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PROTOLITH NATURE AND TECTONOMAGMATIC FEATURES OF AMPHIBOLITES FROM THE QUSHCHI AREA, WEST AZERBAIJAN, NW IRAN

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ABSTRACT

Amphibolites from the Qushchi area in west Azerbaijan province, NW Iran are metabasites containing hornblende, plagioclase, epidote, garnet, relict igneous clinopyroxene and titanite, apatite and opaque minerals as accessory phases. They are spatially associated with an ophiolitic mélange but their relationship is not clear. Based on whole rock geochemistry of the amphibolites, they are formed from sub-alkaline andesite-basalt with a tholeiitic affinity. TiO_2 content of the analyzed amphibolite samples is mainly less than 1%, indicating an EMORB original character for the magma. Major and trace element geochemistry of the studied rocks indicate a volcanic arc setting for the rocks. Chemistry of relict igneous clinopyroxene shows that they are diopside in composition with Mg# of 86.75-88.78 and indicating tholeiitic magma type derived from volcanic arc setting, which is in agreement with the results from the whole rock chemistry. Low Ti content of the clinopyroxene points to a depleted mantle source for the magma of the protoliths of Qushchi amphibolites. There is no isotopic age constrains on the studied amphibolites, therefore their relation to the ophiolitic mélange of the area is uncertain especially that the mélange is allochthonous. Three possibilities can be proposed for the formation of the studied amphibolites. If these rocks are Late Cretaceous- Paleocene in age, they might have been formed as parts of a volcanic arc in the Neotethyan oceanic crust. In this case, the ophiolitic complex and the volcanic arc rocks all are metamorphosed at amphibolite facies following the Neotethys ocean closure and the continental collision. Based on field relations and comparing the studied amphibolites with similar amphibolites from the adjacent Khoy area, alternatively the amphibolite formation can be consider to predate the formation of Neotethys-related ophiolite mélange. Since the serpentinite in the ophiolitic mélange is not metamorphosed, the second explanations can be valid for the formation of the amphibolites. The third possibility is that the protolith of the amphibolites was contemporaneous with ophiolite formation, but this protolith is metamorphosed within the accretionary prism but the obducted ophiolitic rocks (including serpentinite) not subjected to metamorphism.

1. Introduction

The main suture of the Neotethys closure is along the Zagros orogen in Iran, which is continued to the northwest and is connected to the Izmir-Ankara-Erzincan and Bitlis sutures (Figure 1; Okay and Tüysüz, 1999; Göncüoglu et al., 2010; Moazzen et al., 2012; Topuz et al., 2013). Ophiolites in NW Iran appear in the Khoy, Chaldoran, Serow, Salmas and Piranshahr areas (Figure 2). Amphibolite and greenschist always accompany these ophiolites. Also amphibolites occur along with (or within) the ophiolitic rocks from the İzmir-Ankara-Erzincan and Bitlis sutures in Turkey. The main amphibolite

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outcrops associated with Orhanlı, Tavşanlı Karaburhan (Eskişehir) and Dutluca ophiolites along the İzmir-Ankara-Erzincan suture are considered to be of Triassic-Cretaceous age (Sarıfakıoğlu et al., 2010). There are not much studies on amphibolites associated with ophiolitic complexes of NW İran. These amphibolites are considered as old (Precambrian) units or as rocks with unknown ages in most of the geological maps published by the geological survey of Iran.

Amphibolites can be found with considerable exposures along with Chaldoran, Khoy and Salmas ophiolites (Hassanipak and Ghazi, 2000; Khalatbari-Jafari et al., 2004; Juteau, 2004; Aftabi et al., 2006; Azizi et al., 2006; Moazzen and Oberhänsli, 2008; Monsef et al., 2010), (Figure 2). Amphibolites of the Qushchi area are adjacent to the Salmas ophiolitic complex (Figure 3). Two types of amphibolites are introduced on Salmas geological map (Khodabandeh, 2003). These are amphibolites associated with other metamorphic rocks (mainly pelitic schist and gneiss) with a probable Precambrian protolithic age and amphibolites and greenschists within the ophiolitic mélange of the Khoy area with Cretaceous age. Amphibolites with a probable Precambrian age are studied here. This age is proposed on the basis of stratigraphical relations and the fact that Permian limestone with distinctive fossils is not metamorphosed. Also Cambrian sedimentary rocks exhibit very low grade metamorphism. Therefore the reasonable age for the relatively high grade metamorphism is Precambrian. However tectonic contact between the rock units makes this conclusion on the age of the amphibolites uncertain. Exact isotopic age dating can resolve this problem.

