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Constraints on the Petrogenesis of Nosrat-Abad Ophiolite Extrusives, SE Iran

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Abstract

Nosrat-Abad ophiolitic extrusive sequence, located in the Sistan Suture Zone, in south eastern Iran. The extrusive sequence, contains pillow lava, sheet flow and related volcanic-clastic breccias which have undergone low-grade metamorphism. This association shows calc alkaline to tholeiitic affinities. Interpretation of the geochemical data and behavior of the elements in different diagrams reveals two distinct domains in the Nosrat-abad ophiolitic extrusive sequence. The sheet flows are depleted in HFSE similar to those of SSZ. However, the enrichment of the pillow lavas in LILE could be attributed to an enriched mantle source or melting of metasomatized sediments above the subducted slab. It appears that two subduction components (fluids-melt), caused the diversity seen in the chemical composition of the study rocks. The MORB to subduction chemical characteristics of the Nosrat-Abad ophiolitic extrusive sequence could be explained by a shift in the tectonic settings from the mid-ocean ridge to the marginal basin in Sistan during the Late Cretaceous period.

Keywords: *Nosrat-Abad, Sistan Suture Zone, Ophiolite, Extrusive, Supra-subduction, MORB.*

1. Introduction

Iranian ophiolites are a part of the Tethyan ophiolitic belts (Fig. 1a) and record a series of complex plate interactions, which occurred during the late Paleozoic to Cenozoic and they link the eastern Mediterranean (Hellenides–Dinarides) ophiolites in the west, to the Asian ophiolites in the east [1]. Stöcklin, [2]; Sengor, [3]; Wensink and Varekamp, [4] believed that the consumption of Paleo-Tethys as a consequence of the pre-Liassic collision of the Central Iranian microplates with Laurasia (Fig. 1a) is recorded along the Alborz Mountains in northern Iran [1]. The Maastrichtian [5] or Miocene [6, 7] consumption of Neo-Tethys and the associated collision of the Arabian platform in the south with the Central Iranian microplates in the north [2], is recorded by the southern Iranian ophiolites along the main Zagros thrust fault (Fig. 1a) [1]. In southeastern Iran, docking has not yet occurred; the oceanic lithosphere still exists beneath the Gulf of Oman, and subduction continues through the present beneath the Makran [8, 9]. Delaloye and Desmons, [10] believed that in eastern Iran, thick piles of deep-water marine sediments with ophiolitic mélanges have cropped out along the Sistan suture zone and mark the boundary between Lut (eastern sector of the central Iranian microplates) and the Afghan continental blocks (Fig. 1a) [1].

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These ophiolites are interpreted as remnants of the oceanic lithosphere (Sistan Ocean) mainly consumed in a subduction zone and, in part, obducted onto the Lut margin during the Eocene continental collision between the Central Iranian microplates and Afghan block. (e.g., [11]). Many authors (e.g., 11-14, 1]) have discussed geodynamic models of the evolution of the Sistan oceanic basin. Most models except Saccani et al. [1] model, are mainly based on general geological and tectonical evidences, without any petrological data on the ophiolitic rocks. In this case, the tectonic setting of formation of ophiolites from the Sistan Suture Zone has been studied just in Nehbandan [1]. For this reason, new petrological and geochemical data on the Nosrat-Abad ophiolite (Fig. 1b), a key area of the Sistan Suture Zone, are presented. The aims of this study are: (1) to shed light on the geochemical and petrogenetic processes behind the formation of ophiolites in the Sistan Suture Zone, (2) to use this data to test and develop the models proposed in literature for the tectonic evolution of the Sistan Ocean within the context of Neo-Tethyan tectonic reconstruction models in Iran and the Middle Eastern region.

2. Geological Background

Along the Sistan Suture Zone, there are various ophiolitic complexes that form a discontinuous N–S trending belt from Zahedan to Birjand (Fig. 1b); the main ones are Nosrat-Abad (Tchehel Kureh), Nehbandan and Birjand ophiolites [1]. The Nosrat-Abad ophiolite is located in 60 km northwest of

Zahedan (Fig. 1b). According to Tirrul et al. [11], the Sistan Suture Zone can be divided into two geological terranes, the Neh–Ratuk complex and the Sefidabeh basin, that represent an accretionary prism and a forearc basin, respectively (Fig. 1b) [1]. The Neh–Ratuk complex can be further subdivided into two zones, the younger Neh complex to the southwest and the older Ratuk complex to the east; both consist of a mélange incorporating ophiolitic rocks (about 30% in volume) associated with Cretaceous to Eocene phyllites and Paleogene terrigenous marine sedimentary rocks [1]. The Cenomanian to Eocene marine sedimentary rocks of the Sefidabeh basin onlap the accretionary prism of the Neh–Ratuk complex and the major deformation began in the Late Eocene [1].

