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Geochemical Characteristics of Volcanic Suite from the Eastern Guilan Province Ophiolite Complex in North of Iran

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Abstract: The eastern Guilan province ophiolite complex is a dismembered ophiolite complex that is located in northern Iran and belongs to the Alborz orogenic system. It consist of layered ultramafic cumulates, layered gabbro, isotropic gabbro, diabase and a volcanic sequence that exhibits a wide range in composition from subalkaline basalts to alkaline basalts. The associated limestones including of Globotruncana fossils show an upper Cretaceous age for that. The geochemical data clearly identifies some of the volcanic rocks to have formed from two distinct types of basaltic melts: (i) those of the subalkaline suite which formed from an initial melt that are characterized by selective enrichments in fluid-soluble Large Ion Lithophile Elements (LILE) and LREE relative to the High Field Strength Elements (HFSE) and incompatible trace element patterns that suggest an island arc affinity and (ii) those of the alkaline suite with significant enrichment in LILE, HFSE and LMREE and a slight depletion in HREE and incompatible trace element patterns that are virtually identical to typical Oceanic Island Basalt (OIB) pattern. It is suggested that more than one-stage melting process is required to explain geochemical characteristics of back-arc basin and OIB basalts of this area. The overall chemical characteristics indicate that the studied volcanic rocks represent a volcanic units that were formed in an arc-basin system that is characterized by an oceanic lithosphere generation most probably associated with melting of mantle material along a supra-subduction-type spreading centre and alkali rocks were generated from a plume in a local extension regime in an island arc environments in an oceanic basin.

Key words: Iran, Guilan province, volcanic rocks, ophiolite complex, alkaline rocks, subalkaline rocks, supra-subduction, OIB basalts

INTRODUCTION

Today it is widely accepted that ophiolite complexes formed in a variety of tectonic settings (e.g., fast-and slow-spreading mid-ocean ridge, island arc, back-arc basins). The tectonic setting for an ancient ophiolite complex may be ascertained by studying its present geological setting, its internal structure, the timing of emplacement and its magmatic products geochemistry (A'Shaikh *et al.*, 2005). Magmatic products from the crustal parts of ophiolite complexes can provide important information on the processes of melt generation during variable stages of lithosphere production, contribute to our understanding of the original tectonic setting for the formation of oceanic lithosphere and help in understanding the processes of crustal accretion in variable tectonic systems. The igneous geochemistry of volcanic rocks is especially important in identifying the structure and magmatic evolution of oceanic crust formed in ancient spreading centers and in interpreting the geological history of regions which comprise various tectonic units of accreted terranes (Shervais, 2001; Pearce, 2003; Aldanmaz *et al.*, 2008). Geochemical studies of basaltic products in ophiolite suites have been widely used because processes within subduction zones are believed to impart diagnostic geochemical signatures to Suprasubduction Zone (SSZ) basalts that are distinct from those Mid-ocean Ridge Basalts (MORBs) and OIB basalts (A'Shaikh *et al.*, 2005).

The geological characteristics of many of the Neothetyan ophiolites from Iran help to our understanding of the Neotethyan evolution in Iran. The ophiolites of Iran may be classified into two groups, the less abundant Paleozoic (relate to Paleotethyse) and the more abundant Mesozoic (related to Neotethyse) ophiolites (Shojaat *et al.*, 2003). Although geochemical data on the Iranian ophiolites are relatively sparse, most of the earlier available data suggest that Iranian ophiolites have Mid-ocean Ridge Basalt (MORB) and Island Arc Tholeiite (IAT) affinities (Rahgoshay *et al.*, 2007;

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Moazzen *et al.*, 2006; Shahabpour, 2005; Ghasemi and Talbot, 2006; Ghazi *et al.*, 2004; Babaie *et al.*, 2001; Hassanipak and Ghazi, 2000) or suprasubduction affinities (Khalatbari-Jafari *et al.*, 2006; Bagheri and Stampfli, 2007). In Northern Iran a Neotethyan ophiolite

was recognized that is the Southern Caspian Sea ophiolite (SCO) (Salavati *et al.*, 2008; Salavati, 2008) (Fig. 1). The greater part of this ophiolite is volcanic rocks and minor plutonic rocks occur with the volcanic rocks (Fig. 2).
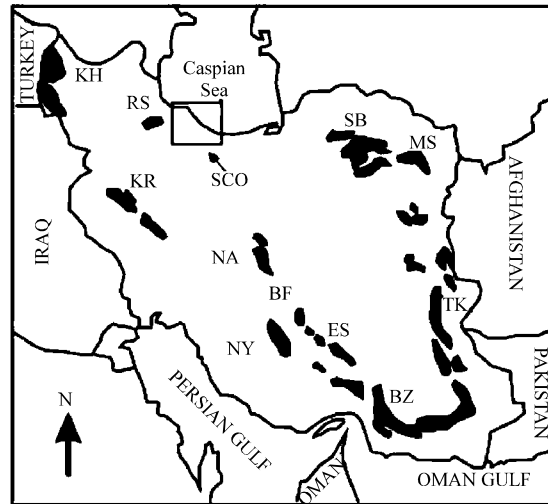

