

GEOCHEMISTRY OF SHEETED DIKES IN THE NAIN OPHIOLITE (CENTRAL IRAN)

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ABSTRACT

The Nain ophiolite is a highly dismembered ophiolite complex cropping out at the north of the Nain town to the west of central Iran. The igneous rocks of this complex consist of both mantle and crustal suites and include serpentinized peridotites, peridotites, harzburgites associated with dunite and lherzolite, pegmatitic and isotropic gabbros, plagiogranites, sheeted dikes and pillow lavas. Several pyroxenite, wehrlite and rodingite dikes are present in the ultrabasic rocks. The sheeted dikes include subalkaline basalts, basaltic andesites and andesites. Their magma was of sub-alkaline (low potassium tholeiite) type and they are chemically similar to island arc tholeiitic basalts. The N-MORB-normalized incompatible elements for the sheeted dike samples indicate depletion in most of the high field strength elements (HFSE). The concentrations of the large ion lithophile elements (LILE) in these rocks are all greater than those in the N-MORB. Significant chemical characteristics of these rocks are the positive anomaly for Th and negative anomaly of Nb that are considered to represent a subduction zone component. The chondrite-normalized rare earth element (REE) patterns of these rocks show HREE enrichment and LREE depletion [$(La_N/Sm_N)_{ave} = 0.63$]. Their geochemistry also shows that the primary melt derived from high degrees of partial melting of a mantle source previously depleted with respect to the source of mid-ocean ridge basalts, and were subsequently enriched by aqueous fluids driven off subducted oceanic lithosphere in an arc-basin setting. We conclude that the Nain ophiolite is a supra-subduction zone type ophiolite.

INTRODUCTION

Sheeted dike complexes are present both in continental and oceanic crust. This magmatism is the consequence of partial melting in the upper mantle during lithospheric extension. The extensional processes may be either related to continental and oceanic rifting or they are associated with minor volcanic systems (Borgia and Treves, 1992; Ahijado et al., 2001). Sheeted dike complexes also comprise a volumetrically significant portion of ophiolite complexes and are thought to form a comparable fraction of the ocean crust as well (e.g., Baragar et al., 1990; Alt, 1996; Francheteau et al., 1992). Sheeted dikes at mid-ocean ridge volcanoes represent the link between deep magma production and storage processes, and shallow processes such as volcanism and hydrothermal activity. As such, they are crucial for the interpretation of many data on mid-ocean ridges and other volcanoes with pronounced rift zones, including their topography, hydrothermal systems, petrology, and geochemistry (Staudigel et al., 1999). The processes of dike emplacement are critical to understand many aspects of crustal accretion at mid-ocean ridges. For example, dike injection at fast and intermediate spreading ridges may control the distribution and longevity of hydrothermal systems either through direct introduction of heat into the extrusive layer or through enhanced permeability allowing access to deeper heat sources (Pollard, 1987; Wilcock and Delaney, 1996; Cherkaoui et al., 1997; Curewitz and Karson, 1998; Schiffman et al., 1990). Dike propagation behaviour provides an indirect means of examining the state of stress at mid-ocean ridges (Pollard, 1987) and, indeed, may also play an important role in modifying the stress field (Rubin and Pollard, 1987). Finally, dikes serve as conduits for delivery of magma for the entire extrusive layer (Staudigel et al., 1999). The goal of this paper is to use geochemical data including REE and incompatible trace element data to (i) chemically characterize the sheeted dike unit of the Nain ophiolite, (ii) shed light on

the petrogenetic processes and, (iii) suggest a possible tectonic environment of formation for this ophiolite.

GEOLOGICAL SETTING

A number of ophiolitic complexes were mapped and described in Iran. Iranian ophiolites are part of the Tethyan ophiolite belt of the Middle East; they are important because of their unique geographic location that links the Middle Eastern and Mediterranean Hellenides-Dinarides ophiolites (e.g. Turkish, Troodos, Greek and East European) to more easterly Asian ophiolites (Hassanipak and Ghazi, 1999). The locations of the major Iranian ophiolites are depicted in Fig. 1. Based on their age and abundance, the Iranian ophiolites form two distinct groups: the less abundant ones are of Paleozoic age (Weber-Diefenbach et al., 1986) (ophiolites of northern Iran along the Alborz Range), the more abundant ones are the Mesozoic ophiolites (Alavi, 1991; Arvin and Robinson, 1994). The Mesozoic ophiolites have been divided into three sub-belts (Takin, 1972; Stocklin, 1974; 1977; McCall, 1997): (i) ophiolites of the Zagros Suture Zone, including the Neyriz and Kermanshah ophiolites, which appear to be coeval with the Oman (Samail) ophiolite emplaced onto the Arabian continental margin, (ii) unfragmented ophiolites of the Makran accretionary prism which includes Band-e-Zeyarat, Dar Anar and Mokhtar Abad (southeast Iran), and (iii) ophiolites and "Coloured Mélanges" that mark the boundaries of the Central Iranian microcontinent (CIM), including Shahr-e-Babak, Nain, Baft, Sabzevar and Tchehel Kureh ophiolites (Fig. 1). Most geochemical studies on the Iranian ophiolites show the occurrence of both mid-ocean ridge basalt (MORB) and island arc tholeiite (IAT) affinities (Davoudzadeh, 1972; Alavi-Tehrani, 1977; McCall and Kidd, 1981; Desmons and Beccaluva, 1983; Arvin and Robinson, 1994; Hassanipak et al., 1996; Wampler et al., 1996; Ghazi et al., 1997; Ghazi and Hassanipak, 1999a; Shojaat et al., 2003).

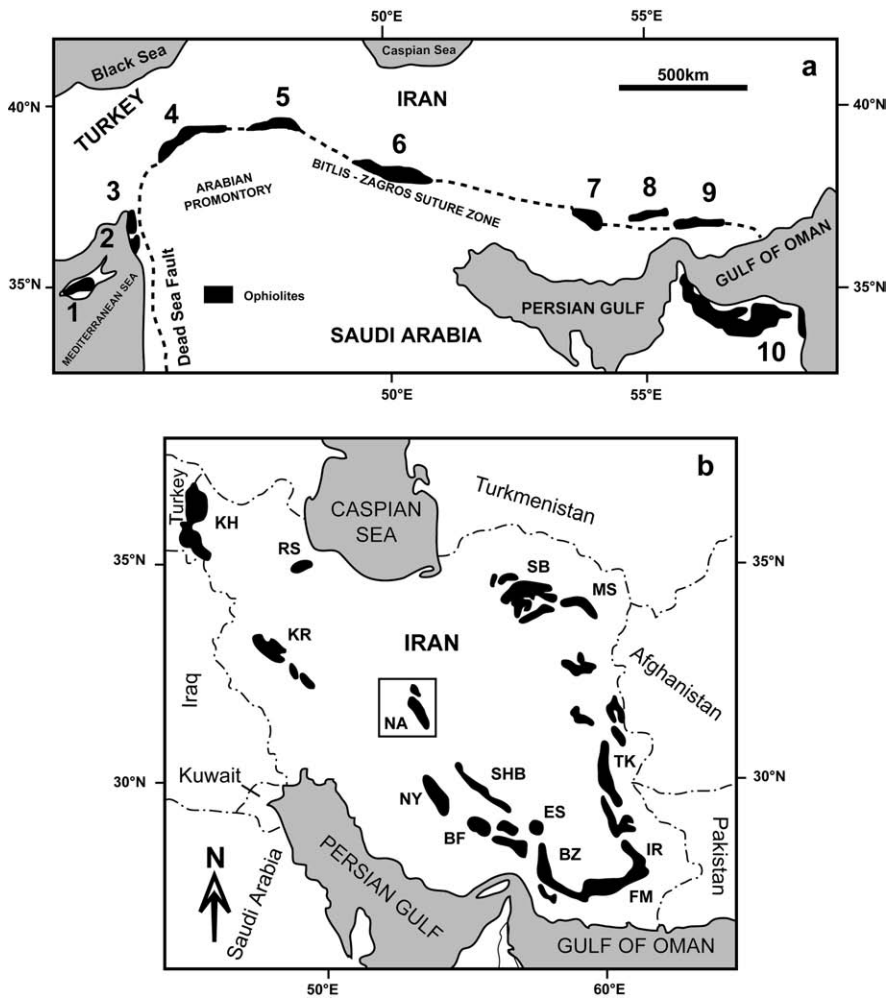


Fig 1 - (a) Distribution of Cretaceous Neo-Tethyan ophiolites around the Arabian promontory along the Bitlis-Zagros Suture Zone (Dilek and Delaloy, 1992). 1- Troodos (Cyprus); 2- Baer-Bassit (Syria); 3- Kızıldağ (Turkey); 4- Guleman (Turkey); 5- Cilo (Turkey); 6- Kermanshah (Iran); 7- Neyriz (Iran); 8- Esphandagheh (Iran); 9- Band-e-zeyarat (Iran); 10- Samail (Oman). (b) Distribution of the ophiolite belts in Iran after Emamie et al. (1993): KH- Khoy; KR- Kermanshah; NY- Neyriz; BZ- Band-e-zeyarat; NA- Nain; BF- Baft; SHB- Shahr-e-Babak; ES- Esphandagheh; FM- Fanuj; IR- Iranshahr; MS- Mashhad; SB- Sabzevar; TK- Tchehel Kureh; RS- Rasht.

