TWO MESOZOIC OCEANIC PHASES RECORDED IN THE BASIC AND METABASIC ROCKS OF THE NAIN AND ASHIN-ZAVAR OPHIOLITIC MÉLANGES (ISFAHAN PROVINCE, CENTRAL IRAN)

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ABSTRACT

The Mesozoic ophiolitic mélanges of Nain and Ashin-Zavar are located in the western part of the Central-East Iranian microcontinent (CEIM), along the major faults of Nain-Baft and Dorouneh. They contain two different groups of highly metamorphosed rocks (amphibolitic rocks, schists, marbles and quartzites) formed through metamorphism of oceanic basaltic and sedimentary units, and also some less metamorphosed rocks (sheeted dikes, pillow lavas, limestones and radiolarian cherts), that were tectonically melanged. These features show that they formed in two distinct phases.

Geochemical data point to an island arc tholeiitic affinity for the amphibolitic rocks, and to a MORB nature for the pillow lavas and sheeted dikes that are related to a back-arc basin. Accordingly, oceanic crust extensional processes should have been active during two phases:

a- In Early Jurassic, the Nain and Ashin-Zavar oceanic crust segments started spreading and producing diabasic dikes and pillow lavas, covered by pelagic sediments, then they suffered a high-grade metamorphism during the closure of this oceanic sector around the Middle Jurassic.

b- During Early-Late Cretaceous to Paleocene, oceanic spreading produced sheeted dikes, massive basalts, and basaltic pillow lavas throughout the Austrian orogenic phase. There is no evidence of high-grade metamorphism as amphibolitic rocks. Radiolarian cherts and Globotruncana limestones of Late Cretaceous age cover the basaltic rocks.

INTRODUCTION

Ophiolites are windows into the geological history of the Earth and clues to the distribution of continental masses and oceans. They provide important data on how ocean basins formed and disappeared in the past and how the dynamic paleogeography looked like in many millions of years ago (Dilek et al., 2000). In Iran, ophiolites of different ages crop out in the Northern and Central regions. In 1994, Arvin and Robinson classified them into two groups: the less abundant Paleozoic and the more abundant Mesozoic ophiolites. Stocklin (1974) on the other hand, divided Iranian ophiolites into four groups: (1) ophiolites of the Zagros, (2) ophiolites (colored mélanges) of northwestern Iran, (3) ophiolites and colored mélanges that mark the boundaries of the Central-Eastern Iranian microcontinent (CEIM), and (4) ophiolites at the northern foot of the Alborz Range. The ophiolites of CEIM include Nain (100 Ma), Shahr-e-Babak (120 Ma), Baft, Sabzevar in north-central Iran (98-70 Ma) and Tchehel-Kureh on the eastern boundary of CEIM (Ghazi and Hassanipak, 2003). Previous geochemical data on Iranian ophiolites are relatively scarce, but most of the older works suggest that they have mid-ocean ridge basalt (MORB) and island arc tholeiite (IAT) affinities (Davoudzadeh, 1972; Alavi-Tehrani, 1977; Desmon and Beccaluva, 1983; McCall and Kidd, 1981, and Lippard et al., 1986).

Two ophiolitic complexes will be considered in this paper: Nain (= Naein) and Ashin-Zavar. The ophiolite of Nain lies west of the Nain-Baft fault (NBF) and northeast of the Isfahan Province, the ophiolite of Ashin-Zavar crops out west of the Dorouneh fault (= Great Kavir fault) (Fig. 1). The Central-Eastern Iranian Microcontinent (CEIM) and its surrounding ophiolitic mélanges are separated from the Central Iran zone by the faults of Nain-Baft and Dorouneh, which are connected together, representing a long major fault. Due to tectonic fragmentation and mixing, the relationships between different units of these two ophiolites are no longer recognizable. However, both ophiolite sequences of Nain and Ashin-Zavar are mainly made of pelagic limestones, basaltic lava flows and pillow lavas, diabasic dikes, plagiogranites, gabbros, pyroxenites, chromitite and mantle peridotites. Syn- and post-tectonic events produced various metamorphic rocks (Torabi, 2009b; 2010; Shirdashtzadeh et al., 2010). The presence of some non-metamorphosed and slightly metamorphosed rock units together with highly metamorphosed units, mixed together, makes it difficult to reconstruct their geological history.

Several papers have addressed ophiolite related metamorphic rocks (e.g., Coleman, 1977; Nicolas, 1989; Dilek and Newcomb, 2003; Celik and Delaloye, 2006, etc.). They classify the metamorphic processes of ophiolites into internal (serpentinization and thermal metamorphism) and external (related to tectonic emplacement and orogenesis), as can be observed in both Nain and Ashin-Zavar (Shirdashtzadeh et al., 2010; Torabi et al., 2011a and 2011b). Metamorphic rocks are the fundamental clues to determine the P-T evolution of terrains in most orogenic belts (Spear, 1993).

In the Nain and Ashin-Zavar ophiolites, non- to slightly-metamorphosed rocks, predominantly including Cretaceous limestones, pillow lavas, and sheeted dikes, are associated with some highly metamorphosed rocks of mainly amphibolitic grade. These metamorphic rocks of both ophiolite units were studied a little in previous reports (Davoudzadeh et al., 1981; Lensch and Davoudzadeh, 1982, and Sharkovski et al., 1984). These studies suggest that all the metamorphic rocks of the Nain and Ashin-Zavar ophiolites were tectonically transported there from the metamorphic massif of Anarak-Khur (northeast of the study area). On the contrary, Torabi (2004) noticed that just some small exotic blocks of meta-alkali granites and highly foliated schists derived from the Anarak-Khur metamorphic massif since they cannot be associated with the geological suites known from that area. Moreover, there is no field evidence for inverted metamorphic gradients to define these rocks as a metamorphic sole (Torabi et al., 2006; 2007 and Shirdashtzadeh, 2007). Regardless of their complex metamorphic history, these ophiolitic units can be a helpful clue in formulating a new scenario for the Central Iran tectonic events.

This paper presents a geochemical comparison between non highly metamorphosed basic rocks (sheeted dikes and pillow lavas) and highly metamorphosed rocks (amphibolitic rocks) of Nain and Ashin-Zavar aimed at developing a model for the Mesozoic tectonics of CEIM ophiolites that distinguishes two stages of magmatism in Jurassic and Early to Late Cretaceous.

GEOLOGIC OUTLINE

The Nain and Ashin-Zavar Mesozoic ophiolitic mélanges are relics of the Neotethys Ocean (Torabi et al., 2011a and 2011b). The Nain-Zavar ophiolitic zone is located along the Nain-Sabzevar suture zone, about 1400 kilometers long, from Sabzevar (Northeast of Iran) to Nain (Central Iran) and the Jazmoorian basin (Southeast Iran) (Stocklin, 1968; Davoudzadeh et al., 1981) (Fig. 1).

The Mesozoic ophiolites of Nain and Ashin-Zavar were emplaced before the Paleocene, since Paleocene-Eocene sediments cover them (Davoudzadeh, 1972). Their emplacement has been inferred to be Late Cretaceous (Stocklin, 1974; Stoneley, 1974 and 1975). Torabi (2004) described the plagiogranites of the Ashin-Zavar ophiolite as the products of magmatic differentiation of the basic melts. Sharkovski et al. (1984) determined on them a K-Ar age of 98 Ma. In addition, three $^{40}Ar/^{39}Ar$ ages of 101.2±0.9, 99.7±0.9, 99±1.2 Ma, for crystallization of the hornblende gabbros, suggest the late Albian for the magmatic formation of the Nain ophiolite (Hassanipak and Ghazi, 2000; Ghasemi and Talbot, 2006). Moreover, an age of 93.4 Ma (Cenomanian) was determined on amphiboles from an amphibolite of the Nain massif by Shafaii Moghadam et al. (2009).

Geochemical studies on volcanics of Iran ophiolite com-

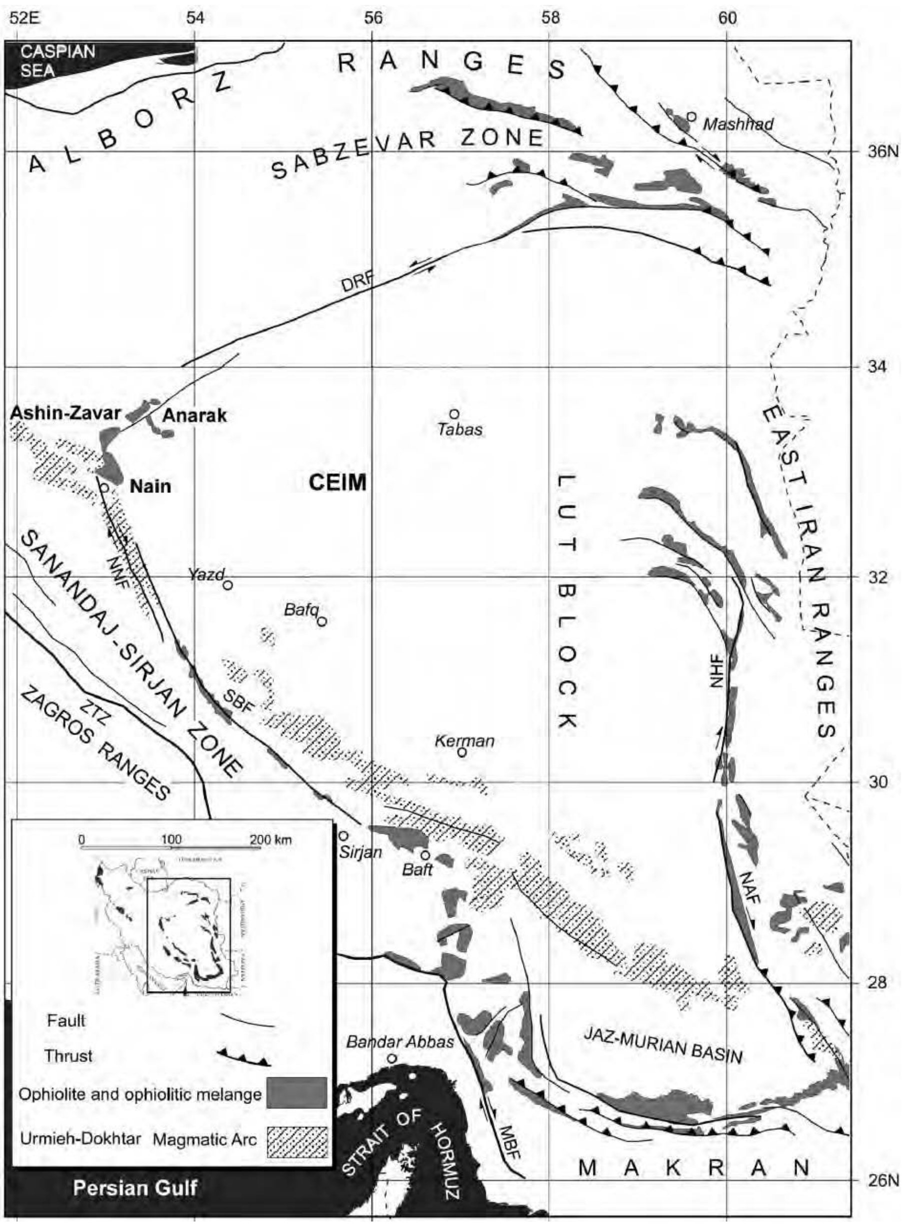

Fig. 1 - Simplified map of Central-Eastern Iran, its crustal blocks, and location of the study area of the Nain and Ashin-Zavar ophiolites (DRF- Doruneh Fault, MBF- Minab Fault, NBF- Nain-Baft Fault, SBF- Shahre-Babak Fault, ZTZ- Zagros Thrust Zone). The figure it taken from Ramezani and Tucker (2003).

plexes (Ghazi and Hassanipak, 1999a and 1999b, Hassanipak and Ghazi, 2000, and Babaie et al., 2001) indicate a suprasubduction zone (SSZ) geochemical affinity for the Nain ophiolites, and suggest their formation in an intra-oceanic island arc environment. In fact, the presence of different extrusive rocks (e.g., basaltic andesite and andesite) intercalated with Late Cretaceous sedimentary rocks, reveal that the Nain ophiolite has both island arc and intra-oceanic components (Hassanipak and Ghazi, 2000) characteristic of a supra-subduction zone (Pearce et al., 1986). Recent geochemical studies on the basaltic and mafic lavas of the Nain-Dehshir ophiolites (Shafaii Moghadam et al., 2008 and 2009), and on the mantle peridotites of Nain (Rahgoshay et al., 2009; Pirnia et al., 2010, and Mehdipour Ghazi et al., 2010) have related the Nain ophiolite to an extensional back-arc basin.

