Alkaline-rich intermediate and felsic melts beneath the NW Iranian plate: New insights from coeval silica-undersaturated and -saturated rocks

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Abstract

New whole-rock major and trace element data, coupled with Sr–Nd isotopic ratios data, zircon Hf isotopes, and U–Pb geochronology are presented for three alkaline intrusions (Hashroud, Sisan and Sarab) in the Zanjan-Takab complex in northwestern Iran, to investigate their sources, petrogenesis and tectonic implications of emplacement. The Hashroud and Sisan plutons are mainly composed of silica-saturated granite and syenogranite, respectively, whereas the Sarab region consists of nepheline-bearing syenite, and associated undersaturated lavas ranging in composition from tephri-phonolite to trachy-basalt/andesite. Zircon U–Pb geochronology gives emplacement ages of 38 and 36 Ma for the Hashroud and Sisan silica-saturated rocks, which are slightly younger than Sarab silica-undersaturated rocks (40 Ma). Silica-undersaturated and silica-saturated rocks differ from each other mostly in terms of their silica content, but show comparable incompatible trace element distributions, typical of subduction-related magmatic rocks. The undersaturated rocks display higher LILE/HFSE (Ba/Th: up to 365), but relatively similar LILE/LREE

(Ba/La: 13–44)) values to those of saturated rocks (Ba/Th: up to 38; Ba/La: up to 27). Silica-undersaturated and -saturated rocks also show distinct Sr–Nd–Pb isotopic compositions, with the former having less radiogenic Sr (^{87}Sr/^{86}Sr, 0.70452–0.70510) and Pb (^{206}Pb/^{204}Pb, 18.61–18.67; ^{207}Pb/^{204}Pb, 15.57–15.60; ^{208}Pb/^{204}Pb, 38.64–38.74) and more radiogenic Nd (^{143}Nd/^{144}Nd, 0.512648–0.512674) than the latter (^{87}Sr/^{86}Sr, 0.70619–0.71409; ^{206}Pb/^{204}Pb, 18.78–18.82; ^{207}Pb/^{204}Pb, 15.60–15.63; ^{208}Pb/^{204}Pb, 38.78–38.82; ^{143}Nd/^{144}Nd, 0.512613–0.512620). Geochemical and isotopic compositions of the silica-undersaturated rocks suggest the involvement of fluids derived from subducted oceanic crust and subordinate sediment as metasomatizing agents in their mantle source. On the other hand, the studied silica-saturated units, which crystallized from mafic parental melts modified by crustal assimilation and fractional crystallization, originated from a lithospheric mantle source that had been metasomatized via a relatively high volume of terrigenous subducted sediment melts. Both the Eocene saturated and undersaturated igneous rocks formed in a post-collisional extensional setting. Our study, along with compiled data, also finally settles the long-standing debate about the geodynamic evolution of the NW Iranian belt, showing that a compressive to extensional tectonic regime existed during the Arabia-Eurasia collision. This was related to Neo-Tethyan slab roll-back, which generated alkali-rich magmatic rocks throughout the NW Iranian belt.

Keywords: Zanjan-Takab complex, silica-undersaturated rocks, Zircon U–Pb dating, NW Iran,

1. Introduction

Alkaline silica-undersaturated and -saturated igneous rocks commonly coexist in active continental margins, and offer a natural laboratory for evaluating tectonic and magmatic processes. Such alkaline igneous rocks can form in many tectonic settings, but are particularly prominent during subduction-related, syn- and late-collisional stages of orogenic cycles, and in rift or intraplate tectonic settings (Sylvester, 1989; Bonin, 1990; Bonin et al., 1998; Black and Liegeois, 1993; Avanzinelli et al., 2009; Conticelli et al., 2015; Lustrino and Wilson, 2007; Prelević et al., 2008). They may form due to (i) partial melting of an enriched phlogopite-bearing lithospheric mantle (e.g., Foley, 1992), (ii) mixing between mantle and crust-derived magmas (e.g., Guo *et al.* 2013), (iii) fractionation of K-free/-poor minerals, such as pyroxene and plagioclase (Ding *et al.* 2014), (iv) assimilation of alkaline-rich crustal components (Foley, 1992), (v) accumulation of feldspar during fractional crystallization (Xu *et al.* 2009) and/or (vi) the melting of mantle sources variously metasomatized by the addition of different sedimentary and/or mafic components (Natali et al., 2024), coupled with a steepening and roll-back of the subducted plate in the late stage of late-collisional setting (e.g., Conticelli et al., 2009, 2015; Conticelli and Peccerillo, 1992; Moghadam et al., 2018). In particular, debate remains about which geological processes dominate the mantle enrichment stage prior to eruption. The most common explanation for mantle enrichment is metasomatism of a wedge driven by the addition of melts (or aqueous fluids) derived from subducted sediments (e.g., Prelević *et al.* 2010) and/or oceanic crust (e.g., Gaffney *et al.* 2007; Khedr and Arai, 2009; Khedr *et al.* 2010).

Well-exposed coexisting alkaline silica-undersaturated and -saturated igneous rocks are widely distributed within the Alborz Magmatic Belt (AMB), and a rear-arc (RA) behind the magmatic front of Urumieh–Dokhtar magmatic arc (UDMA) (Sepidbar *et al.* 2021). These magmatic arc and belts contain complexes of Eocene alkalic igneous rocks, known as Zanjan-Takab (this study) and Ahar-Arasbarn, that include saturated granite and syenogranite, and undersaturated nepheline syenite and associated volcanic rocks (Natali et al., 2024). Both sets formed during subduction-related to syn- and late-collisional tectonic activity associated with closure of the Neo-Tethys Ocean during the Alpine Orogeny and provide a unique opportunity to evaluate the characteristic nature of the mantle source from which they were derived. However, these alkaline igneous rocks are petrologically diverse, and their origin remains a strongly debated topic amongst researchers. Most previous workers have concluded that they formed due to heat and/or mass transfer from the mantle and partial melting of the crust, alongside fractional crystallization (FC) or assimilation-fractional crystallization (AFC) of mantle-derived basaltic magmas (Sepidbar *et al.* 2019; Sepidbar *et al.* 2021; Moghadam *et al.* 2017). In addition, a mantle wedge metasomatized by subducting sediment melts and/or sub-continental lithospheric mantle (SCLM) is suggested to be the main source for the formation of the alkaline rocks in RA regions (Jacques et al., 2014; Laporte et al., 2014).

The Sisan, Hashroud and Sarab rocks are located within the Zanjab-Takab complex, characterized by the co-existence of both alkaline silica-undersaturated and -saturated intrusive and extrusive igneous rocks in the RA region. The origin and evolution of these alkaline-rich magmas are enigmatic, and their tectonic significance for understanding the evolution of the AMB during the Cenozoic is unresolved. Indeed, very few geochronological, geochemical, and isotopic studies of silica-undersaturated alkaline rocks from the rear-arc of NW Iran are available in literature (Moghadam *et al.* 2013; Sepidbar *et al.* 2023). In this study, we present new data for U–Pb zircon dating and in-situ Hf isotopic compositions, whole-rock geochemistry, and Sr–Nd–Pb isotope analyses for the Paleogene igneous rocks around Zanjab-Takab, NW AMB. These alkaline rocks are comparable with Eocene lithologies from the Ahar-Arasbaran complex to the north, including the Lahrud area and Salavat range in the Ardabil province, Moghan area (Amraee et al., 2019), Alborz Mountains (Aghazadeh et al., 2011) and Lesser Caucasus (Dilek et al., 2010; Lustrino et al., 2019). This allowed us to: (1) better establish the geochemical diversity of the alkaline igneous rocks from this region in terms of major, trace element, and Sr–Nd isotopic characteristics; (2) characterize the source and origin of Paleogene high alkaline silica-undersaturated and saturated magmatism in NW Iran and (3) reveal the extent of Paleogene mantle anomalies across NW Iran to Armenia. Using these data, we propose a new petrogenetic model that considers the entire history of Paleogene magmatism in the NW Iranian belt during Eocene.

2. Geological setting

The NW AMB, south Armenia, and NE Turkey represent the hinterland of the Arabia–Eurasia collision zone (Figure 1) in the broad Alpine–Himalayan orogenic belt from the Early Paleocene to the Pleistocene. Northward subduction of the Neo-Tethyan Ocean from the Upper Cretaceous to the end of the Eocene ended with continental collision between the Arabian and Eurasian plates (McQuarrie and van Hinsbergen, 2013), followed by an extensional regime developing in a late-collisional setting related to slab roll-back (Castro *et al.* 2013; Moghadam et al., 2018; Sepidbar *et al.* 2021). The AMB is mainly composed of thick (500–1000 m) Paleocene to Middle-Eocene sequences of deep marine limestones, which vary in thickness and often grade into fine-grained pyroclastic rocks. Eocene flare-up magmatism in the NW Iran corresponds with this marine transgression, which coincides with a rapid fall in global sea level (Miller et al., 2005), suggesting that this subsidence was related to crustal thinning and extension. The late Eocene to late Oligocene regression resulted in the deposition of red volcano-sedimentary sequences. This was followed by an Oligocene to Early Miocene marine transgression and deposition of limestones and marls interlayered with mafic lava flows. The temporal and spatial distribution of Cenozoic magmatic rocks display cycles of magma formation with geochemically distinct characteristics, marked predominantly by coeval high-K calc-alkaline/shoshonitic and alkaline signatures during the Late Paleocene-Early Oligocene, and potassic to ultrapotassic with adakitic characteristics, and/or OIB-like rocks without depletion in Nb and Ta during the Miocene to Pleistocene (Lechmann *et al.* 2018; Neill *et al.* 2015).

