Neogene calc-alkaline volcanism in the Bobak and Sikh kuh, Eastern Iran: Implications for magma genesis and tectonic setting

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Abstract

Neogene volcanism exposed on the Lut block, southeastern Iran is represented by the Sikh Kuh and Bobak high-Na volcanic rocks, which include trachybasalt, trachyandesite, trachydacite, and dacite. All lithologies are calc-alkaline, highly sodic (Na_2O/K_2O = 2.6–3.7), and have low TiO_2 (0.95–1.47 wt. %). Negative Nb–Ti anomalies and enrichment in LREE and LILE relative to HREE and HFSE attest to formation in a supra-subduction zone environment. Felsic rocks record abundant petrographic evidence, major and trace element data, and isotopic ($^{87}Sr/^{86}Sr(i)$ = 0.70727–0.70902) signatures indicative of fractional crystallization, and potentially, crustal assimilation. Such processes however, have not significantly affected the isotopic signatures ($^{87}Sr/^{86}Sr(i)$ = 0.70417–0.70428) of the mafic members, suggesting that they are derived from a mantle source. Geochemical and isotopic data indicate that the parental melts of more mafic rocks formed by low degrees of partial melting (~2–10%) of a spinel-bearing subcontinental lithospheric mantle source that was previously enriched by subduction-related fluids/sediment or melts. The generated more unfractionated mafic magmas erupted during an episode of extensional tectonics, presumably caused by extension that followed Eocene collision between the Lut and Afghan continental blocks. This melts interacted with continental crust during ascent, experiencing crystal fractionation, and crustal assimilation, to produce more evolved felsic volcanic rocks.

Key words: High-Na volcanic rocks • geochemistry • Sr–Nd isotopes • partial melting

1. Introduction

Active orogenic belt, from Alps to the Himalayas, formed in response to plate convergence and collision, and represent primary topographic features of the continents. At the crossroads, the Lut-Sistan zone located at the central part of Alps-Himalaya within the Iranian block and stretches 700 km N-S at a high angle to the adjacent Iranian major structures of Zagros, Makran or Alborz (Whitechurch et al., 2019). It is characterized by extensive Mesozoic ophiolites, large-scale Mezo-Cenozoic sedimentary basins, profuse Cenozoic magmatism, and varied metamorphic rocks, including high pressure-low-temperature relicts (blueschists and eclogites).

Despite its thickened crust, the Lut-Sistan belt also exposes mantle-derived magmatic rocks (e.g. Pang et al., 2012, 2013), which has been attributed to asthenospheric upwelling following either the break-off of the subducted the southern Neo-Tethys oceanic slab or delamination of the lithosphere inboard of the plate suture (e.g. Pang et al., 2012, 2013). . To provide new insights into the nature and cause of this magmatism on the Lut-Sistan belt, this paper focuses on Neogene volcanic rocks from the Lut–Sistan region, eastern Iran (Fig. 1).

Widespread Eocene–Oligocene calc-alkaline volcanic activity in the Lut–Sistan region was followed by voluminous high-Na magmatism and volumetrically minor alkali volcanism between the Miocene and Quaternary. Pang et al. (2012) suggested that this alkali volcanism could have formed by low degrees of partial melting of an enriched mantle source at garnet-stable depths. However, studies of the Late Miocene Na-rich volcanic rocks with calc-alkaline signatures are rare, as they have been erupted from small-volume centres and span a compositional range from basalt to dacite.

In this contribution, the geochemistry and magma plumbing systems of two Late Miocene volcanic centres (Bobak and Sikh Kuh) in eastern Iran have been studied to constrain the dynamics of these eruptions (Fig. 1 and 2). The local tectonic setting and its relationship to magmatism is highlighted, alongside discussion of the magmatic evolution, mantle sources and partial melting behaviour. The main objective of this study is to (1) obtain new insights into the petrological, geochemical and isotopic characteristics of selected samples from eastern Iran; (2)

constrain the mineralogical and chemical characteristics of their mantle source region, and the degrees of partial melting that it experienced; (3) interpret magma chamber processes, such as fractional crystallization, crustal contamination; and (4) develop a new tectonic model for the geodynamic evolution of the region.

2. Geological framework

Northward motion of the Arabian plate was driven by subduction of Neo-Tethys oceanic lithosphere beneath the southern margin of Eurasia during the Late Mesozoic–Early Cenozoic. Neo-Tethys oceanic lithosphere was divided into a northern and a southern segment, which were separated by micro-continental fragments, such as the South Armenian Block and Tauride-Anatolide-Iranian terranes (Sosson et al. 2010). Destruction of the southern segment of the Neo-Tethys Ocean brought Arabia and Eurasia together along the Bitlis–Zagros suture zone (Fig. 1), while the northern segment closed either during the Late Cretaceous (Lordkipanidze 1980) or the Paleocene–Early Eocene (Sosson et al. 2010).

The Lut-Sistan belt extends north–south for over 700 km and is part of the eastern branch of the southern segment of the Neo-Tethys Ocean (the Lut-Sistan Ocean) (Whitechurch et al., 2019). This branch opened during the Early Cretaceous as an embryonic oceanic basin and closed during the Early Paleocene (Sepidbar et al. 2018). Stratigraphically, the Lut-Sistan belt has been divided into five main domains (Tirrul et al., 1983): (i) the Lut Block to the W and (ii) the Afghan Block to the E, characterized by Neoproterozoic to Paleozoic basement rocks, mildly deformed Jurassic phyllites and Early Cretaceous (Barremian-Aptian) Orbitolina limestones; (iii)