Camp and Griffis, [15] believed that the Sistan Suture Zone is characterized by the widespread occurrence of calc-alkaline and alkaline volcanic rocks ranging in age from upper Cretaceous to Neogene. Upper Cretaceous–Paleocene calcalkaline volcanics have cropped out in the eastern margins of the Sefidabeh basin [1]. Moreover, there are some syntectonic to post-tectonic intrusions formed after the closure of the Sistan Suture Zone in the Late Eocene–Early Miocene time span [15, 16].

Davoudzadeh et al. [17] and others believed, lithological relationships show that the ophiolitic emplacements occurred during the late Cretaceous, but deep-water sedimentation continued until the early Eocene. After this time, the collision between the Lut and Afghan blocks resulted in the closure of the basin and consequential regional uplift of the terranes. The structural characteristics of the Sistan Suture Zone may have also been influenced by a counter clockwise rotation of the Lut block from the Jurassic to Tertiary [1]. Early studies suggested that the opening of the Sistan oceanic basin occurred in the Late Cretaceous, as deduced from the occurrence of several mélange blocks consisting of Turonian–Maastrichtian limestones [11, 18-20]. Nonetheless, 40Ar–39Ar dating of high pressure metamorphic rocks which derived from the eastward subduction of the Sistan oceanic crust beneath the Afghan block, is in the range of 140.6 to 112.5 Ma [21], while, Babazadeh and De Wever [22] reported Early Cretaceous (Aptian and Albian) radiolarites from the Sistan Suture Zone. These data suggest that the opening of the Sistan Ocean should be older than the Late Cretaceous [1]. The closure age of the Sistan Ocean and the formation of the suture zone are not well constrained. The only published data reports K/Ar ages in the range of 60 to 100 Ma for southern Nosratabad ophiolitic rocks [10]. In Nosrat-Abad, mantle sequences are mainly exposed on the eastern sides while crustal sequences cover the area to the west. The peridotites from the mantle section of Nosrat-Abad are mostly harzburgite, with small amounts of lherzolite and dunite patches. Nosrat-Abad ophiolite crustal sequences comprise a noncomplete dismembered sequence of plutonic, sub-volcanic and extrusive rocks. The plutonic section comprises massive gabbro with a variety of pyroxene gabbro and gabbro. The plagiogranites are late phase cutting plutonic and sub-volcanic sequences. The sub-volcanic sequence comprises diabasic isolated dikes. The extrusive sequence of Nosrat-Abad are comprised of an alternation of pillow lava and sheet flow, interbeded pelagic limestone, chert and radiolarite wich have been cut by isolated diabasic dikes. Pillow lavas are glandular and tubular, in shapes (Fig. 2a, b) ranging from 0.2 to 2 meter in diameter. The lavas and dikes of the Nosrat-Abad contain low to medium grade hydrothermally altered material which was metamorphosed before tectonic emplacement and as in other ophiolitic complexes (e.g., Pindos [23-25]), Troodos (e.g., [26-29]) is considered to have occurred in the submarine environment. The alteration is a result of water/rock interaction at elevated temperatures through the convection process [30].

