Late Permian blueschist from Anarak ophiolite (Central Iran, Isfahan province), a mark of multi-suture closure of the Paleo-Tethys ocean

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ABSTRACT

Anarak Paleozoic ophiolite is located in western part of the Central - East Iranian Microcontinent. This metaophiolite is covered by Paleozoic schist and marble. Blueschists of the Anarak ophiolite are exposed along the northern Anarak east-west main faults and are considered as remnants of the Paleo-Tethys suture zone in Central Iran. Anarak blueschists are formed by metamorphism of primitive basic lavas. In some cases, they preserve the primary pillow structure. Petrography and microprobe analyses show that they are composed of riebeckite, actinolite, plagioclase (albite), sphene, magnetite, white mica and apatite. Secondary minerals are chlorite (pycnochlorite), epidote, pyrite and calcite. Mineralogical assemblages are consistent with blueschist facies metamorphism, which is followed by a retrograde metamorphism in greenschist facies. Estimation of the metamorphic conditions suggests 300-450 ^{o}C and 4-9 kbar.

Whole rock geochemical analyses show that these rocks can be classified as alkaline basalts. Chondrite-normalized rare-earth element (REE) patterns of the studied rocks display 10-150 times enrichment, high light REE and relatively low heavy REE contents. These geochemical characteristics are representative of mantle-derived magmas. Primitive mantle normalized spidergram of the Anarak samples exhibit negative anomalies of Ba, U, K and Sr, and positive anomalies of Cs, Rb, Th, Nb, Ta and Zr. Similar geochemical features of all analyzed rocks indicate that they were all derived by more than 12% partial melting of an enriched/carbonated garnet lherzolite and underwent similar degree of partial melting. Geochemically, the studied blueschists resemble intraplate alkali-basalts. The presence of Paleozoic ophiolitic rocks along the main faults of central and northern Iran are indicative of a multi-suture closure of the Paleo-Tethys ocean.

Key words: Late Permian, ophiolite, blueschist, Paleo-Tethys, Anarak, central Iran.

RESUMEN

La ofiolita Anarak del Paleozoico se encuentra en la porción occidental del Microcontinente Iraní Centro-Oriental. Esta metaofiolita está cubierta por esquisto y mármol del Paleozoico. Esquistos azules de la ofiolita afloran a lo largo de las fallas principales este - oeste del norte de Anarak, y se consideran relictos de la zona de sutura del Paleo-Tetis en Irán central. Los esquistos azules de Anarak se formaron por metamorfismo de lavas máficas primarias. En algunos casos, estos esquistos preservan la estructura almohadillada primaria. Análisis petrográficos y de microsonda muestran que los esquistos están compuestos por riebeckita, actinolita, plagioclasa (albita), esfena, magnetita, mica blanca y apatita. Los

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minerales secundarios son clorita (picnoclorita), epidota, pirita and calcita. Los ensambles minerales son consistentes con metamorfismo en facies de esquistos azules, seguido por metamorfismo retrógrado en facies de esquistos verdes. Las condiciones de metamorfismo se estiman en 300-450 ^{o}C y 4-9 kbar.

Análisis geoquímicos de roca total muestran que estas rocas pueden ser clasificadas como basaltos alcalinos. Patrones de elementos de las Tierras Raras (REE) normalizados a condrita de las rocas estudiadas muestran enriquecimiento entre 10-150 veces, valores altos de REE ligeras y relativamente bajo REE pesadas. Estas características geoquímicas son representativas de magmas derivados del manto. El diagrama multielemental normalizado a manto primitivo de las muestras de Anarak exhibe anomalías negativas de Ba, U, K y Sr, y anomalías positivas de Cs, Rb, Th, Nb, Ta y Zr. Carcterísticas geoquímicas similares de todas las muestras analizadas indican que todas derivaron de más del 12% del fusión parcial de una lherzolita de granate enriquecida/carbonatada, y fueron sometidas a grados de fusión similares. Geoquímicamente, los esquistos azules estudiados se asemejan a basaltos alcalinos de intraplaca. La presencia de rocas ofiolíticas del Paleozóico a lo largo de las fallas principales del centro y norte de Irán es indicativa de un cierre multi-sutura del Paleo-Tetis.

Palabras clave: Pérmico Tardío, ofiolita, esquisto azul, Paleo-Tetis, Anarak, Irán central.

INTRODUCTION

Ophiolites and associated metabasites provide critical evidence for paleo-oceans and subduction zones. Glaucophane and riebeckite are the key index mineral of blueschist facies metamorphic rocks, and are widely used as indicators of paleo-subduction zones (*e.g.*, Ernst and Liou, 2008). Linear exposure of ophiolitic blueschists along regional structures and main faults can be considered as paleo-sutures.

The Anarak ophiolite is situated in western part of the Central - East Iranian Microcontinent (CEIM) (Figure 1), and is covered by Paleozoic metamorphic rocks (Figure 2). In this ophiolite, the blueschists are exposed along the main faults of northern Anarak following an east-west trend. Field studies shows that these Paleozoic blueschists originally were basic pillow lavas metamorphosed in blueschist facies. In some cases, the primary pillow structures are preserved (Figure 3d). In this article, petrological and geochemical aspects of formation, P-T condition of metamorphism, as well as geotectonic setting of these metavolcanics are presented. This research is the first study carried out on the petrology of late-Paleozoic blueschists of Central Iran. According to geographical and stratigraphical position of these rocks, it is expected that this research will be useful to identify the Paleo-Tethys position and closure in Iran.

REGIONAL GEOLOGY

Zagros, Zagros Thrust zone (ZTZ), Sanandaj-Sirjan, Urumieh-Dokhtar magmatic arc (UDMA), CEIM, Alborz, Kopeh Dagh, Eastern Iran, and Makran are the main structural units of Iran (Figure 1). The CEIM is located between the convergent Arabian and Eurasian plates. It is affected by a complex system of active intra-continental strike-slip faults causing an intensive north-south dextral shearing of the whole area (Figure 1) (Zanchi *et al.*, 2009). The CEIM comprises three major crustal domains from east to the west: the Lut block, the Kerman (Tabas) block, and the Yazd (Naein) block. The study area is located in the western part of the Yazd block and south of Great Kavir fault (GKF). The left-lateral Great Kavir (Doruneh) fault, which is one of the longest and most prominent faults of Iran, is very close to the study area (Figures 1 and 2). It plays an important role in the regional tectonics of Central Iran (Torabi, 2009a, 2010). The drastic direction change of this fault in the Anarak area marks the western border of the CEIM.