The Neh Complex is made of an Aptian to Albian weakly metamorphosed ophiolite and/or ophiolitic melange with radiolarian cherts, marls and/or deep-sea carbonates immediately deposited on top of it or interbedded with ophiolitic pillow basalts. The sedimentary sequence contains Late Cretaceous and Paleocene fine-grained turbidites, interbedded with limestone in places, and then Eocene Red Beds conglomerates. (iv) The Ratuk Complex is characterized by highly deformed ophiolitic material and sediments metamorphosed under HP-LT conditions. These metamorphic units are unconformably overlain by a Maastrichtian conglomerate. An Eocene Red Beds unit excessively unconformably place on top of the Maastrichitain sequence. Plio-quaternary polygenic conglomerates terminate the sequence. (v) The ~8 km thick fore-arc Sefidabeh Basin, which overlies both the Ratuk and Neh Complexes, starts with Aptian to Senonian calci-turbidites. Coeval magmatic activity is attested by the presence of intrusions and interbedded lava flows. Locally, Maastrichtian sediments comprise a basal polygenic breccia reworking ophiolite pebbles and grading upwards into a fine grained turbiditic sequence interbedded in places with a ten-meter-thick Hyppuritic and Orbitoid bearing limestone. An Early Paleocene reefal limestone, with large thickness variations from ~0 to >600 m, unconformably overlies the Late Cretaceous deposits. This formation is in turn overlained by a Late Paleocene channelized turbiditic sequence. The younger, Eocene to Plio-Quaternary sequence resembles that of the Neh Complex.

Cenozoic magmatic events are divided into three stages (see Chiu et al. 2013; Dilek et al. 2010; Sepidbar et al. 2018), including (i) an Late Cretaceous to Eocene ‘flare-up’ of arc magmatism attributed to extension following continental collision (Pang et al. 2013; Sepidbar et al. 2018) or break-off of the eastern branch of the Neo-Tethys slab in southeastern Iran (Chiu et al. 2013; Sepidbar et al. 2018); (ii) a 20–30 Myr period of quiescence and limited magmatic activity between the Eocene and the Late Miocene as continental collision proceeded

(Hosseinkhani et al. 2017); and (iii) an increase of mantle-derived volcanism during the Middle-Late Miocene until the present day (Chiu et al. 2013).

Northeastward subduction of the Lut–Sistan oceanic lithosphere beneath the Afghan block may have caused magmatic activity during the Cretaceous (Jentzer et al. 2020). The Lut–Sistan Oceanic basin closed during the Late Cretaceous–Early Paleocene (Zarrinkoub et al. 2012; Jentzer et al. 2022). Pang et al. (2013) proposed that Paleogene magmatism in the East Iranian Makran Basin (EIMB) occurred in a post-collisional setting and was triggered by convective removal of lithosphere and resultant asthenospheric upwelling accompanying orogenic (extensional) collapse. Continued asthenospheric upwelling led to Middle Miocene basaltic volcanism (^{40}Ar–^{39}Ar; 14–11 Ma) (Pang et al. 2012). This phase of magmatism within the Sikh Kuh and Bobak regions, eastern Lut block, is dominated by rocks with mafic and intermediate compositions (Fig. 2).

3. Field observations and petrography

The Bobak and Sikh Kuh are located at the east of the Lut block domain. The oldest rocks in the Bobak and Sikh kuh areas include a thick pile of Late Triassic-early Jurassic sedimentary rocks, equivalence of Shemshak Formation. They are composed of silty, argillaceous and sandy shale intercalated sandstone which are intruded by the late Jurassic plutonic rocks and Neogene-Quaternary basalic rocks in the Bobak region (Fig. 2) . The Bobak stratovolcano comprises of lava flows intercalated with pyroclastic rocks (Fig. 3d). Trachyandesite and basaltic-andesite lava flows and subordinate equivalent pyroclastic materials are common, although small volumes of basalt and foid-bearing basalt lavas, generating cinder cones, form domains with low topography around the main cone. Trachyandesite and basaltic-andesite lava are characterized by shrinkage fractures and cavities (Fig. 3e, f) that are filled by calcite and zeolite. Thin red soils (paleosols) occur in the lower parts of lava flows.

The Sikh kuh volcano occupies an area of ~ 10 km^2. This monogenetic volcano is dominated by large and thick flows of columnar basalt, basaltic-andesite, trachyandesite and andesite and occurs as an elongated body bounded by NW-SE trending faults (Fig. 2). The intrusive contact of this volcanic rock with late Jurassic granitoids (known as Shah Kuh granite) is obvious in its southern and western parts, whereas in the north and east, the volcanic rocks abuts slightly metamorphosed layers of tuff, agglomerate, sandy limestone, and sandstone (known as the Dehsalm metamorphic complex) (Fig. 2). . Columnar-jointed basaltic lava can be seen at the upper parts (Fig. 3a, b), whereas trachyandesite and basaltic-andesite/andesite lava flows are mainly observed in the lower parts of the sequences (Fig. 3c). They have a clear and concordant contact with columnar basaltic lava, and commonly display a porphyritic texture. Andesite comprises mafic micro-granular enclaves (MMEs), commonly 2–5 cm in size. Trachyandesite and basaltic-andesite lava flows are also products of the Sikh Kuh volcano and occur conformably on andesite.

Petrographically, volcanic rocks in the Sikh Kuh and Bobak areas can be divided according to their mineralogy into sub-groups of basalt/trachybasalt, basaltic andesite and dacitic rocks. Basalt/trachybasalt lithologies contain plagioclase (50–60 vol. %), clinopyroxene (augite) (20–30 vol. %), olivine (5–10 vol. %), and opaque oxides (1–2 vol. %), with glomeroporphyritic to porphyritic textures (Fig. 4a, b). Plagioclase microlites, small augite and olivine crystals, and minor quantities of interstitial glass form the groundmass in these rocks. Plagioclase is euhedral to subhedral and range from 0.1 and 0.7 mm. It commonly shows oscillatory zoning (Fig. 4b) or Carlsbad twinning with partial alteration to sericite and calcite (Fig. 4c). Augite generally occurs as fine grains in the groundmass, but also as phenocrysts. Augite is subhedral and anhedral and varies from 0.2 to 0.8 mm in diameter. Olivine in Sikh Kuh basalts is subhedral and anhedral and ranges from 0.3 to 0.6 mm and occupies interstices between plagioclase laths, forming an intergranular texture. Rims of olivine crystals have been partially altered to iddingsite (Fig. 4d).