3. Petrography

Extrusive rocks of the Nosrat-Abad ophiolite occur mainly as sheet flows and pillow lavas, mainly from andesite to basalt, basaltic andesite and dacite. These rocks can be divided in two groups: aphyric (Fig. 2c) and moderately phyric (Fig. 2d),with the aphyric type being more abundant. Petrographic studies show obvious variations in crystal morphologies and textures between the chilled glassy outer rims and the holocrystalline cores. Although alteration is extensive, igneous textures are well preserved. In hand specimens, the rocks are largely aphyric and contain microvesicles filled with zeolite and carbonate minerals. In most areas, the pillow lavas are usually intercalated with a conglomerate unit containing clasts of lavas, shallow- and deep-water fossiliferous limestone, and reddish clasts of jasper and chert. The limestone and cherty blocks vary in size from a few tons, to tens of meters. Aphyric pillow lavas have microcrystalline to fluidal textures, with plagioclase and clinopyroxene as main mineral phases. Plagioclase megacrysts are common in plagioclase-phyric basaltic pillow lavas (Figs. 2d). Phyric basalts are scarce in the region. Plagioclase megacrysts and phenocrysts have tubular shapes with albite and albite-carlsbad twinning. In the margins of the pillows, plagioclase microlites show typical quenched textures, with 'belt buckles', hollow cores and bifid tips (Fig. 2e, f). Massive sheet flow basalts exhibit fine-grained intergranular textures. As in the pillow basalts, plagioclase and clinopyroxene are the main mineral phases, and Fe–oxides and fine-grained sphene are the accessory minerals. They are generally altered to chlorite, calcite, fine-grained clay minerals and secondary albite. Phyric diabases are found as isolated dike intruded pillow lavas and sheet flows. The plagioclase phenocrysts are set in a fine-grained diabasic groundmass containing plagioclase and clinopyroxene microlites.