The oldest units in the NW AMB belong to the Zanjan-Takab complex, which comprises Late Proterozoic-Early Paleozoic (Cadomian) metamorphic rocks, including meta-granite (gneissic rocks), metabasites (amphibolites), calc-silicate rocks, meta-psammitic to meta-pelitic rocks, meta-ultramafic rocks and migmatites (e.g., Moghadam *et al.* 2017; Sepidbar *et al.* 2019). This complex was exhumed from the middle–lower crust and was intruded by younger plutons during the Triassic and Jurassic. These Mesozoic intrusions are unconformably covered by Paleocene to Eocene volcanic rocks, which are mostly andesite, andesite-basalt, trachyandesite and analcime-bearing trachy-basalt/andesite. Two main Cenozoic volcanic rock types are recognized: (1) silica-saturated potassic trachybasalts, shoshonites, latites, and trachytes, and (2) silica-undersaturated basanites/tephrites, phonolitic tephrites, and phonolites (e.g., Alberti et al., 1980; Dilek et al., 2010; Soltanmohammadi et al., 2018, 2021). Several intermediate to acidic plutonic rocks intrude into Cenozoic volcanic members and have U–Pb zircon ages of ~59–21 Ma (Badr et al. 2013; Castro et al. 2013; Moghadam et al. 2017; Sepidbar et al. 2019; Stockli, 2004). Previous geochemical, isotopic and geochronological studies suggest that NW Iran RA magmatism occurred from ~49 to 36 Ma (Early to Late Eocene), lasting ~15 Myr (Moghadam et al., 2017; Sepidbar et al, 2019, Sepidbar et al., 2021). Most intrusions and accompanying volcanic rocks in this region exhibit shoshonitic and high-K calc-alkaline geochemical signatures (Sepidbar et al. 2019). Asiabanha and Foden (2012) suggested an extensional regime in a post-collisional setting for the formation of shoshonitic intrusions from Zanjan (Figure 2). To expand this dataset and further constrain the timing of the NW Iran magmatism, we conducted new U–Pb geochronological analyses on zircons from both Sarab undersaturated and Sisan-Hashroud saturated igneous rocks collected from the Zanjan-Takab complex. Geochemical and isotopic data are also reported and were used to reconstruct the geochemical evolution of magmatism in the NW Iranian belt during the Paleogene.

3. Geology of the studied rocks and petrography

Eocene alkaline complexes are widely distributed within the Zanjan-Takab region in NW Iran. The oldest unit in the Sarab, Sisan and Hashroud is the Barut Formation, which is comprised of Cambrian shales, sandstones, and dolostone (not shown on Figure 2). This unit is conformably overlain by the middle Cambrian Lalun Formation composed of reddish, mainly quartzitic sandstones, and all of these sequences are unconformably covered by Early to Middle Eocene silica-saturated and -undersaturated volcanic rocks. Finally, Quaternary alluvium and terrace deposits cover all of the aforementioned units (Figure 2). In this paper, we investigated three coeval Eocene alkaline intrusions in the Zanjan-Takab complex: the silica-undersaturated Sarab igneous rock, and the silica-saturated Sisan and Hashroud plutons.

4.1.1. Foid-bearing (silica-undersaturated) rocks

The silica-undersaturated volcanic rocks studied here extend from Asbfroushan Narmiq to Fandoqlu as an elongated body bounded by NE-SW trending faults in the south of Sarab (Figure 2). They are exposed over an area of ~100 km^2 and consist mainly of Eocene analcime (leucite)-bearing trachy-andesite and tephritic phonolites, alongside lesser basalt. The contact between the Eocene analcime (leucite)-bearing trachy-andesite and tephritic phonolites with andesite is well exposed as a series of normal faults at its southern margin, whereas in the north, these rocks are adjacent to Quaternary terraces (Figure 3A). The analcime (leucite)-bearing trachy-andesite rocks of Asbfroushan and Narmiq are characterized by medium grained aphyric to porphyritic textures, with analcime formed from primary leucite, clinopyroxene, plagioclase, and rarer sanidine phenocrysts that are set in a fine-grained groundmass of the same mineral assemblage. The Fandoqlu rocks show petrographic features very similar to the Narmiq volcanic rocks, with the exception of a greater proportion of foid minerals as phenocrysts, and are tephritic-phonolites. Most of these tephritic-phonolites show petrographic evidence of cumulus analcime (or leucite).

Nepheline syenites occur as stock-like plutons and dikes in the south of Asbfroushan (Figure 2). They intrude into foid-bearing trachy-andesites, tuff, and ignimbrite to the south, signifying relatively younger ages with respect to foid-bearing volcanic rocks, and are covered by Late Cenozoic alluvium to the north. Nepheline-bearing syenites are leucocratic and coarse-grained (Figure 3B) and are dominated by nepheline (5–10 vol. %), and perthitic K-feldspar (~50–60 vol. %), accompanied by variable amounts of oligoclase and interstitial albite (10–20 vol. %), amphibole and biotite (2–5 vol. %). Accessory phases mainly include fluorapatite, zircon, allanite, and titanite. Locally, poikilitic micro-textures comprised of fluorite and calcite grains embedded within larger nepheline and oligoclase crystals have been recorded. Secondary alteration is ubiquitous in all nepheline syenite samples, and predominately affects foids and accessory minerals.

4.1.2. Foid-free (silica-saturated) rocks

The Sisan stock is a composite intrusion of syenogranite that is exposed over an area of ~10 km^2 (Figure 2). It intrudes into Eocene volcanic rocks (andesites, trachyandesite, alkali basalts and pyroclastic rocks) in the northeast (Figure 3C), but is overlain by Pliocene conglomerate, lahars and mudflows, pumice and volcanic ash in the northwest and south. It is light pink in color and shows a porphyritic texture, being composed of K-feldspar (40–42 vol. %), quartz (25–30 vol. %), plagioclase (22–24 vol. %), amphibole and/or biotite (4–5 vol. %), and rare pyroxene. Zircon, apatite, titanite and opaque minerals are accessories. Alkali feldspar crystals contain small inclusions of euhedral plagioclase and subhedral biotite. Plagioclase is lath-shaped and zoned, with compositions between oligoclase and andesine. It is partly altered to sericite and carbonate. Anhedral quartz exists as phenocrysts and/or interstitial between feldspars. Orthoclase is interstitial between plagioclase and also forms rims around plagioclase. Amphibole occurs as prismatic crystals and is partly replaced by chlorite and minor epidote. Biotite is common and exists as flaky or fibrous crystals.

Hashroud intrusive rocks are mainly granites, exposed over an area of ~35 km^2, and intrude into Eocene strata comprised of volcanoclastic sandy and silty clay, conglomerate, volcanic ash and pumice (Figure 3D). These granites show medium to coarse-grained granular and porphyritic textures. They comprise quartz (30–35 vol. %), plagioclase (32–35 vol. %), K–feldspar (28–30 vol. %), and biotite (5 vol. %). Magnetite, zircon, apatite, and titanite are accessory minerals. Subhedral to anhedral plagioclase crystals (0.5–2 mm) are sometimes altered to clay minerals and sericite; plagioclase has compositions between oligoclase and albite. Quartz grains are anhedral and/or interstitial between plagioclase and alkali feldspar.

4. Analytical techniques

Zircon grains from samples of Sarab nepheline syenite (S-2), Sisan syenogranite (SI-1) and Hashroud granite (HA-1) were separated using conventional magnetic separation and heavy liquids. Subsequently, zircon grains were handpicked, mounted in epoxy resin, polished and coated with a film of carbon for imaging. All grains were imaged by CL and BSE to provide maps to guide the choice of analytical spots. Zircon U–Pb dating and rare earth element analysis was performed at the State Key Laboratory of state Key Laboratory of Geological Processes and Mineral Resources, School of Earth Sciences, China University of Geoscience (GPMR–CUG) Wuhan by laser ablation ICP–MS. Laser ablation sampling was performed using a Geolas 2005 system equipped with a 193 nm ArF–excimer laser. An Agilent 7500a ICP–MS was used to acquire ion-signal intensities. Detailed instrumental conditions and data acquisition were described by Liu *et al.* (2010). The laser beam had a diameter of 32 μm, a repetition frequency of 6 Hz and laser energy of ~60 mJ. The Agilent Chemstation was utilized for the acquisition of each individual analysis. The offline selection and integration of background and analyte signals, and time–drift correction and quantitative calibration were conducted by ICPMS–DataCal (Liu *et al.* 2010). Zircon 91500 was used as the external standard for U–Pb dating and SRM–610 was analyzed for trace element calibration. Time-dependent drifts of U–Th–Pb isotopic ratios were corrected using a linear interpolation for every five analyses according to the variations in zircon standard 91500 (Liu *et al.* 2010). Preferred U–Th–Pb isotope ratios used for zircon 91500 are from Wiedenbeck *et al.* (1995). The preferred values for the standard 91500 were propagated to the results of the samples. Zircon standard GJ–1 was analyzed as an unknown. A common Pb correction was carried out by using the EXCEL program ComPbCorr#_151 (Andersen, 2002). The results were processed using ISOPLOT (Ludwig, 2003). Zircon U–Pb ages and trace-element data are presented in Supplementary Table 1.