Trachybasalt with porphyritic and trachytic textures occurs in both the Sikh Kuh and Bobak areas. These rocks have hyalomicrolithic porphyritic and flow hyalomicrolitic porphyritic textures, containing plagioclase (10%), pyroxene (15%), hornblende (13%) and olivine (5%) phenocrysts, and a groundmass of the same mineralogy. Clinopyroxene occurs as both the fine grained in groundmass and phenocrysts. Such embayed margins suggest resorption. Clinopyroxene also occurs in glomeroporphyritic aggregates with plagioclase. Most plagioclase occurs in the groundmass and has a microlithic texture.

Basaltic-andesitesin both the Sikh Kuh and Bobak regions, have porphyritic and microlithic textures, and contain phenocrysts of plagioclase (30%), clinopyroxene (5%), and iddingsite (4%). The groundmass consists of microlites of plagioclase, olivine and clinopyroxene. Olivine and clinopyroxene also occur as phenocrysts and microphenocrysts. Some clinopyroxene phenocrysts have groundmass-filled embayments and embayed margins, suggesting resorption. Clinopyroxene also occurs in glomeroporphyritic aggregates with plagioclase and magnetite. On the basis of textural criteria, euhedral to subhedral plagioclase phenocrysts are identified, although these are partly altered to clay minerals. Quartz mainly occurs as rounded phenocrysts (Fig. 4e). Biotite is euhedral, has one dominant set of cleavage and sometimes exhibits opacitization (Fig. 4f). Magnetite is the sole Fe-Ti oxide, and is present as subhedral grains disseminated in the groundmass, mainly in association with mafic minerals.

Dacites are less abundant than other volcanic rock types in Sikh Kuh and occur as lava interlayered with basaltic andesite. The dacites are porphyritic and contain phenocrysts of plagioclase (15–20%), biotite (5–7%), sanidine (~5%), and quartz (1–2%) set in a matrix mainly of glass, quartz, and K-feldspar microlites. Plagioclase occurs as randomly oriented, tabular crystals and shows alteration to sericite. Coarse-grained plagioclase in some dacitic lavas is characterized by disequilibrium dusty and/or sieve textures and corroded margins, which are indicators of rapid decompression during the eruption of magmas and/or signify magma mixing (Nelson and Montana, 1992). Some dacites contain a few clinopyroxene glomerocrysts, but mostly consist of a fine-grained groundmass dominated by prismatic to acicular feldspar.

4. Analytical Techniques

Whole-rock major element oxide concentrations were determined at ALS Chemex (Guangzhou) Co., Ltd, using a Philips PW2404 X-ray fluorescence (XRF) spectrometer. Trace element concentrations were analyzed with an Elan DRC II inductively coupled plasma mass spectrometer (ICP-MS) at the University of Science and Technology of China (USTC). Prior to shipping to ALS, samples for whole-rock analysis were trimmed to remove weathered surfaces. Samples sent to ALS were crushed to >70% passing through a 2 mm mesh, and a 250-g split was pulverized to >85% of the material being <75 μm in diameter. Powders were then analyzed for whole rock major and trace element determinations. In the case of major element determination, powders were fused with a lithium metaborate and lithium tetraborate flux, which also included an oxidizing agent (lithium nitrate), and then poured into a platinum mould. The resultant disk was analyzed by XRF. The measurement procedure and data quality were monitored by simultaneous analyses of repeated samples (one in ten samples) and the standard samples GBW07103, GBW07105, GBW07110, GBW07111, and GBW07112. The analytical uncertainties are generally less than 1% for most major elements. Accuracy from duplicates is less than 5%, and precision is higher with errors less than 2%. For trace element concentrations, fused samples were dissolved in nitric acid and sample solutions were then analyzed by ICP-MS following procedures described in Hou and Wang (2007). Ruthenium was used as an internal standard to correct for matrix effects and instrument drift. Precision of the trace element data is about 5%.

Sr and Nd isotope ratios were determined at the Department of Geological Sciences, University of Cape Town, Rondebosch, South Africa. Samples for Sr–Nd isotopic analysis were dissolved in Teflon bombs using a HF + HNO_3 acid mixture. Sr and Nd were separated using conventional ion exchange procedures and measured using a Neptune Plus MC-ICP-MS. Procedural blanks of the total chemical treatment were at the level of less than 1 ng for Nd and Sr. During the period of laboratory analysis, measurements of the NIST SRM Sr standard yielded a $^{87}Sr/^{86}Sr$ ratio of 0.710250 ± 0.000030 (2σ), and the JNdi-1 Nd standard yielded a $^{143}Nd/^{144}Nd$ ratio of 0.512115 ± 0.000004 (2σ). The detailed Sr–Nd analytical technique and correction procedure is provided in (Wu et al., 2006b)

5. Results

5.1 Whole-rock chemistry

Most samples are petrographically fresh with only minor signs of alteration, as shown by their generally low LOI values (mostly <2 wt. %). Major- and trace-element contents are given in Table 1. No major compositional gap or bimodality is observed; instead, all the compositions lie along a well-defined and relatively tight trend on a Nb/Y *vs* Zr/TiO_2 discrimination and Harker diagramsdiagram (Fig. 5a and Fig. 6).