The Nain ophiolite mélangé, approximately 480 km² in area, is part of the ophiolite belt around CIM that is located at the north of the Nain town, along the Nain-Baft fault zone. This fault zone crops out on the western side of the central Iranian microcontinent, which contains several other relatively dismembered fragments of Neo-Tethyan ophiolitic massifs (Shojaat et al., 2003). Other major complexes of this zone include the Shahr-e-Babak ophiolite to the east (Ghazi and Hassanipak, 1999b), and the Baft ophiolite to the southeast (Arvin and Robinson, 1994). Most studies on the central Iranian ophiolites (Nain-Baft) suggest that they originated in a narrow basin which separated the central Iranian microcontinent from Eurasia (Stocklin, 1974; Berberian and King, 1981; Knipper et al., 1986; Arvin and Robinson, 1994; Arvin and Shokri, 1997; Shojaat et al., 2003). According to Davoudzadeh (1972) the area north of Nain has been divided into three geological units: (I) a "Coloured Mélangé" zone with north-northwest trend through the middle of the area, (II) a Tertiary volcanic zone associated with small Tertiary dioritic intrusions in the west, and (III) a Tertiary sedimentary zone in the east (Fig. 2). Although the ophiolite stratigraphy in the Coloured Mélangé zone is largely dismembered, it contains all the rocks that are representative of an ophiolite suite. The ophiolite is chiefly composed of ultrabasic rocks consisting of dunite, harzburgite, lherzolite, chromite-bearing serpentinite and pyroxenite. All members of the peridotite-pyroxenite group are partly serpentinitized. Harzburgites and serpentinites predominate. Pegmatitic and isotropic gabbros, plagiogranites,

sheeted dikes and pillow lavas subordinately occur. Several dikes of pyroxenite, wherlites and rodingite are present in the ultrabasic rocks (Davoudzadeh, 1972; Rahgoshay and Shafaii, 2004a). Many metamorphic rocks and metamorphosed ophiolitic rocks are distinguished in this zone (Rahgoshay and Shafaii, 2004b). Reddish *Globotruncana* limestones of Campanian-Mastrichtian age, containing thin chert layers, are the oldest sedimentary rocks in this zone. The youngest sedimentary rocks are *Nummulites-Alveolina* limestones and sandy limestones of Lower Eocene age. The ophiolitic sequence falls into the Paleocene to Early Eocene interval (Davoudzadeh, 1972). In the northern part of the Coloured Mélangé is the Kuh-e-Zard zone mostly composed of Upper Cretaceous limestone and Paleocene to Lower Eocene sequences (Fig. 2).

The best exposure of the sheeted dike complex, which is about 5 km², is located northeast of the Separab village (Fig. 2). The thickness of the exposure ranges between 10 cm to 3 m. These dikes cut high-level amphibole gabbros and penetrate upward into plagiogranites; the dikes are in turn included by rhyolitic veins and covered by pillow lavas. Because of tectonic processes (faults), sheeted dikes are not observed clearly inside pillow lavas.

ANALYTICAL METHODS

A total of 8 representative samples from sheeted dikes and 1 sample from the high-level gabbro unit (for compari-

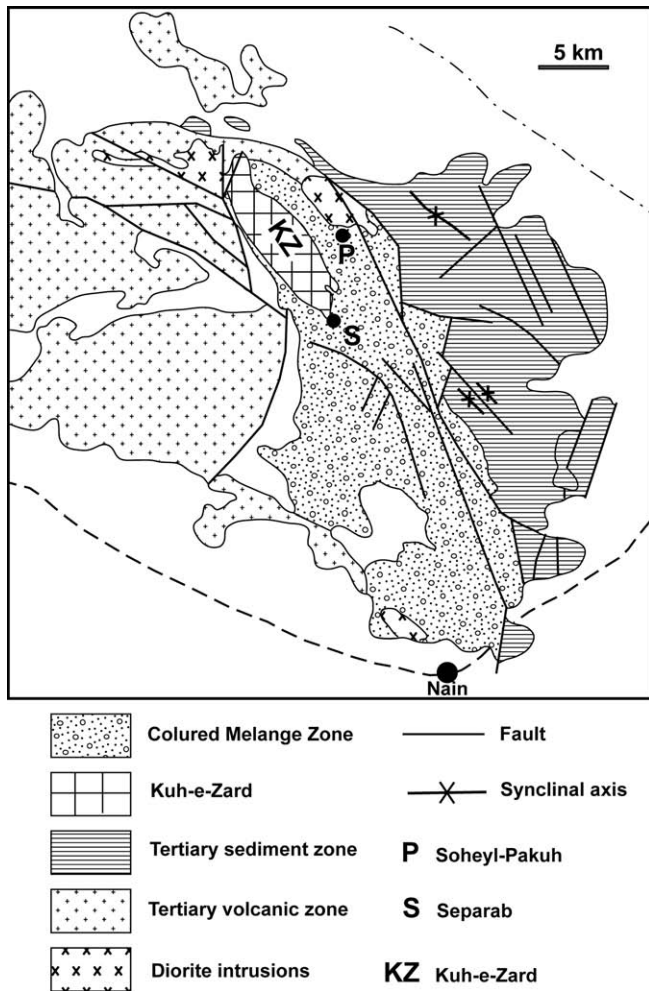


Fig. 2 - Tectonic sketch map of the area north of Nain (after Davoudzadeh, 1972).

son) were analysed for major and trace elements at Acme Labs in Canada. All samples were dried at 60°C and were jaw crushed to 70% passing 10 mesh (2 mm), a 250 g aliquot pulverized to 95% passing 150 mesh (100 μm) in a mild-steel ring-and-puck mill. A 0.2 g samples aliquot was weighed into a graphite crucible and mixed with 1.5 g of Li-BO₂ flux. Crucibles were placed in an oven and heated for 15 minutes at 1050°C. The molten sample was dissolved in 100 mL of 5% HNO₃ (ACS grade nitric acid diluted in demineralised water). The solution was shaken for 2 hours then an aliquot was poured into a polypropylene test tube. Cali-

bration standards, verification standards and reagent blanks were added to the sample sequence. Sample solutions were aspirated into an ICP emission spectrograph (Jarrel Ash AtomComp Model 975) for determination of major oxides elements. For the determination of trace elements, sample solutions were aspirated into an ICP mass spectrometer (Perkin-Elmer Elan 6000). Loss on ignition (LOI) was determined by igniting a 1 g sample split at 950°C for 90 minutes then measuring the weight loss. Standard reference materials (SO-17 and CSB) and blanks were prepared using similar techniques. Standard SO-17 was certified in-house against 38 certified reference materials including CANMET SY-4 and USGS AGV-1, G-2, GSP-2 and W-2.

Several standard representative thin sections were used for chemical analyses of plagioclase, clinopyroxene, opaque, amphibole and chromian spinel minerals. The analyses were performed by Energy Dispersive Spectrometry (EDS) at the University of Dallas. The analyses were obtained with a Cameca SX-50 field-emission scanning electron microscope (FESEM) with super ultra-thin windows (SUTW) detector. The analyses were done at an accelerating voltage of 25 kV. The FESEM images were obtained with an accelerating voltage of 25 kV.

PETROGRAPHY AND MINERAL CHEMISTRY

The petrographic studies show that the sheeted dikes of the Nain ophiolite are composed of basalt (dolerite), quartz dolerite, andesite, and dacite. They are fine-grained rocks and exhibit intergranular, intersertal, glomeroporphyritic and porphyritic textures. Dolerites are formed by plagioclase + clinopyroxene + opaque. Sphe- nene, apatite and chromian spinel are accessory minerals in these rocks. Quartz dolerites have primary amphibole and quartz. Clinopyroxene is a minor phase in andesites, whereas dacites lack clinopyroxene. Plagioclase forms lath-shaped, groundmass microlite, and phenocryst crystals, generally unzoned. Both simple and multiple twins are common. Plagioclase compositions vary from labradorite (An_{59.7}Ab_{35.52}Or_{4.79}) in dolerites, to oligoclase (An_{12.85}Ab_{74.97}Or_{12.18}) in dacites (Fig. 3a). Representative clinopyroxene, amphibole and chromian spinel compositions from the Nain ophiolite sheeted dikes are given in Table 1. The clinopyroxenes mostly occur as euhedral to subhedral phenocrysts alone or as clusters of closely packed crystals (glomeroporphyritic), generally smaller than 0.5 mm on their longest axes. In the Wo-En-Fs diagram (Deer et al., 1978), the clinopyroxenes display augite compositions (Fig. 3b) and are in the range of

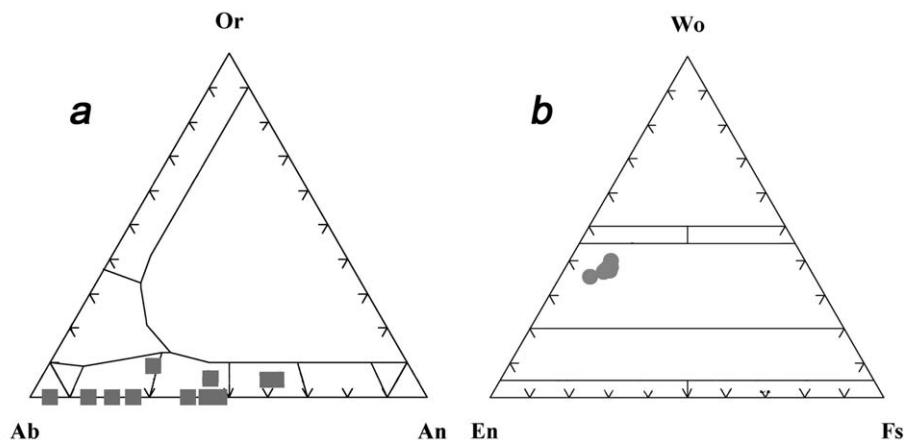


Fig. 3 - Compositions of: a. plagioclases (calculated on the basis of 32 oxygens), and b. clinopyroxenes (calculated on the basis of 6 oxygens), from the sheeted dikes of the Nain ophiolite.

