alborz rear-arc proximal zone, and a significant amount of this sedimentary melt was added to a mantle wedge and/or lithospheric mantle above the down-going oceanic slab. In addition, slab rollback caused more lithospheric extension in the central and NW Alborz rear-arc (Moghadam et al., 2018 and references therein), leading to asthenospheric upwelling that caused heating and lithospheric erosion through the melting of a metasomatized mantle wedge (Verdel et al., 2011). Low degrees of partial melting of the enriched lithospheric mantle (i.e. more sediment contribution) at ~40 Ma coupled with less crustal assimilation in an intracontinental extensional in the NW Alborz rear-arc generated magmas with a geochemical signature showing more subducted slab contributions during the Eocene. However, due to

the decreasing influence of slab-derived fluids and sediments further away from subduction zone, and 628
the increased influence of crustal signatures (high LILE, negative Nb-Ta anomalies and crustal 629
thicknesses), we interpret that the generated magmas interacted with more continental crust in the NE 630
Alborz rear-arc distal zone, leading to more significant AFC signatures (Fig. 11B). 631

8. Conclusions 632

1. Paleogene high K calc-alkaline rocks from the Moalleman magmatic complex, NE Iran, formed 634
during the northward subduction of the Neotethys oceanic slab. Zircon U–Pb geochronology 635
indicates that the high-K and calc-alkaline rocks all formed within the period 49–41 Ma. 636
2. Trace element geochemistry, bulk-rock Nd, and zircon Hf-isotope composition indicate the 637
involvement of both juvenile melts and an older continental crust during the generation of high- 638
K, calc-alkaline and shoshonitic rocks. 639
3. The Alborz magmatic belt formed during northward subduction of Neotethyan oceanic 640
lithosphere simultaneous with crustal extension during the Late Cretaceous and Paleogene. 641
Major and trace element data, and bulk rock Sr–Nd–Pb and zircon Hf isotope analyses record 642
an across-arc shift in the geochemical composition of Alborz Paleogene arc magmas, from more 643
depleted in central Alborz rear-arc to more enriched to the NE and NW. Bulk rock $\epsilon\text{Nd}(t)$ and 644
zircon $\epsilon\text{Hf}(t)$ isotope systematics show that melts of enriched lithospheric mantle with slab 645
derived melt interacted less with crust in the central and NW and more in the NE Alborz rear- 646
arc. The highest Th/Yb and $^{87}\text{Sr}/^{86}\text{Sr}$ ratios, but lowest $^{143}\text{Nd}/^{144}\text{Nd}$ and most variable $^{176}\text{Hf}/^{177}\text{Hf}$ 647
isotopic ratios are found in the NE Alborz rear-arc, where magmas appear to have been more 648
contaminated by the Cadomian continental crust. 649

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Figure captions

Fig. 1. (A) Map of Iran showing the Urumieh–Dokhtar, and Alborz magmatic belts and related Cenozoic igneous rocks; (B) Geological map of the Alborz rear-arc showing the distribution of Eocene volcanic rocks, Eocene–Miocene calc-alkaline and shoshonitic intrusions and Quaternary igneous rocks.

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1/100000 maps, Geological Survey of Iran.	884
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and shoshonitic series (Peccerillo and Taylor, 1976). Field boundaries between I-type and S-type	897
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et al. (2021) and references therein.	902
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Baghu, Chalu, and Gandi igneous rocks for zircons from the (A) granite and (B) granodiorite from	908
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from Chauvel and Blichert-Toft (2001). Mantle array data are after Vervoort and Blichert-Toft (1999).	912
The calculated crustal model ages (T _{DM^C}) relate to a ¹⁷⁶ Lu/ ¹⁷⁷ Hf ratio of 0.015 for a garnet-free crust.	913
The ¹⁷⁶ Lu/ ¹⁷⁷ Hf ratios of 0.047, 0.033, and 0.017 are related to the required variations in the single	914
(melting of isotopically heterogeneous reservoirs) and two-component (interaction between mantle	915
melts and upper crust materials) models that are needed to explain the Cenozoic Lu-Hf isotope	916
systematics. Zircon Lu-Hf isotope results for Iranian arcs are from Moghadam et al. (2017), and	917
Sepidbar et al. (2018); (B) Ratios of ¹⁴³ Nd/ ¹⁴⁴ Nd vs. ⁸⁷ Sr/ ⁸⁶ Sr for Alborz rear-arc units, including the	918
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and Hart, 1986); and CHUR (Chondritic Uniform Reservoir). Data for the Cadomian upper and lower 920
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are from Aghazadeh et al. (2011), Asiabanha and Foden (2012), Castro et al. (2013), and Moghadam et 922
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(2013). The composition of the starting melt was similar to island-arc tholeiitic lavas from NE Iran and 924
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Moghadam et al. (2015). We assume that the main assimilant of Cenozoic Iran arc magmas was Late 926
Neoproterozoic (Cadomian) crust, as these outcrop widely in Iran and there are abundant Cadomian 927
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 $^{87}\text{Sr}/^{86}\text{Sr}$ and (C) $^{207}\text{Pb}/^{204}\text{Pb}$ *vs.* $^{206}\text{Pb}/^{204}\text{Pb}$. Symbols as in Fig. 4. 929

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Fig. 8 (A) Nb/Ta *vs.* Th/Yb, (B) Dy/Yb *vs.* SiO₂ and (C) Th/Yb *vs.* Nb/Yb plots for Moalleman 931
magmatic rocks emphasizing amphibole fractionation and assimilation–fractional crystallization (AFC) 932
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2018; Hosseini et al., 2017; Pang et al., 2016; Wan et al., 2018). Symbols as in Fig. 4. 937

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Fig. 9 Compiled data from the northwestern, central, and northeastern Alborz rear-arc used to identify 939
the variations in magmatism and across-arc geochemical changes. Whole rock major-trace elements 940
crustal thickness and isotope data are from (Aghazadeh et al., 2011; Asiabanha and Foden, 2012; Castro 941
et al., 2013; Moghadam et al., 2017; Honarmand et al., 2013; Sepidbar et al., 2018). 942

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Fig. 10 (A) Initial Hf isotopic composition of the magmatic zircons from the Moalleman magmatic 944
rocks *vs.* $^{206}\text{Pb}/^{238}\text{U}$ age of crystallization. Calculated crustal model ages (T_{DM}^{C}) relate to the $^{176}\text{Lu}/^{177}\text{Hf}$ 945
ratio of 0.015 for a garnet-free crust. The $^{176}\text{Lu}/^{177}\text{Hf}$ ratios of 0.047, 0.033, and 0.017 are related to the 946
required variations in the single (melting of isotopically heterogeneous reservoirs) and two-component 947
(interaction between mantle melts and upper crust materials) models that are needed to explain the 948
Cenozoic Lu-Hf isotope systematics. (B) to (D) show calculated T_{DM}^{C} ages of all zircons from different 949
domains of Alborz rear-arc as histograms. Symbols as in Fig. 4. 950

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Fig. 11 Simplified cross-section of the Cretaceous-Paleocene subduction (A) and Eocene collision 952
zones in Iran, showing special variation and mantle heterogeneity as enriched (AFC) to juvenile (slab- 953
derived) melts processes from NE to NW Alborz rear-arc. 954