The Bobak lavas (~50–55 wt. % SiO_2) plot mostly as basaltic trachyandesite to trachyandesite and basalt on Nb/Y *vs* Zr/TiO_2 discrimination diagram (Pearce 1996; Fig. 5a), and belong to the medium-K series on a Co *vs* Th diagram (Hastie et al. 2007) (Fig. 5c). Lavas are characterized by relatively evolved MgO contents (4.7 to 6.6 wt. %) and have low molar Mg# (0.3 to 0.5). Overall, samples are sodic (Na_2O/K_2O = 2.6–3.7) (Fig. 5b), and have low TiO_2 (0.95–1.47 wt. %), and moderate to high Al_2O_3 (14.7-17.2 wt. %) (Table 1). The lavas also have low Sc (<25 ppm), moderate Ni (86–123 ppm), and large ion lithophile element (LILE) abundances (e.g. Ba = 288–532 ppm and Sr = 526–1126 ppm).

The Sikh Kuh samples are more evolved than the Bobak samples by virtue of higher SiO_2 (~50.3–67.3 wt.%) and lower MgO (1.7–5.8 wt. %, with Mg# = 0.2–0.5), and sub- compositions from basaltic trachy-andesite and andesite basalts through to dacite (Fig. 5a, b). Most samples belong to the Na-series, although one plots in the medium-K series on a Na_2O *vs* K_2O discrimination diagram (Fig. 5c). They have variable TiO_2 (0.65–1.98 wt. %), high Al_2O_3 (16.2–17.8 wt. %), Fe_2O_3(t) (4.2–9.3 wt.%) and P_2O_5 (0.11–0.43 wt. %) concentrations, and are slightly less sodic (Na_2O/K_2O = 1.3–3.3) than the Bobak samples (Fig. 5d). The Sikh Kuh samples have similar Ba (324–654 ppm) and Zr (132–222 ppm) and lower Sr (395–696 ppm) and Nb (7.4–15.7 ppm) concentrations compared to mafic Bobak lavas (Table 1).

Chondrite-normalized (Ch_N) (Sun and McDonough 1989) REE patterns of the Sikh Kuh and Bobak lavas are identical and very similar to OIB (Figs. 7a, b). REE patterns are defined by slight to moderate light REE (LREE) enrichment $(La/Yb)_N$ = 5.2–13.8; calc-alkaline), flat heavy REE (HREE) signatures at 10–20 x chondrite (Fig. 7a, b), and no negative Eu anomalies. Primitive mantle-normalized (PM_N) plots (Fig. 7c, d) show modest positive Cs, Ba, Rb, U, K, and

Sr anomalies, and prominent positive Pb, and negative Nb, P and Ti anomalies relative to LREEs [$(\mathrm{Nb/La})_N$= 0.2–0.4].

5.2 Bulk rock Sr-Nd isotopes

We analyzed nine samples (five from Sikh Kuh and four from Bobak) for Sr–Nd isotopes (Table 2,). Initial ^{87}Sr/^{86}Sr(i) and ^{143}Nd/^{144}Nd(i) of these rocks were recalculated based on reported ^{40}Ar/^{39}Ar ages of 14–11 Ma (Pang et al. 2012). These rocks show initial εNd(t) values of -1.2 to +4.1 for Sikh Kuh volcanic rocks and +3.1 to +4.3 for the Bobak rocks (Fig. 6). ^{87}Sr/^{86}Sr(i) values are very similar for Sikh Kuh and Bobak mafic-intermediate units (0.70417 to 0.70428), which lie within the upper left quadrant of an Sr-Nd isotope diagram (Fig. 8), except for two Sikh Kuh felsic volcanic rocks) lie within the enriched bottom right quadrant (0.7081 to 0.7091, Fig. 8). Mafic-intermediate volcanic rocks of Bobak and Sikh Kuh have radiogenic Nd, but less radiogenic Sr, whereas two felsic volcanic samples of Sikh Kuh have higher (>0.706) ^{87}Sr/^{86}Sr(t) and plot close to isotopic values of the EMII mantle source. A two-stage Nd isotopic model age (T_{DM}) calculation for mafic-intermediate and felsic high-Na volcanic samples ranges from 0.8 to 1.2 Ga and 1.6 to 2.2 Ga, respectively. Felsic volcanic rocks with less radiogenic Nd thus likely show higher degrees of contamination with Late Neoproterozoic continental crust of Iran.

6. Discussion

The origin and evolution of igneous rocks along active margins comprise a series of processes (e.g., Eyuboglu, 2013) involving metasomatism of the mantle wedge by melt and/or fluids released by the downgoing slab (e.g., Pearce, 1982; Hawkesworth et al., 1991; Kelemen et al., 2004; Khedr et al., 2010), variable partial melting degree of the metasomatized mantle (e.g., Pearce and Parkinson, 1993) and subsequent process at shallower depths such as magma mixing, AFC (e.g., DePaolo, 1981) and/or combinations of these processes (Ersoy et al., 2010). In this section we will briefly discuss the role of each process in the genesis of the high-K Saray lavas.