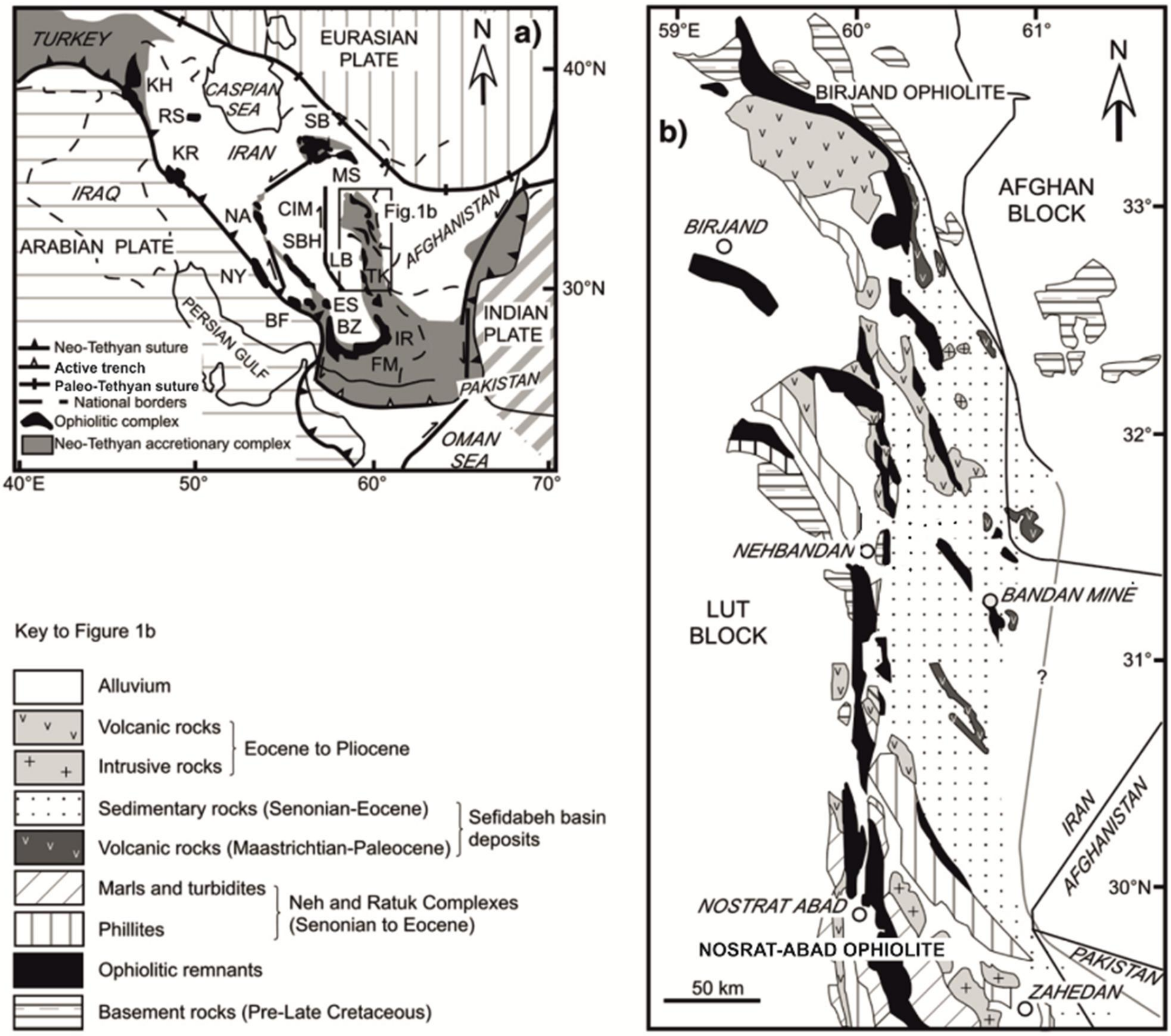

Fig. 1. (a) Generalized tectonic map of the Middle East. CIM: central Iran microplates, which includes the Lut block (LU) as its eastern part. The locations of the major Iranian ophiolites are also reported. Abbreviations, BF: Baft; BZ: Band-e-Zeyarat; ES: Esphandagheh; FM: Fanuj-Maskutan; IR: Iranshahr; KH: Khoy; KR: Kermanshah; MS: Mashhad; NA: Nain; NY: Neyriz; RS: Rasht; SB: Sabzevar; SHB: Shahr-Babak; TK: Tchehel Kureh (Nosrat-Abad). The box indicates the location of the Sistan Suture Zone (expanded in Fig. 1b). (b) Geological sketch map of the northern part of the Sistan Suture Zone (modified after [11]). The box indicates the location of the eastern Iranian ophiolites. Fig 1 and their description adapted from [1].

4. Analytical methods

100 samples were collected from the Nosrat-Abad ophiolite extrusives. On the basis of petrographic observations, fourteen samples with minimal effects of alteration were selected for whole-rock geochemical analysis. Whole-rock major and trace elements and REE compositions were determined at the ALS-Chemex Laboratories, Vancouver, Canada.

5. Geochemistry

The major and trace element geochemistry described here is based on those elements, which are virtually immobile during low-temperature alteration and metamorphism up to the greenschist facies (e.g.,[31-33]). Generally, immobile elements include incompatible trace elements, such as Ti, P, Zr, Y, Nb, Ta, Hf, Th, middle (M-) and heavy (H-) rare earth elements (REE), as well as some transition metals (e.g., Ni, Co, Cr, V). Large ion lithophile elements (LILE) are commonly mobilized during alteration (e.g., [34-37, 1]). The abundance of immobile elements may reflect the geochemistry of the mantle source, which varies, in turn, according to the tectonic setting [38, 39].