Table 1 - Representative chemical analyses of clinopyroxenes, amphiboles and chromian spinels from the Nain ophiolite sheeted dikes.

sample	RS 14	RS 14	RS 159	RS 159	RS 159	RS 155	RS 155	RS 155	RS 1	RS 20A	RS 20A	RS 20A	RS 20A	
Mineral	clinopyroxene							amphibole			chromian spinel			
No.	1	2	1	2	3	1	2	3	1	2	1	2	3	4
SiO ₂	52.74	50.25	52.67	52.43	52.37	52.30	53.30	53.20	55.03	52.35	<0.10	<0.10	<0.10	<0.10
TiO ₂	0.29	0.20	0.30	0.26	0.32	<0.10	0.30	0.36	<0.1	<0.10	<0.10	<0.10	0.53	0.62
Al ₂ O ₃	5.87	6.65	5.91	6.54	5.16	5.38	3.37	2.72	3.9	9.65	31.09	28.59	21.06	28.56
Cr ₂ O ₃	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	33.18	38.50	44.51	36.14
V ₂ O ₅	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	0.87	<0.10	<0.10	<0.10
Fe ₂ O ₃ [*]	5.04	6.53	7.54	6.77	7.19	7.63	6.99	7.17	15.00	10.01	17.54	17.00	18.65	16.50
MnO	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	0.18	0.18	0.18
MgO	18.84	17.45	16.37	15.22	16.76	16.86	17.77	18.15	14.60	16.00	17.33	15.68	15.20	18.10
CaO	16.18	16.63	16.61	18.29	17.47	17.78	17.57	17.65	11.28	9.50	<0.10	<0.10	<0.10	<0.10
Na ₂ O	1.24	1.49	0.70	0.74	0.83	<0.10	<0.10	<0.10	0.20	2.50	<0.10	<0.10	<0.10	<0.10
TOTAL	100.01	99.40	100.00	99.99	100.03	100.00	99.00	99.09	100.01	100.01	100.01	99.95	100.13	100.10

< = below detection limit.

En₅₄Fs₇Wo₃₃ to En₄₆Fs₁₀Wo₄₀. They are mainly high in SiO₂ (50.25-53.30 wt%), MgO [15.22-18.84 wt%; Mg# 0.88-0.99 (Mg/Mg+Fe²⁺ = Mg#)] and low in TiO₂ (< 0.36 wt%) (Table 1). A significant chemical characteristic of the clinopyroxene samples is their low-Ti content. Several authors have proposed the composition of primary magmatic clinopyroxenes as an alternative parameter in paleotectonic reconstructions of the ophiolites, since the composition of clinopyroxene survives unchanged in ophiolitic rocks, even in those with low-grade metamorphism (Nisbet and Pearce, 1977; Hebert and Laurent, 1987; Capedri and Venturelli, 1979; Beccaluva et al., 1989). Beccaluva et al. (1989) reported that Ti differences in ophiolites correspond well to distinct magma types of different modern oceanic settings, and are grouped as high-Ti, low-Ti and very low-Ti ophiolites. They discovered that high-Ti ophiolites compare favorably with the magmatic association occurring at mid-ocean ridges and well developed marginal basins, whereas low-Ti and very low-Ti ophiolites are best equated with the magmatic series of tholeiitic island arc and bonintic types respectively, generated in supra-subduction zone (SSZ) settings.

The results presented in this paper concern the nature of the low Ti content of Nain lavas and the classification of this ophiolite into the low-Ti group, because Ti in clinopyroxenes is thought to reflect the degree of depletion of the mantle source and the Ti activity of the parent magma (Pearce and Norry, 1979). The clinopyroxenes of Nain ophiolite sheeted dikes have similar geochemical characteristics to those of the other Eastern Mediterranean ophiolites such as Troodos, Vourinos, Pindos, Oman (Beccaluva et al., 1989) and Sarikaraman (Yalınız and Göncüoğlu, 1999) which show high-Mg and low-Ti island-arc affinity. The amphiboles are yellow-green and pleochroic. They are cal-

cic and display actinolite-hornblende to magnesio-hornblende compositions, and developed as euhedral to subhedral and sometimes polygonal discrete grains. Opaque minerals include magnetite, titaniferous-magnetite and chalcopyrite. Chromian spinels only occur in dolerites. They are Al and Mg-rich and Ti-poor. Cr# (Cr/Cr+Al) in the chromian spinels vary from 0.42-0.58. It is believed that occurrence of this mineral is likely an indirect evidence of high degrees partial melting of the mantle source. Almost all the sheeted dikes have been overprinted by low-grade hydrothermal metamorphism ranging from zeolite facies to greenschist facies. This process is characterized by formation of tremolite-actinolite (generally rimming relict clinopyroxenes) with epidote, chlorite, albite, prehnite, sericite, zeolite, quartz and sphene. Prehnite, calcite, epidote and chlorite also occur as crosscutting veins. The high-level gabbros are coarse-grained rocks and exhibit granular texture. They include primary hornblende and to a lesser extent plagioclase.

GEOCHEMISTRY

Lava compositions have been used by many workers to infer the tectonic environment during formation of ophiolites (Miyashiro, 1973; Nisbet and Pearce, 1973; Pearce and Cann, 1973; Pearce, 1975; Pearce and Norry, 1979; Saunders et al., 1980; Pearce, 1982; Shervais, 1982; Arvin and Robinson, 1994). The geochemical characteristics of sheeted dikes from the Nain ophiolite can also help to interpret the tectonic environment in which this ophiolite formed. The results of major and trace element analyses for the sheeted dike complex and high-level gabbro unit of the Nain ophiolite are given in the Table 2.

Table 2 - Whole rock (major and trace element) chemical analyses of the sheeted dike complex and high-level gabbro unit of the Nain ophiolite.