6.1. Subduction characteristic; arc-related setting?

The studied samples from Bobak and Sikh Kuh show enrichment in LILE and LREE with respect to HFSE and HREE (Fig. 7), and display negative HFSE anomalies (Nb and Ti) relative to adjacent LILE (such as Th and Ba) and LREE, thus exhibiting a classic subduction signature on a PM- and chondrite normalized incompatible element plots. The orogenic arc fingerprints of these rocks can also confirm by ternary diagrams of MgO-FeO-Al_2O_3 (Pearce et al., 1977) and Th-Hf/3-Nb/16 (Wood, 1980) (Fig. 9a, b). The enrichment in incompatible elements suggests that the source was a metasomatized subcontinental lithospheric mantle (SCLM) in an orogenic setting. Taken together, the high LILE/HFSE, LREE/HREE ratios and low ($^{87}Sr/^{86}Sr$)i and relatively high ($^{143}Nd/^{144}Nd$)i isotopic values imply a subduction-modified mantle source for the Neogene volcanic rocks (Fig. 8). The effects of subduction components on the mantle source of the Sikh kuh and Bobak volcanic rocks can also be detected in a Th/Yb vs. Ta/Yb diagram (Pearce, 1982) (Fig. 9c), where the rocks show high Th/Yb content (tending towards the value of average continental crust). This feature might suggest effects of both subduction influence and/or crustal contamination (see next section) of the lavas (AFC trend). The higher Th/Yb ratios also could indicate a lithospheric mantle source enriched by subduction components (Dilek et al., 2010). On the other hand, more evolved (felsic) lavas from Sikh kuh (the rocks with SiO_2> 55 wt. %) have higher Th/Yb and Ta/Yb ratios than those of the other magmas, indicating that fractional crystallization also played an important role during the genesis of the rocks (See next section).

6.1. Fractional crystallization-assimilation (AFC) *characteristic*

The mineralogy and geochemistry of volcanic rocks from both Bobak and Sikh Kuh show that the former have mafic compositions, whereas the latter have more intermediate to felsic compositions (Fig. 5a). Three least fractionated Bobak basaltic-andesitic samples are characterized by MgO > 6.5 wt. % and Mg# of ~0.4–0.5. Most of volcanic rocks from Bobak and Sikh-Kuh are more fractionated with lower MgO contents (down to 1.6 wt. %), Mg# (<0.5), and Ni (45–123 ppm) and Co (5–42 ppm) instead of Ni = 99–700 ppm and Co = 25–80 ppm (e.g. Frey et al. 1978, Wilson 1989). Major element data (e.g. SiO_2, TiO_2, MgO, and CaO) also show clear trends against typical indices of fractionation (Fig. 6), which is supported by olivine, clinopyroxene and plagioclase phenocrysts being present in the rocks (Fram and Lesher, 1997). Inverse relationships between MgO, CaO and TiO_2 vs. SiO_2 (Fig. 6) indicate a trend towards bulk compositions that are pyroxene-depleted (Fig. 6e,f). However, there is very little variation in Al_2O_3 concentrations between samples, indicating that feldspar fractionation was not important (Fram and Lesher, 1997).. Trace element abundances, such as Th, and Rb, increase with increasing SiO_2, especially in the Sikh Kuh samples, further confirms these fractionation behaviours (Fig. 6).

These characteristics imply that the magmas had already evolved at a depth in the crust at pressure and temperature conditions exceeding that of plagioclase stability, but where olivine and pyroxene were present. For a typical arc geotherm, this would imply initial magma equilibration at least 20-24 km below the surface (c. 6-8 kbar; Palin et al. 2016), prior to eruption.

Enrichment in Y with respect to Rb in volcanic rocks is likely related to fractionation of anhydrous phases (plagioclase, olivine, pyroxenes, and magnetite), whereas low-Y volcanic rocks are often associated with fractionation of hydrous minerals, including amphibole, which is compatible with Y (Pearce et al. 1990). Mafic members of the Bobak and Sikh Kuh volcanic rock series follow a high-Y trend (13-31 ppm) (Table 1), which may indicate fractionation of anhydrous phases in the crust prior to eruption.

When interpreting the petrogenetic history of volcanic units, it is essential to determine whether crustal assimilation has taken place, particularly in mafic rocks. The Bobak and Sikh Kuh display low SiO_2 contents and high compatible element contents. The Th/Ce (0.04–0.54), and Th/La (0.06–0.87) ratios of volcanic samples correlate positively with SiO_2 (not shown; Table 1), indicating that crustal assimilation may have played a minor role in the generation of the rocks. Likewise, there is linear correlation between SiO_2 contents and Rb/Sr ratios (Fig. 6), indicating that crustal assimilation during their emplacement was more prevalent in the felsic Bobak and Sikh Kuh volcanic rocks than in the mafic rocks. The felsic rocks are also characterized by lower εNd (-1.08 to -1.23) values and higher ($^{87}Sr/^{86}Sr$)i (0.70709-0.70902) ratios than the mafic rocks (εNd= +3.1 to +4.3 and ($^{87}Sr/^{86}Sr$)i = 0.704168-0.704349) (Fig. 8), confirming the influence of assimilation during formation of the felsic magma. The effect of assimilation in felsic rocks can also be traced in Th/Yb vs. SiO_2 (Supplementary Table 1), where the fractionated lavas (with higher SiO_2) have a higher Th/Yb ratio.

Many models suggest that assimilation–fractional crystallisation (AFC) processes are important in the evolution of magmas as they rise through the crust (e.g., Keskin et al. 1998; Hernandez-Montenegro et al. 2021).

Aside from felsic volcanic rocks from Sikh Kuh, the mafic samples show only minor variation in isotope ratios (($^{87}Sr/^{86}Sr$)i = 0.704168-0.704349) relative to SiO_2 (not shown);) confirms enriched features of mantle, metasomatized by fluids derived from a subduction zone. The mafic rocks also form a consistent linear trend sub-parallel to the mantle array, with the volcanic rocks having compositions that are more enriched than those of typical continental crust (Rudnick and Gao, 2003), trending towards higher Th/Yb ratios (Fig. 9c). Although, it may be related to contamination of mantle melts with crustal components via assimilation-fractional crystallization (AFC) (e.g. (Hildreth *et al*. 1991; Huang *et al*. 2013), most samples plot to the left of the fractionation trend (Fig. 9c), and are characterized with radiogenic whole rock εNd(t) (+3.08 to +4.27) which suggests that AFC processes may have played a minor role in the genesis of mafic rock.