Ophiolites of Iran can be divided into four groups (Torabi, 2009c, 2011; Torabi *et al.*, 2011): 1) Paleozoic ophiolites of northern Iran which are located along the Alborz mountain range and include the Rasht ophiolites. These ophiolites are considered as remnants of Paleo-Tethys (Bagheri, 2007; Torabi, 2004; Torabi *et al.*, 2011); 2) Mesozoic to Cenozoic ophiolites of the Zagros suture zone including the Neyriz and Kermanshah ophiolites which are apparently an extension of the Oman ophiolites (Torabi, 2009b); 3) Mesozoic to Cenozoic ophiolites and ophiolitic mélanges that mark the boundaries of the CEIM; and 4) Paleozoic metamorphosed ophiolites of the Yazd and Posht-e-Badam blocks, located in the western part of the CEIM. These last ophiolites include the Anarak, Jandaq, Bayazeh and posht-e-Badam metaophiolites (Figure 1). Presence of several ophiolitic belts along the large active intracontinental faults of Iran indicates the opening and closure of several oceanic basins during its complex geological history.

The Anarak metamorphic rocks (schist and marble) include mountains with nearly east-west trend, which have covered the Anarak ophiolite. This ophiolite is composed of mantle peridotites, cumulates, gabbros, basic and ultrabasic dykes, pyroxenite, riebeckite bearing metabasite (blueschist), rodingite, and litswaenite (Sharkovski *et al.*, 1984; Torabi, 2004). Chromitite has not be found yet (Torabi, 2009c). Petrography of mantle peridotites of the Anarak

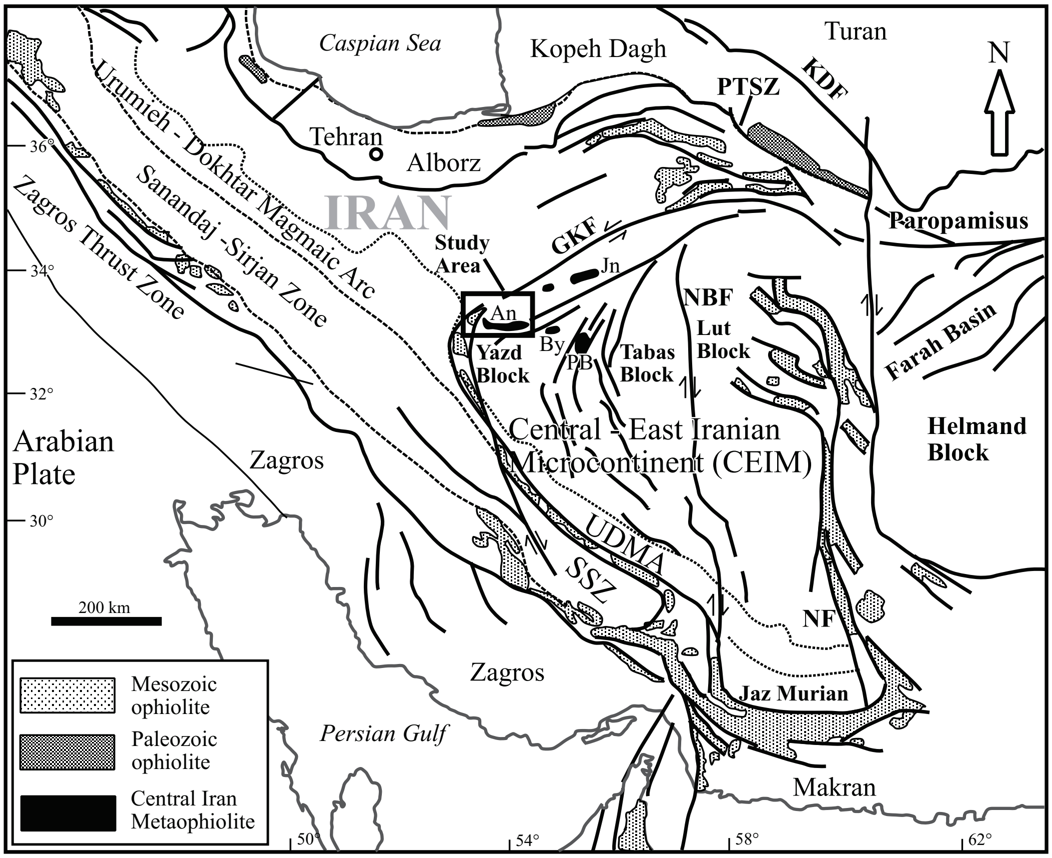


Figure 1. Main structural units of Iran; GKF: Great Kavir fault; KDF: Kopeh Dagh Fault; NBF: Naiband fault; NF: Nehbandan fault; SSZ: Sanandaj-Sirjan zone; PTSZ, Paleo-Tethys suture zone; UDMA: Urumieh - Dokhtar magmatic arc. An, Jn, By and PB represent the Anarak, Jandaq, Bayazeh and Posht-e-Badam metaophiolites, respectively.

ophiolite shows that this ophiolite is of the lherzolitic ophiolite type (LOT) (Torabi, 2004, 2009c). All rock units of the Anarak ophiolite have been metamorphosed, and underwent a high degree of serpentinization (Torabi, 2004).

^{40}Ar-^{39}Ar isotopic analyses on the Anarak metamorphic rocks indicate ages of 318.99 ± 1.63 and 333.87 ± 1.91 Ma (Bagheri, 2007). Furthermore, analysis of sodic amphibole in Anarak blueschist by the ^{40}Ar-^{39}Ar method yielded an age of 285.42 ± 1.65 Ma (Bagheri, 2007), which points to Late Permian metamorphism of the primitive pillow lavas.

Undeformed trondhjemitic intrusions (stocks and dykes) cross cut the Anarak ophiolite and its covering metamorphic rocks (Figures 2 and 3). U-Pb analysis of zircon from Anarak trondhjemite reports 262.3 ± 1.0 Ma (Bagheri, 2007). This indicates that the trondhjemitic magmatism occurred about 23 m.y. after the formation of blueschists in the Anarak ophiolite. Field evidences and whole rocks chemistry of trondhjemites reveal that they have crystallized from magmas derived by melting of subducted Anarak oceanic crust (Torabi, 2004). Geochemical characteristics of the Anarak trondhjemites all reflect melting of a mafic protolith at relatively high pressures (>10 kbar) to form a garnet-rich, plagioclase-free eclogitic residue (Torabi, 2004).

The Anarak area is considered as remnant of a Permo-Triassic accretionary wedge that was active in the Anarak region to the south of Nakhlak (Bagheri, 2007). Detailed petrographical study of the Nakhlak Triassic succession (Alam, Baqoroq and Ashin formations) shows that it consists of pelagic sedimentary rocks including Rosso ammonitico facies, volcanic arenites, alluvial fan conglomerates and sandstones, nodular limestone and marl, and turbidites deposited in a volcanic arc setting along an active margin (Balini *et al.*, 2009). This succession was deposited in a rapidly subsiding sedimentary basin (Zanchi *et al.*, 2009). Previous authors (*e.g.*, Soffel *et al.*, 1996; Alavi *et al.*, 1997) considered that the Anarak ophiolite is a remnant of Paleo-Tethys, transferred to its present position from NE of Iran, by 135^{o} anti-clockwise rotation of CEIM. Whereas, new paleontological and paleomagnetic studies (*e.g.*, Balini *et al.*, 2009; Muttoni *et al.*, 2009) do not support large anti-clockwise rotations.