The applicability of whole rock chemistry to metabasic rocks to determine the magmatic nature and tectonic setting of the parental magma has been debated. Different elements behave differently during metamorphism of mafic rocks. Some elements are mobile and some others act as relatively immobile elements in this regard. For instance K, Na, Si and Ca are mobile during metamorphism while P, Al and Ti are relatively immobile. Elements such as Zr, Sc and Y are practically immobile (Rollinson, 1993; Coish, 1997; Pearce and Cann, 1973; Floyd and Winchester, 1978). White (2001) considers alkali elements with high ionic potential such as K, Ba, Sr, Cs and Rb as mobile elements and Seewald and Seyfried (1990) believe that transitional elements Co, Cr, V, Ni, Nb, Ta and REE are immobile during metamorphism. In overall it is possible to use immobile elements such as P and Ti and rare elements such as Zr, Ta, Nb, V, Cr, Y and REE to distinguish the magmatic nature of the protolith of metamorphosed mafic rocks at greenschist to amphibolite facies. However at higher metamorphic grades, especially at the granulite facies and considering the possibility of partial melting of metabasic rocks at this P-T condition (Hartle and Pattison, 1996; Moazzen et al., 2013) any conclusion on magmatic nature of metabasic rocks protoliths should be treated with caution.

Results from whole rock chemistry of Qushchi amphibolites with emphasis on immobile elements and mineral chemistry of the relict igneous

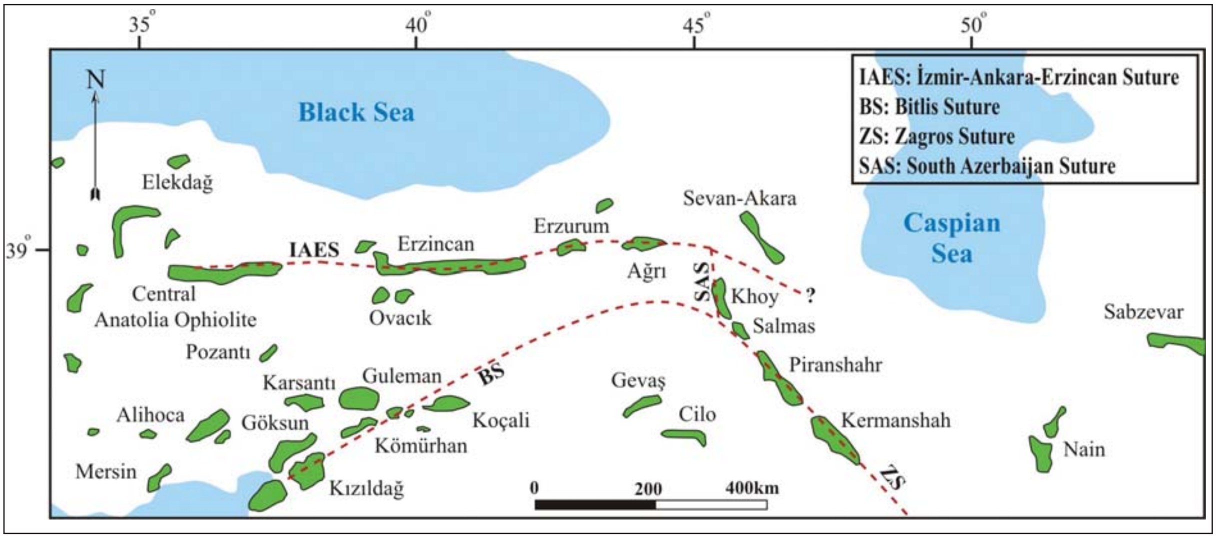

Figure 1- Continuation of accretionary complexes and ophiolites of NW Iran to east Turkey (modified from Dilek and Moores, 1990; Sarıfakıoğlu et al., 2010; Topuz et al., 2013).