Rock	Gabbro	basalt	basaltic-andesitic				andesite		dacite	SO-17	
Sample	RS-22	RS-20A	RS-109	RS-6-1	RS-6-9	RS-7	RS-13	RS-1	RS-100	Meas.	Offic.
SiO ₂ (wt%)	54.28	47.25	51.51	51.06	51.66	50.71	53.51	60.85	63.30	61.68	61.17
TiO ₂	0.47	0.51	0.53	0.47	1.06	0.70	0.51	0.67	0.80	0.60	0.59
Al ₂ O ₃	14.17	14.51	15.38	15.25	13.69	15.17	15.60	15.67	13.45	13.86	13.72
Fe ₂ O ₃ ⁺	9.23	8.84	11.24	8.74	10.69	12.50	8.84	7.26	5.89	5.85	5.80
MnO	0.17	0.21	0.20	0.17	0.21	0.13	0.15	0.07	0.12	0.52	0.53
MgO	6.99	13.76	5.71	8.43	7.11	8.21	6.75	3.01	2.00	2.24	2.33
CaO	8.37	7.23	7.43	7.39	8.34	4.34	5.99	3.15	4.80	4.53	4.64
Na ₂ O	4.34	1.91	4.62	4.06	4.20	4.52	5.42	7.92	5.80	4.09	4.16
K ₂ O	0.14	0.84	0.24	0.21	0.04	0.17	0.04	0.04	0.04	1.41	1.37
P ₂ O ₅	0.01	0.01	0.05	0.05	0.11	0.06	0.04	0.10	0.10	1.00	0.98
Mg#	0.51	0.66	0.39	0.61	0.47	0.48	0.55	0.39	0.30		
LOI	1.70	4.60	3.00	4.10	2.80	3.40	3.10	1.20	3.50	3.40	3.40
SUM	99.89	99.93	99.92	99.95	99.91	99.95	99.93	99.91	99.77	99.75	98.77
Sc _(ppm)	48.00	31.00	40.00	37.00	38.00	35.00	34.00	26.00	19.00	21	24
Ba	19.10	75.30	67.2	41.1	10.80	21.40	22.40	6.60	7.50	388.80	398.00
Co	34.90	48.20	36.40	34.80	38.70	41.40	31.10	16.90	18.30	18.00	18.70
Cs	<0.10	0.50	<0.10	0.30	<0.10	<0.10	<0.10	<0.10	<0.10	3.90	3.80
Ga	9.70	12.30	12.00	14.20	12.70	13.30	15.30	11.10	14.90	18.50	20.30
Hf	<0.50	<0.50	<0.50	<0.50	1.20	1.00	0.90	1.60	1.90	12.80	12.10
Nb	<0.50	<0.50	<0.50	0.60	<0.50	<0.50	<0.50	<0.50	0.60	24.90	25.70
Rb	1.40	7.20	2.10	3.40	<0.50	1.60	<0.50	<0.50	<0.50	23.20	23.70
Sr	108.50	84.50	178.40	82.00	106.20	129.00	67.90	70.90	60.70	319.70	307.50
Ta	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	4.30	4.40
Th	<0.10	<0.10	<0.10	0.40	<0.10	0.20	<0.10	<0.10	<0.10	11.90	11.50
U	<0.10	<0.10	<0.10	<0.10	0.10	<0.10	0.20	<0.10	<0.10	11.30	11.40
V	260.00	198.00	294.00	253.00	337.00	272.00	268.00	162.00	51.00	126.00	132.00
Cr	82.10	780.00	68.42	88.90	20.52	164.20	82.10	0.00	6.84	3078.97	2962.63
Zr	5.20	11.60	10.40	17.40	32.90	23.40	19.50	42.40	47.30	356.70	358.00
Y	12.10	16.70	11.10	13.60	24.20	17.60	12.30	30.10	26.60	27.70	27.20
La	0.60	<0.50	0.80	1.40	1.70	1.30	1.10	1.40	2.40	10.90	11.00
Ce	1.30	1.00	1.90	2.80	4.80	3.60	2.90	4.80	7.20	23.90	23.50
Pr	0.30	0.270	0.30	0.47	0.84	0.61	0.48	0.95	1.19	3.00	2.90
Nd	1.60	1.70	2.10	2.60	4.30	3.30	2.60	5.10	6.80	13.60	13.60
Sm	0.70	1.10	0.70	1.00	1.90	1.20	0.80	2.00	2.40	3.40	3.30
Eu	0.31	0.37	0.34	0.42	0.75	0.62	0.49	0.53	0.91	1.02	1.04
Gd	1.44	1.86	1.44	1.71	2.91	2.07	1.40	3.53	3.77	3.86	3.81
Tb	0.24	0.35	0.29	0.3	0.58	0.42	0.32	0.68	0.63	0.65	0.66
Dy	1.58	2.38	1.58	1.97	3.82	2.82	1.84	4.48	4.53	4.16	4.24
Ho	0.42	0.56	0.43	0.47	0.84	0.65	0.42	0.99	1.03	0.94	0.93
Er	1.31	1.79	1.21	1.36	2.51	1.89	1.26	2.97	3.05	2.70	2.73
Tm	0.20	0.24	0.17	0.18	0.29	0.25	0.22	0.45	0.46	0.44	0.42
Yb	1.30	1.92	1.23	1.57	2.23	1.73	1.30	2.98	3.20	2.80	2.90
Lu	0.18	0.25	0.16	0.23	0.30	0.27	0.20	0.47	0.48	0.43	0.44
Cu	7.30	113.10	50.80	114.60	18.70	11.50	192.1	12.00	235.40	140.60*	142.30*
Pb	0.40	0.40	0.30	0.40	0.40	0.50	0.40	0.20	0.40	24.80*	25.00*
Zn	21.00	71.00	41.00	79.00	40.00	53.00	74.00	12.00	74.00	138.00*	137.00*

Normalizing values for REE are from Sun and McDonough (1989).

< = below detection limit. An indication of the accuracy is given by measured (Meas.) and official (Offic.) values for the SO-17 standard. * Measured and official values for the DS5 standard.

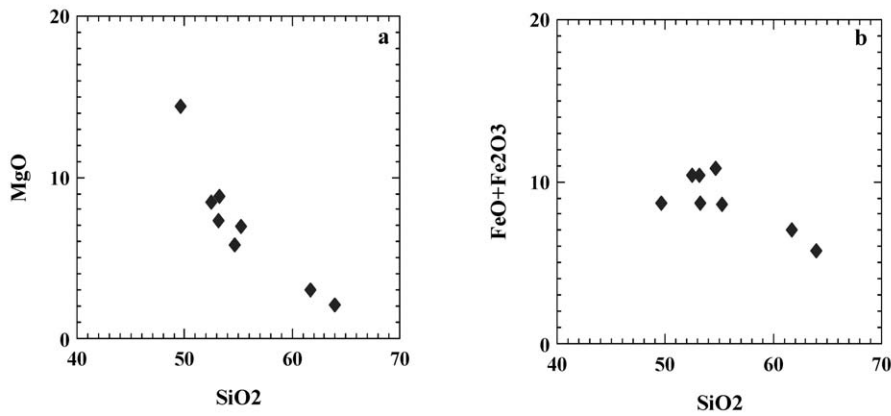


Fig. 4 - a. MgO-SiO₂ diagram showing fractionation in the magma evolution, and, b. FeO+Fe₂O₃-SiO₂ diagram showing iron enrichment in the early stages of magma evolution, Nain ophiolite sheeted dikes.

The studied samples have SiO₂ contents ranging between 47-63 wt%, although most of the samples fall between 50-54 wt% SiO₂. Mg#s (Mg/Mg+Fe⁺²) range from 0.30 to 0.66 in these samples. The samples have low K₂O (< 0.3 wt%) and TiO₂ (0.4-1 wt%) contents. MgO shows a good negative correlation with silica (Fig. 4a), conform to the role of fractional crystallization in the evolution of the magma. Plot of wt% FeO+Fe₂O₃ versus wt% SiO₂ shows iron enrichment in the early stages of evolution of the magma (Fig. 4b). The studied samples plot within the subalkaline/tholeiitic field of the AFM diagram (after Irvine and Baragar 1971) (Fig. 5). In general, it is considered that fractionation under reducing conditions suppresses crystallization of magnetite, thus promoting iron enrichment in the early stages (tholeiitic trend) (Wilson, 1989). In a few samples, the presence of alteration is reflected in the abundances of the more mobile elements and LOI. However, one alkali-silica plot (Fig. 6) shows relatively minor amounts of scatter in the total alkali content of the samples, indicating that the effects of alteration are minimal. Selected minor and trace elements (e.g. Ti, Zr, Y, Th and Nb), believed to be relatively immobile under conditions of metasomatism and low-grade hydrothermal meta-

morphism, are used to characterize extrusive rocks with respect to their original composition and possible tectonic environment of formation (Pearce and Cann, 1973; Winchester and Floyd, 1977; Pearce and Norry, 1979; Meschede, 1986; Jenner, 1996; Pearce, 1996;).

Based on the Zr/TiO₂-Nb/Y diagram (Winchester and Floyd, 1977) the sheeted dikes from the Nain ophiolite have subalkaline basaltic, basaltic-andesitic and andesitic compositions (Fig. 7). The Ti-Zr diagram (Pearce and Cann, 1973) confirms that their magma is of low potassium tholeiite type (LKT) (Fig. 8). Chemical discriminations for the tectonomagmatic environment of the Nain ophiolites sheeted dikes, using selected diagrams based on immobile elements, are presented in Fig. 9. These diagrams are consistent with an island arc geodynamic setting. These patterns are similar to those obtained by Rahgoshay and Shafaii (2004a) for basalts from the Nain ophiolite and also to the patterns for mafic dike swarms of the Pozantı-Karsantı ophiolite (Parlak, 2000). The N-MORB-normalized incompatible elements for the sheeted dike and high-level gabbro samples indicate depletion of most of the high field strength (HFS) elements with respect to N-MORB. The concentrations of the large

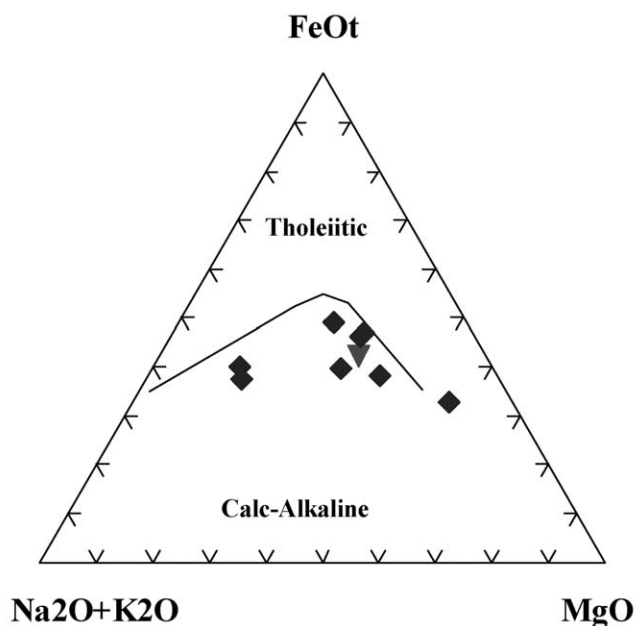


Fig. 5 - AFM diagram (after Irvine and Baragar, 1971) plotting the sheeted dikes (diamonds) and high-level gabbro (triangle) in the field of subalkaline/tholeiitic rocks.