In both ophiolitic complexes, metamorphic rocks including marbles, schists, quartzites, skarns, banded metacherts, spilites, metagabbros, amphibolites, serpentinites, rodingites and listwaenites are enclosed in a matrix of serpentinite matrix (Sharkovski et al., 1984; Torabi et al., 2006; Shirdashtzadeh et al., 2010).

Amphibolitic rocks of the Nain ophiolite are exposed in Soheil-e-Pakuh, Abyaneh-e-Nain, south of Separab, south of Kuh-e-Zard, near the Soucheh farm (Fig. 2a). Amphibolitic rocks of Ashin-Zavar crop out in the south of the Chah-e-Senjed and Sorkh Shad roads (Fig. 2b). Shirdashtzadeh (2007) and Torabi et al. (2011b) divided the amphibolitic rocks of Nain and Ashin-Zavar into two distinct groups, based on their occurrence, morphology and protoliths: first, those that formed by regional metamorphism from diabasic dikes, and second, those produced by metamorphism of basalts and basic pillow lavas. In this paper, the first group is defined as "amphibolitic dikes" and the second one as "amphibolites". The amphibolites of Nain show two foliations, S_1 and S_2 (Torabi et al., 2006). In Nain, some scattered small volumes of skarn rocks on the amphibolites also occur. These skarns are in sharp contact with the underlying amphibolitic rocks (Torabi et al., 2006; Shirdashtzadeh, 2007). In fact, the oceanic basalts have turned into amphibolites and their overlying carbonate layers into skarns (Torabi et al., 2006). Locally some small fragments of amphibolites are reported in these skarns but S_2 is the only foliation in them. Because of these features, Shirdashtzadeh (2007) concluded that the basic protoliths of the amphibolites were older than the skarns. Torabi et al. (2007) and Shirdashtzadeh (2007) linked foliations S_1 and S_2 to two regional metamorphic phases defined as RM_1 and RM_2, respectively, and they suggested that the RM_1 caused formation of the amphibolites and of their S_1 foliation, afterwards, the RM_2 regional metamorphism affected both amphibolitic rocks and skarns and was recorded by foliation S_2.

Other basic rocks in Nain and Ashin-Zavar are sheeted dikes and pillow lavas. Pillow lavas and the pelagic sediments on top (Radiolarian cherts and Globotruncana limestones) clearly provide evidence of sub-marine volcanism. They underwent spilitization and sub-sea floor metamorphisms (Abdullahi, 2007; Torabi et al., 2008a). Pillow lavas are found mostly close to sheeted dikes as they are exposed in the southwest of Soheyl-e-Pakuh and near Kuh-e-Zard (in the Nain ophiolite, see Fig. 2a), and Chah-e-Senjed, Chah-e-Loqeh, Douzakh-Dareh and to the south of the marble mine (in the Ashin-Zavar ophiolite, Fig. 2b).

In Ashin-Zavar, sheeted dikes crop out near Chah-e-Loqeh and Tangeh-Zaqi (Torabi, 2004), and in Nain, around Separab, north of Nain, east of Kuh-e-Zard, and Ahmadabad (Rahmani et al., 2007) (Fig. 2).

ANALYTICAL METHODS

Mineralogical analyses were conducted by a wavelength-dispersive electron probe micro analyzer (EPMA, model JXA-8800R) at the Cooperative Centre of Kanazawa

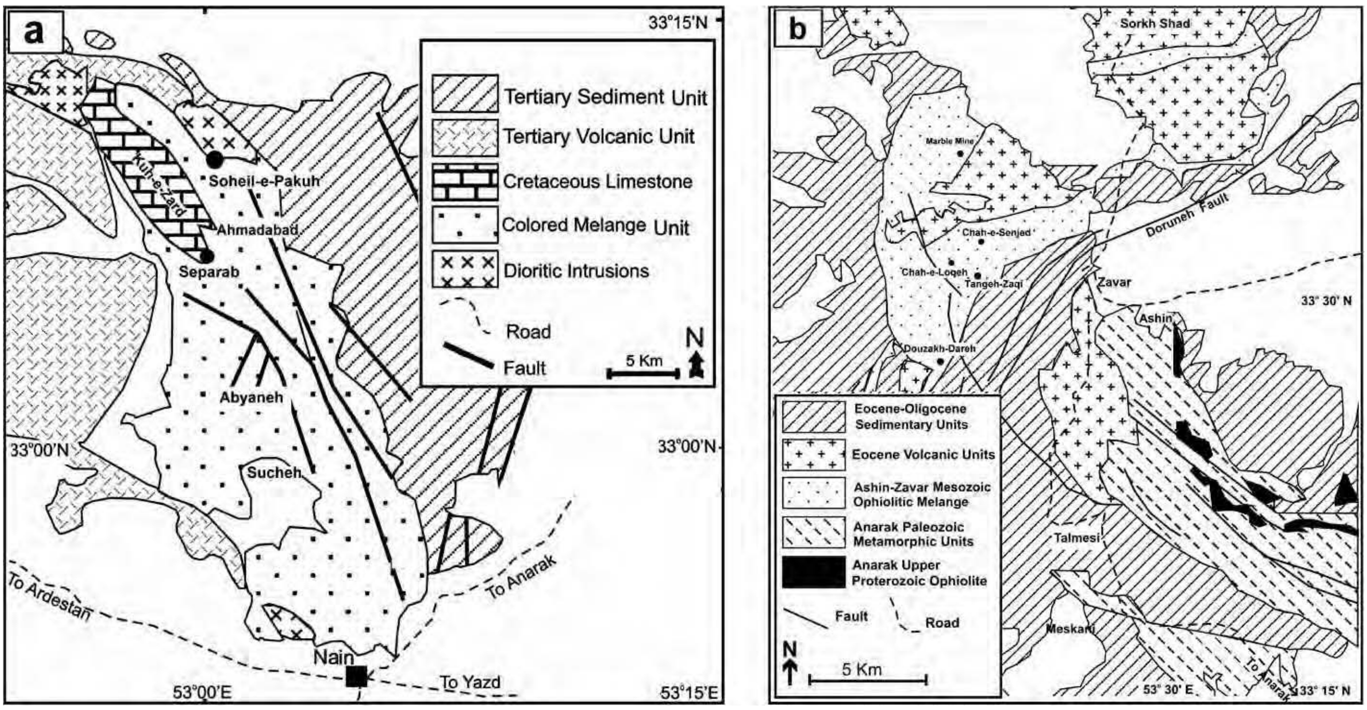

Fig. 2 - Geological maps of the: (a) Nain ophiolitic mélange (after Davoudzadeh, 1972); (b) Ashin-Zavar ophiolitic mélange.

University and under an accelerating voltage of 15 kV and a beam current of 15 nA. JEOL software made ZAF corrections for data reduction. Natural and synthetic minerals of known composition were used as standards. The Fe^{3+} content of minerals was estimated assuming mineral stoichiometry (Droop, 1987). Representative analyses of the minerals, calculated structural formulas and selected mineral end-members are shown in Table 1. Neutron activation analysis (NAA) was used for analysing the whole rock geochemistry of the amphibolitic rocks from Nain (at the Neutron Activation Center, Isfahan, Iran). Amphibolitic rocks and pillow lavas of Ashin-Zavar were analyzed by means of inductively coupled plasma mass spectrometry (ICP-MS) at the University of Nancy, France. Geochemical data for sheeted dikes and pillow lavas of Nain are taken from Rahmani et al. (2007) and Abdullahi (2007).

HIGHLY METAMORPHOSED ROCKS: AMPHIBOLITES AND AMPHIBOLITIC DIKES

Petrography

Amphibolites and amphibolitic dikes are green to dark green rocks (sometimes yellowish, where altered to epidosite). In both ophiolites, the amphibolitic dikes are linked to amphibolites and disappear in them after crossing a matrix of serpentinized mantle peridotites (Fig. 3). Amphibolitic dikes are supposed by Shirdashtzadeh (2007) to have fed these amphibolitic bodies before being metamorphosed.

In general, the mineralogy of amphibolites and amphibolitic dikes of Nain and Ashin-Zavar are completely similar and mainly consist of quartz, hornblendes that are along the schistosity and plagioclase laths that occupied the spaces among them. However, garnet and clinopyroxene are only observed in the amphibolites and amphibolitic dikes of Nain. Garnets formed during high-grade metamorphism, but along their margins and cracks they have been replaced by low degree minerals like chlorite, epidote, actinolite and calcite.

Chloritization, epidotization, prehnitization and transformation of clinopyroxenes into amphiboles is common in amphibolitic rocks, and it is testified by the presence of chlorite, epidote, actinolite, prehnite, calcite and sphene as accessory minerals. Sphene mostly occurs along the lineation formed by amphiboles. Prehnite, chlorite and calcite are also seen in veinlets as secondary products. Other minerals such as pectolite, actinolite, garnet, xonotlite and chlorite also developed in fractures especially those of some amphibolites that were locally transformed into rodingites.

Mineral chemistry

Amphiboles are the main mineral in the amphibolitic rocks and they include tschermakitic hornblende in Nain and magnesio-hornblende in Ashin-Zavar (Table 1). They mainly have a nematoblastic texture but granuloblastic and poikiloblastic textures are also common.

Clinopyroxene in the amphibolites and amphibolitic dikes of Nain is diopside with an average composition of $En_{34.24}Wo_{48.35}Fs_{17.34}$ (Table 1). In their margins, amphiboles show how they were transformed via metamorphic reactions. Berger et al. (2005) suggested to use the diagram of Al vs. Ti + Cr + Na to distinguish metamorphic from igneous clinopyroxenes in the amphibolites of the Limousin ophiolite. Clinopyroxenes from the Nain amphibolitic rocks and pillow lavas studied in this paper plot within the igneous clinopyroxene field of this diagram (Fig. 4).

In the Nain ophiolite, plagioclases are mostly albite and have a high content of Na_2O (Table 1) because they have been affected by sub-sea floor metamorphism and spilitization; in the fresh samples, instead, the feldspar is andesine. Samples from Ashin-Zavar have plagioclases of andesine-oligoclase composition (Table 1). In contrast to the amphibolitic dikes, the amphibolites have higher Na values in plagioclases. This is because of stronger spilitization on the primary pillow lavas and basalts than on the diabasic dikes. Garnets that are only in the Nain samples have high almandine content. They are mostly almandine-grossular (Table 1).

Mineralogical analysis shows that clinopyroxenes and calcic plagioclases were two common primary igneous minerals but amphiboles and albites were produced from those minerals by later metamorphic and spilitization processes.

Geothermobarometry

Application of the hornblende-plagioclase geothermometry (Holland and Blundy 1994) and Al geobarometry in plagioclase (Schmidt 1992) for amphibolites, indicate an average pressure of 7.3 Kbars and temperatures of 727.15 ºC in Nain, and 6.8 Kbars and 675.8 ºC in Ashin-Zavar, respectively (Torabi et al., 2008b).

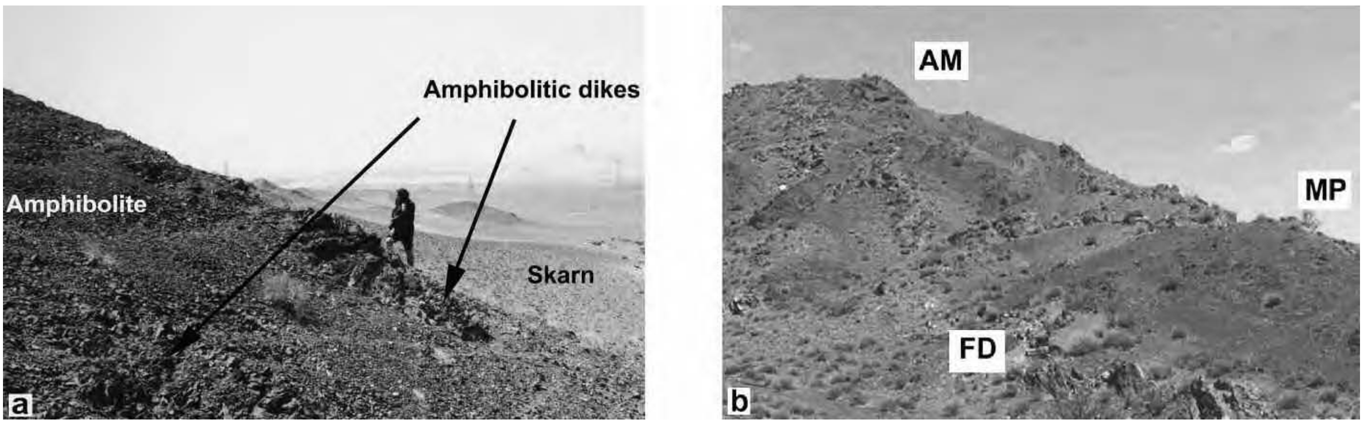

Fig. 3 - Field photos of Nain and Ashin-Zavar. Amphibolitic dike within serpentinized mantle peridotites: (a) Nain ophiolitic mélange, north of the Nain city; (b) Ashin-Zavar ophiolitic mélange, Chah-e-Senjed. (FD- Foliated amphibolitic dikes; MP- mantle peridotites; AM- amphibolites).