Fig. 1: Distribution of the ophiolite belts in Iran after Emami *et al.* (1993) and location of the SCO area. Main Iranian ophiolite complexes: BZ: Band-e-Ziyarat (also called Kahnuj complex). KR: Kermanshah, NA: Nain, NY: Neyriz, SB: Sabzevar, TK: Tchehel Kureh, RS: Rasht, MS: Mshhad, KH: Khoy, BF: Baft, ES: Esfandegheh (SCO: Southern Caspian Sea Ophiolite)
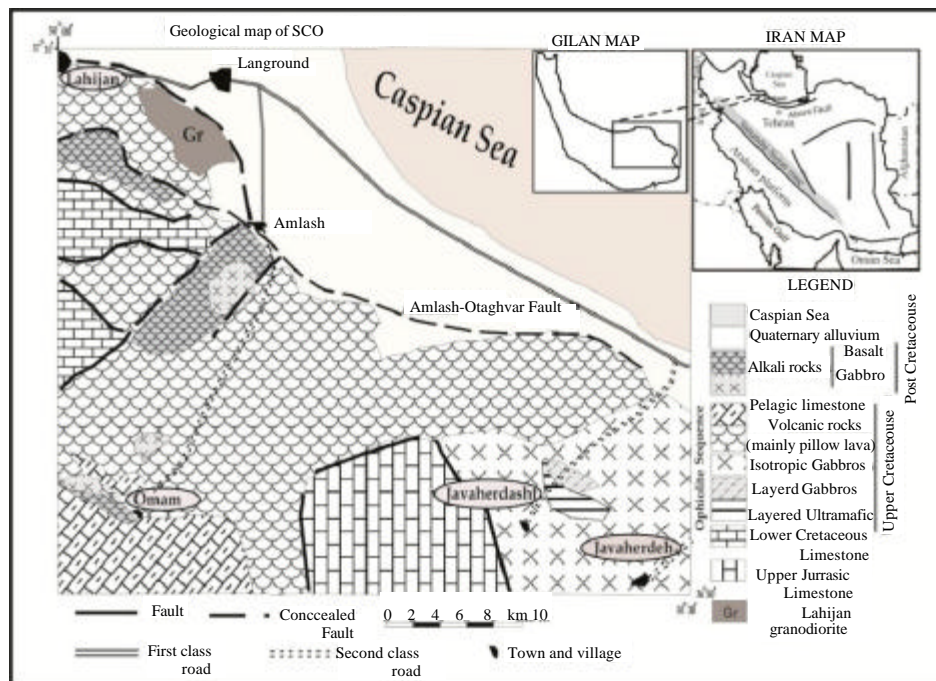

Fig. 2: The geological map of the Southern Caspian Sea ophiolite complex, showing the main geological unites of SCO

In the other study the some basaltic rocks of this region were studied (Salavati, 2008). In this contribution we examine the more mafic extrusive rocks from the Southern Caspian Sea Ophiolite and present a new geochemical dataset for the lavas. The data provide a robust tool for investigating the petrogenetic and geodynamic evaluation of the Southern Caspian Sea ophiolites, so in this paper we use some the previous data with new geochemical data for determination of (1) chemically characterize different basaltic rocks of this complex (2) the characteristics of the mantle source of the mafic magma(s) in terms of chemical composition; (3) suggest a possible tectonic environment(s) in which the oceanic lithosphere(s) were generated prior to emplacement.

METHODS AND ANALYTICAL TECHNIQUES

Seven samples of the best-preserved basaltic rock samples with no signs of alteration were chosen for geochemical analysis. External surfaces of rock samples were removed by splitting the samples into chips which were then ground to a powder in a tungsten carbide ring grinder. The rock samples were analysed for their whole-rock major oxide and their REE and other trace element concentrations. Rock powders were first fused to ensure dissolution of all phases and then dissolved in hot HF and HNO_3 to prepare the solutions from which trace element abundances were determined using Inductively Coupled Plasma Mass Spectrometry (ICP-MS) at the ALS Chemex Analytical Laboratories in Toronto, Canada. Also for comparison, five samples have given from (Salavati, 2008). Whole-rock major and trace element data for the samples are presented in Table 1 as two separate units, namely the alkaline and subalkaline suites.

RESULTS

Geological setting: The SCO ophiolite is one of the best preserved Iranian Neotethyan ophiolites which are located in the north part of the Iranian Guilan Province near the Southern coast of Caspian Sea. Field investigations show that, the SCO is almost a complete oceanic lithospheric section including, from bottom to top (east to west): layered ultramafic cumulates, layered gabbros, isotropic gabbros, sheeted dike complex and extrusive rocks that covered by Campanion-Maestirchtian limestone bearing fossils of Globotruncana (Salavati, 2000; Kanamian *et al.*, 2005).

The plutonic rocks of the Southern Caspian Sea ophiolite are well exposed in the east part of region and includes of layered ultramafic and gabbroic rocks. The

ultramafic rocks consist of small bodies of dunite, wherlite and clinopyroxenite. The gabbroic complex comprises different types of lithology (massive and layered gabbros). The complete sequence of sheeted dike complex is not found.

At the top of the SCO, the extrusive rocks are outcropped. Fine-grained volcanic rocks are the most widespread rock-type in the Southern Caspian Sea ophiolite. The extrusive sequence is entirely basaltic and mainly composed of pillow lava flows (more than 80%), massive flows (10-15%) and pillow breccias (about 5%). The pillow pieces have various sizes and have ranging from 10 cm to 15 m in diameter. At the top of pillow unit, pillows have a carbonate or hyaloclastic breccias matrix. Lenses of pelagic limestone contain microfaunas of Campanian-Maestrichtian age, interbedded with the lava flows. Generally speaking, these basalts show a very poor vesicularity, indicating deep oceanic conditions of extrusion. Interbedded sediments between the lava flows are scarce, very thin and always totally pelagic, suggesting again a deep oceanic environment and a rather permanent volcanic activity, preventing sediment deposition on the back of the flows. The massive lavas form some of the highest and most rugged topographic features in the area, whereas the pillow lava flows generally form rounded, semi-vegetated hills. In general, the lavas have been altered, in particular the pillow lavas but the relic igneous texture is well preserved.