ANALYTICAL TECHNIQUES

Chemical analyses of minerals were carried out with a Cameca SX-100 electron probe micro-analyzer at the Institute of Mineralogy, Leibniz University, Hannover,

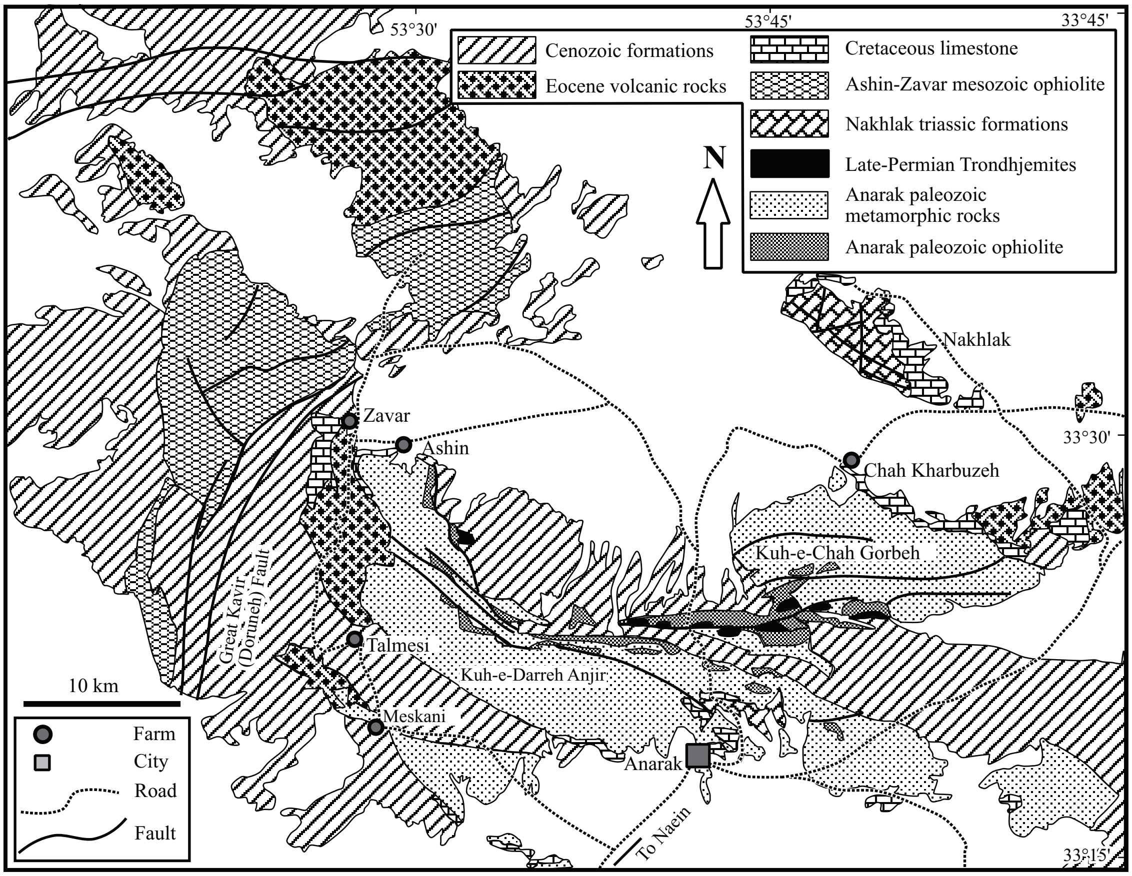


Figure 2. Simplified geological map of the Anarak region (Isfahan province, Central Iran). Presence of both Paleozoic and Mesozoic ophiolites in the Anarak area is evident.

Germany, and a JEOL JXA-8800R at the Cooperative Centre of Kanazawa University, Japan. The machines were operated at a voltage of 15 kV and a beam current of 15 nA with 3-μm probe beam diameter. Natural minerals and synthetic materials of known composition were used as standards. The ZAF program was used for data corrections. The amounts of Fe^{3+} and Fe^{2+} in minerals were estimated by assuming ideal mineral stoichiometry. The Mg# calculated as $Mg/(Mg+Fe^{2+})$ atomic ratio of minerals. Representative chemical analyses of the minerals and calculated structural formulas are presented in Tables 1. Mineral abbreviations in photomicrographs are from Kretz (1983).

Geochemical analyses were carried out on whole-rock samples using a Bruker S4 Pioneer XRF at the Central Laboratory of the University of Isfahan, and by Neutron Activation Analysis (NAA) at the Activation Laboratory of Isfahan (MNSR Department). The quality assurance of the analytical results was evaluated by analyzing certified Standard Reference Materials prepared by the Canadaian Certified Reference Material Project (CCRMP), Republic of South Africa Bureau of Standards (SACCRM), and China National Analysis Center. Analytical uncertainties of all major elements were between 1-4%. Precision for trace elements analyses were estimated to be better than 5% on the basis of repeated analysis of standard materials. Sixteen samples of blueschist from the Anarak ophiolite were selected for analyses. Whole-rock chemical data are presented in Table 2.

PETROGRAPHY AND MINERAL CHEMISTRY

Blueschists are medium to fine grained in hand specimen. The original pillow structure and marginal cavities, which are filled by the secondary minerals, are still visible. In some cases, they display a pervasive foliation marked by the preferred shape orientation of amphibole and chlorite. Main textures are nematoblastic and granoblastic. These rocks contain amphibole, plagioclase, white mica, quartz, sphene (titanite), chlorite, epidote, rutile, apatite, hematite, calcite and pyrite (Figure 4). Sphene and rutile are partly transformed to leucoxene by secondary alteration. Metamorphic differentiation caused separation of dark and light minerals as individual bands in some samples (Figure 4d).