6.3 Mantle source features and partial melting

To investigate the nature of the mantle source region, samples showing evidence of fractional crystallization and crustal assimilation (more felsic samples; see previous section) should be excluded from consideration; thus, only basaltic samples with MgO > 5.5 wt. % are considered further. The HFSE and HREE that are relatively fluid-immobile can be used to interpret magma-related enrichment or depletion in the mantle source.

Pearce and Norry (1979) proposed that the Zr/Nb ratio varies extensively between oceanic basalts, with representative values for OIB of >10, E-MORB of ~10, and N-MORB of ~40. In the Sikh Kuh and Bobak basaltic samples with MgO >5.5 wt. %, the Zr/Nb ratio ranges from 7.5 to 14.3, consistent with derivation from an E-MORB-like source. This also agrees with interpretations made from Nb/Yb or Zr/Yb vs. Ta/Yb tectonic discrimination diagrams in which samples plot near to the average E-MORB composition, intermediate to E-MORB and OIB (Fig. 10a, b). On a PM-normalized incompatible element plot, the studied samples from Bobak and

Sikh Kuh are enriched in LILE and LREE with respect to HFSE and HREE (Fig. 7), and display negative HFSE anomalies (Nb and Ti) relative to adjacent LILE (such as Th and Ba) and LREE, thus exhibiting a classic subduction signature. These findings suggest that the unfractionated mafic samples could have been derived from an enriched mantle source in an orogenic setting. Taken together, the high LILE/HFSE, LREE/HREE ratios and low (^{87}Sr/^{86}Sr)i and relatively high (^{143}Nd/^{144}Nd)i isotopic values imply a subduction-modified mantle source for the Neogene volcanic rocks.

Crustal assimilation may also generate subduction-like patterns on multi-element diagrams (Keskin et al. 1998); however, as mentioned above, the Bobak and Sikh Kuh volcanic samples that show evidence of assimilation alone and/or assimilation combined with fractional crystallization are not considered here. Therefore, since this signature preserved in the samples with limited evidence of fractional crystallization or assimilation, enrichments in mantle source must have been achieved previously by subduction components before the magmas ascended into the crustal reservoir beneath the Bobak and Sikh Kuh volcanoes.

The extent of mantle enrichment was tested by examining Ba/Rb against Nb/La (Fig. 11a), and Th/Yb against Ba/La (Fig. 11b) (Wang et al. 2004). In a Ba/Rb vs. Nb/La diagram (Wang et al. 2004), all of the least evolved volcanic rocks plotted in the GLOSS (i.e., Global Oceanic Subducted sediment; Plank and Langmuir 1998) field, with low Nb/La and high Ba/Rb ratios. Extremely low Ba/Rb ratios indicate metasomatization of a mantle source by fluid (Hart 1988; Wang et al. 2004) (Fig. 10c); however, this is not the case for the samples from the Bobak and Sikh Kuh volcanoes. Their geochemistry suggests that their mantle source region was strongly enriched by both sediment melts (SM) and sediment fluids (SF) (Fig. 11b). To quantify the degree of metasomatic mantle enrichment by sediment melts, a Th/Sm vs. Ba/Yb ratio diagram was constructed, given that Th is mobile in sediment-derived melts themselves, although

Ba is highly mobile in fluids derived from dewatering of subducted material. Yb and Sm are also immobile during the enrichment processes that occur at convergent plate margins (Turner, 2002; Foley et al. 2002; Kessel et al. 2005). Therefore, while infiltration of sediment melts would increase the host rock's Th/Sm ratio, the Ba/Yb ratio would increase more than then Th/Sm ratio due to addition of fluids derived from subducted sediments instead. While a few of the samples from the Bobak and Sikh Kuh region plot towards the area between SM and SF on this discrimination diagram (Fig. 12a), most of the samples lie on a mixing line between primitive mantle (PM) and SM (sediment melts). Therefore, the least evolved and evolved samples of the Sikh Kuh and Bobak volcanic rocks were derived from a mantle source region that was dominantly enriched by fluid and sediment melts. The composition of the samples of the Bobak and Sikh Kuh volcanic rocks do not show a trend towards the upper crust composition (UC).

Residual phases such as garnet, spinle and titanite play a significant role in the genesis of melt with an orogenic geochemical signature (Foley and Wheller, 1990; Pearce and Peate 1995).

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The REEs and their ratios (e.g., La/Yb, Sm/Yb or Dy/Yb) can constrain the depth, composition, and degree of melting in the mantle source region (Thirlwall et al. 1994; Shaw et al. 2003; Oyan *et al.* 2016). Mafic E-MORB type rocks from Bobak and Sikh kuh (with $(La/Yb)N$ = 5.1-13.8 and $(Dy/Yb)N$ = 1.0 - 1.7, respectively) may have resulted from partial melting of a mantle source enriched in LREE than garnet bearing spinel lherzolite ($(La/Yb)N$ = 0.88 and $(Dy/Yb)N$ = 0.94). The melting in the spinel stability field, garnet stability field, or spinel-garnet transitional stability field would produce low Dy/Yb ratios (<1.5), high Dy/Yb ratios (>2.4), and moderate Dy/Yb ratios (1.5–3), respectively. The measured Dy/Yb ratio of all mafic rocks in the study area is between 1.5-2.7, and thus supports mafic rocks having been formed in the spinel-garnet transitional stability field (e.g. McKenzie and O'Nions, 1991). Furthermore, (Gd/Yb)*N* ratios can be used to discriminate between garnet and spinel peridotite sources, as the (Gd/Yb)*N* ratios of each are >2.0 (high) and <2 (low), respectively (Alvarado et al. 2014). If garnet is present as a residual mineral in the mantle source region, then the (Tb/Yb)*N* ratios will be higher than 1.8 (Rooney 2010). The $(Gd/Yb)_N$ and $(Tb/Yb)_N$ ratios of the samples from Bobak and Sikh Kuh are between 1.4–1.9 and 1.1–1.8, respectively, indicating a garnet bearing spinel-rich mineral facies for the mantle source region.