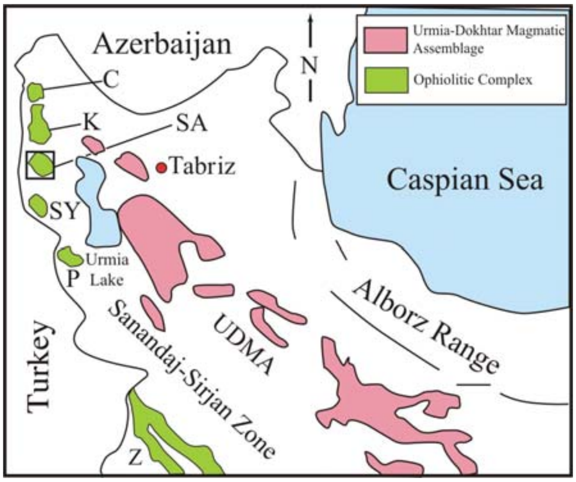

Figure 2- Schematic map of ophiolite outcrops in NW Iran. C; Chaldoran ophiolite complex. K: Khoy ophiolite complex. SY: Sylvana ophiolite complex. P: Piranshahr ophiolite complex. Z: Zagros ophiolites. SA: Study area.

clinopyroxenes in these rocks are used to put constrains on the petrological features and tectonomagmatic aspects of the parental magma forming the protolith of the studied amphibolites.

2. The Geological Background

The study area is located at NW of Iran and within the Sanandaj-Sirjan metamorphic belt according to the definition by Stöcklin (1968). Nabavi (1970) considers this area as a part of the Khoy-Mahabd sub-zone of the Alborz-Azerbaijan zone, based on structural and sedimentary facies relations. Stampfli (1978) suggested that NW Iran, including the study area, is a part of a volcano-molassic depression of central Iran. Stöcklin (1968) assumes that ophiolites of NW Iran have many similarities with ophiolites surrounding the central Iran micro-continent.

According to the field studies, the oldest rocks of the area are a complex of sedimentary, magmatic with granitic to dioritic composition, and greenschist to amphibolite facies metamorphic rocks (Figure 3). These rocks are exposed along the Salmas-Urmia road and are overlain by non-metamorphic Permian carbonates (Figure 4a). The metamorphic complex is always structurally below the Permian carbonates at all localities in NW Iran. Since the carbonate rocks are not metamorphosed, a possible Precambrian age is proposed for this complex. However radiometric