Petrography: Almost 150 samples of the extrusive rocks from the SCO collected and have been studied. In thin section and based on the petrography the lavas can be divided into two groups.

One group of basalts crop out as black to reddish-brown pillows and massive flows and sometimes green to red in surface. In this group, the pillow lavas are generally aphyric or microporphyritic; the groundmass is intersertal to subophitic, consisting of plagioclase, clinopyroxene and titanomagnetite. The average modal abundances of the constituting mineral phases are estimated to be 65% plagioclase, 27% clinopyroxene, 6% titaniumrich magnetite and 2-3% olivine. Quartz-filled amygdales are observed in a few samples from the upper part of the sequence. Massive lavas are moderately porphyritic, with clinopyroxene and minor plagioclase phenocrysts settled in an intergranular groundmass with microlites of clinopyroxene and plagioclase. Fe-Ti oxides are present in both pillow and massive lavas. Olivine crystals can be identified in a few samples as relict pseudomorphs, partially replaced by chlorite and clay minerals. Oxide phases occur as granular crystals in intergranular spaces between the plagioclase and

Table 1: Representative major oxide and trace element data of basalts from the Southern Caspian Sea Ophioite (SCO)

Sample No.	Subalkaline rocks									Alkaline rocks		
	S83	S86	S12	S18	S21	S50	S79	SM23	SM24	SM25	SM21*	SM22*
SiO$_2$	46.8	48.7	46.1	48.4	46.5	47.7	49.1	46.5	46.5	48.7	48.1	48.9
TiO$_2$	0.9	1.0	0.86	0.95	1.10	1.02	0.8	3.4	3.13	3.16	3.4	3.4
Al$_2$O$_3$	11.4	14.0	10.7	13.4	15.4	12.4	12.9	13.7	13.35	14.70	15.2	15.1
Fe$_2$O$_3$	10.6	10.3	9.9	9.7	11.2	10.5	9.2	14.8	13.7	12.2	13	12.3
MnO	0.2	0.2	0.17	0.16	0.19	0.17	0.16	0.3	0.22	0.13	0.2	0.2
MgO	10.6	8.0	10.4	7.3	5.3	8.1	8.3	4.7	4.8	3.4	3.8	3.6
CaO	11.7	10.3	11.8	10.3	6.3	11.6	9.2	9.7	9.6	8.6	8.9	8.1
Na$_2$O	1.7	2.2	1.6	2	4.8	1.9	2.0	2.7	2.6	2.9	3.0	3.0
K$_2$O	1.4	1.4	1.1	1.5	1.4	1.3	1.9	1.2	1.2	1.6	1.5	1.7
P$_2$O$_5$	0.2	0.2	0.21	0.2	0.2	0.2	0.2	0.6	0.6	0.6	0.6	0.6
LOI	4.4	3.8	5.7	3.4	5.4	3.1	4.7	2.3	2.2	2.0	2.1	2.6
Total	99.9	100	98.4	97.6	98.1	98.3	98.4	99.8	98.0	98.2	99.6	99.5
Ba	361	280	226	274	353	250	348	348.0	333	456	485	460
Ce	34.1	36.6	29.8	35.9	41.7	33.7	44.1	64.8	62.1	65.9	68.0	69.0
Co	47.2	41.8	47.7	43.4	40.1	47.1	41.8	42.0	42.7	35.1	33.0	37.0
Cr	530	330	580	390	70	420	690	30.0	40	50	50.0	27.0
Cs	1.1	0.5	1.9	0.3	1.5	0.9	0.5	0.1	0.15	0.1	-	-
Cu	127	103	108	90	100	111	94	109	105	44	-	-
Dy	3.6	3.6	3.4	4.1	4.5	4.0	4.4	6.3	6.9	6.3	5.9	6.1
Er	1.9	2.1	1.8	2.3	2.4	2.1	2.3	3.1	3.2	2.9	2.8	2.9
Eu	1.4	1.3	1.33	1.5	1.8	1.5	1.5	2.8	2.9	2.9	2.8	2.8
Ga	15.3	17.2	13.5	16.8	18.0	14.8	16.6	25.7	23.4	22.9	-	-
Gd	4.3	4.3	4.28	4.8	5.5	4.7	5.3	7.8	8.6	8.3	7.7	7.9
Hf	2.1	2.6	1.8	2.5	2.6	2.4	2.8	5.6	5.3	5.4	-	-
Ho	0.7	0.7	0.62	0.79	0.8	0.74	0.8	1.1	1.2	1.1	-	-
La	15.4	17.2	13.9	17.1	19.5	15.3	21.6	30.5	30.1	31.6	33.5	36.0
Lu	0.2	0.3	0.2	0.3	0.3	0.3	0.3	0.3	0.3	0.3	-	-
Nb	5.1	6.8	4.5	7.1	8.5	6.6	7.6	42.3	41.4	45.3	46.0	47.0
Nd	19.6	19.8	18.2	20.4	24.4	20.2	23.8	34.6	34.1	36.8	38.5	40.0
Ni	130	111	130	104	25	98	182	48.0	46	22	21	24
Pb	5.0	6.0	<5	7	5	7	8	5.0	<5	5	-	-
Pr	4.4	4.6	4.1	4.8	5.7	4.7	5.8	8.0	8.0	8.5	-	-
Rb	36.3	35.4	32.3	36.3	35.2	40.2	41.9	22.4	23.9	26.7	18.0	32.0
Sm	4.6	4.4	4.2	4.81	5.4	4.6	5.5	7.8	8.2	8.2	8.3	8.5
Sr	335	425	373	398	506	410	351	553.0	536	662	700.0	690.0
Ta	0.3	0.4	0.3	0.4	0.5	0.4	0.5	2.5	2.6	2.7	-	-
Tb	0.7	0.7	0.6	0.7	0.8	0.6	0.7	1.2	1.2	1.1	-	-
Th	2.5	3.6	2.2	3.7	3.4	2.6	4.8	2.8	2.9	3.8	3.6	3.8
Tm	0.2	0.3	0.2	0.3	0.3	0.3	0.3	0.4	0.4	0.4	-	-
U	0.7	1.0	0.6	1	1.0	0.8	1.3	0.7	0.7	0.9	-	-
V	266	251	260	242	303	274	236	266.0	251	224	240.0	250.0
Y	17.2	19.0	15.6	19.6	20.4	18.1	20.7	28.2	27.6	25.8	28.0	30.0
Yb	1.5	1.8	1.52	2.02	2.11	1.84	2.1	2.2	2.4	2.2	2.2	2.3
Zn	82.0	91.0	81	103	117	97	93	154	160	150	-	-
Zr	65.0	82.0	59	87	88	75	99	183	187	194	200	200