Electron microprobe analyses of minerals (Table 1), show that plagioclase is albitic (Ab 99.6%) (Figure 5a), which indicates that sub-sea floor metamorphism of primary

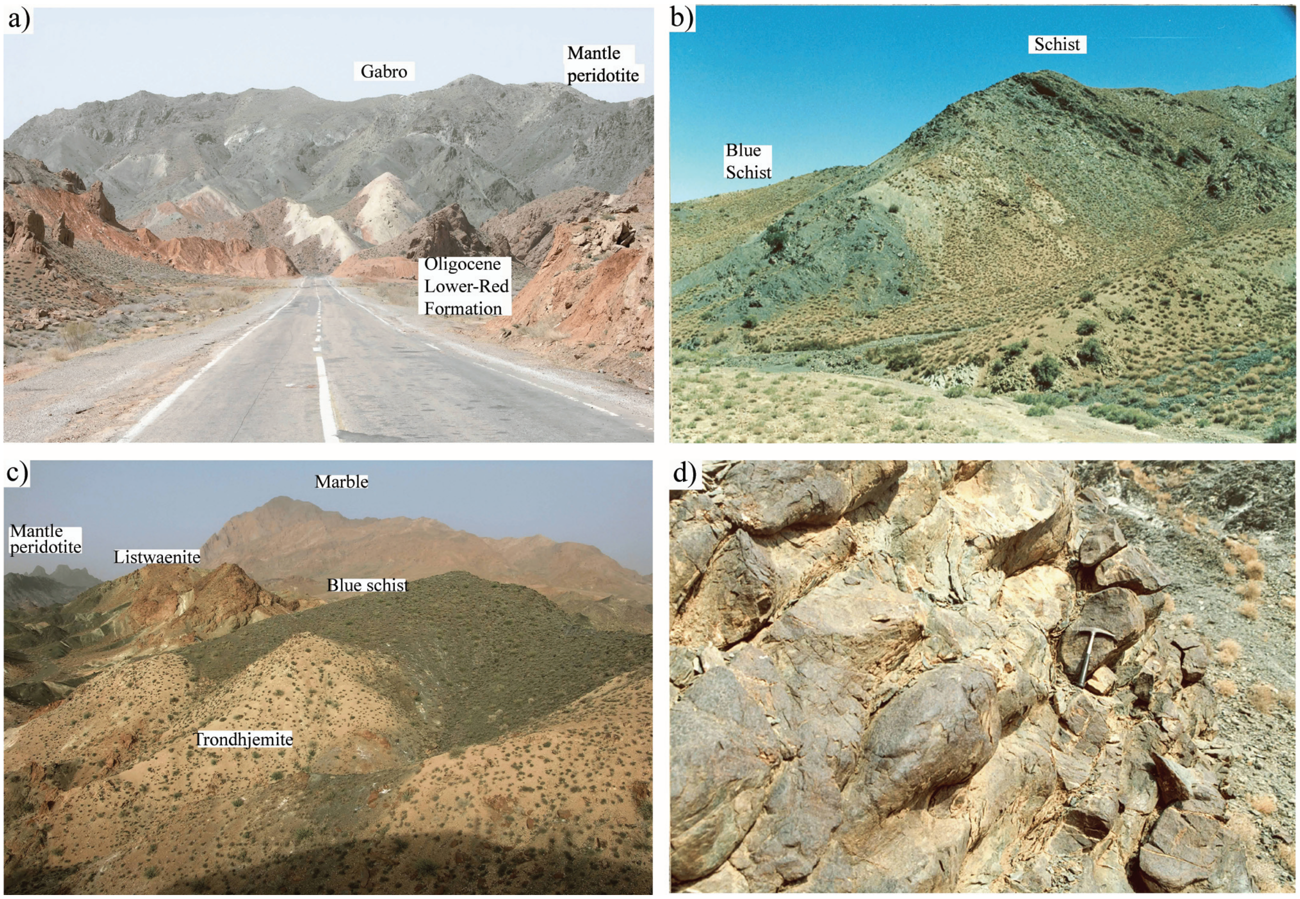


Figure 3. Field photos of the Anarak ophiolite, blueschists and associated rocks; a) Anarak ophiolite exposed near to the Anarak-Khur main road; b) Blueschists are covered by Paleozoic metapelites; c) Anarak ophiolite trondhjemite cross cut the blueschists; d) Blueschists preserved the primary pillow structure.

pillow lavas has changed the primary calcic plagioclases to secondary sodic ones. Amphiboles are magnesio-riebeckite (Figure 5b) and actinolite (Table 1) in composition. All actinolites are fresh but Mg-riebeckites are partly changed to chlorite. Mg# of amphiboles are 0.602 to 0.735 and 0.755 for Mg-riebeckites and actinolite, respectively. Chlorites are pycnochlorite in composition. Mg# of chlorite and white micas is 0.706 and 0.680, respectively.

The above mentioned mineralogical association, probably indicates a transition from blueschist to greenschist facies P-T conditions by retrograde metamorphism. The equilibrium phase assemblage for the blueschist P-T conditions includes Mg-riebeckite, white mica, quartz, titanite, plagioclase and hematite (Zanchi *et al.*, 2009). On the other hand, actinolite, chlorite, epidote and leucoxene are characteristic of the greenschist facies.

WHOLE ROCK GEOCHEMISTRY

Whole rock geochemical data (Table 2) show that SiO_2, TiO_2, Al_2O3, MgO, CaO, Na_2O and K_2O values of the studied blueschists range 47.96–52.91, 1.86–2.64, 12.93–16.76, 4.39–9.95, 2.81–7.62, 4.18–6.69, and 0.30–1.34 (wt. %), respectively. Considerable values of lost on ignition (LOI: 2.40–4.44 wt. %) can be attributed to the presence of hydrous minerals (*e.g.*, Mg-riebeckite, actinolite, mica, chlorite and epidote). According to the sub-sea floor metamorphism and spilitization of the Anarak samples, it can be concluded that most of the major elements have probably been modified by secondary alterations and that only immobile elements (*e.g.*, high field strength elements, HFSE, and rare earth elements, REE) should be considered for geochemical interpretations. In the Nb/Y versus Zr/TiO_2 classification diagram (Winchester and Floyd, 1977), all studied rocks plot in the alkali-basalt field (Figure 6a).

Chondrite-normalized REE patterns (Figure 6b), of the Anarak samples exhibit parallel patterns and enrichment in light REE (LREE) relative to heavy REE (HREE). They are 10 to 150 times enriched in REE relative to chondrite. No evident Eu anomaly is observed. Abundances of LREE are slightly more variable than that of HREE.

In a primitive mantle-normalized multi-elements diagram (Figure 6c) all analyzed samples display parallel patterns from the large-ion lithophile elements (LILE) to the HFSE and REE. In this diagram, the samples exhibit nega-