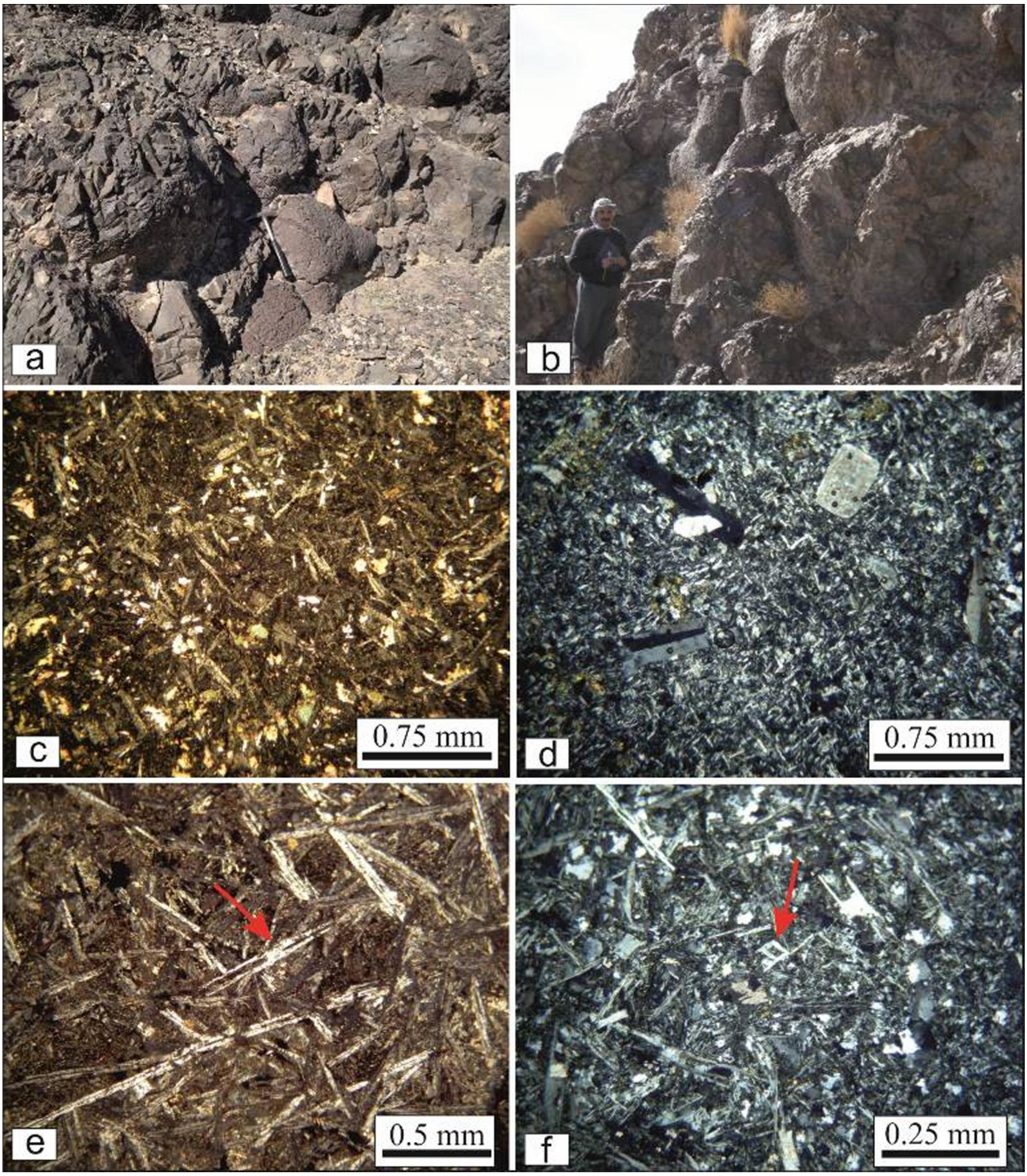

Fig. 2. The extrusive sequence of Nosrat-Abad ophiolitic complex. (a) Field photograph of pillow lavas and (b) tubular lava exposed around Nosrat-Abad area. Photomicrographs showing textures in Nosrat-Abad ophiolite extrusives. (c) General aspect of an aphyric basalt, totally devoid of phenocrysts, and composed of plagioclase, clinopyroxene and Ti–magnetite microlites, set in a devitrified groundmass, under crossed nichols, (d) Megacrysts-bearing phyric basalt containing plagioclase phenocryst set in a groundmass composed of microphenocrysts and microlites, under crossed nichols, (e and f) Typical quenched textures (with the well-known ‘belt buckles’, transverse sections of hollow plagioclase microlites, and ‘bifid tips’ in longitudinal sections), well preserved in the margin of a basaltic pillow lava, under crossed nichols.

These elements were used to investigate the variations of mantle source composition, degree of mantle melting, low-pressure fractionation processes (basaltic crystallization), and finally determine tectonic setting of formation of the Nosrat-Abad ophiolites.

On the SiO_2 vs. Na_2O+K_2O diagram [40], the Nosrat-Abad extrusives plot as trachy-basalt and tephrite-basanite and the sheet flows plot mainly in the andesite-dacite and trachyandesite fields (Fig. 3).

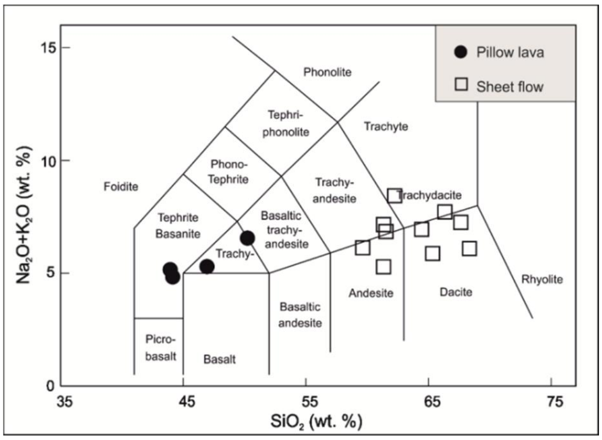

Fig. 3. Na_2O+K_2O vs. SiO_2 (wt. %) diagram [40] showing compositions of the Nosrat-Abad ophiolite extrusive rocks.