The marked samples by * are from Salavati (2008)

pyroxene grains. Majority of the basalt samples have suffered various degrees of alteration which produced albite, Ca-zeolites, calcite and prehnite (replacing plagioclase); chlorite, epidote and actinolite (replacing clinopyroxene). These mineral assemblages represent zeolite to prehnite-pumpellytie facies metamorphism, typical of ocean floor metamorphism or plateau hydrothermal metamorphism before accretion (Bazargani-Guilani *et al.*, 2008).

Basalts of the other group are the second most common rock types within the lava suites. Petrographically, these basalts are predominantly phyric, with phenocrysts forming 18 to 40 vol. % of the rock. The major phenocryst phases are plagioclase and clinopyroxene with some rocks also containing olivine microphenocrysts. Clinopyroxene (24-30 vol. % of the rock) is also abundant both as a phenocryst and as a groundmass phase, the clinopyroxenes are titanaugite and have a clear high Ti rim, the olivine microphenocrysts make up 5-25 vol. % of the rock, Plagioclase makes up about 15 to 45 vol. % of the rock, occurring mostly as groundmass material (0.1 to 0.4 mm long microlaths) and rarely as microphenocrysts or phenocrysts (0.6 to 1 mm long) (Salavati, 2008). The Fe-Ti oxides and apatite are the abundant phase in groundmass.

Major-element geochemistry: Analyses of volcanic rocks from the SCO ophiolite reveal the presence of two

chemically distinct rock types (Table 1). The rocks as a whole can be classified as basalt with their silica concentrations ranging from 46.1 to 49.1 SiO_2 wt. %. Similar to petrograpgy the analyses of volcanic rocks from the Southern Caspian Sea ophiolite reveal the presence of two chemically distinct types of basalts, alkaline and subalkaline basalts (Table 1). The major difference between the two groups of basalts is the CaO/MgO ratios which are higher for the alkali basalts (1.9-2.5) than for the subalkaline type basalts (1.1-1.4). The basalts of the alkali group are distinguished by high TiO_2 (3.1-3.4 wt. %) and P_2O_5 (0.50-0.60 wt. %) which most likely reflects the presence of titanoaugite, Fe-Ti oxides and apatite crystals, as well as low Mg# (21.8-26.1 wt. %), whereas the subalkaline type relatively have lower TiO_2 (0.8-1.1 wt. %) and P_2O_5 (0.20-0.25 wt. %) and higher Mg# (32.1-50.0 wt. %).

Both types of basalts have suffered extensive alteration, largely due to ocean-floor hydrothermal activity which is responsible for the loss and gain of some or most of the major elements (Irvine and Barager, 1971). Although

an attempt has been made to minimize the effect of alteration by screening the samples for primary volcanic features, such as pillow structures and for absence of secondary mineralization, relatively high loss-on-ignition values (2.0-4.5 wt. %) for most of the basaltic rocks imply a possible sea-floor alteration. Thus, selected minor and trace elements (e.g., Ti, Zr, Y and Nb) that are believed to be relatively immobile under conditions of alteration and low-grade hydrothermal metamorphism are used to characterize such basalts in respect to original composition and possible tectonic environment of formation (Saccani and Photiades, 2004; Parlak *et al.*, 2004; Farahat *et al.*, 2004; Krienitz *et al.*, 2006; Dawoud *et al.*, 2006; Manikyamba *et al.*, 2004; Kadarusman *et al.*, 2004; Yibas *et al.*, 2003) and we consider it unlikely that the measured mobile element abundances are pristine and we based our modelling and interpretation largely on immobile HFSE, REE and Th.