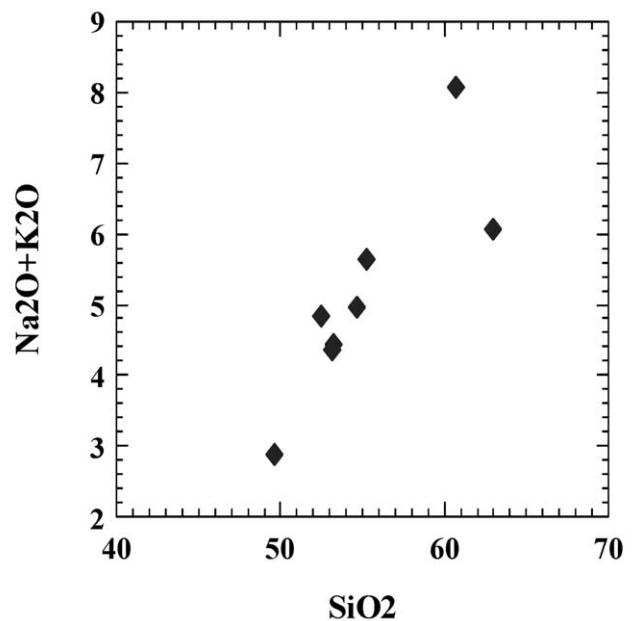


Fig. 6 - Total alkalis versus SiO₂ diagram showing the pervasive but weak nature of alteration in the Nain ophiolite sheeted dikes.

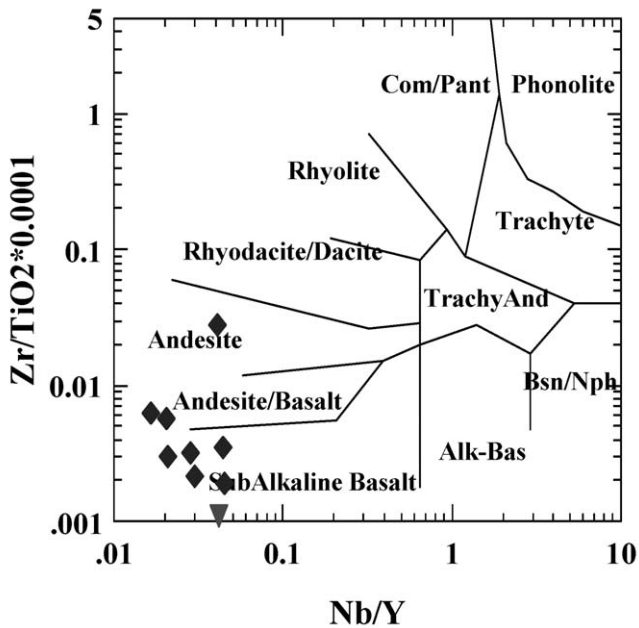


Fig. 7 - Discrimination diagram (after Winchester and Floyd, 1977) showing sheeted dikes and high-level gabbro from the Nain ophiolite. Symbols as in Fig. 5.

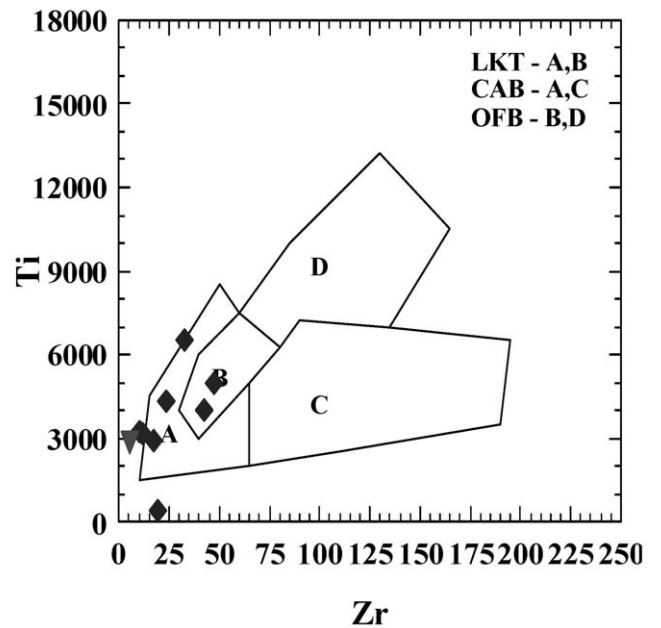


Fig. 8 - Ti-Zr diagram (after Pearce and Cann, 1973) plotting the sheeted dikes and high-level gabbro in the field of low potassium tholeiite (LKT). Symbols as in Fig. 5.

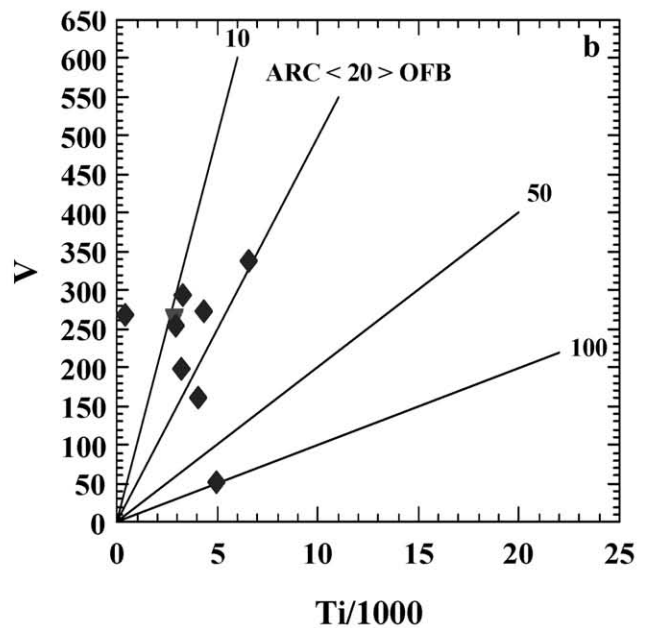
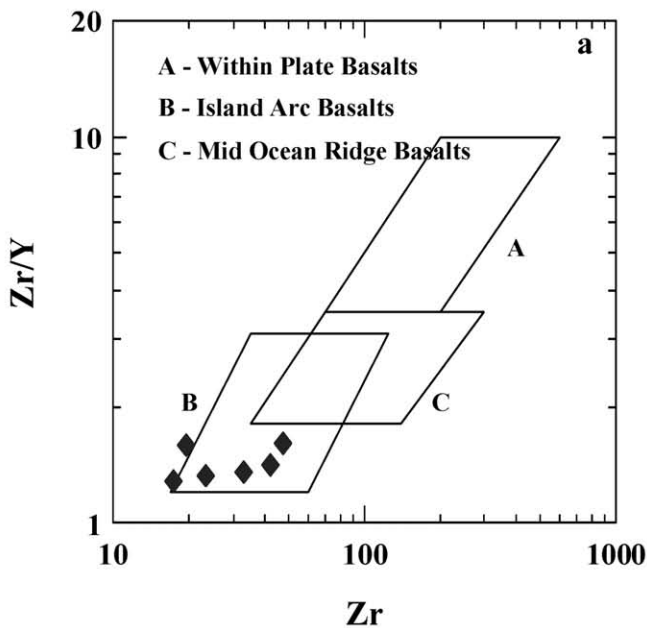


Fig. 9 - Selected tectonomagmatic discrimination diagrams for the sheeted dikes and high-level gabbro: a. after Pearce and Norry (1979), b. after Shervais (1982). Symbols as in Fig. 5.

ion lithophile (LIL) elements in these rocks are all greater than those in the N-MORB (Fig. 10). The LIL elements are those most readily mobilized by a fluid phase, and their enrichment in island-arc basalts has been attributed to metasomatism of their mantle source by hydrous fluids derived from the subducted oceanic crust (Wilson, 1989). The low abundances of HFS elements have been variously attributed to: (I) high degree of partial melting of the mantle source (Pearce and Norry, 1979), (II) stability of minor residual phases (e.g. rutile, zircon and sphene) in the mantle source (Dixon and Batiza, 1979), and (III) remelting of an already depleted mantle source (Green, 1973).

One of the most conspicuous features of the diagram of

Fig. 10) is the positive Th anomaly and negative anomaly of Nb and Zr. Briquet et al. (1984) observed that the negative Nb anomalies in modern arc volcanics were independent of the degree of fractional crystallization. Remarkable Th enrichment and Nb depletion relative to other incompatible elements are considered to represent a subduction zone component (Wood, 1980; Pearce, 1983; 1996). In this case, the presence of clearly arc-type rocks in combination (Fig. 9) with depletion of both Nb and Zr (Fig. 10) suggests an arc-like tectonic environment for the Nain ophiolite oceanic lithosphere. The N-MORB-normalized incompatible elements patterns for the Nain ophiolite sheeted dikes are similar to those obtained by Nicholson et al. (2000) for the

Tangihua ophiolite lavas. The chondrite-normalized rare earth element (REE) patterns for the sheeted dike and high-level gabbro samples of the Nain ophiolite are shown in Fig. 11. The high-level gabbro has the lowest concentrations of REE (2-8 x chondrite) and the convex upward pattern is characterized by LREE depletion ($La_N/Sm_N = 0.54$) and enrichment in MREE and HREE. A small negative Eu anomaly ($Eu/Eu^* = 0.94$) can be observed. The overall concentrations of REE in the sheeted dikes are slightly higher (2-20 x chondrite), however Eu/Eu^* ratio varies between 0.61-1.4, and the dikes also show LREE depletion [$(La_N/Sm_N)_{ave} = 0.63$] and HREE enrichment. The partition coefficients (D) for REE and other trace elements between melt or fluid and phases are different according to the minerals concerned (Abe et al., 1998).