Whole-rock major and trace element analyses of the Sarab silica-undersaturated and Sisan and Hashroud saturated rocks were conducted using inductively coupled plasma optical emission spectrometry (ICP–OES) and inductively coupled plasma mass spectrometry (ICP–MS), respectively, at the ACME Analytical Laboratories (Vancouver), Canada. Powdered samples (~0.2 g) were dissolved using lithium metaborate/tetraborate flux and digested by nitric acid. Analytical precision, based on repeated analyses, is ±1% for major elements, whereas most trace elements have an uncertainty of ±5%. Whole-rock major- and trace-element data are presented in Supplementary Table 2.

Lead (Pb), Sr and Nd isotope ratios were determined at the State Key Laboratory of Isotope Geochemistry, Guangzhou Institute of Geochemistry, Chinese Academy of Sciences. Samples for Sr–Nd isotopic analysis were dissolved in Teflon bombs by an HF + HNO_3 acid mixture. Sr and Nd were then separated using conventional ion exchange procedures and measured using a Neptune Plus MC–ICP–MS. Procedural blanks contained <100 pg of Nd and <500 pg of Sr. During laboratory analysis, measurements of the NIST SRM Sr standard yielded a $^{87}Sr/^{86}Sr$ ratio of 0.710263 ± 0.000016 (2σ), and the JNdi–1 Nd standard yielded a $^{143}Nd/^{144}Nd$ ratio of 0.512080 ± 0.000004 (2σ). A detailed description of the Sr–Nd analytical technique and correction procedure is provided in Wu *et al.* (2006). Pb isotope ratios were also measured at the State Key Laboratory of Isotope Geochemistry, Guangzhou Institute of Geochemistry, Chinese Academy of Sciences. An amount of powder containing ~1μg of Pb was weighed and placed in a 7 ml Savillex screw-top breaker. Silicate samples were completely discomposed in a mixture of HF–HNO3 (3:1 v/v) at 100 °C for one week and then dried down on a hotplate at 120 ºC. Samples were then treated with 3N HCl and dried down several times to break down insoluble CaF_2. Pb was separated in Micro Bio–Spin columns (Bio–Rad) packed with 0.35 ml AG1–X8 (200–400 mesh). Matrix elements were rinsed with 5 ml 1N HBr and 1 ml 2N HCl, and Pb was collected with 2 ml 6N HCl. The Pb cuts were dried down and re-dissolved into 2% HNO_3 for mass determination. The procedural blank for Pb was less than 0.3 ng, which is insignificant relative to the amount of processed Pb in the sample. Pb isotope ratios were measured on a Thermo–Fisher Scientific Neptune Plus MC–ICP–MS using a Tl standard to correct instrumental mass-dependent fractionation. All whole rock Sr–Nd–Pb isotope data are presented in Supplementary Table 3.

In situ zircon Hf isotopic analyses were obtained using a Neptune Plus multi–collector inductively coupled plasma mass spectrometry MC–ICP–MS, in combination with a Geolas 2005 excimer ARF laser ablation system, at GPMR–CUG. During the analysis, a laser repetition rate of 20 Hz at 200 mJ was used with the spot size of 44 μm. Details of the analytical technique are described in Hu *et al.*(2011). During analysis, raw count rates for ^{172}Yb, ^{173}Yb, ^{175}Lu, $^{176}(Hf+Yb+ Lu)$, ^{177}Hf, ^{178}Hf, ^{179}Hf, ^{180}Hf and ^{182}W were collected. Isobaric interference corrections for ^{176}Lu and ^{176}Yb on ^{176}Hf must be determined precisely. ^{175}Lu was used for interference correction of ^{176}Lu on ^{176}Hf. The $^{176}Yb/^{172}Yb$ value of 0.5887 and mean βYb value obtained during Hf analysis on the same spot were applied for the interference correction of ^{176}Yb on ^{176}Hf. In addition, the $^{176}Hf/^{177}Hf$ ratio of the standard zircon (GJ–1) was 0.282013 ± 0.000022 (2σ), agreeing with the recommended values within 2σ error (Wu *et al.* 2006). The zircon Hf isotope data are presented in Supplementary Table 4.

5. Results

5.1 Zircon U–Pb geochronology

We analyzed three samples from foid-bearing and -free igneous rocks of the Zanjan-Takab magmatic complex for zircon U–Pb ages, including nepheline-syenite (S-2), syenogranite (Si-1), and granite (HA-1). CL images and U–Pb age results are shown in Figure 4 and are further given in Supplementary Table 1

Zircons from the Sisan syenogranite (SI-1; Figure 4A-B) are prismatic with length to width ratios of 2:1 to 1:1. Inherited cores are also readily distinguished in CL images. U and Th contents of zircons vary from 92 to 449 and 68 to 514.5 ppm, respectively. Th/U ratios range from 0.6 to 1.1, which are similar to the values of magmatic zircons (Belousova et al., 2002). Analyzed zircons reveal a weighted mean $^{206}Pb/^{238}U$ age of 38.6 ± 0.8 Ma (MSWD = 0.4) (Fig. 4A), which is interpreted as the crystallization age of this syenogranite.

Zircons from the Hashroud granite (HA-1; Figure 4C-D) are prismatic with length to width ratios of 3:1 to 1:1 (Fig. 6F). U and Th contents of zircons vary from 173 to 3585 and 207 to 2776 ppm, respectively. Th/U ratios range from 0.7 to 2. The analyzed zircons display a weighted mean $^{206}Pb/^{238}U$ age of 36.8 ± 0.5 Ma (MSWD = 0.8) (Figure 4C), which is considered the crystallization age of the Hashroud granite.

Zircons from the Sarab nepheline syenite (S-1; Figure 4E-F) have length to width ratios of 2:1 to 1:1 and show oscillatory zoning. U and Th contents of zircons vary from 541 to 1708 and 341 to 3042 ppm, respectively. Th/U ratios range from 0.5 to 1.9, which are similar to magmatic zircons (Belousova et al., 2002).The analyzed zircons reveal a weighted mean $^{206}Pb/^{238}U$ age of 40.3 ± 0.5 Ma, MSWD = 0.87 Ma (MSWD = 3.5) (Figure 4E), which we interpret as the crystallization age of this nepheline syenite.

5.2 Whole-rock geochemistry

5.2.1. Silica-saturated igneous rocks

The Hashroud and Sisan silica-saturated rocks mostly include differentiated products of the whole studied sample set, with SiO_2 contents of 63.9-64.0 to 73.5-73.6 wt. %, respectively (Supplementary Table 2). They display high-K calc-alkaline signatures, akin to the leucite-bearing units, and are classified as alkaline rocks with high K_2O+Na_2O contents of 8.8 to 10.7

wt. %. Relative to the foid-bearing rocks (Supplementary Table 2), the investigated silica-saturated rocks have lower MgO (0.21 to 2.73 wt. %), Al_2O_3 (13.5-15.8 wt. %), CaO/Al_2O_3 ratios (0.01-0.21), Sr (321-351 ppm), Y (14-21 ppm) and Yb (0.6-1.8 ppm) contents. The foid-free intrusive samples mostly plot in equivalent fields to granite and syenogranite on the TAS diagram (Figure 5A), and plot in the silica-saturated field in the K_2O/Na_2O *vs.* Q-(Lu+Ne+Kal+Ol) (Figure 5B). Chondrite-normalized REE patterns for the foid-free rocks are enriched in light rare earth elements (LREE) compared to heavy rare earth elements (HREE) (e.g., La(n)/Yb(n) = 10–33), with negative Eu anomalies (Eu/Eu* = 0.5–0.92). These rocks show all nearly identical chondrite- and NMORB-normalized patterns, and are weakly fractionated in HREEs compared to MREE ((Gd/Yb)n = 1.2–1.7) (Figure 6A-B). In a NMORB-mantle-normalized diagram (Sun and McDonough 1989), the plutonic rocks show notable enrichment in Rb, Ba, Th, Zr, and Pb, and negative anomalies in high field strength elements (HFSE) such as Nb, and Ti (Figure 6B).