The Nb/Y-Zr/Ti discrimination diagram (Winchester and Floyed, 1977) confirms the presence of two different types of extrusive rocks (Fig. 3a). Also in a
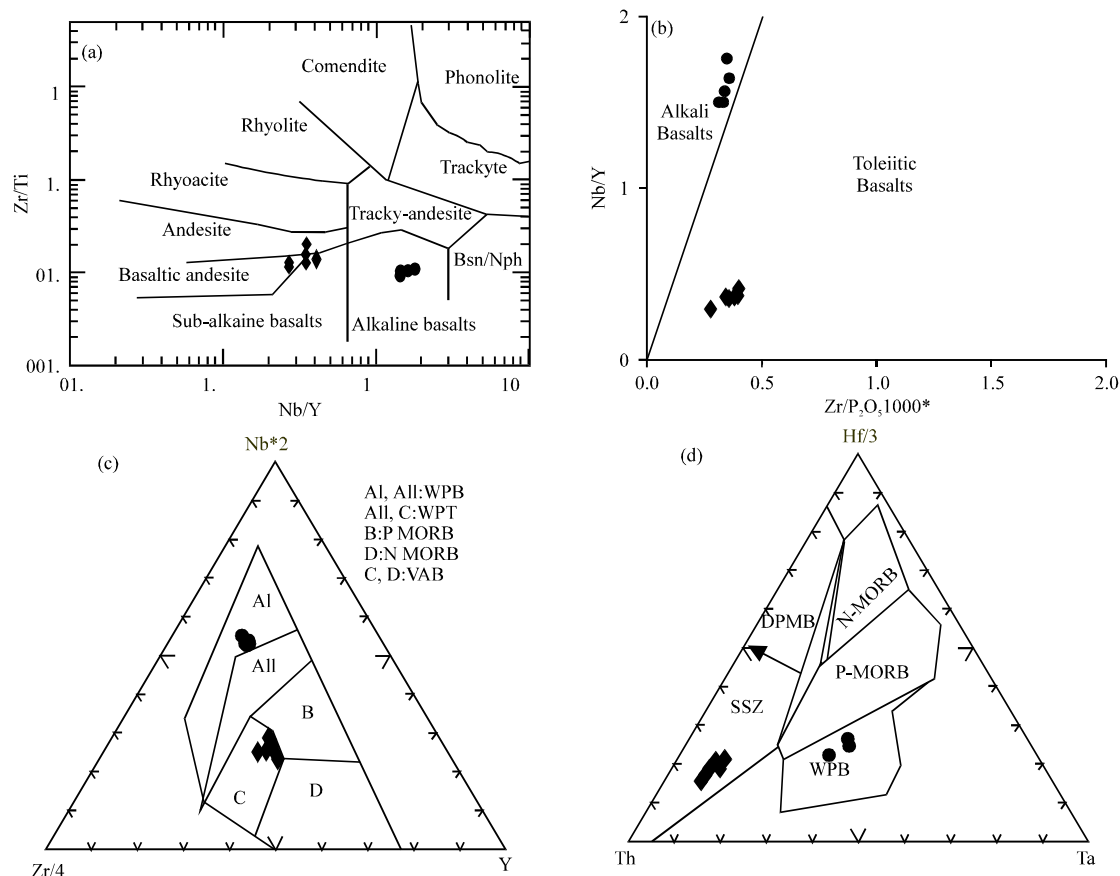

Fig. 3(a-d): (a) Geochemical classification of SCO basalts using Zr/Ti vs. Nb/Y diagram (Winchester and Floyed, 1977), (b) bivariant trace element diagram (Winchester and Floyd, 1976), (c) and (d) showing two chemically distinct groups of basalt from the SCO ophiolite in Nb-Zr-Y diagram (Meshede, 1986) and in the Th-Hf/3-Ta diagram developed by Wood (1980)
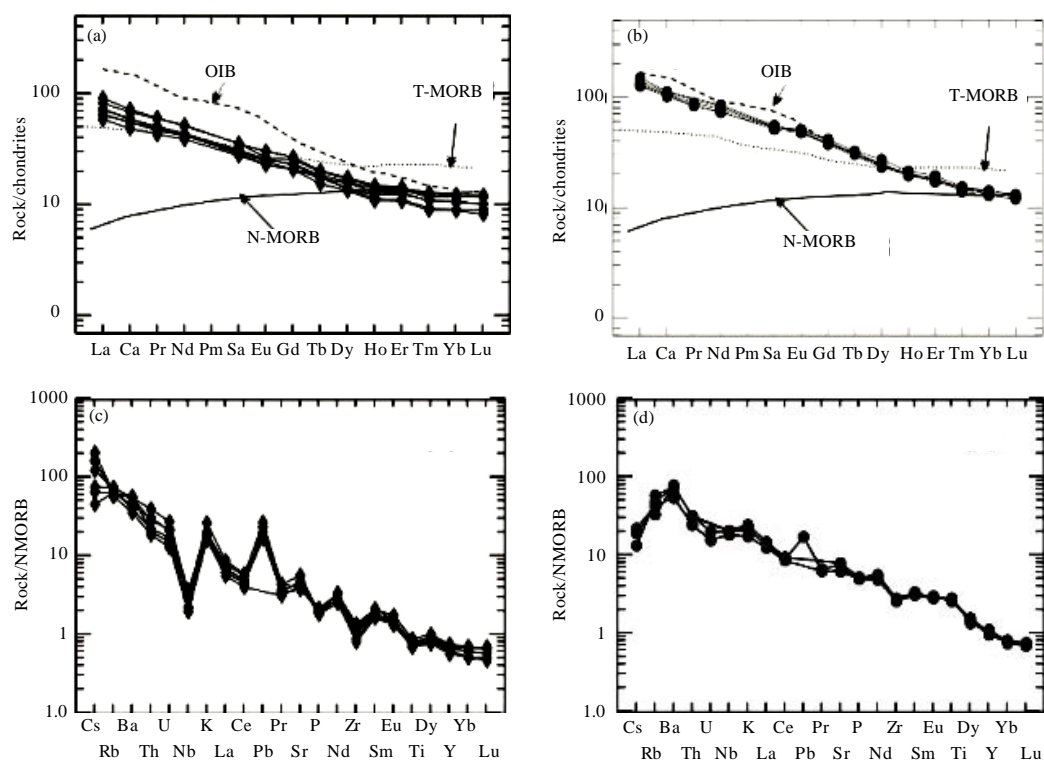
Fig. 4(a-d): (a-b): Chondrite-normalized REE patterns for basalts, normalization values, (c) and (d) incompatible element patterns of basalts normalized to NMORB. The field of T-MORB from Khalatbari-Jafari *et al.* (2006) and the fields of OIB and N-MORB and Normalizing values of chonderite and N-MORB are from Sun and McDonogh (1989)