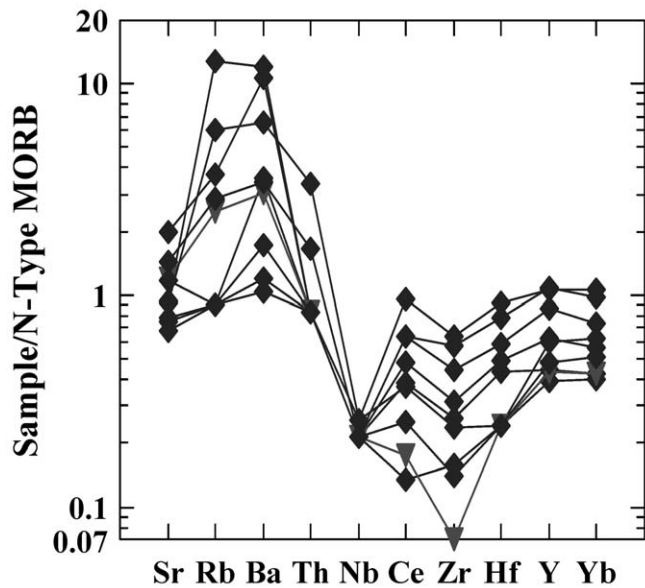


Fig. 10 - Incompatible element patterns of the sheeted dikes and high-level gabbro, normalized to N-type MORB (Sun and McDonough, 1989). Symbols as in Fig. 5.

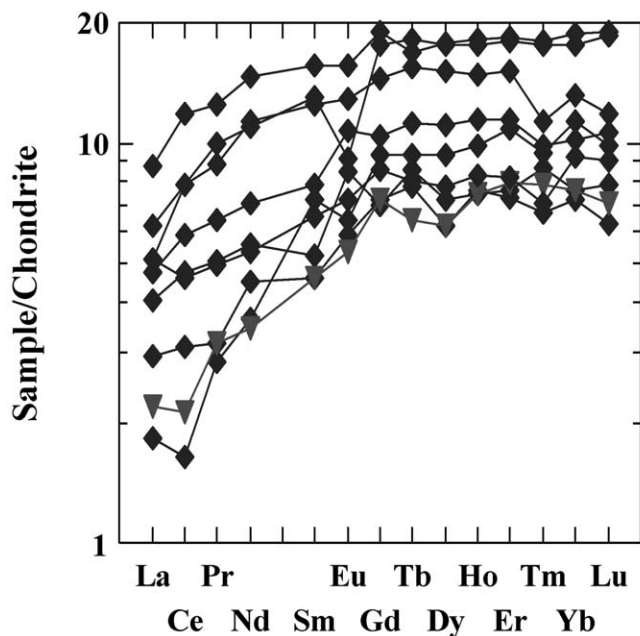


Fig. 11 - Chondrite-normalized REE patterns for the sheeted dikes and high-level gabbro. Normalizing values from Sun and McDonough (1989). Symbols as in Fig. 5.

Formation of the Nain sheeted dikes was dominated by clinopyroxene fractionation and presence of hornblende. Plagioclase crystallization has typically only minor effects on the REE of the melt, except for the large positive anomaly in the Europium distribution coefficient, which will contribute to a negative Eu anomaly in the melt (Hanson, 1989). The REE patterns for these rocks are similar to those obtained by Shojaat et al. (2003) for NMORB-like basalts from the Sabzevar ophiolite and also to the patterns for a group of pillow basalts from the Khoy ophiolite (Hassani-pak and Ghazi, 1999) and from the Samail ophiolite sheeted dikes (Pallister and Knight, 1981). The Cr-Y diagram (Pearce, 1982; Malpas et al., 1994; Lippard et al., 1986) shows a simple equilibrium partial melting adapted to model primary melt composition from a simple mantle lherzolite having about 2000 ppm Cr (Fig. 12). When applied to the data from the Nain ophiolite sheeted dikes, this model shows that the rocks have IAT affinity. Furthermore, the model also suggests that these rocks formed from a melt that was produced by 30 to 40% partial melting of a mantle lherzolite. Similarly, Lippard et al. (1986) suggested 20-30% partial melting to produce the melt for the Cpx-phyrlic basalt unit of the Semail ophiolite.

DISCUSSION AND CONCLUSIONS

Ophiolites are thought to form in diverse tectonic settings including: mid-oceanic ridge spreading centers, supra-subduction zones (SSZ), back arc basin and fore arc extensional regimes (Pearce et al., 1984; Lytwyn and Casey, 1995; Katzir et al., 1995; Thompson et al., 1997). Moreover, in some cases, the various constituents of ophiolites are proposed to have been originated in different and contrasting tectonic regimes (Berhe, 1990; Helmstaedt and Scott, 1992; Lytwyn and Casey, 1995). MORBs are the characteristic rock type of the mid-oceanic ridge spreading centers ophiolite, whereas in supra-subduction zones ophiolites, lavas have geochemical characteristics of island arc tholeiites (Pearce et al., 1984). Distinguishing between back-arc lava and MORB signatures is difficult, especially if the samples have undergone some degree of metamorphism, but negative anomalies in the HFS elements are widely accepted as

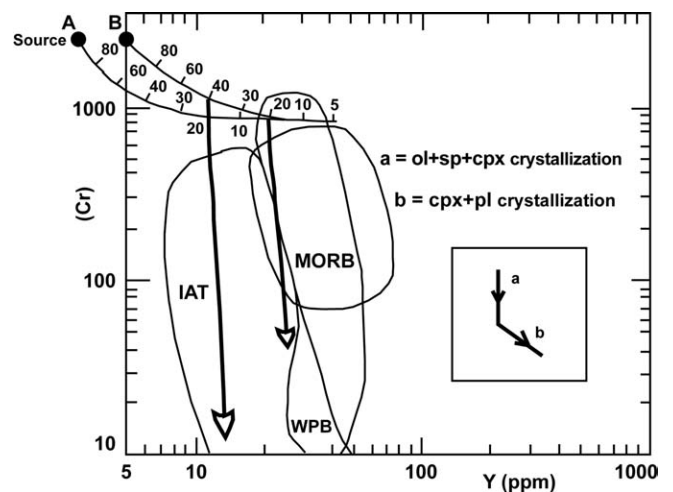


Fig. 12 - Cr-Y diagram (Pearce 1982; Malpas et al., 1994; Lippard et al., 1986) showing the Nain ophiolite sheeted dikes. MORB- mid ocean basalt; WPB- within plate basalt; IAT- island arc tholeiite.

indicators of a subduction zone setting (Nicholson et al., 2000). Furthermore, boninites are the characteristic rock type of the forearc regions of modern oceanic arcs (Cameron et al., 1979; Meijer, 1980). Lavas that erupted at destructive plate boundaries are commonly considered to derive from mantle sources previously depleted with respect to the sources of mid-ocean ridge basalts, and subsequently enriched by aqueous fluids driven off subducted oceanic lithosphere in an arc-basin setting. (Pearce, 1980; Gill, 1981; Knittel and Oles, 1994). The assumption of previously depleted sources is supported by the presence of harzburgites at the inner trench walls of several island arcs (Bonatti and Michael, 1989) and by the eruption of boninites, which undoubtedly derive from very depleted sources (Crawford et al., 1989).

Geochemical and petrological studies confirm that the Nain ophiolite represents a supra-subduction zone type ophiolite. Their magma is sub-alkaline (low potassium tholeiite) and chemically similar to island arc tholeiitic basalts. The geochemistry also shows that the primary melt of these rocks derived from high degrees of partial melting of a mantle source previously depleted with respect to the source of mid-ocean ridge basalts, and are subsequently enriched by aqueous fluids driven off subducted oceanic lithosphere in an arc-basin setting.