The normalized mid-ocean ridge basalt (MORB) multi-element diagrams (Fig. 4a) show that the lavas are enriched in large ion lithophile elements (LIL). The chondrite-normalized rare earth element (REE) patterns (Fig. 4b) show a relatively mild enrichment in light rare earth elements (LREE) relative to HREE. The patterns lack the LREE typical depletion of N-type MORB and many island arc tholeiitic (IAT), but show similarities to E-type MORB [41-43].

6. Discussion

6.1. Tectonic setting of Nosrat-Abad ophiolite extrusive rocks

For this purpose, we examined the behaviour of some incompatible elements (mostly, high field strength element, HFSE), and especially their inter-element relationships (Th/Yb, Ta/Yb). These elements generally have low bulk distribution coefficient (D) in basic magmas [36]. Pearce [44] and Pearce et al. [45] demonstrated that plots of an incompatible element against a compatible element provide useful information on the process responsible for the observed geochemical variations in a particular lava suite.

For the petrogenetic discrimination of basalts, oceanic or not, Pearce and Peate [46], Pearce et al. [47] and Pearce [48] used two ratio plots of Th versus Nb (i.e. Th/Yb-Ta/Yb) as proxy to highlight the crustal contamination. In the Th/Yb vs. Ta/Yb diagram (Fig. 5), the Nosrat-Abad extrusives are plotted in two fields. The pillow lavas plot in enriched (MORB) mantle source with a trend to the supra-subduction zone (SSZ) but the sheet flows clearly plotting in the SSZ field. This suggests a hetrogenetic source for the Nosrat-Abad extrusives mantle. Most likely, due to this heterogeneity, Nosrat-Abad extrusives in the condrite normalized diagram are located at different levels. Also, the relatively scattered vertical distributions in this diagram indicate that the mantle source of Nosrat-Abad extrusives was modified by a moderate to high ratio of subduction components.

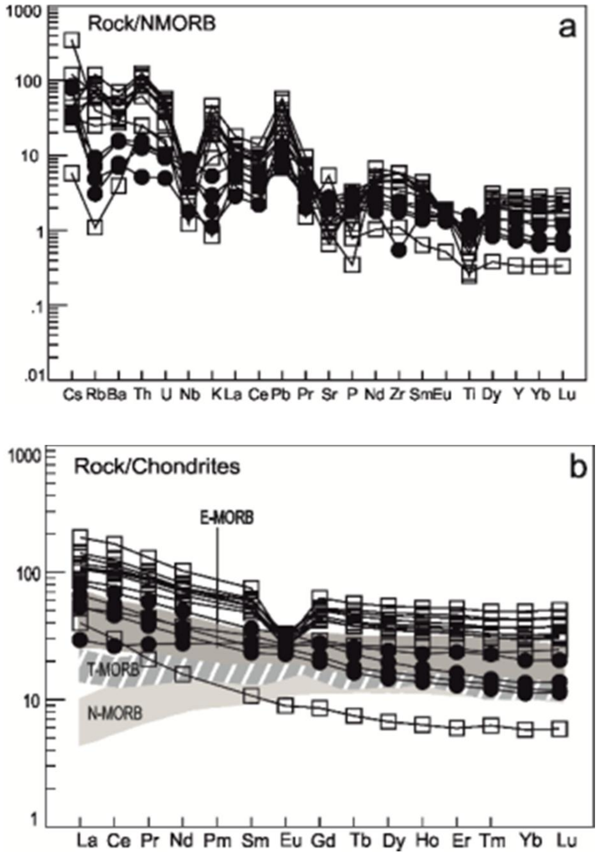

Fig.4. N-MORB normalized incompatible element patterns (a) and chondrite-normalized REE patterns (b) for Nosrat-Abad extrusive rocks. Normalizing values are from [50]. Compositional variations (grey fields) from [50] are reported for comparison. Symbols are the same as in Fig.3.