diagram of Nb/Y ratios versus Zr/P_2O_5, the two types of basalts are clearly distinguishable as two clusters (Fig. 3b). One group of extrusive rocks show alkali basalts chemical affinities and the other extrusive rocks plot largely at the transition between andesite, andesitic-basalt and subalkaline basalt fields (Fig. 3c). In a Zr-Nb-Y discrimination diagram (Meshede, 1986), the extrusive rocks plot in two different fields. The first group clearly plot as within-plate basalts and the second group show volcanic arc chemical affinities (Fig. 3d). In a ternary element plot of Th-Hf-Ta (Wood, 1980), the samples classify as within-plate and the other samples having relative enrichment in Th present in subduction-related basalts and hence plotting in the field of volcanic arc basalts (Fig. 3c).

REE-normalized incompatible element patterns for basalts from the SCO ophiolite clearly show two different groups. Chondrite-normalized Rare Earth Element (REE) patterns for basalts are shown in Fig. 4a and b. In general, the two types of basalts are characterized by Light Rare

Earth Element (LREE) enrichment. For comparison, the patterns of T-MORB, N-MORB and Ocean Island Basalt (OIB) (Sun and McDonogh, 1989), are plotted along with the data for each of these sets in Fig. 4a and b. The alkaline samples mostly fall near of the average ocean island basalt in these patterns and subalkaline type basalts fall near of the T-MORB pattern. However, they have different REE patterns, the alkaline basalts are more LREE enriched [(La_N/Yb_N)ave = 10.27] than the subalkaline basalts [(La_N/Yb_N)ave = 6.7]. Furthermore, the patterns for samples within each suite are largely parallel to one another and form narrow envelopes, suggesting that the basalts within each group are cogenetic. Both the subalkaline basalts and OIB basalts patterns show LIL elements enrichment relative to HFS elements and in both type basalts REE profiles are linear and homogeneous with a moderate positive slope from HREE to LREE and overall, the REE patterns are subparallel. This feature in subalkaline rocks may be related to the transfer of elements from the subducted plate to the overlying mantle

stage also in the alkaline rocks; enrichment in the LREE is a characteristic feature of OIB-type alkali basalts (Sun and McDonogh, 1989; Abdel-Rahman and Nassar, 2004; Maheo *et al.*, 2005).

MORB-normalized incompatible element patterns for basalts from the SCO ophiolite are illustrated in Fig. 4c and d. Furthermore, the patterns for these basalts form two narrow but recognizably different envelopes that show significant differences. Major differences include: (i) sizeable troughs at Nb, Ti and Zr for subalkaline basalts and (ii) relative depletion in Rb and Zr and spike at Ti for the alkaline basalts. These differences between the two sets of patterns further confirm that these basalts are petrogenetically unrelated and were most likely derived from melts formed in different tectonic settings. The subalkaline basalts have Nb, Zr and Ti negative anomalies. The elevated concentrations of LILE relative to

HFSE in subduction zone magmas originate from fluid and/or siliceous melts derived from the subducting oceanic slab. These slab-derived fluids carry high concentrations of LILE while the HFSE, most notably Ta and Nb, are retained in the slab (Pearce, 1982). The negative Nb (Ta) and positive Th anomalies obtained from the SCO rocks clearly indicate a suprasubduction tectonic environment. The alkaline rocks have all the classic enrichments in LILE, HFSE and LMREE and slight depletion in HREE that characterize basalts from intra-plate oceanic settings (Fig. 4d).