Table 1 - Mineral compositions (wt%) of amphibolites, amphibolitic dikes, and pillow lavas from Nain and Ashin-Zavar ophiolitic mélanges

Region	**Nain**										**Ashin -Zavar**					**Nain** (from Abdullahi 2007)					**Ashin -Zavar**	
Rock Type	**Amphibolite**						**Dike of Amphibolites**				**Amphibolite**			**Dike of Amphibolites**		**Pillow Lavas**					**Pillow Lavas**	
Sample	**4 Amp**	**1 Pl**	**2 Pl**	**1 Grt**	**4 Cpx**	**2 Prh**	**4 Amp**	**2 Grt**	**4 Cpx**	**Prh**	**3 Amp**	**2 Pl**	**1 Ilm**	**4 Amp**	**1 Pl**	**9 Cpx**	**2 Pl**	**2 Pl**	**8 Spl**	**5 Pmp**	**5 Spl**	**2 Amp**
SiO_2	42.62	61.91	68.05	37.88	51.10	43.51	43.00	38.43	51.00	42.85	45.29	61.40	0.04	48.12	60.31	52.58	66.64	60.21	0.07	35.53	0.06	49.83
Al_2O_3	12.41	11.62	19.50	21.48	2.42	24.16	12.66	21.75	2.20	21.07	11.61	24.06	0.24	7.97	24.59	2.69	21.24	23.09	30.62	20.18	32.06	14.13
TiO_2	1.17	0.00	0.00	0.19	0.25	0.09	1.12	0.09	0.21	0.00	0.73	0.01	50.31	0.94	0.01	0.35	0.18	0.27	0.25	0.25	0.31	1.48
Cr_2O_3	0.03	0.00	0.00	0.03	0.01	0.00	0.05	0.02	0.02	0.00	0.06	0.00	0.03	0.02	0.00	0.23	0.00	0.00	35.38	0.04	34.37	0.80
FeO*	17.08	0.17	0.14	24.32	10.11	0.22	17.32	23.62	10.42	4.08	14.41	0.03	43.63	15.40	0.06	5.50	0.14	1.88	14.41	7.86	14.44	8.55
MgO	10.21	0.00	0.20	2.95	11.73	0.01	9.91	2.67	11.70	0.00	12.23	0.01	4.16	13.46	0.00	18.46	0.01	0.69	16.46	2.82	18.35	4.23
MnO	0.43	0.03	0.01	3.28	0.41	0.03	0.20	2.05	0.25	0.00	0.31	0.00	0.04	0.28	0.00	0.18	0.03	0.07	0.13	0.12	0.23	4.87
CaO	11.57	15.40	0.07	10.40	22.82	26.28	11.60	12.00	23.21	26.51	11.07	5.31	0.00	10.79	6.25	19.82	1.41	9.70	0.04	20.68	0.03	11.76
Na_2O	1.61	9.80	11.98	0.03	0.59	0.08	1.91	0.06	0.56	0.06	1.60	8.34	0.00	0.98	7.75	0.22	10.63	3.82	0.01	0.16	0.00	2.25
K_2O	0.86	0.06	0.10	0.00	0.00	0.01	0.35	0.00	0.01	0.01	0.67	0.10	0.00	0.24	0.09	0.01	0.03	0.10	0.00	0.07	0.01	0.08
NiO	0.03	0.00	0.00	0.00	0.04	0.02	0.00	0.00	0.02	0.00	0.02	0.00	0.00	0.01	0.00	0.04	0.00	0.00	0.05	0.00	0.00	0.00
Total	97.97	99.00	100.03	100.56	99.48	94.35	98.12	100.67	99.61	94.58	97.98	99.25	98.46	98.20	99.07	100.02	100.29	99.82	97.44	87.71	99.86	97.95
Oxy*	23.00	8.00	8.00	12.00	6.00	22.00	23.00	12.00	6.00	22.00	23.00	8.00	3.00	23.00	8.00	6.00	8.00	8.00	32.00	26.00	32.00	23.00
Si	6.30	2.90	2.98	2.97	1.93	6.06	6.35	3.00	1.92	6.09	6.53	2.74	0.00	6.84	2.70	1.91	2.91	2.69	0.02	6.58	0.01	7.29
Al	2.16	0.64	1.01	9.03	0.11	3.97	2.17	9.01	0.10	3.53	1.97	1.28	0.01	1.34	1.30	0.11	1.09	1.22	8.40	4.40	8.64	2.06
Ti	0.13	0.00	0.00	0.01	0.01	0.01	0.13	0.01	0.01	0.00	0.08	0.00	0.95	0.10	0.00	0.01	0.01	0.01	0.04	0.03	0.05	0.16
Cr	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.01	0.00	0.00	6.64	0.00	6.22	0.10
Fe^{2+}	1.41	0.01	0.01	1.54	0.25	0.03	1.60	1.54	0.25	0.00	0.94	0.00	0.92	0.66	0.00	0.11	0.01	0.07	2.18	1.22	1.76	1.06
Fe^{3+}	0.70	0.00	0.00	0.06	0.07	0.00	0.54	0.01	0.09	0.49	0.80	0.00	0.00	1.17	0.00	0.06	0.00	0.00	0.67	0.00	1.00	0.00
Mg	2.25	0.00	0.01	0.35	0.66	0.00	2.18	0.31	0.66	0.00	2.63	0.00	0.16	2.86	0.00	1.00	0.00	0.05	5.82	0.78	6.25	1.95
Mn	0.05	0.00	0.00	0.22	0.01	0.01	0.03	0.14	0.01	0.00	0.04	0.00	0.00	0.04	0.00	0.01	0.00	0.00	0.02	0.02	0.04	0.03
Ca	1.83	0.77	0.00	0.87	0.92	3.92	1.84	1.01	0.94	4.04	1.71	0.26	0.00	1.65	0.30	0.77	0.07	0.47	0.01	4.09	0.01	1.85
Na	0.46	0.89	1.02	0.01	0.05	0.02	0.55	0.01	0.04	0.02	0.45	0.73	0.00	0.27	0.67	0.02	0.90	0.33	0.00	0.06	0.00	0.59
K	0.16	0.00	0.01	0.00	0.00	0.00	0.07	0.00	0.00	0.00	0.12	0.01	0.00	0.04	0.01	0.00	0.00	0.01	0.00	0.02	0.00	0.02
Ni	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	15.46	5.22	5.03	15.05	4.00	14.01	15.44	15.01	4.00	14.16	15.28	4.99	2.04	14.96	4.98	4.00	4.99	4.85	24.00	17.21	24.00	15.50
Albite		53.40	99.15									73.55			68.80		93.05	43.10				
Anorthite		46.40	0.35									25.90			30.70		6.80	56.20				
Orthoclase		0.20	0.50									0.55			0.50		0.15	0.70				
Wollastonite					48.14				48.57							39.68						
Enstatite					34.42				34.06							51.43						
Ferrosilite					17.32				17.36							8.88						
Almandine				51.65				51.54														
Andradite				2.70				0.25														
Grossular				26.52				33.21														
Pyrope				11.57				10.36														
Spessartine				7.31				4.54														
Uvarovite				0.08				0.05														

* Oxygen per formula unit

Amp- Amphibole; Cpx- Clinopyroxene; Pl- Plagioclase; Grt- Garnet; Prh- Prehnite; Pmp- Pumpellyite; Spl- Spinel; Ilm- Ilmenite.

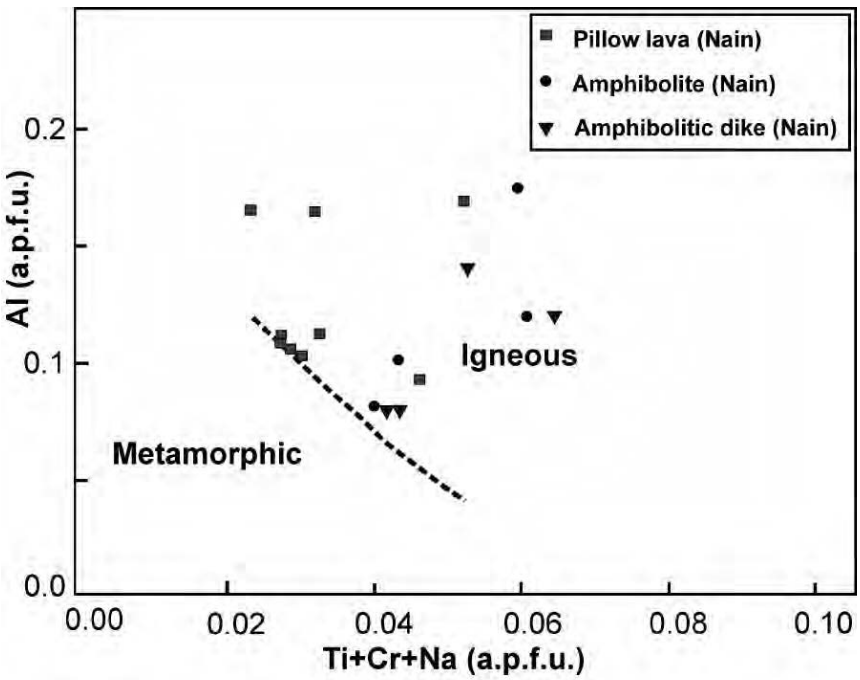

Fig. 4 - Clinopyroxenes compositions from amphibolitic rocks of the Nain ophiolite. The compositional gap between metamorphic and magmatic pyroxenes has been defined by Berger et al. (2005).

These intermediate to high pressure and temperature values confirm that initial basaltic and diabasic rocks have been turned into amphibolitic units by high-grade regional metamorphism in P-T conditions of amphibolite to lower granulite facies. This regional metamorphism is defined as RM_1.

Whole rock geochemistry

Based on the geochemical data, the SiO_2 content is about 41-49% for Nain and 44-55% for the Ashin-Zavar samples. Therefore, they commonly show a basaltic to picrobasaltic composition. However, spilitization caused alteration of the alkalis.

The amphibolite samples show an alkaline character on the total alkali versus silica diagram of Irvine and Baragar (1971) because they have been possibly affected by alkali enrichment before/during metamorphism (spilitization and sub-sea floor metamorphism) of the primary rocks that strongly changed their whole rock major elements geochemistry.

The chemical variations of major elements make it hard to interpret the geochemical data, especially regarding major elements and fluid mobile elements. Immobile elements data can be more successful in interpreting the original oceanic character of these ophiolitic basic rocks.

On the chondrite normalized REE patterns, the samples from Nain have more variable frequency range of Rare Earth elements than those from Ashin-Zavar. Amphibolites from both areas display a relatively flat pattern, suggesting an arc related origin (Fig. 5a), while the amphibolitic dikes show LREE depletion implying a mid-ocean ridge setting (Fig. 5b). On the other hand, their low LREE contents confirm that they did not form from alkaline magmas.

On elemental ratio diagrams such as Ta/Yb vs. Th/Yb (Fig. 5e), calc-alkaline basalts (CAB) have higher Th/Yb than island arc tholeiitic (IAT) basalts. This provides further evidence of the chemical effects of fluids derived from the subduction zone carrying Th to the mantle-wedge source of arc basalts (Pearce 1996). Whereas MORB and WPB plot near the mantle array, arc basalts (both CAB and IAT) have lower Ta/Yb than rift-related basalts and typically plot above the mantle array.

Nevertheless, the Nain amphibolitic units have slightly higher Ta/Yb and Th/Yb ratios in contrast to the samples from Ashin-Zavar (Fig. 5e). This diagram clearly shows that they must have originated from a relatively depleted mantle source with an oceanic rift-related and tholeiitic affinity.