In summary, extrusive rocks from Nosrat-Abad ophiolite show geochemical characteristics similar to those observed in island-arc basin basalts. It follows that the mantle source of SSZ basalts was most likely enriched in LILE and LREE prior to melting. In fact, the high Th/ Yb ratios compared to Ta/Yb ratios suggest that these rocks are influenced by a SSZ component [51, 34-36]. Similar enrichments in LILE and LREE prior to melting from the subducted slab are observed in many SSZ rocks (e.g., [52, 53, 34-37, 1, 54, 55]).On the Hf/3–Th–Nb/16 and Zr/117-Th-Nb/16 diagrams [56], sheet flows indicate a clear supra-subduction zone (SSZ) signature (Fig. 6) whereas pillow lavas lies in E–MORB fields.

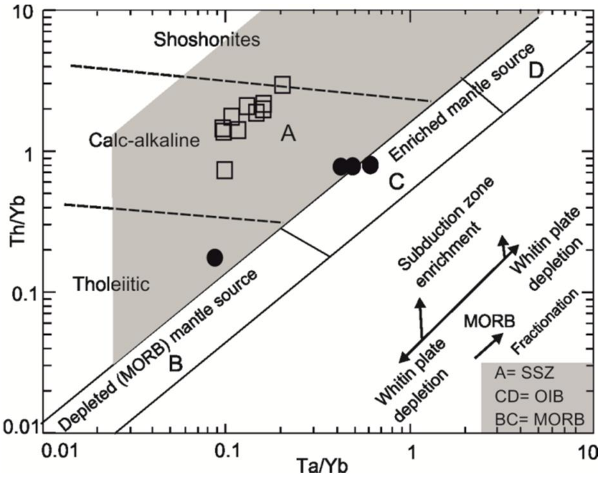

Fig. 5. Th/Yb vs. Ta/Yb diagram (modified from [39, 44]) for the Nosrat-Abad extrusive rocks. Fields for shoshonite, calc-alkaline and tholeiite from [49]. SSZ: supra-subduction zone , OIB: Oceanic island basalt, MORB: Mid ocean ridge basalt. Symbols are the same as in Fig. 3.

6.2. Subduction components in the magma source

It has been proposed that the distinctive geochemical characteristics of arc lavas that indicate subduction processes, such as elevated volatile contents and enrichment in LILE relative to HFSE and HREE, are transferred into the mantle wedge from the subducting slab via aqueous fluids or melts (e.g., [57-59, 47, 68, 61]).Water contents of MORB vary between 0.05 and 1.3 wt.% [62], although most normal-MORB have between 0.1 to 0.4 wt.% H_2O [63, 64]). The trace element concentration patterns (Fig. 4) also show the influence of subduction components in the mantle source [61]. As noted above, the LILE>LREE>HFSE concentrations in subduction-related magmas are widely attributed to their selective addition by fluids and/or melts from the subducting slab (e.g., [47, 60, 61]).

Nosrat-Abad extrusives in Fig. 7 show two groups that form a vertical trend in the Ba/Th versus Th/Nb plot [61]. Such a chemical trend indicates that there is two subduction components influencing the mantle beneath the Nosrat-Abad ophiolite [61]. The high Ba/Th component represents low–temperature aqueous fluid derived from the dehydration of altered oceanic crust or dewatering of sediments, whereas high Th/Nb component suggests addition of partial melt of subducted sediments (e.g., [61]). Fluids released from altered oceanic crust and/or plagic sediments along with the melting of sediments comprise the "subduction components" (e.g., [65-67]). Samples from the Nosrat-Abad extrusives are plotted between the Indian MORB and the Tonga Arc basalts. They generally trend away from MORB and toward subduction-related aqueous liquids and melts. This implies that the two subduction components (aqueous fluids and melts from the crust/sediment) in the Nosrat-Abad ophiolite also influence the composition of extrusive rocks (e.g., [61]).