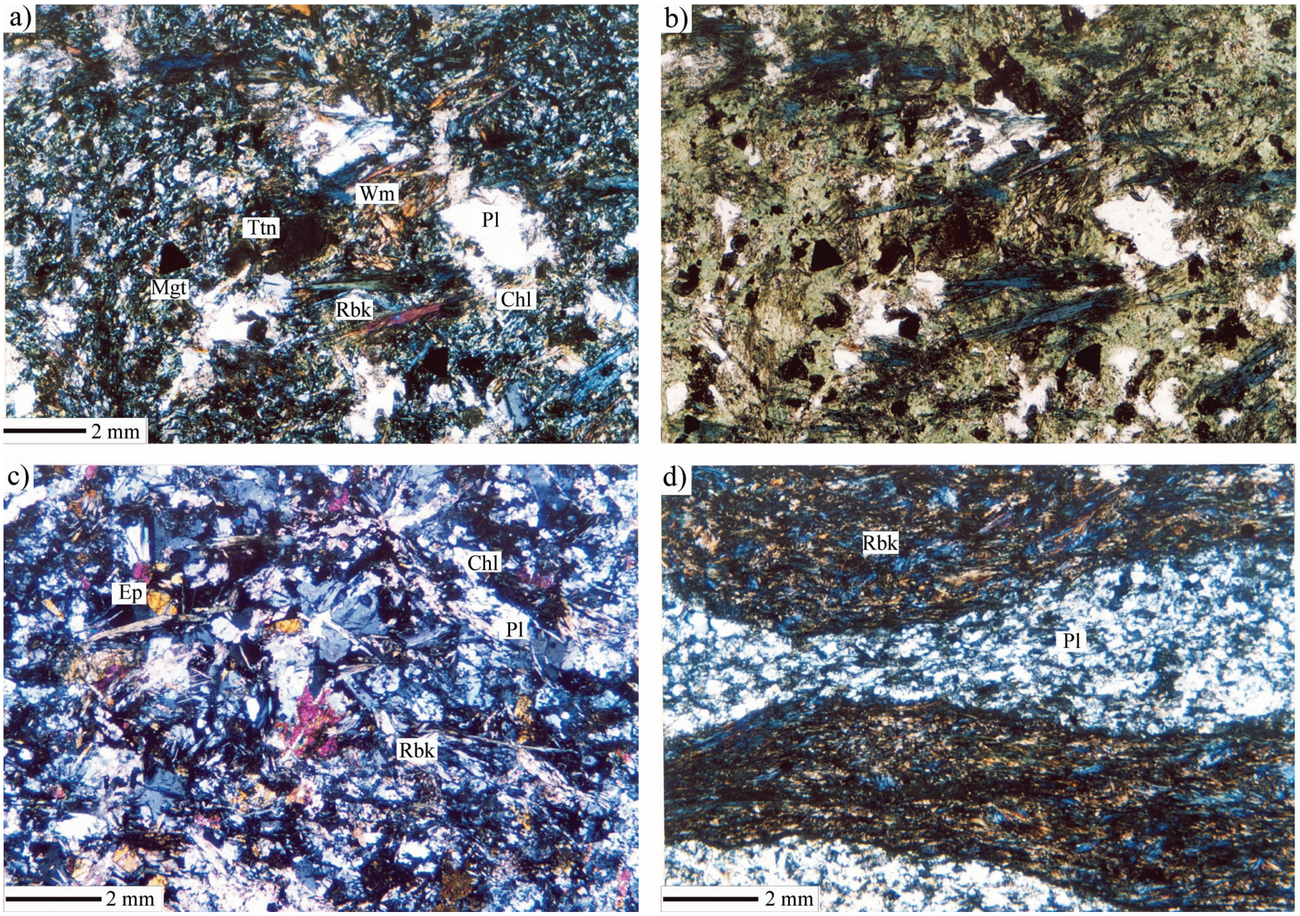


Figure 4. Photomicrographs of the studied blueschists. a, c and d in crossed polarized light (XPL); b: same as (a) in parallel polarized light. Blue riebeckite needles and separation of dark and light minerals (d) by metamorphic differentiation are evident.

tive anomalies of Ba, U, K and Sr, and positive anomalies of Cs, Rb, Th, Nb, Ta and Zr. The studied blueschists are similar in petrography and geochemistry; therefore their parental melts probably derived from the same or from very similar mantle sources.

Geochemical characteristics and patterns of the analyzed samples shown in Figures 6a to 6c and their comparison with non-metamorphosed Paleozoic alkali-basalts (Torabi, 2009a), as well as young and fresh ones from Central Iran (Torabi, 2004 and 2010) confirm that originally they were basalt and belong to the alkaline magmatic series.

DISCUSSION

Magma generation

Analyzed samples of the Anarak area exhibit high TiO_2 (1.86 to 2.64 wt. %) values and strong LREE enrichment relative to HREE (Figure 6b) (La/Lu ratio = 29.7-124.8), presumably indicating alkaline mafic partial melts. Relatively low HREE contents of these metabasalts indicate that garnet was present as a residual phase in their mantle sources. Although the asthenosphere is dominantly garnet peridotite, dry garnet peridotite is not a suitable source for the Anarak ophiolite primary alkalibasalts. In order to generate melts with such high LREE and incompatible trace element contents, the mantle source must have been previously metasomatically enriched. The chondrite normalized REE patterns of all individual samples are remarkably parallel, thereby implying that they were all derived from a similar mantle source region and underwent similar degree of partial melting. Additionaly, parallel REE patterns indicate fractional crystallization of a co-genetic suite. Partial melting of a mantle source with garnet will buffer HREE at low concentrations and variable LREE. The high incompatible element enrichments of the Anarak studied rocks are coupled with comparatively low abundances of Al_2O_3, Yb and Sc. This effect is almost certainly caused by the persistence of garnet in the melt residue, which has high partition coefficients for these elements, and keeps them buffered at relatively low abundances (Hofman, 2005). Residual garnet is stable in peridotites at depths greater than ~80 km (Hofman, 2005).

The high HFSE contents of the studied alkalibasalts suggest that their source was significantly enriched in

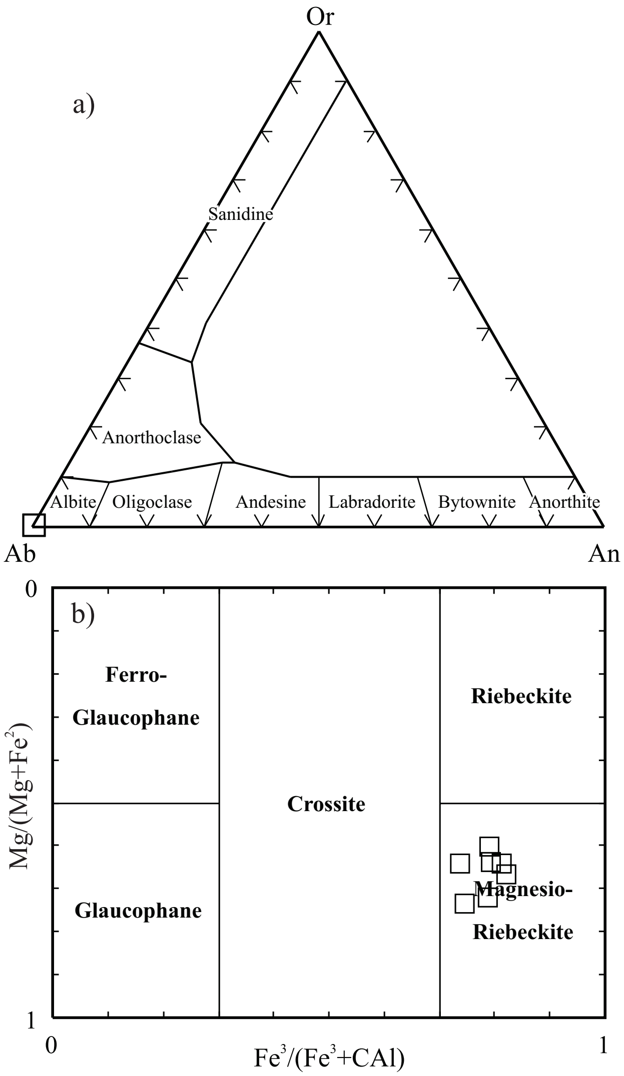


Figure 5. a) Plagioclases of the Anarak blueschists are albite in composition (Deer *et al.*, 1992); b) Blue amphiboles present magnesio-riebeckite composition (Leake *et al.*, 1997).