Summing up, the geochemical data indicate that diabasic dikes, pillow lavas, and massive basalts have been generated in a mid oceanic ridge related to a back arc basin, then they have been metamorphosed to the present amphibolitic units. Thus, their current composition is a consequence of spilitization, sub-sea floor metamorphism and RM_1 regional metamorphism and, as it will be explained later, the retrograde metamorphism of RM_2.

NOT HIGHLY METAMORPHOSED ROCKS: PILLOW LAVAS AND SHEETED DIKES

Pillow lavas and sheeted dikes of Ashin-Zavar have been studied by Torabi (2004). A comparable research on pillow lavas and basic sheeted dikes of the Nain ophiolite by Abdullahi (2007) and Rahmani et al. (2007) shows that generally these rocks partially suffered greenschist facies metamorphism.

PILLOW LAVAS

Petrography

In the Nain and Ashin-Zavar ophiolitic mélanges, pillow lavas are green, dark green to brown and occur as spherical and elliptical masses ranging between 40 cm and 2 m in diameter. Volcanoclastic and marine sediments mostly occupy the spaces between pillows. Polygonal fractures, produced by sudden cooling, are observed on the pillow surface and appear radial in section (Abdullahi, 2007; Torabi et al., 2008a).

These fractures speeded up the spilitization process. Radiolarian cherts and then Globotruncana limestones covered these rocks.

Pillow lavas of Nain and Ashin-Zavar contain plagioclase and chloritized olivine as main minerals and clinopyroxene, chromian spinel, chlorite, pumpellyite, calcite, amphibole and magnetite as accessory minerals, with common intersertal, variolitic, and porphyric microtextures (Abdullahi, 2007; Torabi et al., 2008a). Pillow lavas from Ashin-Zavar are mainly made up of plagioclase and olivine, but clinopyroxene, chlorite, pumpellyite, chromian spinel, calcite and magnetite are also present in minor amounts. In the Nain samples, clinopyroxenes and chromian spinels were not strongly affected by metamorphism, while olivines are

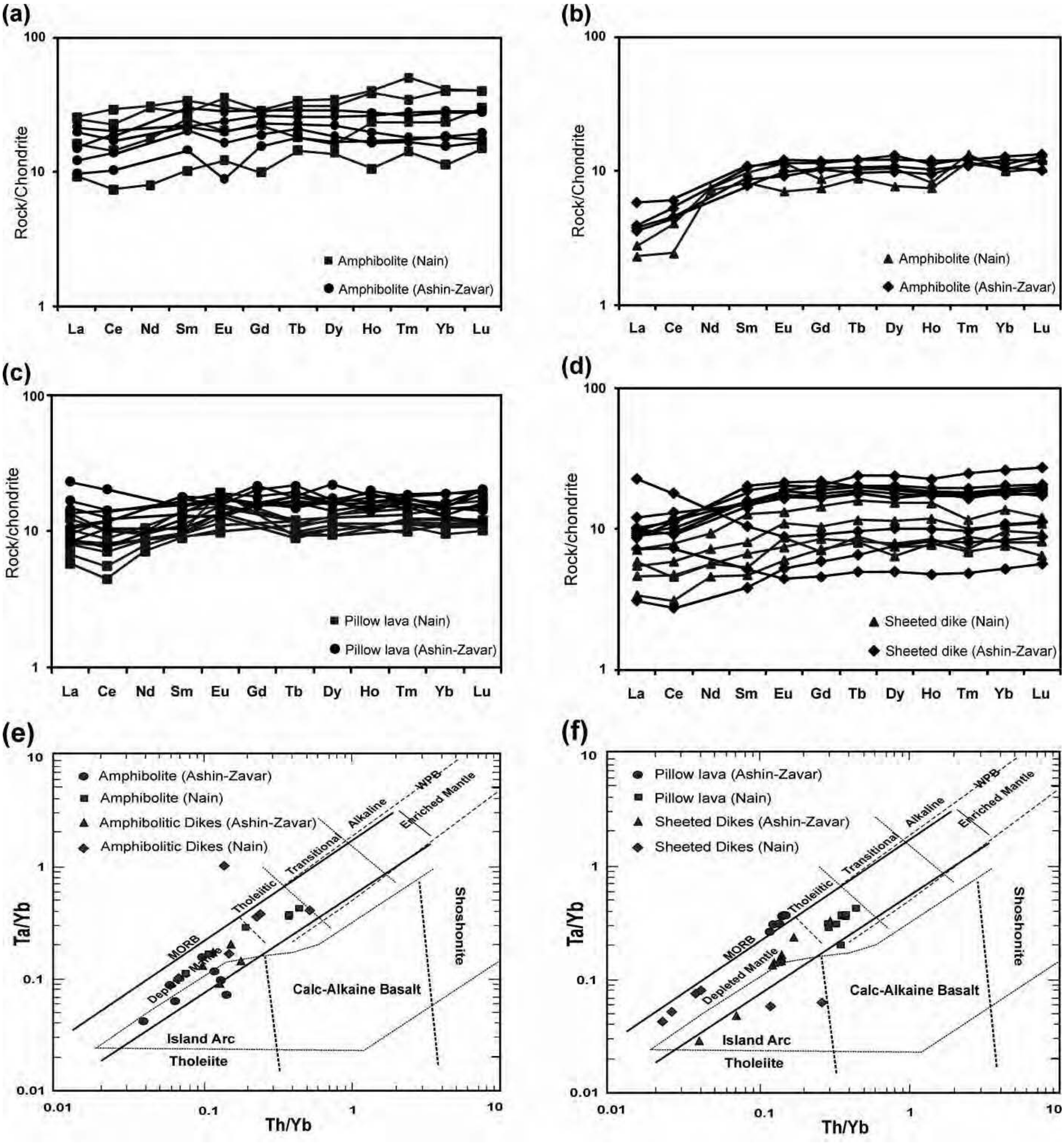

Fig. 5 - Whole rock compositions of amphibolitic rocks (Torabi, 2004; Shirdashtzadeh, 2007), sheeted dikes (Rahmani et al., 2007) and pillow lavas (Torabi, 2004; Abdullahi, 2007): (a) and (b) Chondrite-normalized REE plots for amphibolites and amphibolitic dikes from the Nain and Ashin-Zavar ophiolitic mélanges (normalizing values from Sun and McDonough, 1989); (c) and (d) Chondrite-normalized REE plots for pillow lavas and sheeted dikes from the Nain and Ashin-Zavar ophiolitic mélanges (normalizing values from Sun and McDonough, 1989); (e) and (f) Ta/Yb vs. Th/Yb tectonomagmatic discrimination diagrams for amphibolites, amphibolitic dikes, pillow lavas and sheeted dikes in the ophiolitic mélanges of Nain and Ashin-Zavar (from Pearce, 1982).

entirely chloritized. Clinopyroxenes are surrounded by plagioclase laths. This mineral assemblage shows a greenschist facies low-grade sub-seafloor metamorphism.

Mineral chemistry

The Nain clinopyroxenes (that are primary and igneous, see Fig. 4) changed into amphiboles and even pumpellyite (Torabi et al., 2008a), but the fresh ones have a composition of augite with Mg# of 0.85 (Table 1). The spinels are brown fine-grained and euhedral with Cr# of 0.39 to 0.47 (Torabi et al., 2008a).

The Ashin-Zavar spinels have Cr# of 0.40 to 0.44 (Torabi, 2004) and they sometimes contain inclusions of amphiboles (magnesio-hornblende) and chlorites (Table 1). Plagioclases are mostly albitized primary basic plagioclases and show Na enrichment (~ 2.25-7.2 wt%, see Table 1) that classifies them chemically as labradorite to albite, but the fresh samples are labradorites (Table 1; Abdullahi, 2007; Torabi et al., 2008a).

Whole rock geochemistry

According to whole rock data, the SiO_2 content is about 45-58% in the Nain pillow lavas and 44 to 54% in the Ashin-Zavar ones. Pillow lavas from Nain show a basaltic to andesitic composition (Torabi et al., 2008a) whereas they are mostly olivine-basalt to andesite in Ashin-Zavar (Torabi, 2004).

Pillow lavas underwent sub-sea floor metamorphism and spilitization, so they show Na enrichment in both plagioclase and whole rock compositions (~ 1.49-4.49%, see Table 2) due to the Na and some other major elements mobility (i.e., Mg, K, and Fe) (Pearce, 1982). Because of this, despite being subalkaline rocks, they display a close similarity to alkaline rocks on the $K_2O + Na_2O$ vs. SiO_2 diagram, especially in the Ashin-Zavar samples.

The low Mg# of pillow lavas in Nain and Ashin-Zavar, which is less than 0.40, together with the abundance of clinopyroxenes indicate that these rocks were not primary melts (Allan et al., 1988). Some immobile elements can be mobile to some extent during hydrothermal alteration in submarine hydrothermal systems (Nesbitt et al., 1999 and Jiang, 2000). Thus, the best geochemical data can be obtained by studying the HFS elements.

On the chondrite normalized REE spider diagram (Fig. 5c), the samples from Ashin-Zavar show more REE enrichment than the samples from Nain. Similarity in LREEs is more apparent rather than in HREEs. They roughly display an identical tendency to island arc tholeiites. On the Ta/Yb-Th/Yb diagram (Fig. 5f) they show a depleted mantle source and rift-related tholeiitic affinity.

Therefore, the whole rock geochemistry of pillow lavas shows an island arc tholeiitic affinity, suggesting their origin in a mid ocean ridge setting related to a back arc basin.

Chromian spinel geochemistry

Many authors (i.e. Arai, 1992; Lanaz and Kamenetsky, 2000; Barnes and Roeder, 2001; Kamenetsky et al., 2001; Matsumoto and Arai, 2001) utilized chromian spinels to monitor magma evolution in different tectonic settings. The mineralogical and compositional variations of the pillow lavas, and the metamorphic events that affected them, caused uncertainty in whole rock geochemistry, therefore, only chromian spinels are considered here as reliable petrogenetic indicators. In pillow lavas of Nain and Ashin-Zavar, chromian spinels occur either as micro phenocrysts or as inclusions in other phenocryst minerals. Three major types of magmas, including within-plate basalts, MORB and island arc basalts, have been discriminated based on the TiO_2 content of spinels against their Fe^{3+}# [= $Fe^{3+}/(Cr + Al + Fe^{3+})$] (Arai, 1992). In fact, TiO_2 occurs in very small amount (possibly up to 0.5 vol%) in MORBs and it seems to be restricted to the most primitive olivine-rich basalts with picritic character and other Cr-rich primitive melts (Sigurdsson and Schilling, 1976). Typical low FeO/(FeO + MgO) ratios of this magma type mentioned to no significant fractionation during the ascent (Yong, 1999). Spinels of MORBs appear to be Al-rich (Sigurdsson and Schilling, 1976) and with a range of Cr# of 0.2 to 0.6 in a not wide range of Mg# and low Ti (Dick and Bullen, 1984).

Chromian spinels in pillow lavas are used to compare the Nain and Ashin-Zavar ophiolites genesis. In Fig. 6, spinels from two areas fall in the MORB field. Consequently, spinel compositions suggest that pillow lavas from Nain and Ashin-Zavar were produced in an identical tectonic setting: a mid oceanic ridge with tholeiitic magmas.

SHEETED DIKES

Petrography and mineral chemistry

These rocks have been investigated chiefly by Torabi (2004) in Ashin-Zavar and by Rahmani et al. (2007) in the Nain ophiolites. These authors found that the sheeted dikes have andesite, quartz-dolerite to basalt compositions in Nain, and diabase, diorite to quartz-diorite compositions in Ashin-Zavar.

Rahmani et al (2007) examined the general mineralogy of the sheeted dikes from Nain which includes plagioclase (labradorite to oligoclase), clinopyroxene (augite) and opaque minerals (magnetite, titanomagnetite and chalcopyrite). Sphene, apatite and chromian spinel are also present as accessory minerals. High Mg and low Ti chromian spinels in the Ashin-Zavar sheeted dikes can testify the high partial melting of a depleted mantle (cf. chromian spinel data by Rahmani et al., 2007).

In Ashin-Zavar, the sheeted dikes are composed mainly of plagioclase (bytownite to albite) and include clinopyroxene, amphibole (actinolite), chlorite, quartz and magnetite as minor minerals (Torabi, 2004).

Whole rock geochemistry

Sheeted dikes from both areas show the effects of spilitization. However, their geochemistry suggests that they were originally subalkaline rocks.