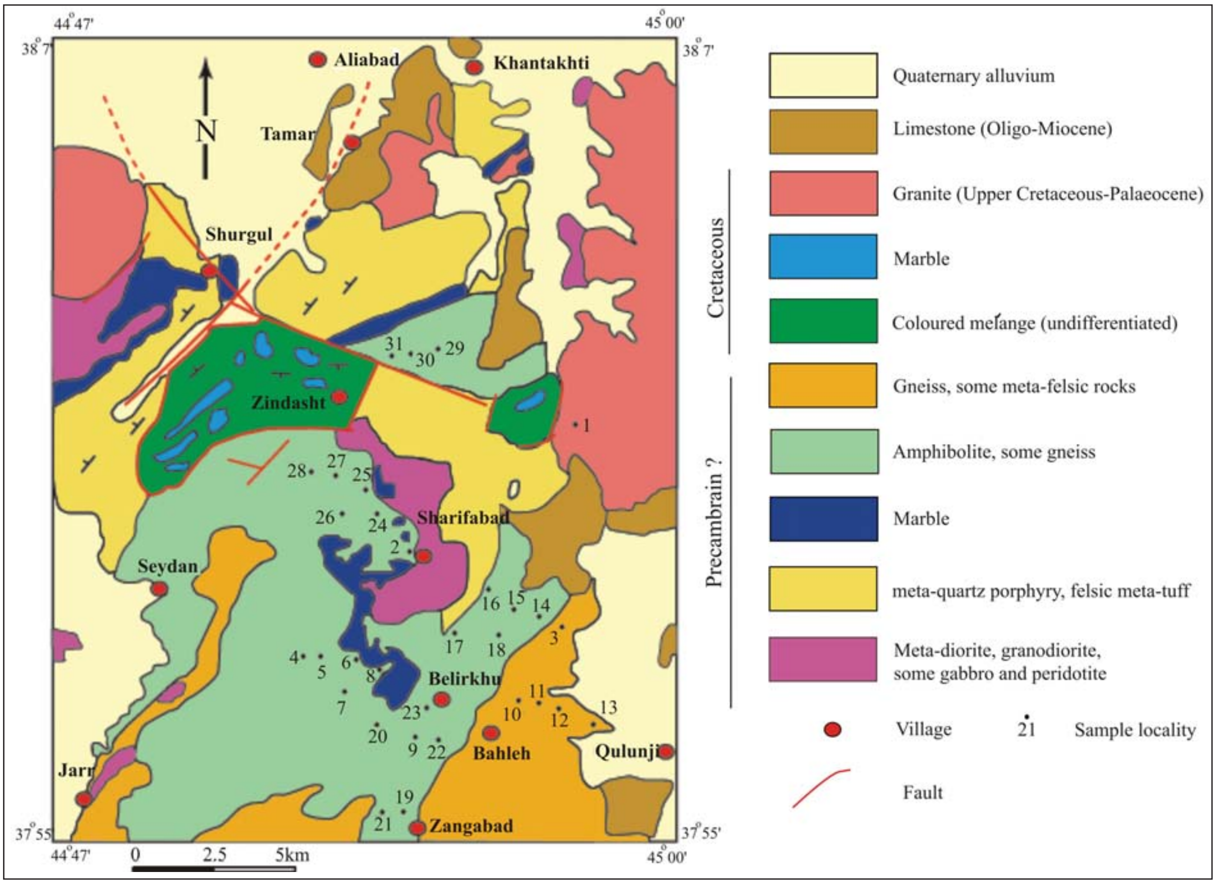

Figure 3- The geological map of the Qushchi area. The location of amphibolite samples are shown on the map.

age dating is necessary to prove this. The rock types of this complex in the studied area are voluminous amphibolites, both as coarse-grained foliated and fine-grained massif amphibolites, sometimes in lithological contact (Figure 4b) with lesser pelitic and psammitic schists, gneiss, meta-rhyolite, meta-rhyodacite, metabasalt, metadiorite and white crystalline marble. These rock types are mixed together due to severe tectonics and finding the original contacts is difficult, however the lithostratigraphic relations in some places show that amphibolites are covered by felsic metavolcanic rocks, which themselves are covered by marble. Granite of upper Cretaceous-Palaeocene age cut the metamorphic complex. Lower Cambrian Kahar formation with very low metamorphism is located at the top of the metamorphic rocks with a tectonic contact. The Cretaceous ophiolitic mélange of the area is composed of serpentinized peridotites, mafic rocks (gabbro, diabase and basalt), felsic rocks (diorite and andesite) and metamorphic rocks (greenschist and amphibolite with diorite and gabbro protolith (Khodabandeh, 2003) along with deep sea sediments such as radiolarian chert and pelagic limestone (Figure 3). Shale, sandstone and limestone of Cretaceous age show weak metamorphism. The Miocene rocks are represented by sandstone, conglomerate, shale and marl. Paleocene conglomerate covers these rocks discordantly.

Recent studies by Azizi et al. (2011) on metamorphic complex associated with the Khoy ophiolite (to the north of the study area, Figure 2) reveals that the protolith of metabasites of this complex have an Upper Proterozoic age which are metamorphosed at upper Jurassic to Lower Cretaceous at amphibolite facies. Amphibolites of the Qushchi area are spatially close to the Khoy amphibolites studied by Azizi et al. (2011). Also they show a similar structural position. Probably amphibolites from the Salmas area formed contemporaneously with the Khoy area amphibolites.