Finally, all basalt samples plotted on a La/Yb vs Tb/Yb diagram (i.e. LREE/HREE vs MREE/HREE diagram) are shown in Fig. 12b, together with two mantle sources and seven source facies, which each have a unique mineralogy and chemistry. Spinel-rich PM (and/or DMM) mantle compositions could produce compositions similar to those of the analyzed Late Cenozoic volcanic rocks. Notably, all of our samples plot on the melting curve of the amphibole-bearing spinel peridotite DMM-1 and spinel peridotite PM sources, at melting degrees ranging between 2 to 10% and 1–3%, respectively, indicating relatively low melt fractions.

6.4. Geodynamic implications

Magmatic rocks rich in K and/or Na may form in diverse tectonic settings, such as active continental margins, orogenic post-collisional zones, and within plate settings (e.g., Muller et al. 1992; Mitchell et al. 1994; Elitok et al. 2010; Eyuboglu 2010; Aclan et al. 2020). Late Cenozoic magmatism in Iran occurred in a post-collisional setting and resulted from partial melting of subduction-related, metasomatized subcontinental lithospheric mantle (SCLM, e.g., Aldanmaz et al. 2000; Ersoy et al. 2010; Altunkaynak et al. 2012; Ersoy et al. 2012a,b). Post-collisional volcanic rocks can occur due to crustal over thickening (Allen and Armitage 2008), extensional collapse, regional lithospheric delamination (Pearce et al. 1990; Keskin et al. 1998; Oyan et al. 2016), slab break-off (Keskin 2003) and plume-related melting of the base of the overlying crust.

Most of the high-Na magmatic rocks from eastern Iran (Pang et al. 2012, 2013) and the Anatolian plateau are thought to have been derived from partial melting of a mantle source similar to the Timar basalts east of Lake Van, Eastern Anatolia, which was either contaminated by multiple episodes of oceanic subduction events during an extended period and/or contaminated by continental crust (Ersoy et al. 2010, 2012a, b). In the former case, partial melting would have occurred in a metasomatized lithospheric mantle source that had a predominantly spinel-bearing mineralogy, and magmas reached the surface through fissures related to extensional tectonics. This process is mostly responsible for the genesis of high-Na volcanic rocks (Aclan et al. 2020 and references therein).

The Bobak and Sikh Kuh volcanic rocks are enriched in Na, LILEs and LREEs relative to PM and. These features suggest that the Bobak and Sikh Kuh magmas were derived from small degrees of partial melting of a subduction-metasomatized SCLM source.

Magmatism within the Lut-Sistan zone along are linked to the northeastward subduction of the Lut-sistan oceanic basin beneath the Afghan block (Bröker et al. 2013, Angiboust et al., 2013, Bonnet et al., 2018, Jentzer et al, 2020, Jentzer et al., 2022). Zircon from the Lut-Sistan suprasubduction zone-type gabbros have yielded ages of 113–107Ma (Zarrinkoub et al., 2012), showing that subduction was active during early-late Cretaceous time. High–P rocks give ages of ~89–86Ma (Brocker et al., 2013), denoting the exhumation of the metamorphosed oceanic slab in the Coniacian (Late Cretaceous). The collision between the Lut and Afghan block is suggested to have occurred during latest Cretaceous (*ca.* 60Ma) to early Eocene (~50 Ma) time (Jentezar et al., 2022) and therefore, the Paleogene magmatism in the Lut-Sistan zone arose after closure of the Lut-Sistan oceanic basin, in an extensional basin following the post-collisional setting (Angiboust et al., 2013; Zarrinkoub et al., 2012). Melting of the SCLM could be related to thermal perturbation caused by this extensional basin (e.g., Aldanmaz et al. 2000; Zhao et al. 2009; Ersoy et al. 2010, 2012a,b; Prelević et al. 2012; Hernandez-Uribe and Palin 2019). This phase of magmatism was dominated by mafic-intermediate compositions within the Sikh Kuh and Bobak regions, eastern part of Lut block (Fig. 1). The magma source was located in the upper mantle and had been modified by fractionation, which produced felsic volcanic rocks. The Jentezar et al. (2022) suggested that onset of collision, which must therefore have started during the Late Paleocene and/or Early Eocene, is marked by a drastic change in sedimentation. The collision-related horizontal shortening is achieved at (~20 Ma) followed by occurrence of steepend tectonic contact. Such primary contacts, steepened by later deformation, are used as pathways by the Plio-Quaternary magmatism.

. Iran is currently undergoing north–south shortening, probably since the Arabia–Eurasia collision (Verdel et al. 2011); many faults, extensional fissures (Pang et al. 2012), volcanic centers, and volcanic activities have been recognized around east Iran during the Late Cenozoic, confirming this geodynamic model.

7. Conclusions

(1) High-Na volcanic rocks from the Sikh Kuh region, east Lut Block, eastern Iran, comprise basalt/trachybasalt and andesite-dacite, whereas rocks from the Bobak region are more mafic, with basaltic to basaltic trachyandesite composition. The mafic rocks are enriched in incompatible trace elements and have no radiogenic Sr (0.70416-0.70436).

(2) Their geochemical features suggest a metasomatized subcontinental mantle source, which was pre-enriched by subduction-related fluids or melts, and underwent low degrees of melting (probably ~2–10%) to produce high-Na rocks.