Their chondrite normalized REE patterns are approximately identical to those of MORBs (Fig. 5d). They have not undergone high-grade metamorphism as amphibolitic rocks. In the sheeted dikes, the average chondrite normalized amount of La/Yb is about 0.587 whereas it is 0.330 in the amphibolitic dikes. Thus, their LREE depletion is higher than in the amphibolitic dikes and they show a relatively higher affinity to MORB. Moreover, the sheeted dikes (and pillow lavas) have higher Ta/Yb and Th/Yb contents (in contrast to amphibolitic rocks).

On the Ta/Yb vs. Th/Yb diagram, they are distributed in MORB and depleted mantle fields (Fig. 5f).

Table 2 - Major and trace element compositions of amphibolitic rocks, pillow lavas and sheeted dikes taken from Nain and Ashin-Zavar ophiolitic mélanges.

Sample	SiO_2	TiO_2	Al_2O_3	Fe_2O_3*	MnO	MgO	CaO	Na_2O	K_2O	LOI	Total	Mg#
Nain – Amphibolites:												
39	42.89	1.75	12.62	14.08	0.21	8.44	14.90	3.88	0.20	1.02	99.99	0.37
44	42.31	2.17	13.02	15.78	0.23	8.16	15.63	1.19	0.36	1.15	100.00	0.34
45	41.07	2.27	12.87	14.90	0.17	8.60	17.45	1.21	0.25	1.21	100.00	0.37
63	48.37	0.63	14.31	9.36	0.14	11.06	10.23	2.53	2.01	1.35	99.99	0.54
Ashin-Zavar – Amphibolites:												
225	45.14	2.07	13.64	13.70	0.26	8.99	11.42	2.83	1.08	0.87	100.00	0.40
F-269-1	48.62	1.78	13.77	13.06	0.24	6.76	10.80	2.59	0.84	1.20	99.66	0.34
372	55.20	1.12	13.87	10.19	0.21	4.64	8.49	3.73	1.20	1.34	99.99	0.31
374	54.94	1.43	13.99	10.62	0.21	4.66	7.99	3.83	1.08	1.25	100.00	0.30
376	44.08	0.98	13.61	12.67	0.22	10.46	13.96	1.91	0.61	1.49	99.99	0.45
Nain - Amphibolitic Dikes:												
42	49.25	0.52	16.40	9.61	0.17	8.62	10.59	2.20	0.54	2.10	100.00	0.47
66	41.93	0.72	11.53	11.47	0.18	15.90	16.16	0.98	0.20	0.93	100.00	0.58
Ashin-Zavar - Amphibolitic Dikes:												
239	49.43	0.48	15.93	8.68	0.15	7.56	12.56	2.55	0.28	2.37	99.99	0.47
F-239-1	47.60	0.60	15.26	9.27	0.15	7.88	14.23	1.87	0.14	2.76	99.76	0.46
251	51.36	0.82	15.99	8.61	0.15	7.16	9.40	3.84	0.76	1.91	100.00	0.45
397	55.41	0.85	15.93	9.28	0.17	4.19	7.54	4.07	1.10	1.46	100.00	0.31
Nain - Pillow Lavas (taken from Abdullahi 2007):												
p1	54.95	0.45	14.36	8.56	0.13	4.05	10.58	3.22	0.55	3.14	99.99	0.32
p2	54.89	0.73	15.82	8.95	0.14	4.43	8.45	3.13	0.55	2.91	100.00	0.33
p4	54.03	0.92	14.50	8.89	0.14	4.49	10.28	3.11	0.60	3.03	99.99	0.34
p10	54.75	0.98	15.48	10.77	0.18	3.68	5.93	4.34	0.71	3.18	100.00	0.25
p11	53.37	1.23	15.46	11.47	0.19	3.51	6.60	4.49	0.71	2.97	100.00	0.23
p18	55.28	0.63	15.44	8.76	0.15	3.66	9.44	2.71	0.72	3.20	99.99	0.29
p19	57.63	0.70	14.02	7.61	0.12	3.68	9.75	3.18	0.26	3.03	99.98	0.33
p19-1	57.99	0.63	14.74	8.14	0.13	3.43	8.83	2.80	0.31	2.99	99.99	0.30
p22	56.85	0.80	14.46	9.04	0.13	3.80	9.39	2.25	0.18	3.11	100.01	0.30
Ashin-Zavar - Pillow Lavas:												
7	45.13	2.12	13.61	11.55	0.21	5.85	12.72	3.90	1.82	3.10	100.01	0.34
171	45.58	1.57	16.61	7.01	0.13	2.72	10.86	6.42	0.29	8.82	100.01	0.28
246	45.74	1.18	14.14	9.11	0.19	4.68	13.11	4.04	0.46	7.35	100.00	0.34
271	47.14	1.00	15.89	8.78	0.15	4.23	12.96	3.09	1.20	5.56	100.00	0.33
165	49.54	1.22	17.71	9.31	0.17	5.34	11.28	3.23	0.39	1.82	100.01	0.36
168	50.37	1.33	15.99	9.09	0.13	5.31	9.65	4.19	0.59	3.34	99.99	0.37
164	51.93	1.13	15.57	9.02	0.15	5.32	9.46	4.27	0.27	2.87	99.99	0.37
255	52.63	0.83	15.33	7.95	0.65	3.08	8.44	3.68	1.81	5.61	100.01	0.28
284	52.78	1.03	13.42	9.78	0.22	3.60	8.27	5.66	0.24	5.00	100.00	0.27
321	54.97	1.43	14.57	9.06	0.15	2.44	6.30	7.58	0.30	3.20	100.00	0.21
Nain - Sheeted Dikes (taken from Rahmani et al. 2007):												
RS 6-1	51.06	0.47	15.25	8.74	0.17	8.43	7.39	4.06	0.21	4.10	99.88	0.49
RS 6-9	51.66	1.06	13.69	10.69	0.21	7.11	8.34	4.20	0.04	2.80	99.80	0.40
RS 7	50.71	0.70	15.17	12.50	0.13	8.21	4.34	4.52	0.17	3.40	99.85	0.40
RS 13	53.51	0.51	15.60	8.84	0.15	6.75	5.99	5.42	0.04	3.10	99.91	0.43
RS 20A	47.25	0.51	14.51	8.84	0.21	13.76	7.23	1.91	0.84	4.70	99.76	0.61
Ashin Zavar - Sheeted Dikes:												
1	40.47	1.15	11.98	13.11	0.19	4.76	25.47	1.60	0.08	1.18	99.99	0.27
4	44.87	1.32	14.36	13.74	0.21	6.25	14.33	3.38	0.11	1.43	100.00	0.31
2	48.50	1.52	14.00	13.02	0.21	5.30	12.42	3.30	0.22	1.50	99.99	0.29
F2-1	48.58	1.21	13.96	12.20	0.19	4.67	12.84	2.89	0.16	0.09	96.79	0.28
3	49.25	1.53	13.64	13.50	0.22	6.37	10.91	3.36	0.12	1.10	100.00	0.32
5	50.64	1.27	13.82	13.61	0.19	5.74	9.49	3.92	0.24	1.09	100.01	0.30
241	51.29	0.52	13.89	6.83	0.11	11.22	10.45	3.42	0.12	2.14	99.99	0.62
248	55.97	0.53	15.61	10.48	0.17	3.60	7.09	3.44	0.88	2.23	100.00	0.26
208*	42.84	1.23	18.82	15.00	0.15	5.47	12.69	1.64	0.46	1.69	99.99	0.27
209*	62.37	0.42	14.57	6.48	0.05	4.97	5.01	4.85	0.24	1.04	100.00	0.43

Table 2 (*continued*)

Sample	Ta	Th	La	Ce	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Tm	Yb	Lu
Nain – Amphibolites:														
39	0.61	0.41	3.81	8.83	8.04	3.66	1.14	4.39	0.65	3.95	1.28	0.58	3.79	0.74
44	0.61	0.41	5.83	13.84	13.71	4.10	2.00	5.69	1.22	8.49	2.20	1.24	6.60	0.98
45	0.69	0.49	6.08	17.97	14.23	5.04	1.72	5.50	1.12	7.67	2.12	0.86	6.49	0.99
63	0.50	0.34	2.21	4.54	3.67	1.51	0.69	1.98	0.52	3.39	0.58	0.35	1.82	0.37
Ashin-Zavar – Amphibolites:														
225	<0.30	<0.30	2.88	8.46		3.21	1.34	5.26	0.93	6.37	1.43	0.69	4.57	0.70
F-269-1	0.19	0.18	3.59	11.60		4.44	1.60	5.72	1.05	7.09	1.53	0.65	4.46	0.69
372	<0.30	<0.30	4.67	10.56		3.00	0.93	3.75	0.75	4.52	<0.90	0.41	2.50	0.41
374	0.46	<0.30	5.13	12.58		3.23	1.13	4.62	0.83	5.49	1.08	0.45	2.93	0.43
376	<0.30	<0.40	2.33	6.33		2.16	0.50	3.11	0.65	4.16	0.94	0.43	2.98	0.48
Nain - Amphibolitic Dikes:														
42	0.55	0.38	0.55	1.5	3.27	1.21	0.40	1.49	0.32	1.9	0.41	0.29	1.66	0.30
66	0.55	0.38	0.66	2.5	3.43	1.44	0.65	1.74	0.37	2.6	0.45	0.33	1.61	0.26
Ashin-Zavar - Amphibolitic Dikes:														
239	<0.30	<0.20	0.90	2.80		1.28	0.52	2.07	0.35	2.44	<0.52	0.28	1.71	0.25
F-239-1	0.04	0.00	0.93	3.23		1.62	0.65	2.28	0.44	3.02	0.66	0.30	2.07	0.33
251	<0.26	<0.20	0.85	2.72		1.15	0.56	2.08	0.38	2.66	<0.56	0.27	1.95	0.29
397	<0.27	<0.33	1.38	3.70		1.59	0.69	2.39	0.44	3.26	0.62	0.31	1.83	0.32
Nain - Pillow Lavas (taken from Abdullahi 2007):														
p1	0.65	0.61	2.06	4.74	4.02	1.44	1.10		0.36	2.32		0.25	1.80	0.27
p2	0.73	0.72	1.39	2.76	3.30	1.32	0.58		0.40	2.94		0.30	1.95	0.28
p4	0.72	0.70	3.22	6.29	4.41	1.64	0.86		0.39	2.99		0.31	2.01	0.30
p10	0.69	0.67	2.96	6.20	4.50	2.11	0.86		0.44	3.10		0.33	2.38	0.37
p11	0.79	0.73	2.44	5.40	4.92	2.02	0.98		0.41	3.17		0.36	2.56	0.41
p18	0.62	0.63	1.62	3.43	3.68	1.42	0.72		0.35	2.60		0.28	1.73	0.27
p19	0.69	0.65	1.94	4.88	3.97	1.37	0.55		0.34	2.32		0.29	1.87	0.28
p19-1	0.56	0.57	1.90	4.34	3.98	1.43	0.65		0.32	2.61		0.28	1.80	0.29
p22	0.66	0.67	2.02	5.07	4.03	1.46	0.77		0.36	2.73		0.27	1.56	0.25
Ashin-Zavar - Pillow Lavas:														
7	3.27	10.48	47.33	81.34		8.55	1.83	5.67	1.01	6.17	<1.00	0.49	3.42	0.53
171	1.00	1.43	15.49	28.35		3.20	1.11	3.42	0.58	3.94	0.85	0.40	3.01	0.54
246	<0.27	<0.25	5.51	12.42		2.28	1.00	<3.17	0.54	4.03	0.80	0.40	2.35	0.37
271	<0.26	<0.30	2.27	7.44		2.60	0.88	4.06	0.79	4.23	1.04	0.40	2.11	0.40
165	<0.26	<0.26	3.21	8.58		2.02	1.00	3.20	0.65	3.91	1.08	0.45	3.02	0.50
168	<0.25	<0.25	3.50	7.70		1.87	0.73	3.07	0.60	3.90	0.87	0.43	2.45	0.45
164	<0.30	<0.26	2.10	4.67		1.96	0.72	3.10	0.56	4.13	0.76	0.42	2.62	0.50
255	<0.25	<0.20	1.99	6.50		1.56	0.76	<3.15	0.60	3.54	0.85	0.37	2.08	0.29
284	<0.40	<0.30	4.00	8.86		2.26	0.95	4.31	0.64	4.31	0.90	0.44	2.41	0.35
321	<0.22	<0.27	2.51	7.19		2.68	0.98	3.13	0.65	5.45	<1.00	0.43	2.43	0.50
Nain - Sheeted Dikes (taken from Rahmani et al. (2007):														
RS 6-1	<0.1	0.4	1.4	2.8	2.6	1.0	0.42	1.71	0.30	1.97	0.47	0.18	1.57	0.23
RS 6-9	<0.1	<0.1	1.7	4.8	4.3	1.9	0.75	2.91	0.58	3.82	0.84	0.29	2.23	0.30
RS 7	<0.1	0.2	1.3	3.6	3.3	1.2	0.62	2.07	0.42	2.82	0.65	0.25	1.73	0.27
RS 13	<0.1	<0.1	1.1	2.9	2.6	0.8	0.49	1.40	0.32	1.84	0.42	0.22	1.30	0.20
RS 20A	<0.1	<0.1	<.5	1.0	1.7	1.1	0.37	1.86	0.35	2.38	0.56	0.24	1.92	0.25
Ashin Zavar - Sheeted Dikes:														
1	<0.40	<0.38	2.08	6.89		2.35	1.05	3.57	0.68	4.41	<0.95	0.43	3.05	0.46
4	<0.40	<0.40	2.42	6.91		2.98	1.20	4.34	0.72	4.60	0.97	0.44	2.92	0.47
2	<0.40	<0.38	2.88	8.08		2.20	0.93	3.77	0.72	4.80	1.02	0.45	3.10	0.49
F2-1	0.09	0.13	2.29	7.19		2.77	1.15	3.96	0.74	5.02	1.07	0.48	3.29	0.51
3	<0.41	<0.40	2.22	6.25		2.36	0.96	3.31	0.64	4.12	<0.95	0.43	2.84	0.44
5	<0.45	<0.41	2.15	5.84		2.30	0.99	3.39	0.66	4.13	1.00	0.41	2.93	0.43
241	<0.25	<0.25	1.73	4.54		0.77	0.25	0.91	<0.18	1.23	<0.26	0.12	<0.84	0.14
248	<0.25	<0.25	5.46	11.16		1.56	0.50	1.83	0.35	2.51	0.55	0.24	1.77	0.28
208*	<0.30	<0.23	0.74	<1.70		0.57	0.30	<1.19	0.24	1.89	0.45	0.20	1.35	0.22
209*	<0.20	0.3	2.40	5.61		2.11	1.07	4.10	0.87	5.91	1.24	0.62	4.26	0.68