5.2.2. Silica-undersaturated igneous rocks

Major and trace-element compositions of 24 volcanic samples from Sarab are presented in Supplementary Table 2. Measured loss of ignition (LOI) values were mostly < 3 wt. %, except for three samples that recorded slightly higher values of 3.1-4.7 wt. %. These volcanic samples are predominantly shoshonitic, with high-K calc-alkaline characteristics (Supplementary Table 2). The silica-undersaturated volcanic rocks have K_2O contents ranging between 3.4 and 6.9 wt. %. They are classified as alkaline rocks that are rich in K_2O+Na_2O (7.8 to 11.5 wt. %) and are characterized by the presence of foids (Sokoł *et al.* 2018). Collectively, the studied volcanic samples mostly plot in the tephri-phonolite and trachy-andesite fields on a TAS diagram (Figure 5A). They plot in the silica-undersaturated fields in the K_2O/Na_2O *vs.* Q-(Lu+Ne+Kal+Ol) (Peccerillo and Taylor, 1976) diagram (Figure 5B), respectively. The undersaturated volcanic rocks have an intermediate composition, with SiO_2 contents of 48.8-57.7 wt. % (Supplementary Table 2). MgO varies between 0.66 to 3.59 wt. %, except for one mafic sample (S21-34) with much higher MgO (7.02 wt. %). They have high Al_2O_3 (15.3-19.6 wt. %), low CaO/Al_2O_3 ratios (0.17-0.58), variable Sr (387-856 ppm), coupled with low Y (16-29 ppm) and Yb (1.5-2.8 ppm) contents (Supplementary Table S2). The Sr/Y ratios (16-45) of these igneous rocks correspond to normal arc rocks (Supplementary Table S2). All samples show enrichment in LREE relative to the HREE with $La_{(n)}/Yb_{(n)}$ = 7–19 and negative Eu anomalies (Eu/Eu* = 0.62–0.95; Figure 6C). In a NMORB-normalized (Sun and McDonough 1989) multi-element diagram, the samples show strong enrichment in Cs, Rb, Ba, Th, U and Pb, and negative anomalies in high field strength elements (HFSE) such as Nb, (e.g., $Nb_{(n)}/La_{(n)}$ ~ 0.4-0.8), noticeable features for the unsaturated magmatic rocks (Figure 6D). These rocks are weakly fractionated in HREEs compared to MREEs ($Gd_{(n)}/Yb_{(n)}$ = 1.5–2.2).

The major and trace element compositions of the 11 intrusive samples from Sarab are presented in Supplementary Table 2. Their LOI is mostly below 2 wt. %, apart from two samples that have 2.4-2.7 wt. %. Similar to the volcanic rocks, intrusive bodies also have intermediate compositions and mostly plot in the syenite fields of the TAS diagram (Figure 5A) (Le Maitre et al., 2005). They have 54.5 to 58.3 wt. % SiO_2, 0.9 to 2.4 wt. % MgO, 3.9 to 4.8 Na_2O and 5.8 to 7.5 wt. % K_2O (Supplementary Table S2). Most of the intrusive rocks have variable CaO/Al_2O_3 ratios (0.16-0.25) and Al_2O_3 (16.7-20.3 wt. %). They are characterized by variable Sr (396-813 ppm), with low Y (15-33 ppm) and Yb (1.5-3.2 ppm). The Sr/Y ratios (12-56) of these igneous rocks also show a similar range to normal arc rocks (Supplementary Table 2).

Chondrite-normalized REE patterns for nepheline syenite are enriched in LREE compared to HREE (e.g., La(n)/Yb(n) = 8–12), with negative Eu anomalies (Eu/Eu* = 0.67–0.97), except for sample (S21-8) with Eu/Eu* = 1.1 (Figure 6E). These rocks show all nearly identical chondrite- and NMORB-normalized patterns, being weakly fractionated in HREEs compared to MREE (Gd/Yb)n= 1.2–1.9) (Figure 6E). In a NMORB-mantle-normalized diagram (Sun and McDonough 1989), the plutonic rocks show notable enrichment in Rb, Ba, Th, Zr, Hf, U and Pb, and negative anomalies of some high field strength elements (HFSE) such as Nb and Ti, along with Sr (Figure 6F).

5.3 Sr–Nd–Pb isotope geochemistry

Supplementary Table 3 shows Sr–Nd–Pb isotopic ratios of rocks from the silica-saturated Hashroud and Sisan and silica-undersaturated Sarab igneous rocks, and their initial ratios are plotted in Figure 9. The initial $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ ratios, and εNd(i) values have been recalculated on the basis of zircon U–Pb indicating crystallization at 40 Ma (Figure 9A). The foid-bearing volcanic and plutonic rocks similar $(^{87}Sr/^{86}Sr)_i$ ratios between 0.70484 and 0.70529. The $(^{143}Nd/^{144}Nd)_i$ ratios of 0.51264 and 0.51272 for both volcanic and plutonic rocks display positive εNd(i) values between 1.2–2.5 (Supplementary Table S3). Corresponding single-stage (T_{DM1}) and two-stage depleted mantle Nd model ages (T_{DM2}) are in the ranges of 0.66–0.76 Ga and 0.65–0.75 Ga, respectively. The foid-free plutonic rocks have wider ranges of ($^{87}Sr/^{86}Sr$)i between 0.70619 and 0.71409. The ($^{143}Nd/^{144}Nd$)i ratios of 0.512613 and 0.51268, correspond to positive εNd(i) values between 0.4–1.6 (Supplementary Table 3). The corresponding single-stage (T_{DM1}) and two-stage depleted mantle Nd model ages (T_{DM2}) are in the ranges 0.62–1.04 Ga and 0.72–0.81 Ga, respectively. They partially plot in overlap fields defined by Eocene alkaline rear-arc magmatic rocks from NW Iran (Figure 9A). Both foid-bearing and foid-free rocks show little variation in Pb isotopic composition, with $^{206}Pb/^{204}Pb(i)$ = 18.56–18.58, $^{207}Pb/^{204}Pb(i)$ = 15.58–15.59, $^{208}Pb/^{204}Pb(i)$ = 38.65–38.68 and $^{206}Pb/^{204}Pb(i)$ = 18.78–18.82, $^{207}Pb/^{204}Pb(i)$ = 15.61–15.63, and $^{208}Pb/^{204}Pb(i)$ = 38.78–39.67, respectively. In a conventional Pb isotope diagram (Figure 9B-C), both the Hashroud-Sisan foid-free and foid-bearing Sarab igneous rocks display the same composition and plot above the Northern Hemisphere Reference Line (NHRL; Hart, 1984). Indeed, the Pb isotopic composition lies between the Pb isotopic composition of Indian MORBs and subducting trench sediments (Figure 9C).

5.4 Zircon Hf isotopes

In-situ Hf isotopic analyses of zircons from three representative samples are listed in supplementary Table 4 and shown in Figure 10. Zircons from the foid-free Sisan syenogranite (Si-1) and granite Hashroud (HA-1) have homogeneous $^{176}Hf/^{177}Hf$ ratios (0.28253 to 0.28293) with εHf(t) values ranging from −4.0 to +6.3 (Fig. 8), depleted mantle model ages (TDM) ranging from 0.5 to 1.04 Ga and crustal model ages (TDM_C) of 0.7 to 1.2 Ga (Supplementary Table S4). Zircons from the Sarab silicate-saturated intrusion (S-1) have relatively homogeneous and higher $^{176}Hf/^{17}7Hf$ ratios (0.28293 to 0.28323) and εHf(t) values ranging from +6.4 to +16.9 (Fig. 8). The Hf “crustal” model ages, or TDM_C values of the nepheline syenite zircons vary between ~0.3 and 0.5 Ga, using a $^{176}Lu/^{177}Hf$ ratio of 0.015 (Griffin *et al.*, 2004).

6. Discussion

Our new data provide important insight into the petrogenesis of both Eocene alkaline-rich silica-undersaturated and -saturated magmas in NW Iran, including source characteristics and magma genesis processes. We have provided petrological descriptions for most Eocene alkaline rear-arc magmatism in NW Iran, alongside indicating the nature of the metasomatic agents affecting their mantle sources, in turn associated with the subduction framework in this sector of the NW Iran.

6.1. Petrogenesis of the silica-undersaturated and -saturated melts

The Sarab nepheline-bearing syenite, foid-free Hashroud granite and Sisan syenogranite are formed during the Eocene (Figure 4). However, the Hashroud granite and Sisan syenogranite are relatively younger (36.8 Ma and 38.6 Ma, respectively) than that of the nepheline-bearing syenite (40 Ma). They are also characterized with distinctly higher whole-rock $^{87}Sr/^{86}Sr$ and lower zircon Hf isotopic compositions from the nepheline-bearing syenite, discounting a simple magmatic process, such as evolution of a single parental magma, having formed all units. These geochemical and isotopic compositions thus show they could not have been generated from the same sources or by the same petrogenetic processes.

6.1.1. Eocene silica-undersaturated magmas

The Sarab nepheline-syenite rocks have lower SiO_2 (54.5–57.8 wt. %), MgO (0.9–2.4 wt. %), Cr (0.9–17 ppm), and Ni (2.7–58.5 ppm) contents than the Hashroud and Sisan silica-saturated rocks (SiO_2 = 63.9 wt. %, MgO = 0.21-2.73 wt. %, Cr up to 31 ppm, and Ni = 2-8 ppm). These features indicate that these nepheline-bearing syenite samples are not primary mantle-derived magmas. However, these silica-undersaturated rocks are characterized with positive and higher εHf(t) (+6.4 to +17.0) and εNd(t) (+1.2 to +2.5) (Supplementary Tables 2-4), indicating the role of mantle melting in their genesis. In addition, the existence of basaltic counterparts (this study) (Supplementary Table 2) and gabbroic rocks (Moghadam et al., 2022) from Kelaybar, show derivation of the nepheline bearing syenitic magma from mantle-derived melts via FC. The investigated primary basaltic rocks (Sarab; this study) and gabbroic rocks (Kelaybar; Moghadam et al., 2022) are enriched in LILE and LREE but depleted in HFSE (purple line; Figure 6), indicating that their parental magma was derived from a mantle source metasomatized by subduction-related melts/fluids. Similar geochemical features can also be recognized in both nepheline-bearing syenite and associated foid-bearing volcanic rocks, showing the same enriched-mantle source (e.g., Nelson et al., 1988; Rogers et al., Mahotkin et al., 2000; Larson et al., 2003).