3. Petrography

Amphibolites from the Qushchi area can be divided into three main categories including amphibolites composed of plagioclase and hornblende, relict igneous clinopyroxene-bearing amphibolites and biotite-amphibolites. Plagioclase-hornblende amphibolites are dark green rocks with medium to coarse grain minerals composed of plagioclase, hornblende, titanite, with lesser amount of quartz and oxide minerals. Hornblende and plagioclase are the main mineral phases in the rocks. Titanite can be seen in two different forms, as primary and secondary titanite. Primary titanite is prismatic and is present among the other minerals with granoblastic texture, while the secondary titanite resulted from alteration of ilmenite is restricted to ilmenite rims. These type of amphibolites are mainly deformed and lineated. However some samples display relict doleritic texture inherited from the igneous rocks (Figure 5a). Hornblende alignment parallel to the rock lineation makes the rock orientation in some samples. Relict igneous clinopyroxene can be seen as core in some hornblende crystals (Figure 5b). Some samples are rich in hornblende (Figure 5c) and relatively large hornblende crystals give way to porphyroblastic

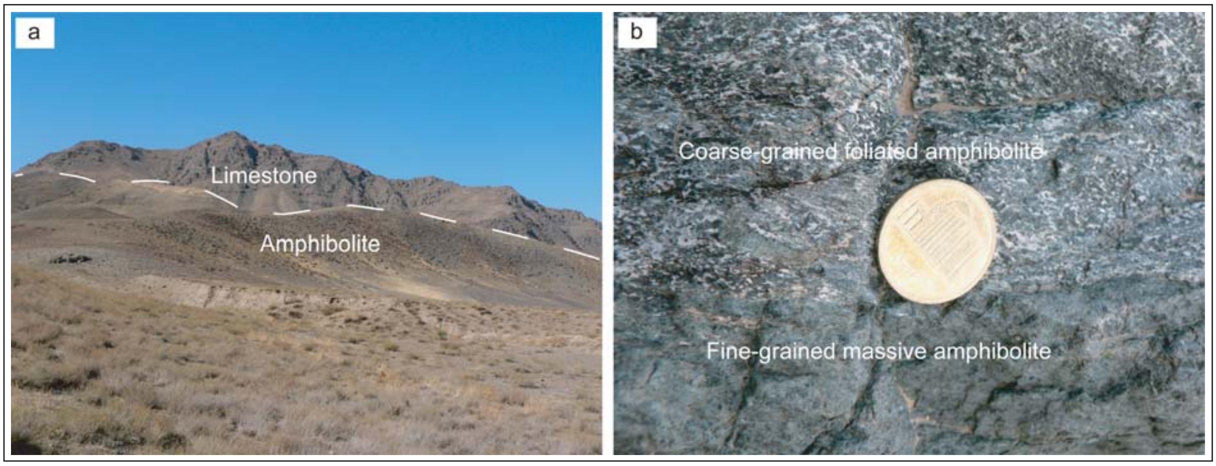

Figure 4- Field photos from the Qushchi amphibolite. a- amphibolites covered by non-metamorphosed Permian limestone. b- coarse-grained foliated amphibolite in contact with fine-grained massif (probably a former dyke) amphibolite.

texture in other samples (Figure 5d). In contrast, some samples have larger plagioclase crystals (Figure 5e). Fine-grain amphibolites are metamorphic products of basalts and fine-grained dolerites (Figure 5f). Some samples with relatively higher quartz contents are the results of metamorphism of quartz-diorite (Figure 6a). Small idioblastic hornblende crystals are formed on the larger hornblende in a few samples (Figure 6b). Existence of the apatite needles is a distinctive feature of many samples (Figure 6c).

Relict igneous clinopyroxene-bearing amphibolites are composed of hornblende, plagioclase, clinopyroxene, titanite and oxide minerals. Quartz is present in these rocks occasionally. Clinopyroxene always is surrounded by hornblende and is not in direct contact with other minerals in the rock (Figures 6e and 6d). This textural disequilibrium shows that the clinopyroxene crystals are relict igneous phases changed to amphibole from the rims during metamorphism. The studied amphibolites are similar to amphibolites from the Khoy area (Moazzen and Oberhänsli, 2008) in this regard.