these elements. Compared with OIB (TiO_2= 2.87 wt. %) (McDonough and Sun, 1995), Anarak meta-alkalibasalts have lower TiO_2 concentrations (1.86 to 2.64 wt. %; average: 2.14 wt. %).

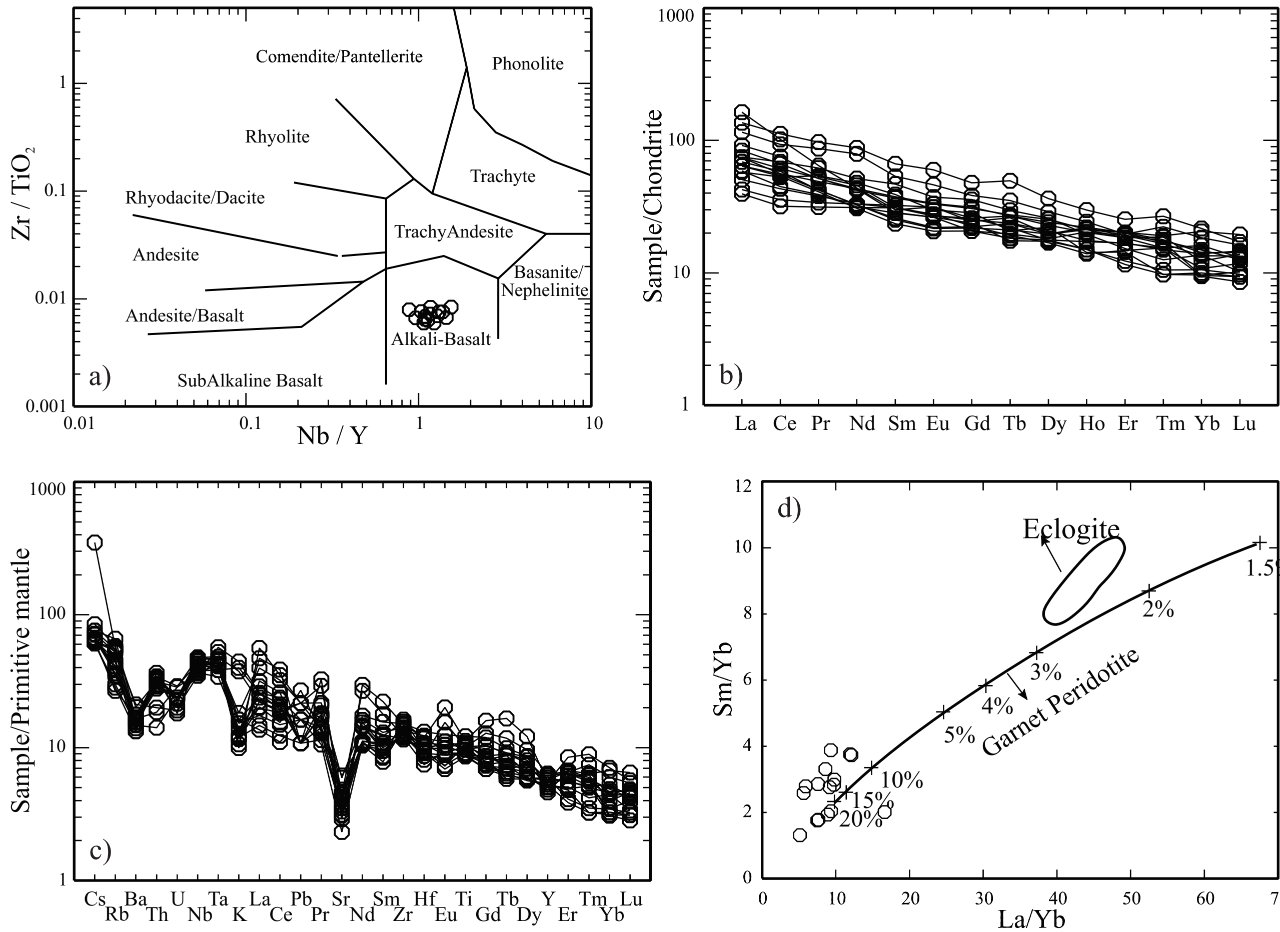
The petrogenesis of intra-plate alkaline basalts remains controversial, and following sources have been proposed for such OIB-like melts (Zeng *et al.*, 2010): (1) hornblendite produced by hydrous metasomatism, (2) silica-deficient eclogite and garnet pyroxenite, and (3) carbonated peridotite. TiO_2 content of Anarak meta-alkalibasalts (1.86 to 2.64 wt. %; average: 2.14 wt. %) is lower than the expected values to be originated from an hornblendite source. The elevated Zr/Hf ratios of the Anarak metabasalts (40–62), which are higher than chondritic Zr/Hf values (~36), can have resulted from melting of an eclogite (or garnet pyroxenite) with high clinopyroxene/garnet modes (≥70) in their source (Gómez-Tuena *et al.*, 2011; Klemme *et al.*, 2002). But significant variations of Zr/Hf (40–62), Zr/Ta (68–114), Nb/Ta (11–19) and Gd/Yb (1.3–4.0) ratios can not be explained by such sources (Gómez-Tuena *et al.*, 2011; Zeng *et al.*, 2010). Because of the high solubility of zircon in pyroxenite-eclogite originated alkaline melts, it cannot survive in such melts and even if zircon did crystallize, it would not significantly fractionate Zr from Hf (Linnen and Keppler, 2002) and Zr/Hf ratio will be low. Superchondritic Zr/Hf ratio in basalts and mantle rocks are rarely observed and appear to be restricted to carbonate metasomatism (Weyer *et al.*, 2003). Universally, carbonatite is one of the most incompatible-elements enriched rocks. Melting of a carbonated mantle will produce enriched melts (Dasgupta *et al.*, 2007). According to the very similar geochemical behavior of Zr and Hf, the elevated values and wide range of Zr/Hf ratios (40–62) are related with an enrichment by carbonate-rich metasomatic melts/fluids (*e.g.*, Rudnick *et al.*, 1993; Pearson *et al.*, 2005). It is suggested that such geochemical characteristics of alkali basalts are inherited from an asthenospheric source that had undergone enrichment with carbonatitic liquids. On the basis of the above mentioned evidences, it seems that the best candidate for source rock of the Anarak alkaline basalts is a carbonated peridotite.