It generally agreed that the geochemical characteristics of rocks related to subduction zones reflect the input of slab-derived fluids/liquids released from altered (subducted) oceanic crust (AOC) and/or slab-derived melts formed from the subducted sediments, leading to metasomatism in mantle source (Scambelluri et al., 2004; Khedr and Arai, 2009; Khedr et al., 2010; Natali et al., 2024). Slab-derived fluids that drive magmatism are characterized by high Ba/Th > 1000, low $(La/Sm)_N$ values (~1), as well as radiogenic Sr isotope ratios (Elliott, 2003). In contrast, slab-derived melts are generally characterized by low Ba/Th, high La/Sm ratios (Elliott, 2003) and higher trace element contents. Silica-undersaturated rocks share some geochemical similarities with sediment dominated melts, being characterized by low Ba/Th (14–38) and high $(La/Sm)_N$ = 4.2-8.7 (Figure 12). The mantle derived melts influenced by sediment-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). The silica-undersaturated rocks show significant enrichment in Th (~2 times) over Ba (Figure 6), proposing that sediment contributions dominated over fluids. They are characterized with high Sr/Y (12.2-56.2), La/Yb (10.5-27.8), and Th/Yb (2-4.9) ratios when compared with those of depleted mantle (<15; <5; < 0.1; respectively; Plank and Langmuir, 1998; Drummond et al., 1996). This feature confirms the voluminous addition of sedimentary components to the magma. The plots of Pb isotopic results (Figure 9) also suggest metasomatism of mantle by recycled material (Furman et al., 2021). Specially, the $^{207}Pb/^{204}Pb$ values plot above the Northern Hemisphere Reference Line (NHRL), suggesting a variable contributions of recycled sediment. Skora et al. (2015) evaluated the melting of sediments with a variable amount of carbonate component in subduction zone environments (3 GPa at 800–1100 °C). This work showed that carbonate-rich sediments generate partial melts enriched in ‘fluid-mobile’ elements such Cs, Ba, Rb, K, Sr and high Ba/Th ratios, but depleted in HFSE such as Ti, Nb, and Ta, due to their retention in residual rutile at temperature <1000 °C. Accordingly, the studied silica-undersaturated rocks are consistent with the involvement of recycled carbonate-poor lithologies in their genesis (Figure 8B). The isotopic composition of ($^{87}Sr/^{86}Sr$: 0.70619-0.71409) further confirms the involvement of carbonate-poor sedimentary ($^{87}Sr/^{86}Sr$: ~0.710; Skora et al., 2015) partial melts, rather than fluids (~0.703; Skora et al., 2015) as a metasomatizing agents of the Sisan and Hashroud mantle sections.

Due to their relatively higher REE contents, but showing similar REE trends (Figure 6) with respect to primary basalt, we suggest that the silica-undersaturated rocks could have been sequentially generated by fractionation/accumulation from more mafic (basalt) to more evolved (nepheline syenite) compositions. For example, with increasing SiO_2, most samples track along a liquid line of descent and show decreasing CaO/Al_2O_3, Nb/U, Ce/Pb, and increasing Al_2O_3, alkalis, and La/Nb (Figure 7). Amphiboles in magmatic systems often have high Nb/U ratios. Therefore, decreasing Nb/U with increasing SiO_2 and/or increasing La/Nb, (Figure 7G) (Moghadam et al., 2022) can act as a proxy for amphibole fractionation among the Sarab samples. The fractionation of amphibole in Sarab foid-bearing rocks may also be determined via a La/Yb *vs* Nb/Yb plot (Figure 8). This is inconsistent with petrographic observations showing amphibole in evolved samples (e.g. nepheline-bearing syenite). Rutile and titanite strongly favor incorporation of Ta and so their fractionation will increase Nb/Ta (Tiepolo et al., 2002) with increasing SiO_2, which is not observed in Sarab samples (not shown). Except for intrusive rocks, none of the samples have Eu anomalies, which suggests that plagioclase fractionation only played a minor role in the evolution of the syenitic magmas.

Nonetheless, the Sarab undersaturated rocks are characterized by a high Th/Yb ratio (2-10), which can be attributed to the subduction processes and/or interaction of ascending magmas with the continental crust through AFC processes. Plots of SiO_2 vs, $^{87}Sr/^{86}Sr$, $^{206}Pb/^{204}Pb$ and $^{207}Pb/^{204}Pb$ show no correlations (Figure 11C-D), suggesting that the interaction of ascending magmas with the continental crust through AFC processes can be excluded. In addition, the role of AFC processes on the undersaturated rock samples can be excluded based on Th/Yb vs SiO_2 (supplementary Table 2) profiles. Here, more fractionated samples with higher SiO_2 contents have lower Th/Yb ratios, suggesting that assimilation processes cannot affect magma during the generation of Sarab undersaturated igneous rocks. In addition, the high values and positive range of zircon Hf (εHf = +6.4 to +17.0) isotopic compositions from the dated undersaturated intrusive rocks also preclude crustal assimilation processes having taken place. Nepheline-bearing syenites and associated foid-bearing volcanic rocks are characterized by higher Ba/Th (34–217), and a similar $(La/Sm)_N$ = 3.6-6.4, lower $^{87}Sr/^{86}Sr_i$ (0.70503–0.70510) (Figure 12), and share some geochemical similarities with both slab-derived sediment melts (Natali et al., 2024). Therefore, it can be suggested that relatively higher $^{87}Sr/^{86}Sr$ values of igneous rock with respect to depleted mantle, and lower radiogenic Nd–Hf isotopes, in addition to radiogenic Pb isotopes, point to the involvement of components derived from subducted sediments and/or oceanic crust in their genesis.

6.1.2. Eocene silica-saturated magmas

The Eocene granite and syenogranite from the Hashroud and Sisan plutons have relatively similar mineral assemblages, except for the former having more quartz. The geochemical features and whole rock Sr–Nd and zircon Hf isotopic compositions of these granites (Supplementary Tables S2–4) indicate they were formed from the same metasomatized mantle source to those of under-saturated magmas (*e.g.*, DePaolo and Daley, 2000).

Granite and syenogranites also share some geochemical similarities with sediment-dominated melts, being characterized by low Ba/Th (14–38) and high $(La/Sm)_N$ = 4.2-8.7 (Figure 12), and significant enrichment in Th (~2 times) over Ba (Fig. 6B), which indicates more sediment contribution than fluids. These samples are characterized with higher ratios of Sr/Y (15.6-22.9), La/Yb (14.3-42.9), and Th/Yb (11-39) then those of depleted mantle (<15; <5; < 0.1; respectively; Plank and Langmuir, 1998; Drummond et al., 1996). This feature confirms that large proportions of sediment were incorporated into the magma. In addition, the studied silica-saturated rocks are consistent with the involvement of recycled carbonate-poor lithologies in their genesis (Figure 8B). The isotopic composition of ($^{87}Sr/^{86}Sr$: 0.70619-0.71409) further indicates the involvement of carbonate-poor sedimentary ($^{87}Sr/^{86}Sr$: ~0.710; Skora et al., 2015) partial melts, rather than fluids (~0.703; Skora et al., 2015) as metasomatizing agents of the Sisan and Hashroud mantle sections.

The investigated granitoids have high silica contents (64.0–73.6 wt. %), but low MgO, TiO_2, total Fe_2O_3, Cr, Co and Ni contents, implying their genesis via fractionation of alkaline melts derived from an enriched mantle or crustal source in a subduction zone. The Eocene granites and syenogranites have Nd isotopic compositions (($^{144}Nd/^{143}Nd$)i: 0.512614-0.512628) comparable to the Eocene silica-saturated volcanic rocks (~40 Ma; ($^{144}Nd/^{143}Nd$)i: 0.512572 to 0.512627; Natali et al., 2024) in the Ahar-Arasbaran complex, suggesting that they crystallized from same melts derived from a metasomatized mantle source. They are enriched in LREE and LILE and depleted in HFSE, specifying the role of an enriched lithosphere mantle source in their genesis (Zhang et al., 2009a). A mantle source for the intrusive rocks can be also deduced from positive εNd(t) values (+0.4 to +1.6) for the Sisan and Hashroud silica-saturated rocks (Supplementary Table 3).