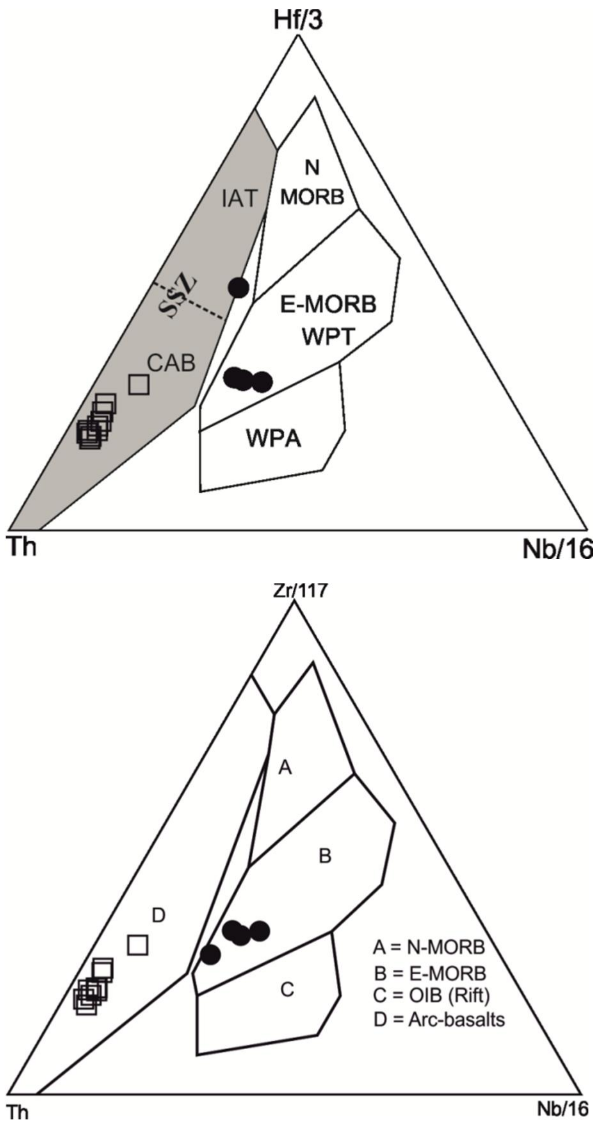

Fig. 6. Discriminant diagrams for Hf/3–Th–Ta (a) and Zr/117-Th-Nb/16 (b) from [56]. CAB: calc-alkaline basalts; WPT: within-plate tholeiites; WPA: within-plate alkaline; SSZ: supra-subduction zone basalts; IAT: island arc tholeiites.Symbols are the same as in Fig. 3.

7. Conclusion

This study revealed the presence of geochemically distinct extrusives in the crustal section of the Nosrat-Abad ophiolite. The Nosrat-Abad ophiolite mainly includes extrusive rocks generated in a supra-subduction setting that consists of sheet flows. Sheet flows display geochemical characteristics, which are typical of SSZ-type ophiolites. REE patterns show that sheet flows have REE compositions similar to those of SSZ extrusives. The Nosrat-Abad ophiolite also include extrusive rocks generated in a mid-ocean ridge setting; they consist of pillow lavas. The pillow lavas show typical MORB-type geochemical characteristics. Pillow lavas are an enriched variety. Most likely, EMORBs originated from mantle plumes or the melting of metasomatizsed sediments above the subducted slab. These lithological variations and their relationships in ophiolites can be explained by a shift in the tectonic setting from the mid-ocean ridge to the marginal basin.

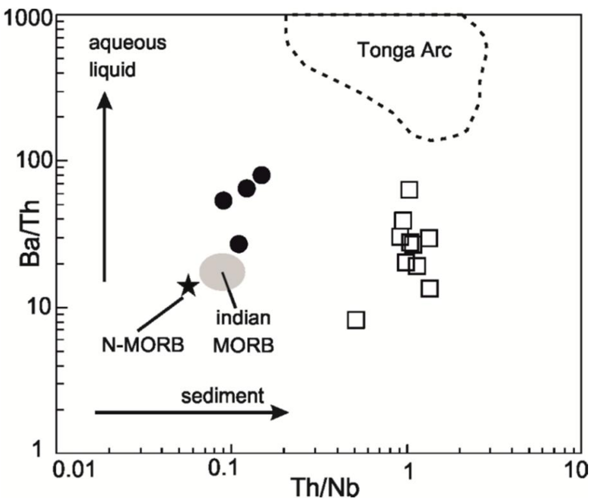

Fig. 7. Ba/Th vs. Th/Nb diagram from [61] for Nosrat-Abad extrusive rocks. Indian MORB and the average N-MORB composition are shown for reference (see [61] for data source). Solid lines with arrows indicate element enrichments, interpreted to have been caused by the addition of aqueous fluid (e.g. increasing Ba/Th at a constant and low Th/Nb ratio) and minimal input from sediment addition (e.g. increasing Th/Nb at a constant and low Ba/Th ratio) from the subducting slab. Symbols are the same as in Fig. 3.

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