DISCUSSION

Two distinct oceanic phases have been recorded in the Mesozoic ophiolites (Nain and Ashin-Zavar) of Central Iran. In the following chapter we discuss the petrographic and geochemical data and compare them to interpret the geochemistry of not highly metamorphosed (sheeted dikes and pillow lavas) and highly metamorphosed rocks (amphibolitic dikes and amphibolites):

a. In the Nain and Ashin-Zavar ophiolites, the presence of amphibolitic dikes in amphibolites and mantle peridotites simply shows that these metamorphic rocks formed through metamorphism of igneous basic sequences (sheeted dikes and basic rocks).
b. Clinopyroxenes of highly metamorphosed rocks (amphibolitic rocks) and not highly metamorphosed rocks (pillow lavas and sheeted dikes) have different compositions, diopside and augite, respectively.
c. In both areas, the protoliths of amphibolitic rocks had a basaltic composition while the pillow lavas and sheeted dikes were mostly basalt to andesite, based on major elements chemistry and petrography.

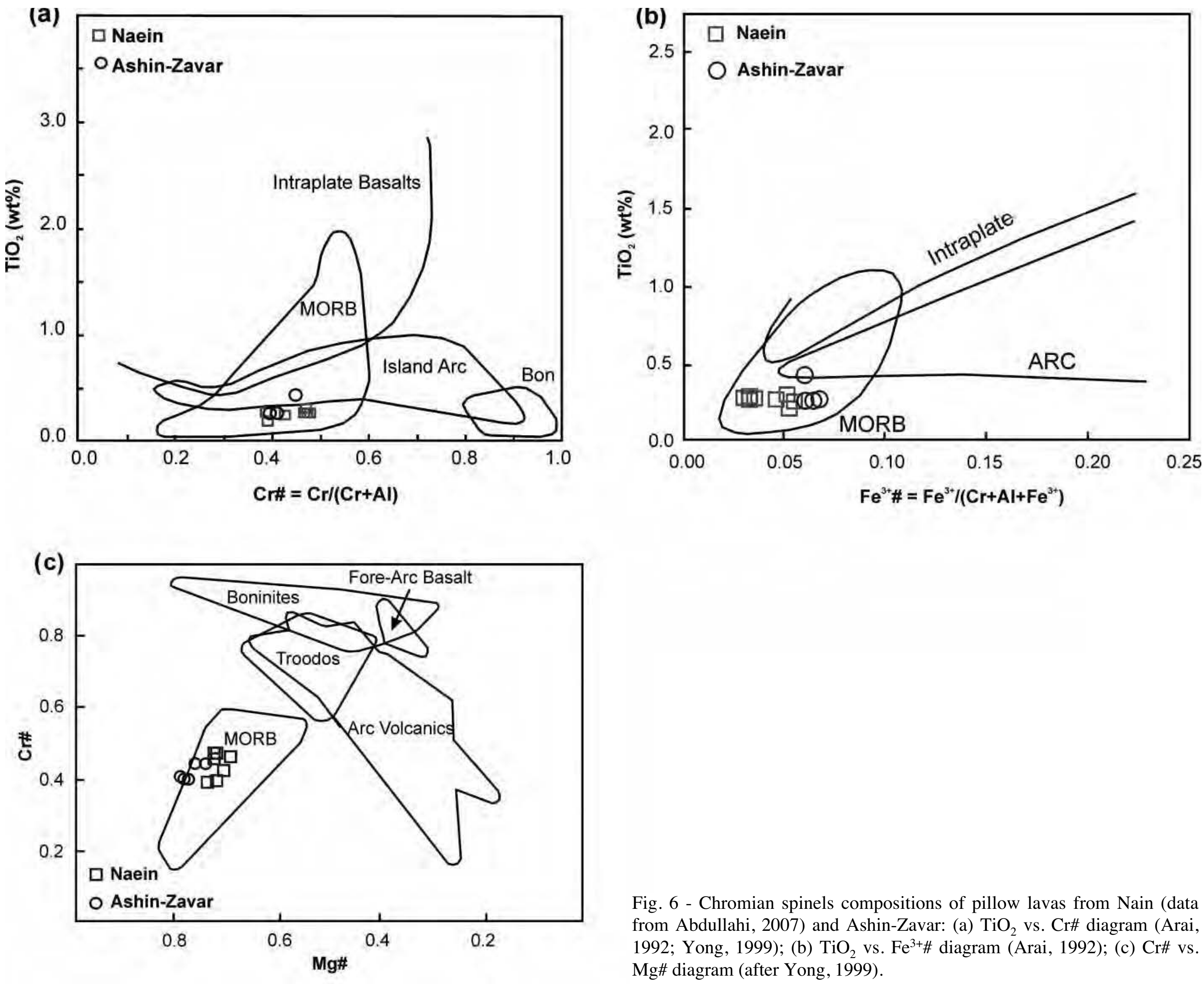

Fig. 6 - Chromian spinels compositions of pillow lavas from Nain (data from Abdullahi, 2007) and Ashin-Zavar: (a) TiO_2 vs. Cr# diagram (Arai, 1992; Yong, 1999); (b) TiO_2 vs. Fe^{3+}# diagram (Arai, 1992); (c) Cr# vs. Mg# diagram (after Yong, 1999).

d. Geochemical data on pillow lavas and sheeted dikes from both regions reveal lower Mg, Mg# and Ti and higher Na and K contents than in their equivalent high-grade metamorphic rocks (amphibolites and amphibolitic dikes, Table 1).
e. Although in both areas, the amphibolites are geochemically similar in part to island arc tholeiites (Fig. 5a and 5c), a MORB affinity is evident in the pillow lavas. Moreover, chromian spinels compositions of pillow lavas reveal a MORB origin (Fig. 6).
f. The amphibolites are a little enriched in REE compared to pillow lavas (Fig. 5a and c).
g. The amphibolitic dikes have slightly lower REE concentrations than the sheeted dikes (Fig. 5b and d).
h. There is a marked LREE depletion especially in the sheeted dikes that causes a closer similarity to mid ocean ridge magmas (Fig. 5b and d). In fact, in the sheeted dikes the average chondrite normalized amount of La/Yb is about 0.587, whereas it is 0.330 in the amphibolitic dikes. Thus, their LREE depletion is higher than in the amphibolitic dikes.
i. In addition, the amphibolitic units (compared to pillow lavas and sheeted dikes) have lower contents of Ta/Yb and Th/Yb ratios (Fig. 5e and f) and are closer to the island arc tholeiite field, which supports their MORB and tholeiitic affinity.
j. Before the RM_1 phase in Early Jurassic, chert and shale-limestone successions covered the protolith of the amphibolites, whereas in Late Cretaceous, Radiolarian cherts and pelagic Glaubotruncana limestones covered the spilitized basaltic rocks (Shirdashtzadeh, 2007). These distinct features suggest that sedimentation took place in two different sedimentary basins.
k. Not highly metamorphosed rocks (sheeted dikes and pillow lavas) formed later, so they were not affected by high-grade metamorphism of the RM_1 and even RM_2 phases, based on the mineralogy and on the lack of S_1 and S_2 foliations (Shirdashtzadeh, 2007).

Thus, these two rock groups should have formed in different times and magmatic settings. Ghasemi and Talbot (2005) sketched the tectonic evolution of the South Sanandaj-Sirjan Zone (SSZ) and Nain-Baft Ocean and ophiolitic mélange. The authors of the present paper made some changes in this scheme to display their findings on it. Both Nain and Ashin-Zavar ophiolites lie along the west CEIM margin and have an identical history; just the Nain one is mentioned in this scheme. The tectonic evolution illustrated in Fig. 7, is described briefly as follows:

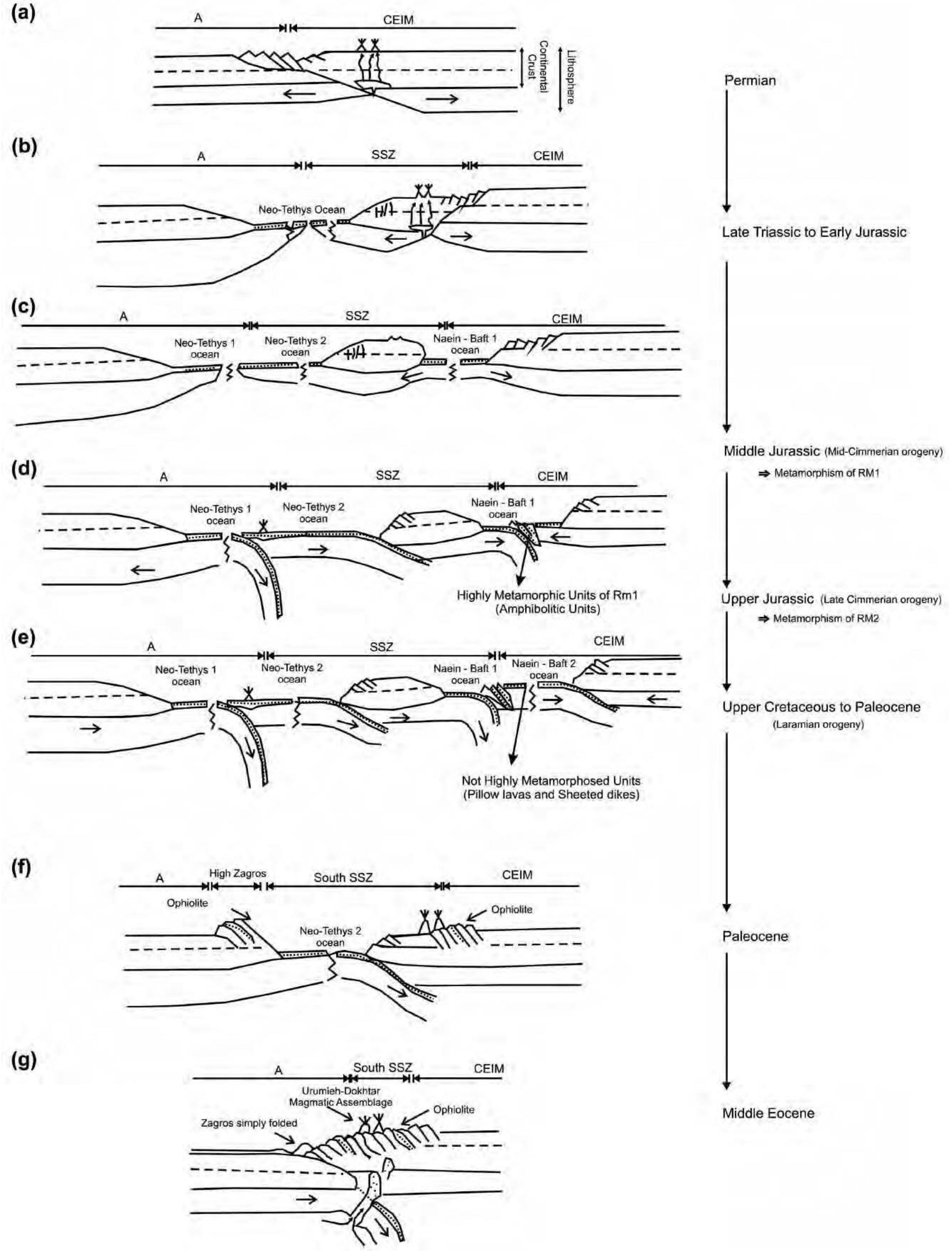

Fig. 7 - Tectonic evolution of the South Sanandaj-Sirjan Zone (SSZ) and Central-East Iranian Microcontinent (CEIM) (taken from Ghasemi and Talbot, 2006): (a) Permian rifting; (b) and (c) Late Triassic to Early Jurassic; second rifting phase of Neo-Tethys in the West and first rifting in CEIM (Nain-Baft 1 Ocean to the East); (d) Middle Jurassic: the closure of the Neo-Tethys and Nain-Baft Oceans occurred at first through collision with an oceanic island arc and the Nain-Baft oceanic crust was affected by RM_1 regional metamorphism, RM_2 metamorphism, sub-seafloor metamorphism and spilitization; (e) Late Jurassic: second rifting phase and generation of pillow lavas and sheeted dikes in the Nain-Baft 2 Ocean, not highly metamorphosed; (f) Ophiolite emplacement along the SSZ and on the CEIM and formation of the Nain ophiolitic mélange by mixing of highly and not highly metamorphosed rocks of the Nain-Baft oceanic crust; (g) Middle Eocene slab break-off (Ghasemi and Talbot, 2006).

Late Paleozoic

The extensional phase in Late Paleozoic caused simple shears and rifting processes that lead to sea-floor spreading and rift volcanism (Fig. 7a and b, Ghasemi and Talbot 2006).

Early Mesozoic

Based on field and laboratory observations, in Late Paleozoic/Early Mesozoic (Sharkovski et al., 1984; Mohajjel et al., 2003; Torabi 2009a and 2010), the Nain-Baft 1 oceanic crust started to spread along the active continental margin of the Central Iranian microplate, as documented in the Nain and Ashin-Zavar ophiolites. Paleomagnetic data (Soffel and Forster, 1984) indicate that the Central-East Iranian Microcontinent rotated counter-clockwise during the Jurassic opening of the Nain-Baft Ocean (Sengor, 1990). This rifting (R_1) produced diabasic dikes and basalts (i.e., the basic source of the amphibolitic rocks) and then pelagic sedimentary rocks including banded cherts, limestones and a shale succession covered them (Shirdashtzadeh, 2007).

According to the whole rock data on the metabasic rocks (Fig. 5a and b), the igneous protolith of amphibolites and amphibolitic dikes had an arc related tholeiitic and MORB character, respectively and they all originated from a depleted mantle in an oceanic setting (Fig. 5e and f).

Early to Middle Jurassic

Sharkovski et al. (1984) obtained an age of 188 Ma (Early Jurassic) for the closure of this oceanic basin, based on K-Ar dating (Torabi, 2004). During closure, the oceanic crust suffered metamorphism in amphibolite facies. The following lithological changes occurred due to RM_1 metamorphism: diabasic dikes were transformed into foliated amphibolitic dikes, basalts and pillow lavas into amphibolites, banded cherts into banded meta-cherts, and limestone-shale successions into marble-shale successions. A later high-grade metamorphic phase caused the complete disintegration of fossil relics and other structures in the sedimentary units.

Davoudzadeh (1972), Lensch and Davoudzadeh (1982), and Sharkovski et al. (1984) claimed that the metamorphic rocks might represent exotic blocks in the Nain ophiolite transported from the metamorphic massif of Anarak-Khur (in the northeast) thorough the counter-clockwise rotation of the Dorouneh fault; instead, field observations show that they are not exotic blocks but they are metamorphic rocks formed through metamorphism of the different ophiolitic rock units. In non highly tectonized areas of both the Nain and Ashin-Zavar ophiolites, it is possible to track the amphibolitic dikes in the mantle peridotites and to observe how they intrude into the amphibolites and gradually disappear in them. This feature is seen in both areas, and demonstrates that the present amphibolitic dikes were originally diabasic dikes that cut through the overlying basalts and pillow lavas, which then were metamorphosed and presently occur as amphibolites.

As mentioned above, the amphibolitic rocks within mantle-peridotites of the Nain and Ashin-Zavar ophiolitic mélanges have a S_1 foliation (reported by Shirdashtzadeh et al., 2010). This foliation could have formed by compressional stress during the closure of the Nain-Baft 1 oceanic basin and the RM_1 metamorphic phase, in the middle Cimmerian orogeny in Middle Jurassic (Fig. 7d). Aghanabati (2006) and Torabi et al. (2011a and 2011b) suggested that the amphibolitic rocks are metamorphic products of the mid-Cimmerian (Middle Jurassic) orogenic phase that caused a sedimentation gap, metamorphism and erosion.

Amphibole and garnet formed during the high-grade RM_1 metamorphism (at P-T conditions of amphibolite to lower granulite facies, based on thermobarometry and mineralogy). The presence of clinopyroxene and garnet in the Nain samples suggests higher RM_1 metamorphism correlated with the granulite facies in the Nain ophiolite, in contrast to the amphibolite metamorphic facies in Ashin-Zavar.

Late Jurassic

In Late Jurassic, the late Cimmerian and other later compressive orogenic phases affected the amphibolites and their associated rocks (banded metacherts, marbles and schists; Shirdashtzadeh, 2007) causing the later metamorphism (RM_2) until oceanic spreading reactivated and produced sheeted and swarm dikes, massive basalts and pillow lavas in the Cretaceous (Fig. 7d).

Foliation S_2 in the amphibolitic units and skarns, chloritization, epidotization, prehnitization and transformation of clinopyroxenes into amphiboles support the idea of a retrograde metamorphism (defined as RM_2) in both study areas. RM_2 has a metamorphic grade up to greenschist facies and correlates with pre-tectonic events of the second phase of the Nain-Baft 2 oceanic rifting (R_2) in Early to Late Cretaceous.

Early to Late Cretaceous

Oceanic magmatism resumed producing sheeted and swarm dikes, massive basalts and pillow lavas in the late Albian (Hassanipak and Ghazi, 2000; Ghasemi and Talbot, 2006), in correlation with the Austrian orogeny (Fig. 7e). A plagiogranite from the Ashin-Zavar ophiolite (Sharkovski et al., 1984; Torabi, 2004) yielded a K/Ar age of 98 Ma. Moreover, three $^{40}Ar/^{39}Ar$ ages of 101.2±0.9, 99.7±0.9, 99±1.2 Ma have been obtained for the crystallization time of hornblende gabbros from Nain (Hassanipak and Ghazi, 2000 and Ghasemi and Talbot, 2006).

Shafaii Moghadam et al. (2009) proposed a back-arc spreading phase in the Nain-Baft basin, lasting a maximum of 45 Ma from Cenomanian to Paleocene. Fig. 7e shows that in early Late Cretaceous, pillow lavas and sheeted dikes might have been produced in the younger rifting system of the Nain-Baft 2 Ocean in which Radiolarian cherts and Globotruncana limestones covered all the oceanic rock units in Late Cretaceous.

Therefore, a new oceanic spreading phase could have started in the upper part of the Early Cretaceous (i.e., Albanian) in both areas, based on datations and on the presence of Late Cretaceous sedimentary rocks (Radiolarian cherts and Glaubotruncana limestones) over the massive basalts and pillow lavas. Pillow lavas and sheeted dikes from both areas are similar in petrography, whole rock geochemistry and chromian spinels compositions (Figs. 5 and 6). Mineralogically, they underwent spilitization and low-grade subseafloor metamorphism (Fig. 7d).

According to the extended RM_1 regional metamorphism, if pillow lavas and sheeted dikes were produced concurrently with the amphibolitic units, then they must have experienced amphibolitic metamorphism too. Nevertheless, RM_1 and RM_2 did not affect the Late Cretaceous limestones and basic rocks (sheeted dikes and pillow lavas), so they should have been formed during the second oceanic rifting phase (R_2) (Fig. 7d). Their different metamorphic degree and their different geochemical and mineralogical features suggest that they formed in a different times.

However, Fig. 7e shows the possible occurrence of older and highly metamorphosed units (e.g., amphibolitic rocks) beside the younger non highly metamorphosed units (e.g., pillow lavas and sheeted dikes).

CONCLUSION

The main result of this study is a metamorphic and tectonic model for two important ophiolites of Central Iran (Nain and Ashin-Zavar), and for the formation of metamorphic rocks in the ophiolitic mélanges through metamorphism of oceanic crust and its overlying sediments.

This study points out that the Jurassic and Cretaceous lithologic sequences are different in Nain and Ashin-Zavar. In fact, there are amphibolites, metamorphosed diabasic dikes (amphibolitic dikes), schists, marbles and quartzites (first formed in rifting R_1 in Early Jurassic and then metamorphosed during later orogenic phases in Middle Jurassic and later) together with spilitized pillow lavas, diabasic dikes and non-metamorphosed limestones (produced via rifting R_2 in Early to Late Cretaceous, dated by Hassanipak and Ghazi 2000, etc.).

Mineralogical and geochemical data revealed that not highly metamorphosed (sheeted dikes and pillow lavas) and highly metamorphosed rocks (amphibolitic dikes and amphibolites) formed in two distinct extensional phases:

A. In Early Jurassic the Nain and Ashin-Zavar oceanic crust started spreading and diabasic dikes and pillow lavas were produced in fissures within the rift. They were covered by pelagic sediments (banded cherts, and then a limestone and shale succession) and they suffered high-grade metamorphism during the closure of this oceanic basin in the mid-Cimmerian orogeny (Middle Jurassic). In Late Jurassic, the late Cimmerian and other later compressive orogenic phases caused the amphibolites and their concurrent rocks (banded metachert, marble and schist) to experience a later metamorphism (RM_2) until oceanic spreading resumed and produced sheeted dikes and pillow lavas in the Cretaceous. Chloritization, epidotization, prehnitization and conversion of clinopyroxenes into amphiboles in amphibolitic rocks were also related to the RM_2 phase. RM_2 reaches a metamorphic grade up to greenschist facies and was correlated with pre-tectonic events of the second phase of oceanic rifting (R_2) in Early to Late Cretaceous.

B. In Early to Late Cretaceous to Paleocene, a new ocean spreading phase occurred and sheeted dikes, massive basalts, and basaltic pillow lavas were generated. They hold no evidence of RM_1 high-grade metamorphism nor of S_2 foliation, developed during RM_2. They just experienced sub-seafloor metamorphism and spilitization and were covered by Late Cretaceous Radiolarian cherts and Glaubotruncana limestones.

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REFERENCES

Abdullahi E., 2007. Petrology of Nain ophiolite pillow lavas (Isfahan Province). M.Sc. Thesis in Petrology, Dept. Geology, Islamic Azad Univ., Khorasgan, Iran, 133 pp.

Alavi-Tehrani N., 1977. Geology and petrography in the ophiolitic range of Sabzevar (Khorassan/Iran). Geol. Survey Iran. Report No. 43.

Allan J.F., Sack R. and Batiza R., 1988. Cr-rich spinels as petrogenetic indicators: MORB-type lavas from the Lamont seamount chain, eastern Pacific. Am. Mineral., 73: 741-753.

Arai S., 1992. Chemistry of chromian spinel in volcanic rocks as a potential guide to magma chemistry. Mineral. Mag., 56: 173-184.

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.

Babaie H.A., Ghazi A.M., Babaie A., La-Tour T.E. and Hassanipak A.A., 2001. Geochemistry of arc volcanic rocks of the Zagros crush zone, Neyriz, Iran. J. Asian Earth Sci., 19 (1/2): 61-76.

Barnes S.J. and Roeder P.L., 2001. The range of spinel compositions in terrestrial mafic and ultramafic rocks. J. Petrol., 42: 2279-2302.