REFERENCES

- Abe N., Arai S. and Yurimoto H., 1998. Geochemical characteristics of the uppermost mantle beneath the Japan island arcs: implications for upper mantle evolution. *Phys. Earth Planet. Inter.*, 107: 233-248.
- Ahijado A., Casillas R. and Hernandez-Pacheco A., 2001. The dyke swarms of the Amanay Massif, Fuerteventura, Canary Islands (Spain). *J. Asia. Earth Sci.*, 19: 333-345.
- Alavi M., 1991. Tectonic map of the Middle East. *Geol. Surv. Iran*, Scale 1:5,000,000, Sheet 1.
- Alavi-Tehrani N., 1977. Geology and petrography in the ophiolitic range of the Sabsevar (Khorassan-Iran) *Geol. Surv. Iran*, Report 43.
- Alt J.C., 1996. Hydrothermal alteration of a section of upper oceanic crust in the eastern equatorial Pacific: A synthesis of results from Site 504 (DSDP legs 69, 70, and 83, and ODP legs 111, 137, 140, and 148). *Proc. O.D.P. Sci. Results*, 148: 417-434.
- Arvin M. and Robinson P. T., 1994. The petrogenesis and tectonic setting of lavas from the Baft ophiolitic mélange, southwest of Kerman, Iran. *Can. J. Earth Sci.*, 31: 824-834.
- Arvin M. and Shokri E., 1997. Genesis and eruptive environment of basalts from the Gogher ophiolitic mélange, Southwest of Kerman, Iran. *Ophiolite*, 22 (2): 174-182.
- Baragar W.R.A., Lambert M.B., Baglow N. and Gibson I.L., 1990. The sheeted dike zone in the Troodos ophiolite, Cyprus. In: J. Malpas, E. Moores, A. Panayiotou and C. Xenophontos (Eds.), *Ophiolites, oceanic crustal analogues*. *Proc. Troodos Ophiolite Symp.*, 1987. *Geol. Surv. Dept., Nicosia, Cyprus*, p. 53-64.
- Bebard J.H., 1991. Cumulate recycling and crustal evolution in the Bay of Island ophiolite. *J. Geol.*, 99: 225-249.
- Beccaluva L., Macciotta G., Piccardo G.B. and Zeda O., 1989. Clinopyroxene composition of ophiolite basalts as petrogenetic indicator. *Chem. Geol.*, 77: 165-182.
- Berberian M. and King G.C., 1981. Towards a paleogeography and tectonic evolution of Iran. *Can. J. Earth Sci.*, 18: 210-265.
- Berhe S.M., 1990. Ophiolites in Northeast and East Africa: Implications for Proterozoic crustal growth. *J. Geol. Soc.*, 147: 41-57.
- Bonatti E. and Michael P.J., 1989. Mantle peridotites from continental rifts to ocean basins to subduction zones. *Earth Planet. Sci. Lett.*, 91: 297-311.
- Borgia A. and Treves B., 1992. Volcanic plates overriding the ocean crust: structure and dynamics of Hawaiian volcanoes. In: L.M. Parson, B.J. Murton and P. Browning (Eds.), *Ophiolites and their modern oceanic analogues*. *Geol. Soc. London Spec. Publ.*, 60: 277-299.
- Briqueu L., Bougault H. and Joron J. L., 1984. Qualifications of Nb, Ta, Ti and V anomalies in magma associated with subduction zones: petrogenetic implications. *Earth Planet. Sci. Lett.*, 68: 297-308.
- Cameron W.E., Nisbet E.G. and Dietrich V.J., 1979. Boninites, komatiites and ophiolitic basalts. *Nature*, 280: 550-53.
- Capedri S. and Venturelli G., 1979. Clinopyroxene composition of ophiolitic metabasalts in the Mediterranean area. *Earth Planet. Sci. Lett.*, 43: 61-73.
- Cherkaoui A.S.M., Wilcock W.S.D. and Baker E.T., 1997. Thermal fluxes associated with the 1993 dike event on the Coaxial segment, Juan de Fuca ridge: A model for the convective cooling of a dike. *J. Geophys. Res.*, 102 (24): 887-902.
- Crawford A.J., Falloon T.J. and Green D.H., 1989. Classification petrogenesis and tectonic setting of boninites. In: A.J. Crawford (Ed.), *Boninites*. Unwin Hyman, London, p. 1-49.
- Curewitz D. and Karson J.A., 1998. Geological consequences of dike intrusion at mid-ocean ridge spreading centers, in faulting and magmatism at mid-ocean ridges. *Monogr. Ser.*, 106: 117-136.
- Davoudzadeh M., 1972. Geology and petrology of the area north of Nain, Central Iran. *Geol. Surv. Iran, Rep.*, 14-1972.
- Deer W.A., Howie R.A. and Zussman J., 1978. *Rock forming mineral, 2A. single-chain silicates*. Longman, U.K. and Wiley, New York, 528 pp.
- Desmons J. and Beccaluva L., 1983. Mid-oceanic ridge and island arcs affinities in ophiolites from Iran: Paleogeographic implication. *Chem. Geol.*, 39: 39-63.
- Dilek Y. and Delaloye M., 1992. Structure of the Kızıldağ ophiolite, a slow-spread Cretaceous ridge segment north of the Arabian promontory. *Geology*, 20: 19-22.
- Dixon T.H. and Batiza R., 1979. Petrology and chemistry of recent lavas in the northern Marianas: implications for the origin of island arc basalts. *Contrib. Mineral. Petrol.*, 70: 167-182.
- Emami M.H., Sadegi M.M. and Omrani S.J., 1993. Magmatic map of Iran. *Geol. Surv. Iran*, Scale 1:1,000,000.
- Floyd P.A. and Winchester J.A., 1975. Magma type and tectonic setting discrimination using immobile elements. *Earth Planet. Sci. Lett.*, 27: 211-218.
- Francheteau J., Armijo R., Cheminee J.L., Hekinian R., Lonsdale P. and Blum N., 1992. Dike complex of the East Pacific Rise exposed in the walls of Hess Deep and the structure of the upper oceanic crust. *Earth Planet. Sci. Lett.*, 111: 109-121.
- Ghazi A.M. and Hassanipak A.A., 1999a. Geochemistry of subalkaline and alkaline extrusive from the Kermanshah ophiolite, Zagros Suture Zone, western Iran: implications on Tethyan plate tectonics. *J. Asia. Earth Sci.*, 17: 319-332.
- Ghazi A.M. and Hassanipak A.A., 1999b. Geochemistry and petrology of the island arc component of the Shahr Babak ophiolites, Central Iran; Implication for Neo-Tethyan plate tectonics. In: Y. Dilek (Ed.), *Proc. Penrose Conf. on Ophiolites and Oceanic Crust: New insights from field studies and Ocean Drilling Program*. *Geol. Soc. Am. Mem., Spec. Publ.*, in press.
- Ghazi A.M., Hassanipak A.A., Duncan R.A., Hogen L.G. and Mahoney J.J., 1997. Geochemistry, $^{40}\text{Ar}/^{39}\text{Ar}$ ages and preliminary isotopic analyses of the Khoy ophiolite, northwestern Iran. *EOS*, 78: F654.
- Gill J.B., 1981. *Orogenic andesites and plate tectonics*. Springer, Berlin.
- Green D.H., 1973. Experimental melting studies on a model upper mantle composition at high pressure under water-saturated conditions. *Earth Planet. Sci. Lett.*, 19: 37-53.
- Hanson G.N., 1989. An approach to trace element modeling using a simple igneous system as an example. *Rev. Mineral.*, 21: 79-97.
- Hassanipak A.A. and Ghazi A.M., 1999. Petrology, geochemistry and tectonic setting of the Khoy ophiolite, Northwest Iran. *J. Asia. Earth Sci.*, 18: 43-55.