The Eocene granite and syenogranites have relatively high total alkaline contents (Na_2O + K_2O = 8.8–10.7 wt. %) and are potassic with K_2O/Na_2O ratios of 1.5 to 3.5, similar to those of the Eocene high-K_2O and alkaline saturated igneous rocks of NW AMB (Sepidbar et al., 2021; Natali et al., 2024), indicating formation via crystal fractionation of a potassic mafic magma or assimilation following the fractional crystallization (AFC). Due to co-occurrences of more primary basaltic rocks (MgO = 7.02 wt. %; See Supplementary Table 2), which are interlayered with undersaturated Sarab volcanic rocks, fractional crystallization of a mafic magma can be inferred. In addition, the Sisan and Hashroud saturated rocks are characterized by relatively higher values of REE with the same trend, when compared to the primary basalt (Figure 6), showing a fractionation/accumulation sequence from more mafic (basalt) to more evolved (granite and syenogranite) compositions. For example, with increasing SiO_2, most samples track an approximate liquid line of descent, showing decreasing CaO/Al_2O_3, Nb/U, Ce/Pb, ratios and increasing in alkalis, and La/Nb ratio (Figure 7). Amphiboles in magmatic systems often have high Nb/U ratios; thus, decreasing Nb/U (and/or increasing La/Nb, Figure 7) with increasing SiO_2 (Moghadam et al., 2022) can act as a proxy for amphibole fractionation among the Hashroud and Sisan samples. The fractionation of amphibole in Hashroud and Sisan saturated rocks is also often determined via a La/Yb *vs* Nb/Yb plot (Figure 8). This is consistent with petrographical observations, showing the occurrence of amphibole in the evolved samples (granite). Rutile and titanite commonly host Ta, such that fractionation of these minerals will increase bulk-rock Nb/Ta (Tiepolo et al., 2002) with increasing SiO_2, which is not observed in Hashroud and Sisan samples (not shown). In contrast to Hashroud granite, Sisan syenogranite samples display Eu anomalies, suggesting that plagioclase fractionation played an important role in the formation of syenogranitic magmas (Figure 6A-B).

The Sisan and Hashroud saturated rocks show high Th/Yb ratios (5.9-17.4; Supplementary Table 2), which can result from subduction processes or interaction of ascending magmas with continental crust through AFC processes. The effect of AFC processes on these samples can be deduced from Th/Yb vs SiO_2 values (supplementary Table 2). In this case, the more fractionated samples with high SiO_2 contents are characterized by higher Th/Yb ratios, confirming that igneous rocks assimilated more continental crustal materials during ascent. In addition, based on (i) the Sr–Nd–Pb isotope characteristics: lower whole-rock Nd isotopic and higher Sr compositions of the Sisan and Hashroud rocks with respect to those of depleted mantle; (ii) the enriched LILE and K signature of the saturated rocks; and (iii) the wide range of zircon Hf ($\varepsilon Hf(t) = -4.0$ to $+6.3$) isotopic composition of the dated saturated intrusive rocks; the mantle-derived magma is thought to have assimilated continental/material crust component during magma ascent, storage and evolution. Conservative (e.g. Zr–Hf and Nb–

Ta) elements can be used to explore whether fractionation of these element pairs initially occurred in the mantle region or whether fractionation was related to AFC processes (Pearce and Peate, 1995). Mantle-derived magmas are characterized by a Zr/Hf ratio of 36 (Sun and McDonough, 1989). More primitive mafic basalts from the Zanjan-Takab complex and silica-saturated magmatic rocks have chondritic to super-chondritic Zr/Hf ratios of 24–43, which are higher than those of mantle-derived melts. They have Nb/Yb ratios of ~6.1 to 16.9, akin to *E*-MORB (*i.e.*, Nb/Yb ~3.5), significantly differ from those of N-MORB (*i.e.*, Nb/Yb ~0.3).

6.2 Implications for both silica-undersaturated and -saturated magmatism

The formation of arc-related magmatic rocks is often assumed to require partial melting of metasomatized lithospheric mantle, which contains 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 2). Enrichment of U, Th, Rb, Ba, Pb, and Sr in both rocks also suggests that mica formed in the deep crust (Villemant et al., 1981) in response to metasomatism.

The Sarab silica-undersaturated and Hashroud-Sisan saturated intrusive rocks have similar ages (40 Ma and 38-36 Ma, respectively) (Figure 4), indicating almost-coeval formation of both lithotypes in the Zanjab-Takab complex, NW Iran. However, the Eocene Sarab nepheline- syenites have distinctive whole rock Sr–Nd and zircon Hf isotopic compositions from the saturated rocks, indicating different sources and/or petrogenetic processes. Sarab undersaturated rocks are generally characterized by a higher LILE/HFSE ratio (Ba/Th: up to 365); Supplementary Table 2) compared to coexisting silica-saturated ones (Ba/Th: up to 38). In this case, the Sarab undersaturated volcanic and plutonic samples mostly show higher average Ba/Nb ratios (53 and 73, respectively) with respect to Sisan and Hashroud saturated rocks (29 and 42, respectively) representing more fluid-dominated signatures in the former (Figure 12). However, the LILE/REE (Ba/La) ratios show relatively similar ranges for undersaturated rocks (Ba/La: 13–44) and saturated rocks (Ba/La: 15–27), similar to other Late-Cretaceous-Eocene undersaturated and saturated rocks from NW Iran (10-40: Lahrud: Moghadam et al., 2018; Moghan: Amraee et al., 2019). While both saturated and undersaturated rocks from Sisan-Hashroud and Sarab show overlapping REE patterns, the La_N/Yb_N of Sarab undersaturated rocks varies from 7.0 to 17.9, which is generally lower than those from Sisan-Hashroud with La_N/Yb_N (6.9 to 33.2), possibly related to fractional crystallization of the most evolved rocks. Remarkably, silica-undersaturated rocks have relatively higher zircon Hf isotopic values, showing that the undersaturated rocks retain more prominent mantle signatures (Figure 12). In addition, the greater influence of mantle melting in Sarab silica-undersaturated rocks can also be deduced from lower Pb radiogenic values ($^{206}Pb/^{204}Pb$: 18.61–18.67; $^{207}Pb/^{204}Pb$: 15.57–15.60; $^{208}Pb/^{204}Pb$ 38.64–38.74) than those of silica-saturated rocks ($^{206}Pb/^{204}Pb$: 18.78–18.82; $^{207}Pb/^{204}Pb$: 15.61–15.63; $^{208}Pb/^{204}Pb$: 38.74–38.86).

The characteristics of the mantle source for both Sarab saturated and undersaturated rocks is difficult to evaluate from major- and trace-element data, because the composition of the sampled units does not directly reflect the initial melts derived from mantle. Therefore, the fine-grained gabbros of Kelaybar near the studied region, with the lowest SiO_2 (45.2–48.5 wt. %) and highest MgO (4.1–5.1 wt. %) reported by Moghadam et al. (2022) have been used for comparison and evaluation of mantle source region. It has been proposed that alkaline magmas in subduction zones may form due to melting of a subducted sedimentary source, especially those formed in the rear-arc region of continental arcs (Kimura *et al.* 2014; Kimura *et al.* 2015). To estimate the degree of source contamination, we applied a two-component mixing model (Faure, 1986) by using the $\varepsilon Nd_{(i)}$ and $^{87}Sr/^{86}Sr$ ratios (Figure 13A):

$$\varepsilon i(M) = \varepsilon i, A.\frac{Ci,A}{Ci(M)}.XA + \varepsilon i, B.\frac{Ci,B}{Ci(M)}.(1 - XA)$$

where *i* is the element, *A* the mantle source, *B* the contaminant, *ε* the isotope value and *C* the concentration of the element with $Ci(M) = X_A*C_{i,A} + (1-X_A)*C_{i,B}$, with X_A being the proportion in the main mantle source *A*.

Since all the Cenozoic magmatic rocks from the Sisan-Hashroud and Sarab regions show a subduction signature, the main source *A* in our modelling corresponds to E-DMM ($^{87}Sr/^{86}Sr$ = 0.70307; $^{143}Nd/^{144}Nd$ = 0.513), which is a depleted MORB mantle modified by subduction-derived components (Workman and Hart, 2005). In addition, the typical composition of Makran trench sediments ($^{87}Sr/^{86}Sr$ = 0.71109 and $^{143}Nd/^{144}Nd$ = 0.51203; Plank, 2014) and sediments from the Eastern Mediterranean Sea ($^{87}Sr/^{86}Sr$ = 0.70953 and $^{143}Nd/^{144}Nd$ = 0.51227; Klaver *et al.* 2015) are the most suitable lithologies in the area to consider as contaminant (B), being the input of slab-derived sediments in the mantle. Further, since our samples had evolved during fractionation, we also used more primitive samples of gabbro in the Kelaybar near the region reported by Moghadam et al. (2022) for comparison. According to these authors, these samples have non-radiogenic Nd and Hf isotope and require the involvement of a depleted component (DM) in their mantle source, similar to the more enriched end of the MORBs with radiogenic Sr and Pb but non-radiogenic Nd and Hf isotope ratios. To evaluate the mantle source composition and fractionation and melting processes, we used the PRIMACALC2 spreadsheet to estimate a primary melt in equilibrium with the upper mantle, using back calculation along the fractional crystallization path of the magma and the mantle source (Kimura and Ariskin, 2014). Modelling shows that the isotopic compositions of the more primitive gabbro samples of Moghadam et al., (2022) and both Cenozoic saturated and undersaturated igneous rocks (this study) resemble those that formed by adding ~ 0.4-0.5 wt. % and 1-2 wt. %, respectively, of sediments similar to those from the Makran trench to the E-DMM reservoir ($^{87}Sr/^{86}Sr$)i = 0.70307; εNdi = 0.513; $^{207}Pb/^{204}Pb$ = 15.568) (Figure 13).