Berger J., Femenias O., Mercier J.C.C. and Demaiffe D., 2005. Ocean-floor hydrothermal metamorphism in the Limousin ophiolites (western French Massif Central): evidence of a rare preserved Variscan oceanic marker. J. Metam. Geol., 23: 795-812.

Celik O.F. and Delaloye M.F., 2006. Characteristics of ophiolite-related metamorphic rocks in the Beysehir ophiolitic mélange (Central Taurides, Turkey), deduced from whole rock and mineral chemistry. J. Asian Earth Sci., 26: 461-476.

Coleman R.G., 1977. Ophiolites: Ancient oceanic lithosphere. Springer-Verlag, Berlin, 229 pp.

Davoudzadeh M., 1972. Geology and petrography of the area north of Naein, Central Iran. Geol. Survey Iran, Report 14, 89 pp.

Davoudzadeh M., 1981. On the rotation of the central-east Iran microplate. N. Jahr. Geol. Paläont., 3: 180-192.

Desmon J. and Beccaluva L., 1983. Mid-oceanic ridge and island arc affinities in ophiolites from Iran: Paleogeographic implication. Chem. Geol., 39: 9-63.

Dick H.J.B. and Bullen T., 1984. Chromian spinel as a petrogenetic indicator in abyssal and alpine-type peridotites and spatially associated lavas. Contrib. Mineral. Petrol., 86: 54-76.

Dilek Y. and Newcomb S., 2003. Ophiolite concept and the evolution of geological thought. Geol. Soc. Am., Spec. Paper, 373, 504 pp.

Dilek Y., Moores E., Elthon D. and Nicolas A., 2000. Ophiolites and oceanic crust: New insights from field studies and the Ocean Drilling Program. Geol. Soc. Am., Spec. Paper, 349, 552 pp.

Droop G.T.R., 1987. A general equation for estimating Fe^{3+} concentrations in ferromagnesian silicates and oxides from microprobe analyses, using stoichiometric criteria. Mineral. Mag., 51: 431-435.

Ghasemi A. and Talbot C.J., 2006. A new tectonic scenario for the Sanandaj-Sirjan Zone (Iran). J. Asian Earth Sci., 26 (6): 683-693.

Ghazi A.M. and Hassanipak A.A., 1999a. Geochemistry, petrology and the origin of Shahr-Babak ophiolite, Central Iran. Ofioliti, 24 (1a): 96-97.

Ghazi A.M. and Hassanipak A.A., 1999b. Geochemistry of sub-alkaline and alkaline extrusive from Kermanshah ophiolite, Zagros suture zone, western Iran: implications for Tethyan plate tectonics. J. Asian Earth Sci., 17 (3): 319-332.

Ghazi A.M. and Hassanipak A.A, 2003. Paleo- and neo-Tethyan ophiolites of Iran: A progress report. Geophys. Res. Abstr., 5: 13476.

Hassanipak A.A. and Ghazi A.M., 2000. Petrochemistry, $^{40}Ar/^{39}Ar$ ages and tectonics of the Naein ophiolite, Central Iran. GSA Ann. Meeting, Reno, Nevada, p, 237-238.

Holland T.J.B. and Blundy J., 1994. Non-ideal interactions in calcic amphiboles and their bearing on amphibole-plagioclase thermometry. Contrib. Mineral. Petrol., 116: 433-447.

Irvine T.N. and Baragar W.R.I., 1971. A guide to the chemical classification of the common volcanic rocks. Can. J. Earth Sci., 8: 523-548.

Jiang S.Y., 2000. Controls on the mobility of high field strength elements (HFSE), U and Th in an ancient submarine hydrothermal system of the Proterozoic Sullivan Pb-Zn-Ag deposit, British Columbia, Canada. Geochem. J., 34: 341-348.

Kamenetsky V.S., Crawford A.J. and Meffre S., 2001. Factors controlling chemistry of magmatic spinels: an eperical study of associated olivine, Cr-spinel and melt inclusions from primitive rocks. J. Petrol., 42: 655-671.

Lanaz D. and Kamenetsky V.S., 2000. Melt inclusions in detrital spinels from SE Alps (Italy-Slovenia): a new approach to provenance studies of sedimentary basins, Contrib. Mineral. Petrol., 139: 748-758.

Lensch G. and Davoudzadeh M., 1982. Ophiolites in Iran. N. J. Geol. Palaont., Mh., p. 306-320.

Lippard S.J., Shelton A.W. and Gass I.G., 1986. The ophiolite of Northern Oman. Geol. Soc. London Mem., 11, 178 pp.

Matsumoto L. and Arai S., 2001. Morphological and chemical variations of chromian spinels in dunite-harzburgite complexes from the Sangun zone (SW Japan): implication for mantle/melt reaction and chromite formation processes, Mineral. Petrol., 73: 305-323.

McCall 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.

Mehdipour Ghazi J., Moazzen M., Rahgoshay M. and Shafaii Moghadam H., 2010. Mineral chemical composition and geodynamic significance of peridotites from Nain ophiolite, central Iran. J. Geodyn., 49: 261-270.

Mohajjel M., Fergusson C.L. and Sahandi M.R., 2003. Cretaceous - Tertiary convergence and continental collision, Sanandaj - Sirjan Zone, western Iran. J. Asian Earth Sci., 21: 397-412.

Nesbitt R.W., Pascual E., Fanning C.M., Toscano M., Saez R. and Almodavar G.R., 1999. U-Pb dating of stockwork zircons from the eastern Iberian Pyrite Belt. J. Geol. Soc., 156: 7-10.

Nicolas A., 1989. Structures of ophiolites and dynamics of oceanic lithosphere. Kluwer, Dordrecht, 367 pp.

Pearce J.A., 1982. Trace element characteristics of lavas from destructive plate boundaries. In: R.S. Thorpe (Ed.), Andesites. Wiley, Chichester, p. 525-548.

Pearce J.A., 1996. A user's guide to basaltic discrimination diagrams. In: D.A. Wyman (Ed.), Trace element geo-chemistry of volcanic rocks: applications for massive sulphide exploration. Geol. Ass. Can., Short Course Notes, 12: 79-113.

Pearce J.A., Lippard S.J. and Roberts S., 1986. Characteristics and tectonic significance of supra-subduction zone ophiolites. Geol. Soc. London Spec. Publ., 16: 77-94.

Pirnia T., Arai S. and Torabi G., 2010. Post deformational impregnation of depleted MORB in Nain lherzolite (Central Iran). J. Mineral. Petrol. Sci., 105: 74-79.

Rahgoshay M., Mehdipour Ghazi J. and Shafaii Moghadam H., 2009. Geochemistry and mineralogy of mantle succession in ophiolites of Naein. Iranian Quart. J. Geosci., 71: 31-44.

Rahmani F., Noghreyan M. and Khalili M., 2007. Geochemistry of sheeted dikes in the Nain ophiolite (Central Iran). Ofioliti, 32 (2): 119-129.

Ramezani J. and Tucker R.D., 2003. The Saghand region, central Iran: U-Pb geochronology, petrogenesis and implications for Gondwana tectonics. Am. J. Sci., 303: 622-665.

Schmidt M.W., 1992. Amphibole composition in tonalite as a function of pressure: An experimental calibration of the Al-in-hornblende barometer. Contrib. Mineral. Petrol., 110: 304-310.

Sengor A.M.C., 1990. A new model for the Late Paleozoic-Mesozoic tectonic evolution of Iran and implications for Oman. In: A.H.F. Robertson, M.P. Searle and A.C. Ries (Eds.), The geology and tectonics of the Oman Region. Geol. Soc. London, Spec. Publ. 49: 797-831.

Shafaii Moghadam H., Rahgoshay M. and Whitechurch H., 2008. Mesozoic back-arc extension in the active margin of the Iranian continental block: constraints from age and geochemistry of the mafic lavas. Ofioliti, 33 (2): 95-103.

Shafaii Moghadam H., Whitechurch H., Rahgoshay M. and Monsef I., 2009. Significance of Nain-Baft ophiolitic belt (Iran): Short-lived, transtensional Cretaceous back-arc oceanic basins over the Tethyan subduction zone. C. R. Geosci., 341: 1016-1028.

Sharkovski M., Susov M., Krivyakin B., Morozov L., Kiristaev V. and Romanko E., 1984. Geology of the Anarak area (Central Iran). Geol. Survey Iran, V/O "Technoexport", Rep. TE/No. 19, 143 pp.

Shirdashtzadeh N., 2007. Petrology of metamorphic rocks of Naein ophiolitic mélange (Isfahan province). M. Sci. Thesis in Petrology, Dept. Geology, Univ. Isfahan, Iran, 192 pp.

Shirdashtzadeh N., Torabi G. and Arai S., 2010. Metamorphism and metasomatism in the Jurassic Nain ophiolitic mélange, Central Iran. N. J. Geol. Paläon., 255 (3): 255-275.

Sigurdsson H. and Schilling J.G., 1976. Spinels in Mid-Atlantic Ridge basalts: Chemistry and occurrence. Earth Planet. Sci. Lett., 29: 7-20.

Soffel H.C. and Forster H.G., 1984. Polar wander path of the Central-East-Iran microplate including new results. N. J. Geol. Paläont., Abhandl., 168: 165-172.

Spear F.S., 1993. Metamorphic phase equilibria and pressure-temperature-time paths. Monograph. Mineral. Soc. Am., 970H, 799 pp.

Stocklin J., 1974. Northern Iran: Alborz Mountain, Mesozoic-Cenozoic orogenic belts, data for orogenic studies. Geol. Soc. London Spec. Publ., 4: 213-234.

Stocklin J., 1968, Structural history and tectonics of Iran, A review. A.A.P.G. Bull., 52 (7): 1229-1258.

Stoneley R., 1974. Evolution of the cntinental mrgins bounding a former Southern Tethys. In: A. Burk and C.A. Drake (Eds.), The geology of continental margins. Springer-Verlag, New York, p, 889-903.

Stoneley R., 1975. On the origin of ophiolite complexes in the southern Tethys region. Tectonophysics, 25: 303-322.

Torabi G., 2004. Petrology of Anarak area ophiolites (NE of Isfahan Province, Iran). PhD Thesis, Tarbiat Modarres Univ., Iran, 240 pp.

Torabi G., 2009a. Subduction-related Eocene shoshonites from the Cenozoic Urumieh-Dokhrat magmatic arc (Qaleh-Khargooshi area, West of the Yazd Province, Iran). Turkish J. Earth Sci., 18: 583-613.

Torabi G., 2009b. Chromitite potential in mantle peridotites of the Jandaq ophiolite (Isfahan province, Central Iran). C. R. Geosci., 341: 982-992.

Torabi G., 2010. Early Oligocene alkaline lamprophyric dykes from the Jandaq area (Isfahan Province, Central Iran): An evidence of CEIM confining oceanic crust subduction. Island Arc, 19 (2): 277-292.

Torabi G., Abdullahi E. and Shirdashtzadeh N., 2008a. Application of mineral and whole rock analysis in identification of petrogenesis of pillow lavas in the Nain ophiolite. Iranian J. Crystall. Mineral., 16 (2): 295-312.

Torabi G., Arai S. and Koepke J., 2011a. Metamorphosed mantle peridotites from Central Iran (Jandaq area, Isfahan province), N. J. Geol. Paläont., Abhandl., 261 (2): 129-150.

Torabi G., Arai S., Shirdashtzadeh N., Shirasaka M., Jabbari A. and Torabi H., 2006. Study of skarns in north of Naein Ophiolitic Mélange (Isfahan province, Iran). Research J. Univ. Isfahan, 23 (1): 221-228.

Torabi G., Shirdashtzadeh N., Noorbehesht I. and Pirnia T., 2008b. Study of amphibolitic rocks in ophiolitic mélanges of Nain and Ashin-Zavar. Research J. Univ. Isfahan, 29 (3): 109-128.

Torabi G., Noorbehesht I., Shirdashtzadeh N. and Pirnia T., 2007. Geothermometry of skarns in the Nain ophiolitic mélange (Isfahan Province), Iranian J. Crystall. Mineral., 2: 357-382.

Torabi G., Shirdashtzadeh N., Arai S. and Koepke J., 2011. Paleozoic and Mesozoic ophiolites of Central Iran: amphibolites from Jandaq, Posht-e-Badam, Nain and Ashin ophiolites. N. Jb. Geol. Paläont. Abh., 262 (2): 227-240.

Yong I.L., 1999. Geotectonic significance of detrital chromian spinels: a review. Geosci. J., 3 (1): 23-29.

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