(3) The collision between the Lut and Afghan block in latest Cretaceous (*ca.* 60Ma) to early Eocene (~50 Ma) time followed by extensional basin and melting of the SCLM and generating a mafic-intermediate compositions melts in the Sikh Kuh and Bobak regions. Some of these melts interacted with the crust during their ascent to the surface, incorporating and assimilating these materials and generating more evolved volcanic rocks.

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The authors have no conflicts of interest to declare that are relevant to the content of this article.

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9. Figure captions

Fig. 1 Geological map of Iran showing the distribution of Cenozoic igneous rocks especially Miocene-Quaternary volcanic rocks, and the location of Sikh Kuh and Bobak within the Lut block.

Fig. 2. Geological map of the Bobak and Sikh kuh *(Modified after 1:250,000 geological map of Dehsalm, Geological Survey of Iran.)*

Fig. 3 Field photographs of the volcanic rocks from Sikh Kuh and Bobak; (a) Sikh Kuh volcanic center, which intrudes Jurassic metamorphic rocks (view to the north); (b) Cross section of Sikh Kuh columnar basaltic prisms and (c) view of them to the south; (d) Bobak volcanic center (view to the north); (e) and (f) shrinkage fractures and abundant gas cavities in lava flows , in part filled by calcite and zeolite due to fluid infiltration through rapid cooling lava.

Fig. 4 Photomicrographs of volcanic rocks from the Sikh Kuh and Bobak localities. (a) Glomeroporphyritic texture in basalt from Sikh Kuh; (b) euhedral plagioclase with oscillatory zoning in the trachy basalt ; (c) sieve texture in plagioclase in the trachy basalt; (d) iddingsitization of the olivine grains from the edges in the trachy basalt and (e) corroded quartz within the andesitic-dacitic lava flow; (f) biotite in andesitic-dacitic lava flow.

Fig. 5 Alkali *vs* SiO_2 and (a) Zr/TiO_2 *vs* Nb/Y (b)plots for the classification of volcanic rocks from Sikh Kuh (red circle) and Bobak (green star); Na_2O (wt. %) vs. K_2O (wt. %) diagram of Middlemost (1975) (c) and Th *vs* Co (d) plot showing that the these rocks is high Na rocks in calc-alkaline series.

Fig. 6 SiO_2 vs. selected major and trace element Harker diagrams for Sik Kuh and Bobak volcanic rocks. Symbols are as in Fig. 5.

Fig. 7 Chondrite-normalized rare earth element (a and b) and primitive mantle-normalized trace element patterns (c and d) for the volcanic rocks from Sikh Kuh and Bobak. Chondrite and primitive mantle normalized values of OIB and E-MORB are taken from Sun and McDonough (1989).

Fig. 8 Sr-Nd isotope diagram of volcanic rocks from Sikh Kuh and Bobak. Data from Turkey are from Oyan *et al*. (2017), GLOSS is from Plank and Langmuir (1998), Iranian volcanic rocks are from Allen *et al*. (2013), and alkaline basalts of east Iran are from Pang *et al*. (2012). Symbols are as in Fig. 5.

Fig. 9 Basalt tectonomagmatic discrimination diagram of (a) Pearce *et al*. (1977) and (b) Wood (1980) for the mafic lavas of Bobak and Sikh Kuh; (c) Th/Yb vs. Ta/Yb diagram (Pearce, 1983) for the Sikh Kuh and Bobak lavas, showing an FC vector, taking into account increasing partition coefficients during magmatic evolution (after Keskin *et al.* 1998), and an AFC vector as described on the figure. Crust compositions (UCC: upper continental crust; MCC: middle crust; LCC: lower crust; BCC: bulk continental crust) are from Rudnick and Gao (2003). Data for rocks from active margins come from Pearce (1983). Symbols are as in Fig. 5.

Fig. 10 Binary diagrams of incompatible element ratios illustrating the mantle source feature for the least evolved mafic volcanic rocks from Bobak and Sikh Kuh. (a) Nb/Yb *vs* Ta/Yb; (b) Zr/Yb *vs* Ta/Yb. N-MORB, E-MORB and OIB values are after Sun and McDonough (1989). Solid lines denote mantle arrays extrapolated from N-MORB and OIB values. Only basaltic and relatively primitive andesitic samples (>3 wt.% MgO) are plotted. Data for Eocene–Oligocene magmatic rocks elsewhere in Iran or in the eastern Mediterranean region, which were screened using the same criterion come from Pang *et al.* 2013 and references therein. East Iranian Eocene–Oligocene magmatic rocks come from Pang *et al.* 2013. Symbols are as in Fig. 5.

Fig. 11 (a) and (b) comparison of Sikh Kuh and Bobak volcanic rocks with average subducted global oceanic sediment (GLOSS) (Plank and Langmuir, 1998). SM: subducting sediment melts, AOC: altered oceanic crust, PM: primitive mantle and UC: continental upper crust. Symbols are as in Fig. 5.

Fig. 12 (a) Ba/Yb vs. Th/Sm diagram for Sikh Kuh and Bobak volcanic rock samples. Sediment melt (SM) was calculated by 10% batch melting of global oceanic sediments (GLOSS). UC is upper crust from Taylor and McLennan (1985). Sediment fluid (SF) was obtained by 1% batch melting of GLOSS by using the D values from Johnson and Plank (1999). AOCF (AOC fluid) was calculated by 1% batch melting of AOC by using the D values from Brenan *et al*. (1994). OIB and PM are from Sun and McDonough (1989). UC GLOSS and AOC are from Taylor and McLennan (1985), Plank and Langmuir (1998) and Staudigel *et al*. (1996), respectively); (b) Non-modal batch melting models for partial melting processes in the source of the Quaternary mafic volcanism. This model used two mantle sources and seven source mineral facies based on different mineralogy and chemistry for comparison.