Thus, based on geochemical and isotopic data, we conclude that the Eocene (40 Ma) undersaturated magmas likely formed via low degree partial melting of enriched mantle-derived mafic magmas. As mentioned in the section 6.1.2, such melts were underplated beneath lower crust and modified by AFC processes, forming silica-saturated magmas. To further evaluate the role of the AFC hypothesis, we use isotope composition of the end-member melt geochemically and isotopically similar to EMM-like (e.g., $^{87}Sr/^{86}Sr(t)$ ~ 0.703, $^{143}Nd/^{144}Nd(t)$ ~ 0.5130; Stracke et al., 2005) – and Cadomian upper and lower continental crust (i.e., $^{87}Sr/^{86}Sr(t)$ ~ 0.713 and $^{143}Nd/^{144}Nd(t)$ ~ 0.5121, and $^{87}Sr/^{86}Sr(t)$ ~ 0.707 and $^{143}Nd/^{144}Nd(t)$ ~ 0.5112, respectively; Moghadam et al., 2015) (Figure 13C). All silica-saturated rocks of Sisan and Hashroud plot between mantle and continental crust (CC) melts, showing that at least 4% of continental crust was assimilated into the mantle-derived melts (Figure 13C) (cf. Hosseini et al., 2017; Moghadam et al., 2023).

6.3. *Tectonic setting of silica-undersaturated and -saturated alkaline rocks*

Alongside the results of several recent studies, our new data highlight important characteristics of Eocene magmatism in NW Iran (Figure 14). These magmas were emplaced in pulses that lasted ~5 to 10 Myr, roughly contemporaneously in the Zanjan-Takab complex

(Sarab undersaturated rocks: 40 Ma and Sisan-Hashroud saturated rocks: 38-36 Ma; this study), Glojeh (40 Ma; Ghasemi *et al.* 2015), Ahar-Arasbaran complex (41 Ma; Natali *et al.*, 2024), Lahrud (40 Ma; Moghadam *et al.* 2018), Tarom-Olya (40-36 Ma; Nabatian *et al.* 2014), Mineh-Hashroud (44-36 Ma; Rabiee *et al.* 2020), Lubin-Zardeh (36 Ma; Zamanian *et al.* 2020), and Kleybar (42 Ma; Moghadam *et al.* 2022). In NW Iran, coeval calc-alkaline (42.4 Ma; Moghadam *et al.* 2018; van der Boon *et al.* 2021), and alkaline (saturated and under-saturated) magmatism was followed by the generation of Late Miocene Saray ultrapotassic rocks (Sepidbar *et al.* 2023) and Late Miocene-Pleistocene adakitic Sabalan volcanism (Chiu et al., 2013). This temporal evolution of magmatism from calc-alkaline to high-K calc-alkaline/shoshonitic to alkaline and adakitic compositions has also been described in southern Armenia (Rezeau *et al.* 2017, 2016).

The Early Cenozoic geodynamic evolution of NW Iran was mainly controlled by the subduction of the Neo-Tethys Ocean beneath central Iran and collision between the Iranian and Arabian terrains (McQuarrie and van Hinsbergen, 2013; Castro *et al.* 2013; Sepidbar *et al.* 2021). Exposures of fragmentary ophiolites in the Zagros suture zone has shown that the final amalgamation of these terrains occurred from the Oligocene to the Early Miocene (e.g., Sengör et al., 1993). This is supported by Late Cenozoic magmatism in northern NW Iran. The collision between Arabia and Eurasia in the Tethyan realm generated thickened crust in the northern parts of Iran. The tectonic evolution of the Iranian plateau during closure of the Neo-Tethyan Ocean marks a significant transition from a compressive regime associated with subduction and collision to an extensional regime driven by slab rollback. The timing of slab rollback and the associated tectonic transition can be constrained by U–Pb zircon ages of 50–40 Ma reported Chiu et al. (2013) and Moghadam et al., (2022) for adakitic rocks in the UDMB and non-adakitic rocks of NW Iran, respectively, which are interpreted as evidence of slab melting during the early stages of rollback. The transition from compression to extension is also recorded in the structural evolution of the Iranian plateau. During the compressive phase (Late Cretaceous to Eocene), the Zagros orogeny was characterized by the development of thrust faults, fold-and-thrust belts, and HP-LT metamorphic rocks, as described by Alavi (1994) and Mohajjel et al. (2003). In contrast, the extensional phase (late Eocene to Miocene) is marked by the formation of normal faults, core complexes, and widespread magmatic activity (Verdel et al., 2011). This extensional phase is further supported by the presence of sedimentary basins, such as the Zagros foreland basin, which record a shift from marine to continental deposition during the Oligocene (Horton et al., 2008).

The tectonic evolution of Iran can be placed in a broader regional context by comparing it with other segments of the Neo-Tethyan belt. For example, magmatic rocks in NW Iran reveal geochemical and isotopic (εNd(i)) links with neighboring Cenozoic magmatic rocks in the south Armenia block (Supplementary Figure 4). Those units show less enriched mantle isotopic compositions than coeval magmas that formed in the nearby south Armenia block (Figures 9A and supplementary Figure 4). Most of the alkaline (this study) and high-K calc-alkaline (Sepidbar et al., 2019) rear-arc rocks in NW Iran have εNd(i) < 3, whereas rocks from south Armenia mostly show higher εNd(i) values (Grosjean *et al.* 2022) (Supplementary Figure 4). This signifies that AFC played a greater role in the genesis of NW Iran rear arc magmatism than in South Armenia. In addition, many previous workers have reported the influence of AFC processes during evolution of magmatism in various parts of Iran (i.e. Naqadeh complex, NW Iran, Mazhari *et al.* 2011; Zanjan-Takab complex, Moghadam *et al.* 2017; Konya volcanic complex, Temel *et al.* 1998) (Figure 13A), which reflects a higher input of slab-related sediments in the mantle source with respect to the south Armenia block, as also suggested by Grosjean *et al.* (2023). The spread of $^{207}Pb/^{204}Pb$ ratios for NW Iran data (Figure 9) may be described by mixing of mantle source components beneath NW Iran with slab-derived Mediterranean sediments based on the Pb-Nd isotope data discussed in Section 6.2 and shown in Figure 9. In summary, our modelling indicates a systematically higher sedimentary/crustal component in the NW Iranian tectonic zones during magma petrogenesis than in those from South Armenia. This explanation is corroborated by wider variations in Hf(i) (Figure 13B) isotopes reported in the literature and in the intrusive rocks of NW Iran examined here with respect to those of south Armenia. In Anatolia, the transition from compression to extension occurred during the late Eocene to Oligocene, coinciding with the onset of slab rollback and the formation of the North Anatolian Fault (Jolivet et al., 2016). These regional comparisons highlight the importance of slab rollback as a driving mechanism for tectonic transitions in convergent settings. Geodynamic models provide further insights into the mechanisms driving the compressive to extensional transition. For example, numerical simulations by Stern (2002) and Jolivet et al. (2016) demonstrate that slab rollback can induce back-arc extension and the formation of extensional structures in the overriding plate.

Eocene silica-saturated granites and syenogranites and undersaturated nepheline-bearing syenites in the Zanjan-Takab complex have geochemical features similar to the alkaline rocks (Turner et al., 1996; Chung et al., 1998; Miller et al., 1999; Yang et al., 2005) formed in an extensional basin. The convective instability of a thickened mantle boundary layer during post-collisional magmatism may induce lithospheric thinning and crustal extension (Houseman et al., 1981; Chung et al., 1998; Yang et al., 2005). Therefore, the Eocene silica-saturated and -undersaturated rocks provide time constraints on the major geodynamic transition from convergence to extension at the northern margin of Gondwana. Although silica-undersaturated alkaline magmas are normally formed within continental plates, such as in rift systems, there is no evidence for mantle plumes or hot spots in NW Iran at this time. Therefore, geochemical features and Sr–Nd–Hf isotopic compositions indicate that the studied Eocene silica-undersaturated intrusive rocks and associated volcanic rocks were derived from small degrees of partial melting of an enriched lithospheric mantle or metasomatized mantle, following the transition from convergence to extension, where crustal subducted sediment and fluid components are dominant in the extensional (i.e., fore-arc extension or intra-arc rifting) setting. For this mechanism, our geochemical modeling shows that the source of the Iranian Cenozoic magmatic rocks is best reproduced by mixing E-DMM with more than 1% of the Makran trench or Mediterranean sediments (Figure 13), which reflects a higher input of slab-related sediments in the mantle source. The spread of $^{207}Pb/^{204}Pb$ ratios for NW Iran data (Figure 9) may be described by mixing of mantle source components beneath NW Iran with slab-derived Mediterranean sediments based on the Pb-Nd isotope data discussed in the previous section and shown in Figure 9. Our results also indicate a systematically higher crustal component in the NW Iranian saturated rock magma petrogenesis with respect to those of the silica-undersaturated units. This explanation is corroborated by wider variations in Hf(i) (Figure 10) isotopes of saturated rocks (Hashroud and Sisan intrusive rocks) of NW Iran with respect to those of undersaturated igneous rocks (nepheline-bearing syenite).

In this framework, since Neo-Tethyan subduction was active beneath Iran during the Eocene, the subducting sediments continued to melt, and a significant amount of this sedimentary melt was added to a mantle wedge and/or lithospheric mantle above the down-going oceanic slab (Figure 14). Slab rollback caused lithospheric extension in NW Iran (Moghadam et al., 2018 and references therein) leading to asthenospheric upwelling that caused heating and lithospheric erosion through the melting of the metasomatized mantle wedge, which was particularly intense during the Eocene (Verdel et al., 2011). Low degrees of partial melting of the metasomatized mantle sources occurred at ~40 Ma, leading to the formation of undersaturated magmas. From 38 to 36 Ma, partial melting of such an enriched lithospheric mantle, coupled with crustal assimilation and crystal fractionation in an intracontinental extensional setting, resulted in the formation of silica-saturated magmas.