For determination of tectonic environments of basalts from the SCO, the studied rocks are plotted in different tectonic diagrams (Fig. 5). In all diagrams subalkaline basalts are plotted in arc environment (SSZ type basalts) and alkaline basalts show plum signature and fall in oceanic island basalts (OIB type basalts) (Fig. 5).
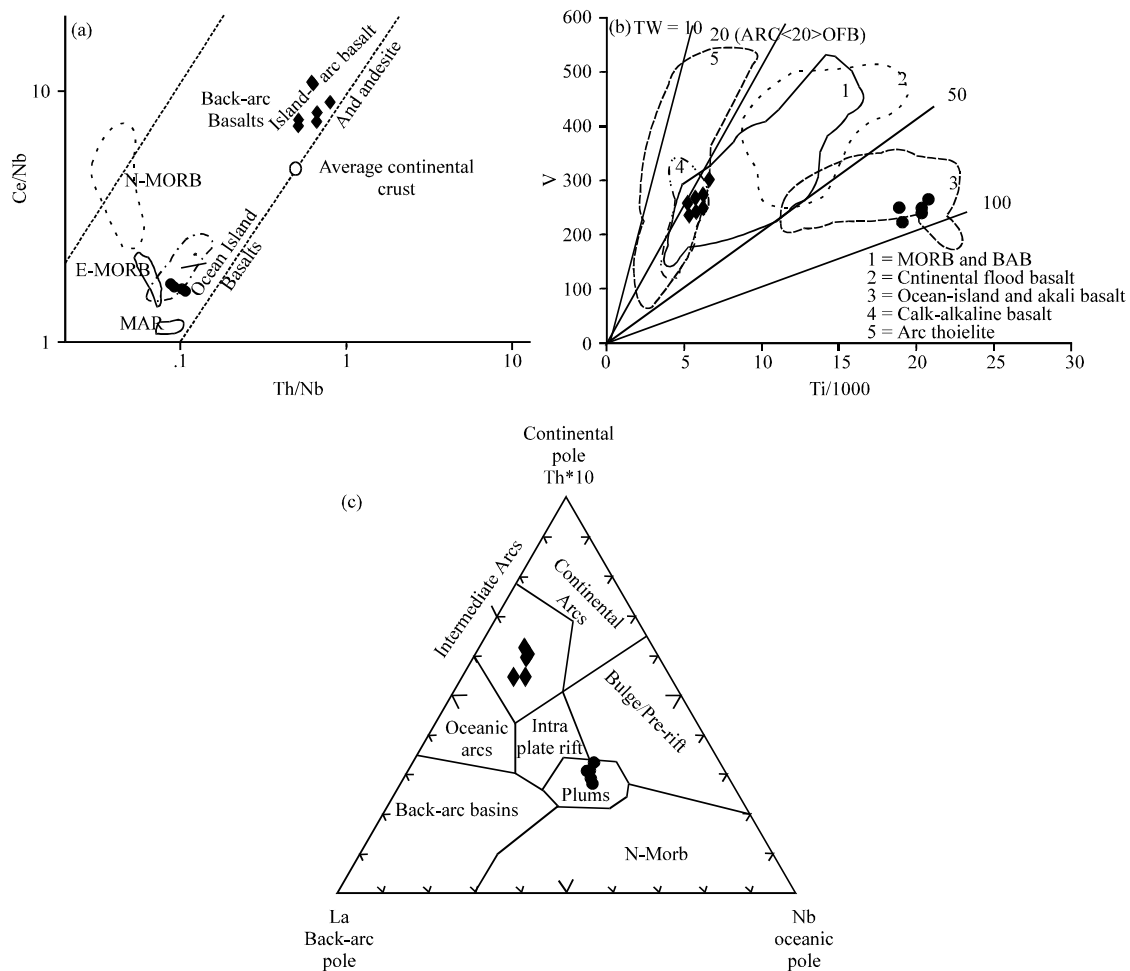

Fig. 5(a-c): Different tectonic discrimination diagrams of basalt from the SCO in binary diagram of (a) Ce/Nb vs. Th/Nb diagram (Saunders and Tarney, 1984); (b): V vs. Ti (Floyd *et al.*, 1991) and (c) Ternary plot of La-Th-Nb (Monnier, 1996) used to discriminate further between different arc basalts and plum rocks
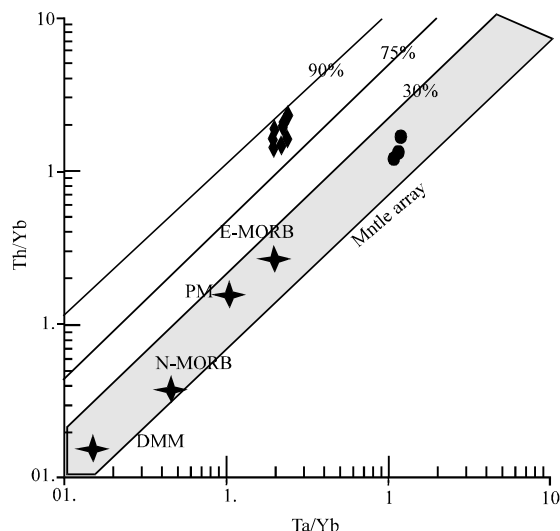
Fig. 6: Plot of Th/Yb vs. Ta/Yb for the alkaline and subalkaline basaltic lavas from the SCO ophiolite also for comparison, some typical oceanic basaltic and mantle compositions including the depleted MORB mantle, primitive mantle (PM), N-MORB and E-MORB are plotted. Partial melting trends predicted using the depleted MORB mantle and PM compositions as the source are shown as solid lines with the calculated degrees of melting on each curve (shown as thick marks). Contours parallel to the mantle array denote the percentage of subduction-derived element Th in the mantle source, assuming that Ta is subduction-immobile (Pearce, 2005)

Thus, from the evidence of the normalized incompatible trace element diagram (Fig. 4) and the discrimination plots (Fig. 3), it appears that the subalkaline basalts were derived from melts generated in an island arc environment or in a SSZ environment, similar to some of the transitional island-arc tholeiitic basalt reported for the Neyriz ophiolite (Sarkarinejad, 1994), subalkaline basalt from the Kermanshah ophiolite and basaltic rocks from the Khoy and Band-e-Zeyarat/Dar Anar ophiolites (Khalatbari-Jafari *et al.*, 2006; Khalatbari-Jafari *et al.*, 2004; Khalatbari-Jafari *et al.*, 2003; Ghazi *et al.*, 2003; Ghazi *et al.*, 2004).