Highly incompatible elemental ratios can be used to trace petrogenetic processes. For instance, the Zr/Y ratio generally remains constant during fractional crystallization, but varies during partial melting in basaltic systems (Nicholson and Latin, 1992). Zr is more incompatible than Y in the mantle, so Zr/Y ratios tend to be higher at small degrees of partial melting. Differences in FeO contents in primary magma could be related to the various depths and/or source compositions (Nicholson and Latin, 1992; Tang *et al.*, 2006). The Anarak samples have low Zr/Y ratios (4.76–7.61) and moderate total FeO contents (9.42–14.70 wt. %; average: 11.22 wt. %). These features suggest that the Anarak basalts were generated by intermediate degrees of partial melting. La/Yb versus Sm/Yb diagram (Figure 6d) (Zeng *et al.*, 2010), confirms this result and indicate more than 12% partial melting of a mantle garnet peridotite for the studied rocks.

In summary, moderate degrees of partial melting of a carbonated garnet-bearing lherzolitic mantle source are required to explain the trace and REE patterns observed in these basalts. The systematic presence of garnet as a residual phase requires melting depths in excess of 70–80 km, where garnet becomes stable (Tang *et al.*, 2006).

P-T conditions of metamorphism

Estimation of pressure and temperature of metamorphic episodes for Anarak ophiolite blueschists is not straightforward (Zanchi *et al.*, 2009). The absence of omphacitic clinopyroxene, indicates that the upper pressure limit of peak metamorphism should be lower than 12



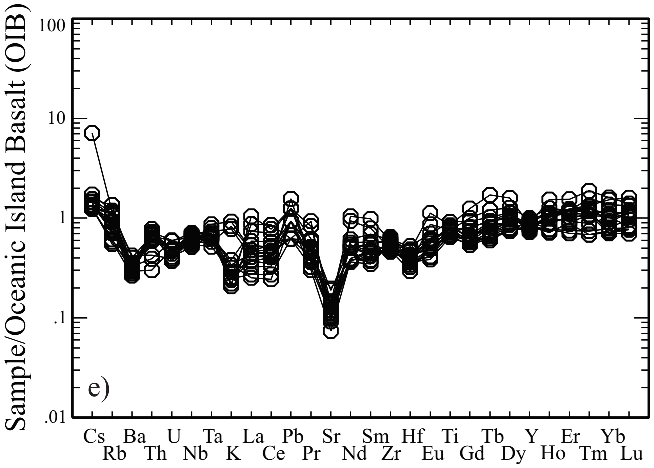


Figure 6. Geochemical diagrams of the Anarak blueschists. a) Nb/Y versus Zr/TiO_2 classification diagram (Winchester and Floyd, 1977); b) Chondrite normalized REE patterns of the analyzed rocks. The REE contents of chondrite are taken from Sun and McDonough (1989); c) Primitive mantle-normalized multi-element variation diagram. Normalizing values are from McDonough and Sun (1995); d) La/Yb vs. Sm/Yb diagram for Anarak metamorphosed alkaline basalts (Zeng *et al.*, 2010); e) OIB-normalized multi-element patterns of the Anarak blueschists. OIB data are from Sun and McDonough (1989).

kbar. In addition, the lack of aragonite reveals that calcite was the stable carbonate phase during peak conditions, and constrains the upper pressure boundary to 8-9 kbar. An upper temperature limit is also provided by the absence of garnet (Apted and Liou, 1983; Guiraud *et al.*, 1990), which is stable above 400-450 ^oC for pressure conditions ranging between 4 and 9 kbar. The absence of lawsonite could be tentatively used as a lower temperature boundary, confining the peak phase mineral assemblage with Na-amphibole, albite, white mica and titanite at a temperature above 300 ^oC for a 4–9 kbar pressure range. The pressure peak recorded by the phase assemblage was followed by a decrease in pressure and an increase in temperature, suggested by the crystallization of actinolite and chlorite. This suggests that the blueschists of the Anarak ophiolite were subducted into an accretionary wedge at a depth of at least 15–20 km (Zanchi *et al.*, 2009).