- Hassanipak A.A., Ghazi A.M. and Wampler J.M., 1996. REE characteristics and K/Ar ages of the Band Ziarat ophiolite complex, southeastern Iran. *Can. J. Earth Sci.*, 33: 1534-1542.
- Hébert H. and Laurent R., 1987. Mineral chemistry of the plutonic section of the Troodos ophiolite: new constraints for genesis of arc-related ophiolites. In: J. Malpas, E. Moores, A. Panayiotou and C. Xenophontos (Eds.), *Ophiolites, oceanic crustal analogues*. Proc. Troodos Ophiolite Symp. 1987, Geol. Surv. Dept., Nicosia, Cyprus, p. 149-163.
- Helmstaedt H.H. and Scott D.J., 1992. The Proterozoic ophiolite problem. In: K.C. Condie (Ed.), *Proterozoic crustal evolution*. Develop. Precamb. Geol., 10: 123-124.
- Irvine T.N. and Baragar W.R.A., 1971. A guide to chemical classification of common volcanic rocks. *Can. J. Earth Sci.*, 8: 523-574.
- Jenner G.J., 1996. Trace element geochemistry of igneous rocks: geochemical and nomenclature and analytical geochemistry. In: D.A. Wyman (Ed.), *Trace element geochemistry of volcanic rocks: Applications for massive sulphide exploration*. Geol. Ass. Can., Short Course Notes, 12: 51-78.
- Katzir Y., Matthews A., Garfunkel Z., Schliested M. and Avigad D., 1995. The tectono-metamorphic evolution of a dismembered ophiolite (Tinos, Cyclades, Greece). *Geol. Mag.*, 133: 237-254.
- Knipper A., Ricou L.E. and Dercourt J., 1986. Ophiolite as indicator of the geodynamic evolution of the Tethyan ocean. *Tectonophysics*, 123: 213-240.
- Knittel U. and Oles D., 1994. Basaltic volcanic associated with extensional tectonics in the Taiwan-Luzon island arc: evidence for non-depleted sources and subduction zone environment. In: J.L. Smellie (Ed.), *Volcanic associated with extension at consuming plate margine*. Geol. Soc. London. Spec. Publ., 81: 77-93.
- Lippard S.J., Shelton A.W. and Gass I.G., 1986. The ophiolite of Northern Oman. *Geol. Soc. London Mem.*, 11: 178.
- Lytwyn J.N. and Casey J.F., 1995. The geochemistry of post kinematic dyke swarms and sub-ophiolitic metabasites, Pozanti-Karsanti ophiolite Turkey: evidence for ridge subduction. *Geol. Soc. Am. Bull.*, 107: 830-850.
- Malpas J., Calon T.J. and MacDonald R.W.J., 1994. The Shulaps ophiolite complex of British Columbia, Canada: a Palaeozoic/Mesozoic arc-related microterrane. In: A. Ishiwatari et al. (Eds.), *Circum-Pacific ophiolites*. Proc. 29th Intern. Geol. Congr., Part D, p. 69-87.
- McCall G.J.H., 1997. The geotectonic history of the Makran and adjacent areas of southern Iran. *J. Asia. Earth Sci.*, 15: 517-531.
- Mc Call G.J.H. and Kidd R.G.W., 1981. The Makran, southeastern Iran: the anatomy of a convergent plate margin active from cretaceous to present. In: J. Legget (Ed.), *Trench-fore arc geology*. Geol. Soc. London Spec. Publ., 10: 387-397.
- Meijer A., 1980. Primitive arc volcanism and a boninite series: examples from the Western Pacific Island arcs. In: Hayer (Ed.), *The tectonic evolution of Southeast Asian seas and islands*. Am. Geophys. Union Geophys. Monograph.
- Meschede M., 1986. A method of discriminating between different types of mid-oceanic ridg basalts and continental tholeiites with the Nb-Zr-Y diagram. *Chem. Geol.*, 56: 207-218.
- Miyashiro A., 1973. The Troodos ophiolite complex was probably formed in an island arc. *Earth Planet. Sci. Lett.*, 19: 218-224.
- Nicholson K.N., Black P.M. and Picard C., 2000. Geochemistry and tectonic significance of the Tangihua ophiolite complex, New Zealand. *Tectonophysics*, 321: 1-15.
- Nisbet E.G. and Pearce J.A., 1973. TiO₂ as a possible guide to past oceanic spreading rates. *Nature*, 246: 468-470.
- Nisbet E.G. and Pearce J.A. 1977. Clinopyroxene composition in mafic lavas from different tectonic settings. *Contrib. Mineral. Petrol.*, 63: 149-160.
- Pallister J.S. and Knight R.J., 1981. Rare-Earth Element geochemistry of the Samail ophiolite, near Ibra, Oman. *J. Geophys Res.*, 86 (4): 2673-2697.
- Parlak O., 2000. Geochemistry and significance of mafic dike swarms in the , Pozanti-Karsanti ophiolite, southern Turkey. *Turkish J. Earth Sci.*, 9: 29-38.
- Pearce J.A., 1975. Basalt geochemistry used to investigate past tectonic environments on Cyprus. *Tectonophysics*, 25: 41-67.
- Pearce J.A., 1980. Geochemical evidence for genesis and eruptive setting of lavas from Tethyan ophiolites. In: A. Panayiotou (Ed.), *Proc. Intern. Ophiolite Symp.*, Geol. Surv. Dept., Cyprus, Nicosia, 1979, p. 261-272.
- Pearce J.A., 1982. Trace element characteristics of lavas from destructive plate boundaries. In: R.S. Thrope (Ed.), *Andesites*. Wiley and Sons/,New York, p. 525-548.
- Pearce J.A., 1983. Role of the sub-continental lithosphere in magma genesis at active continental margins. In: C.J. Hawkesworth and M.J. Norry (Eds.), *Continental basalts and mantle xenoliths*. Shiva, Nantwich, p. 230-249.
- Pearce J.A., 1996. A user's guide to basalt discrimination diagrams. In: D.A. Wyman (Ed.), *Trace elament geochemistry of volcanic rocks: Applications for massive sulphide exploration*. Geol. Ass. Can., Short Course Notes, 12: 79-113.
- Pearce J.A. and Cann J.R., 1973. Tectonic setting of basic volcanic rocks determined using trace element analyses. *Earth Planet. Sci. Lett.*, 19: 290-300.
- Pearce J.A., Lippard S.J. and Roberts S., 1984. Characteristics and tectonic significance of supra-subduction zone ophiolites. In: B. P. Kokelaar and M. F. Howells (Eds.), *Marginal basin geology*. Geol. Soc. London Spec. Publ., 16: 77-94.
- Pearce J.A. and Norry M.J., 1979. Petrogenetic implications of Ti, Zr, Y, and Nb variations in volcanic rocks. *Contrib. Mineral. Petrol.*, 69: 33-43.
- Pollard D.D., 1987. Elementary fracture mechanics applied to the structural interpretations of dikes, in mafic dike swarms. In: H.C. Hall and W. F. Hahrig (Eds.), *Geol. Ass. Can.*, p. 5-24.
- Rahgoshay M. and Shafaii M.H., 2004a. Petrology, tectonic and geodynamic environment of Nain ophiolitic Massif. Proc. 5th Intern. Symp. Eastern Mediterranean Geology, Thessaloniki, Greece, 2004, p. 275-278.
- Rahgoshay M. and Shafaii M.H., 2004b. Metamorphism stages in Nain's ophiolitic Massif, Central Iran. Proc. 5th Intern. Symp. Eastern Mediterranean Geology, Thessaloniki, Greece, 2004, p. 271-274.
- Rubin A.M. and Pollard D.D., 1987. Origins of blade-like dikes in volcanic rift zones. *U. S. Geol. Surv. Prof. Pap.*, 1350: 1449-1470.
- Saunders A.D., Marsh N.G. and Wood D.A., 1980. Ophiolites as ocean crust or marginal basin crust: a geochemical approach. In: A. Panayiotou (Ed.), *Proc. Intern. Ophiolite Symp*. Geol. Surv. Dept., Cyprus, Nicosia, p. 193-204.
- Schiffman P., Bettison L.A. and Smit B.M., 1990. Mineralogy and geochemistry of episodites from the Solea Graben, Troodos ophiolite, Cyprus. In: J. Malpas, E. Moores, A. Panayiotou and C. Xenophontos (Eds.), *Ophiolites, oceanic crustal analogues*. Proc. Troodos Ophiolite Symp., 1987. Geol. Surv. Dep., Nicosia, Cyprus, p. 673-684.
- Shervais J.W., 1982. Ti- V plots and the petrogenesis of modern and ophiolitic lavas. *Earth Planet. Sci. Lett.*, 59: 101-118.
- Shojaat B., Hassanipak A.A., Mobasher K. and Ghazi A.M., 2003. Petrology, geochemistry and tectonics of the Sabzevar ophiolite, North Center Iran. *J. Asia. Earth Sci.*, 21: 1053-1067.
- Staudigel H., Tauxe L., Gee J.S., Bogaard P., Haspels J., Kale G., Leenders A., Meijer P., Swaak B., Tuin M., Van Soest M.C., Verdurmen E.A.Th. and Zevenhuizen A., 1999. Geochemistry and intrusive directions in sheeted dikes in the Troodos ophiolite: implications for mid-ocean ridge spreading centers. *Electronic J. Earth Sci.*, 1, Paper No. 1999GC000001.
- Stocklin J., 1974. Possible ancient continental margins in Iran. In: C. A. Burke and C. L. Drake (Eds.), *The geology of continental margin*. Springer, New York, p. 873-887.
- Stocklin J., 1977. Structural correlation of the Alpien ranges between Iran and Central Asia. *Soc. Géol. France, Mém. Hors-série*, 8: 333-353.
- Sun S.S. and McDonough W.F., 1989. Chemical and isotopic systematics of oceanic basalts: implications for mantle composition and processes. In: A.D. Saunders and M.J. Norry (Eds.),

- Magmatism in ocean basins. Geol. Soc. London Spec. Publ., p. 313-345.
- Takin M., 1972. Iranian geology and continental drift in the Middle East. *Nature*, 235: 147-150.
- Thompson M.G., Malpas J. and Smith I.E.M., 1997. The geochemistry of tholeiitic and alkalic plutonic suites within Northland ophiolite, northern New Zealand: magmatism in a back arc basin. *Chem. Geol.*, 142: 213-239.
- Wampler J.M., Mahoney J.J., Ghazi A.M. and Hassanipak A.A., 1996. REE characteristics and K/Ar ages and preliminary isotopic analysis of the Band Ziarat ophiolite complex, southeastern Iran. *EOS*, 78: 836.
- Weber-Diefenbach K., Davoudzadeh M., Alavi-Tehrani N. and Lench G., 1986. Paleozoic ophiolites in Iran, Geology, geochemistry and geodynamic implication. *Ophioliti*, 11: 305-338.
- Wilcock W.S.D. and Delaney J.R., 1996. Mid-oceanic ridges sulfide deposits: Evidence for heat extraction from magma chambers or cracking fronts? *Earth Planet. Sci. Lett.*, 145: 49-64.
- Wilson M., 1989. *Igneous petrogenesis*. Publ. Unwin Hyman, London, 466 pp.
- Winchester J.A. and Floyd P.A., 1977. Geochemical discrimination of different magma series and their differentiation products using immobile elements. *Chem. Geol.*, 20: 325-342.
- Wood D.A., 1980. The application of a Th-Hf-Ta diagram to problems of tectonomagmatic classification and to establishing the nature of crustal contamination of basaltic lavas of the British Tertiary volcanic province. *Earth Planet. Sci. Lett.*, 50: 11-30.
- Yalınız K. M., and Göncüoğlu C. M., 1999. Clinopyroxene composition of the isotropic gabbros from the Sarikaraman ophiolite: New evidence on suprasubduction zone type magma genesis in Central Anatolia. *J. Turkish Earth Sci.*, 8: 103-111.

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