On a Th/Yb v. Ta/Yb ratio-ratio plot (Fig. 6), designed to discriminate between depleted mantle (MORB) and enriched mantle (intraplate) sources for subduction related magmatic rocks (Pearce, 1982), data from the subalkaline basalts of the SCO exhibit clear displacements from the MORB-OIB array to higher subduction mobile element Th. It is known that Ta/Yb ratios are not affected or little affected, by additions of components during plate subduction, whereas an increase in Th/Yb, due to the introduction of additional Th into the source, reflects additions of slab-derived components (Pearce and Peate, 1995). These components are widely thought to be crust-derived aqueous fluids and sediment-derived siliceous fluid, that is, supercritical fluid or melt (Pearce and Peate, 1995; Hawkesworth *et al.*, 1997). In this diagram Contours parallel to the mantle array denote the percentage of subduction-derived element Th in the mantle source, assuming that Ta is subduction-immobile (Pearce, 2005). The subalkaline type basalts of the SCO are ploted between 75 to 90% of subduction-derived elements Th in the mantle source. The addition of a subduction component to a constant mantle source would be expected to give a vertical trend on the diagram, as only Th is added while Ta and Yb remain nearly constant. The OIB-type alkaline rocks are characterized by strong enrichments in highly incompatible elements relative to less incompatible elements. They plot on the MORB-OIB mantle trend on a Th/Yb v. Ta/Yb diagram, indicating that their mantle source had no subduction influence and the resulting magmas were not affected by any significant contamination of lithospheric material 9 (Aldanmaz *et al.*, 2008).

DISCUSSION

In terms of the tectonics of the Neo-Tethyan oceanic lithosphere and the Mesozoic-Cenozoic geologic evolution of the eastern Mediterranean region, the SCO complex represents a dismembered ophiolite. In the southern Caspian Sea ophiolite the alkaline basalts relationship with dominant subalkaline rocks varies. The age relationship between the subalkaline and alkaline basalts is equivocal and field studies indicating that the alkaline rocks are younger than the subalkalines. The subalkaline basalts show a Back-arc basin environment and are SSZ type basalts whereas the alkaline basalts show oceanic island basalts in the Southern Caspian Sea Ophiolite. A distinctive geochemical feature of many back-arc magmas is the depletion in HFSE, enrichment in LILE and common enrichment in LREE relative to N-MORB compositions. Since both HFSE and LILE behave incompatibly during partial melting of mantle rocks, this characteristic is difficult to reconcile with a single-stage melting and melt extraction from a source with geochemical characteristics similar to that of the ambient MORB mantle. Thus, it is commonly suggested that more than a one-stage melting process is required to explain geochemical characteristics of back-arc basin and OIB basalts of the SCO 9 (Pearce, 2005). The commonly

used model predictions suggest that the initial stage of melt extraction depletes the source in all incompatible trace elements (e.g., LILE and HFSE), leaving a depleted and refractory mantle residue. A subsequent melting occurs after or during, a hydrous LILE (and LREE)-enriched but HFSE depleted component, most probably a subduction component, is added to the source mantle. The association of alkaline rocks lacking the subduction signature with these subalkaline suggests a variety of potential sources in a back arc environment. Thus, from the evidence of the normalized incompatible trace element diagram and the discrimination plots, it appears that the alkaline rocks of the SCO have WPB signatures and display OIB affinities. In some ophiolite, was proposed the presence of deep mantle plumes to account for the enriched chemical nature of the rocks observed at the surface, such mantle plumes are unlikely to exist in a subduction setting (Thompson *et al.*, 1997). Some theories (Thompson *et al.*, 1997) on the mechanisms of subduction suggest that slab sink rather than pushes through the mantle and migrates oceanward through the rollback effect. The effect is to create a flow of undepleted mantle material into the expanded supra-subduction wedge. If these magmas erupt close to or at the spreading centre, tholeiitic and alkalic rocks will spatially overlap (e.g., the North Philippine Sea and the Northland ophiolite; (Thompson *et al.*, 1997). Alkaline rocks erupting off axis will be slightly younger than the tholeiilic rocks (e.g., the Salahi lavas in the Oman ophiolite and the crust of the Japan Sea). Based on this theory we thus suggest that the alkali rocks of the SCO were generated from a plume in a local extension regime.

CONCLUSION

Rocks corresponding to an ophiolitic sequence are presented at the SCO, including layerd ultramafic (including clinopyroxenite and dunite), layered gabbros, isotropic gabbros, diabase and basalts. The petrographical and geochemical characteristics of basaltic lavas from the Southern Caspian Sea ophiolite allow them to be divided into two broad subdivisions (1) the subalkaline (SSZ)-type basalts originated from mantle sources that are characterized by selective enrichments in fluid-soluble Large Ion Lithophile Elements (LILE) and LREE relative to the High Field Strength Elements (HFSE); (2) the OIB type alkaline basaltic rocks that are characterized by significant enrichment in LILE, HFSE and LMREE and a slight depletion in HREE, relative to MORB compositions.

The limestones are intercalated with basalt and contain Upper Cretaceous fossils (Campanian-Maestrichtian), suggesting Late Cretaceous ages for the subalkaline basalt during the final phase formation of

oceanic crust. The alkaline rocks occur together but are generally younger than the subalkaline basalts and crosscutting that.

The geochemical characteristics and temporal distributions of the eruptive products suggest two distinct stages of melt production and indicate their generation from two different magmatic sources: the first of these stages is characterized by a source that produced the LREE-enriched subalkaline basalts from a magma that was generated in a suprasubduction type environment while the second stage is marked by a source that produced the alkaline eruptive rocks from a basaltic melt and was generated in a within-plate environment (e.g., intraplate-oceanic island).

The existence of SSZ-type tholeiites with geochemical signatures indicative of pre-melting subduction influence provides evidence for the development of arc-like crust by melting of a mantle source above a subduction zone. This first-stage melt generation is likely to be explained by development of an arc-back-arc system. The modelling indicates that OIB compositions in the second stage are intimately linked in the melting process and a compositionally distinct mantle sources play a role in producing these subduction unmodified basaltic lavas. Among the subduction unmodified basaltic lavas the most enriched (OIB) compositions can be interpreted to represent melting of the enriched components.

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