Mineral assemblages and geochemistry (Na_2O con-

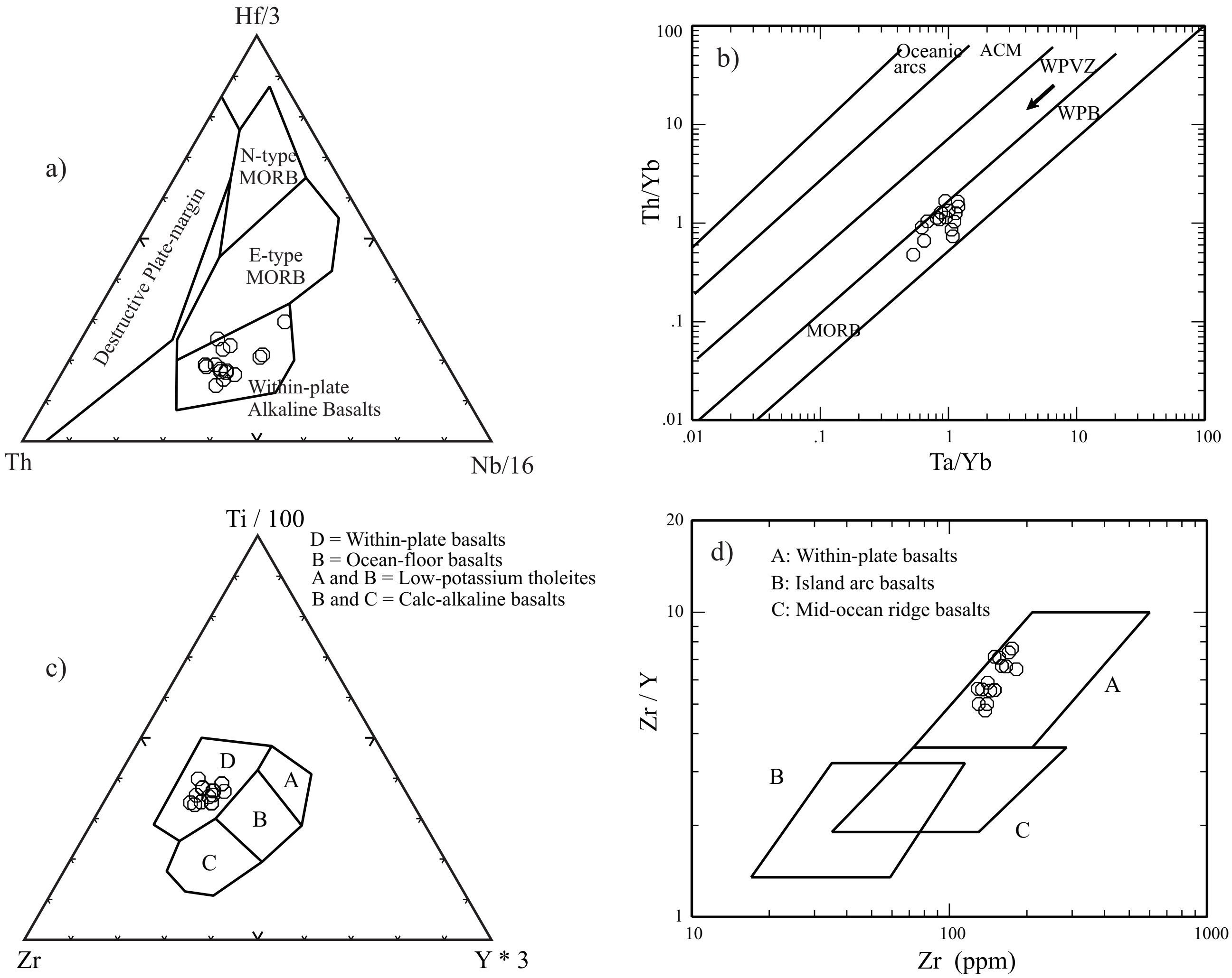


Figure 7. Discrimination geotectonic diagrams of the Anarak rocks. a) Th-Hf/3-Nb/16 triangle (Wood, 1980); b) Ta/Yb versus Th/Yb log-log diagram (Gorton and Schandl, 2000); WPB, WPVZ and ACM are abbreviation of within plate basalt, within plate volcanic zone and arc magmatism, respectively; c) Zr –Ti*100-Y*3 triangle (Pearce and Cann, 1973); d) Zr against Zr/Y plot (Pearce and Norry, 1979). The analyzed samples lie in the within-plate alkaline basalt field.

tent) of the studied rocks indicate that they passed a prograde metamorphism in blueschist facies (M2) from a sub-sea metamorphosed and spilitized basalt (M1) and changed to blueschist in response to subduction. The M2 was followed by retrograde metamorphim in greenschist facies (M3). It has been demonstrated that transformation of blueschist-facies mineral assemblages to greenschist or amphibolite-facies assemblages by volatization reactions can be triggered by channelized infiltration of external fluids during the uplift of the rocks (Schulz *et al.*, 2001).

Tectonic setting

The studied metabasalts present LREE enrichment (La/Yb = 4.60–16.12) and no Eu anomalies, which is typical of OIB and intraplate alkali basalts (Turner and Hawkesworth, 1995). OIB-normalization of the studied rocks in a multi-element diagram (Figure 6e) indicates that the Anarak blueschists present some similarities to OIB. The negative Sr anomaly of the Anarak samples in both the primitive mantle and the OIB-normalized multi-element diagrams can be attributed to the alteration of primitive calcic plagioclase. The variable Sr contents (49–130 ppm) confirm different degrees of alteration in the analyzed rocks.

Several geotectonic discrimination diagrams (Figures 7a, 7b, 7c and 7d) have been used for these rocks to determine their tectonic setting. All diagrams suggest a within-plate setting. Geological situation of these rocks confirm these diagrams. The Paleo-Tethys ocean spreading in Central Iran commenced in Late Ordovician-Early Devonian and terminated in the Late Paleozoic-Triassic (Torabi, 2009a, 2009c; Torabi *et al.*, 2011). Subduction of Paleo-Tethys is the cause of volatile enrichment of the mantle and OIB-like magmatism in the Upper Paleozoic. For an extensive subduction-related metasomatism of the mantle, a considerable time span is necessary. Therefore, the former subduction of Paleo-Tethys from lower Paleozoic to Late Permian and Early Triassic is the cause of the mantle enrichment in volatiles and intraplate alkaline magmatism in the upper Paleozoic of Anarak area. It is well known that carbonate can be effectively transported into the Earth's interior by subduction processes (Shaw *et al.*, 2003). Therefore, a formerly subducted slab can have been the source of the carbon-rich agent that metasomatized the mantle source beneath the Anarak area.

The occurrence of the Anarak, Jandaq, Bayazeh and Post-e-Badam Paleozoic ophiolites within continental Iran poses several questions regarding its evolution and especially on the number of Paleo-Tethys sutures (single rather than multiple) between Eurasia and Iran (Zanchi *et al.*, 2009). Previous authors (*e.g.*, Soffel *et al.*, 1996; Alavi *et al.*, 1997) explained the anomalous position of the Nakhlak–Anarak region by sparse palaeomagnetic data that apparently showed a post-Triassic 135^{O} anti-clockwise rotation of central Iran. That rotation was supposed to be responsible for transferring a large fragment of the Paleo-Tethys suture from the present-day Afghanistan - Iran border (Aghdarband and Mashhad areas) to central Iran. However, new palaeomagnetic data obtained from the Triassic succession of Nakhlak (Muttoni *et al.*, 2009) challenges that interpretation and suggests that no large rotations have occurred in the area since the Middle Triassic (Zanchi *et al.*, 2009). Fauna studies by Balini *et al.* (2009), regional facies analysis of Upper Silurian–Lower Carboniferous successions by Wendt *et al.* (2005), and Late Triassic paleomagnetic data of Besse *et al.* (1998), also are not consistent with a large 135^{O} anticlockwise rotation of central Iran.

On the basis of the above mentioned geological data, it can be concluded that the presence of Paleozoic ophiolitic rocks along the main faults of central and northern Iran reveals multi-suture closure of the Paleo-Tethys ocean in late-Paleozoic to Early Mesozoic.

CONCLUSIONS

Field and petrographical studies of the Anarak ophiolite bluschists reveal that they were originally basalts with pillow structure that have passed three metamorphic episodes. The order of metamorphic phases is sub-sea floor metamorphism and spilitization (M1), blueschist facies metamorphism (M2), and metamorphism in greenschist facies (M3). Geochemically, the studied rocks are sodic alkaline basalts with trace element patterns characteristic of within-plate alkali basalts. Geochemical features of these metabasite indicate role of a metasomatized/carbonated asthenospheric garnet lherzolite in their petrogenesis. The metasomatism of Paleozoic asthenospheric mantle is attributed to subdution of Paleo-Tethys oceanic crust. The long term subduction of an oceanic crust from Late Ordovician to Late Paleozoic is the cause of the mantle metasomatism and OIB-like magmatism.

The exposure of blueschists with pillow lava structure along the main faults of the Anarak area are considered as remnants of a subduction and suture zone. The presence of Paleo-Tethys ocean remnants along the deep intracontinental faults of the Yazd and Posht-e-Badam blocks, and northern Iran, as well as new paleontological and paleomagnetic data indicate a Paleo-Tethys multi-suture closure in Iran.

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