7. Conclusions

Regional-scale correlation of various independent datasets has shown that NW Iran-South Armenia experienced widespread intrusion of alkaline-rich magmas and emplacement of associated volcanic rocks with a mantle-dominated signature during the Eocene. New U–Pb ages of ~42–41 Ma (Middle Eocene) have been determined for silica-undersaturated, Sarab alkaline rocks in NW Iran, which match ages from within other igneous units produced during magmatic 'flare up' events during the Middle to Late Eocene in NW Iran. Geochemical signatures indicate that most Sarab rocks underwent various degrees of fractional crystallization. Further, correlations between various indices of differentiation, such as bulk SiO_2 content and isotope ratios, indicate that the more evolved rocks most likely assimilated small volumes of continental crust.

The Sarab Rocks formed in an extensional setting, likely driven by roll-back of the Neo-Tethyan subducting plate. Together with published data from NW Iran, the geochemical, isotopic and geochronological magmatic record of the Sarab region during the Cenozoic indicates a different mantle signature when compared to nearby tectonic zones in the south Armenian block. In addition, Eocene rocks from the Sarab region show less mantle-dominated and K-rich signatures than those situated to the south in Armenia. New geochemical data for Sarab magmatic rocks indicate a magmatic origin matching an enriched Indian MORB-type mantle, metasomatized by sediment-derived melts produced during heating of the downgoing Neo-Tethyan oceanic lithosphere. We therefore suggest a regional-scale geodynamic scenario for evolution of the Sarab region involving Neo-Tethyan slab retreat and upper-plate extension, along with melting of the subducting sediments and a fluxed high-temperature fertilization of the mantle wedge during the Eocene.

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Figure captions

Figure 1. Geological map of the Armenia-Iran part of the central Tethyan belt, showing different pulses of Cenozoic magmatism (modified after Moritz *et al.* 2016).

Figure 2. Simplified geological map of the BostanAbad-Sarab region in NW Iran (modified after Sarab 1/100000 map, Geological Survey of Iran, sheet 5565 (Davari *et al.* 1992).

Figure 3. A- The faulted contact of Eocene foid bearing volcanic rocks with; B-Leucocratic and coarse-grained Sarab nepheline-bearing syenites; C- Sisan syenogranite intrudes into Eocene volcanic rocks; D- Hashroud granite intrude into Eocene volcanoclastic rocks.

Figure 4. A-B. U–Pb zircon concordia ages and trace element plots from the A-B- Sisan syenogranite; C-D- Hashroud granite; E-F- the nepheline bearing syenite.

Figure 5. A- Total alkalis vs SiO_2 (Lebas *et al.* 1986) for the Hashroud-Sisan-Sarab volcanic and plutonic rocks; B- K_2O+Na_2O (wt. %) vs. Q-(lc+Ne+Kal+Ol). Data for NW Iran igneous rocks are from Sepidbar *et al.* (2021), Sepidbar *et al.* (unpublished data), Moghadam *et al.* (2022), Castro *et al.* (2013), Nabatian *et al.* (2016), and those from South Armenia are from Grosjean *et al.* (2022) and references therein.

Figure 6. Chondrite-normalized rare earth element (left) and N-MORB-normalized trace element patterns (right) for the (A-B) silica-saturated Hashroud-Sisan plutonic rocks; (C-D) Sarab volcanic rocks; (E-F) undersaturated Sarab plutonic rock. Chondrite and N-MORB normalized values are taken from Sun and McDonough (1989). Data for NW Iran igneous rocks are from Moghadam *et al.* (2018), Moghadam *et al.* (2022) and Natali *et al.* (2024).

Figure 7. Geochemical variation plots including major oxides and their ratios (*e.g.*, Alkali, Al_2O_3, TiO_2 and CaO/Al_2O_3) and trace elements and ratios (Sr, Ce/Pb, La/Nb and Nb/U) *vs* SiO_2 for the Sarab igneous rocks. All major-element analyses have been recalculated as volatile-free and normalized to 100 wt. %. Compiled data for NW Iran potassic rocks including leucite-bearing phono-tephrites and trachy-basalts to trachy-andesites are from (Moghadam *et al.* 2018). Data for Eocene magmatic rocks from the south Armenia block come from (Grosjean *et al.* 2022).

Figure 8. Geochemical variation plot of (A) La/Yb vs. Nb/Yb and (B)– Ba/Th vs. (La/Sm)N, showing the distribution of undersaturated and saturated magmatic rocks from the Zanjan-Takab magmatic complex. The composition of worldwide arc magmas, as well as the fields of Mariana arc (representative of AOC predominant fluid metasomatism) and of Neapolitan district of the Roman province (Vesuvius, representative of predominant carbonate melt metasomatism) are shown for comparison. Data from Natali et al. (2024) and Moghadam et al. (2018) from NW Iran are shown for comparison. Data from Eocene magmatic rocks from the south Armenia block come from Grosjean *et al.* (2022).

Figure 9. A- $^{143}Nd/^{144}Nd$ *vs* $^{87}Sr/^{86}Sr$ plot for the saturated Hashroud-Sisan and undersaturated Sarab magmatic rocks compared with depleted mantle (DM) (Zindler and Hart, 1986), and with Indian and Pacific MORBs. The Northern Hemisphere Reference Line (NHRL) is from Hart (1984). Data for Indian and Pacific MORBs are from EarthChem (https://www.earthchem.org). The composition of Cadomian continental crust (CC) comes

from (Moghadam *et al.* 2020a). Composition of trench sediments are from (Jacques *et al.* 2014; Kimura *et al.* 2009). Compiled data for NW Iran potassic/alkaline rocks including leucite-bearing phono-tephrites and trachy-basalts to trachy-andesites are from Moghadam *et al.* (2018) and Moghadam *et al.* (2022), whereas data for the composition of trench sediments from the southern Andean subduction system and OIB tephrites are from Jacques et al. (2013), Jacques et al. (2014) and Kheirkhahet al. (2015) respectively. Data on back-arc ophiolites come from Moghadam and Stern (2015). Data on Eastern Mediterranean Sea sediments are from Klaver *et al.* (2015). All data including those for Indian and Pacific MORBs, subducting sediments and magmatic rocks from NW Iran have been corrected for 40 Ma radiogenic growth.

Figure 10. εHf(i) vs εNd(i) for the the saturated Hashroud-Sisan and undersaturated Sarab magmatic rocks. MORB and OIB data are from (Chauvel and Blichert-Toft, 2001; Pearce *et al.* 1999). Mantle array data are after (Vervoort and Blichert-Toft, 1999). Isotope data for NW and N Iran magmatic rocks are from (Aghazadeh *et al.* 2011; Asiabanha and Foden, 2012; Castro *et al.* 2013) and (Moghadam *et al.* 2017). Data on Eocene magmatic rocks from the south Armenia block come from (Grosjean *et al.* 2022).AFC modelling was performed using the formulae presented by Ersoy and Palmer (2013).

Figure 11 Plots of initial $^{87}Sr/^{86}Sr$ (A), $^{208}Pb/^{204}Pb$ (B), $^{206}Pb/^{204}Pb$ (C) and $^{207}Pb/^{204}Pb$ (D) *vs* SiO2 distinguish the role of fractionation and/or assimilation-fractional crystallization (AFC) for the evolution of the the saturated Hashroud-Sisan and undersaturated Sarab magmatic rocks magmatic rocks. Data from Natali et al. (2024) and Moghadam et al. (2018) from NW Iran are shown for comparison. Primitive Kleybar gabbroic rocks also come from Moghadam et al., 2022.

Figure 12 Histogram diagrams showing chemical and isotopica variations between saturated and undersaturated magmatic rocks of Hashroud-Sisan and Sarab magmatic rocks, respectivey. Data for MORB, OIB and Arc end-members are from Weaver (1991)

Figure 13. A) εNd(i) vs. $^{87}Sr/^{86}Sr(i)$ reservoir modelling for the the saturated Hashroud-Sisan and undersaturated Sarab magmatic rocks. Different end member sources DMM and E-DMM are from Workman and Hart (2005), Makran sediments are from Plank (2014) and Mediterranean sediments are from Klaver *et al.* (2015). The mantle + bulk sediment mixing lines are obtained from simple mixing line equation between E-DMM and the Makran or Mediterranean sediments (from Faure, 1986); see text for more details); the curvature of the lines is a function of the Sr/Nd(sed.) Sr/Nd(mantle) ratio. In the case of the mixing line between E-DMM and the Makran sediments, this ratio is almost equal to 1. The dashed line is the result of a simple mixing line between E-DMM and 20% partial sediments melts. The partition coefficients were taken from the experiments of Hermann and Rubatto (2009) (D_{Sr} = 7.3 and D_{Nd} = 0.35). Tick marks indicate the proportion of bulk sediments or sediment melt added to the mantle in weight percent. b. Whole-rock εNd(i) vs. zircon Hf isotopic ratios (in Ma). See Rezeau *et al.* (2017) for details on Armenia.

Figure 14. Geodynamic outline showing the formation of the undersaturated and saturated magmas in the Zanjan-Takab complex, NW Iran.

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