Hornblende, plagioclase and biotite are the main phases in the biotite-amphibolites. Other minerals include quartz, apatite and oxide minerals. Biotite flakes contain inclusions of zircon. Oxide minerals are as both tiny xenoblastic and larger idioblastic crystals. The idioblastic ones are usually surrounded by an envelope of hornblende (Figure 6f). Biotite-amphibolites lack relict clinopyroxene and form a small part of the Qushchi amphibolites.

4. Methods

In order to determine the magmatic features of the protolith of Qushchi amphibolites, major and trace element analysis were carried out on whole rock samples. The samples were pulverized using a tungsten carbide mill at University of Potsdam, Germany. Then pressed pellets were made from the rock powders for trace elements analysis. About 2 gr of rock powder, 2% polyvinyle alcohol and borax were mixed to make the pressed pellets. Glass bids obtained from alkaline fusion of the sample powders were used for major elements analysis. A X-ray fluorescence at GeoForschungZentrum (GFZ) was employed for the analysis. The results are provided in table 1. Calibration was done using international and internal standards following the method described by Potts et al. (1992). The matrix corrections were done using the appropriate software. Repetition of analysis of standards, indicate relative errors of 1-3% for the major elements and ~5% for the trace elements.

Clinopyroxene in representative, optically well studied samples of the relict clinopyroxene-bearing amphibolites were analysed by a JEOL, JXA-8800 microprobe at Potsdam University. An accelerating voltage of 15 kv, a specimen current of 20 nA and current diameter of 1-3 μm were used. Counting time was 30 seconds on peaks and half-peak on background. Natural and synthetic standards (Fe_2O_3[Fe], rhodonite [Mn], rutile [Ti], MgO [Mg], wollastonite [Si, Ca], fluorite [F], orthoclase [Al, K] and albite [Na]) were used for calibration. Representative data are provided in table 2. Fe^{2+}/Fe^{3+} ratio is calculated based on stoichiometry (Droop, 1987). The analysed clinopyroxenes are diopside, based on the classification of Morimoto et al. (1988). The Mg# (Mg#=Mg/(Mg+Fe^{2+})) calculated for the clinopyroxenes is high and ranges from 86.75 to 88.78. The cationic values of Ti (0.003 atom per formula unit, apfu), Al (0.03-0.06 apfu), Fe^{3+}(0.03-0.05 apfu), Fe^{2+}(0.106-0.125 apfu), Mn (<0.005 apfu) and Na (0.015-0.028 apfu) are low and Si (1.96-1.98 apfu), Mg (0.815-0.856 apfu) and Ca (.958-0.975 apfu) values are relatively high in the studied clinopyroxenes. The Al^{VI}/Al^{IV} ratio is also low and ranges from 0.240 to 0.577.

5. The Nature Of The Amphibolite's Protolithic Magma And Its Tectonomagmatic Features

Major and trace elements composition of the Qushchi amphibolites indicate that they are products from metamorphism of the former igneous rocks (ortho-amphibolite). The evidence for this are the high Cr and low K_2O and Na_2O contents of the rocks pointing to an igneous source material. To identify the original rock type, Zr/TiO_2 versus Nb/Y diagram (Winchester and Floyd, 1977, immobile elements) is used (Figure 7a). As it is evident from this diagram, the parental rocks have andesite-basalt to basalt magmatic composition. This diagram also shows that the magma was of sub-alkaline type. Using major oxides also shows that the magma was sub-alkaline to K-poor sub-alkaline (Figure 7b). The chemistry of immobile and relatively immobile elements indicates that the magma had a tholeiitic affinity. All samples plot in the tholeiite field on diagram of Ti/Y versus Nb/Y (Figure 7c). Also TiO_2 versus Zr/P_2O_5 diagram shows tholeiitic basalt as the source material (Figure 7d). Therefore a tholeiitic magma can be considered for the parental igneous rocks of the Qushchi amphibolites. Only three samples out of 16 analyzed

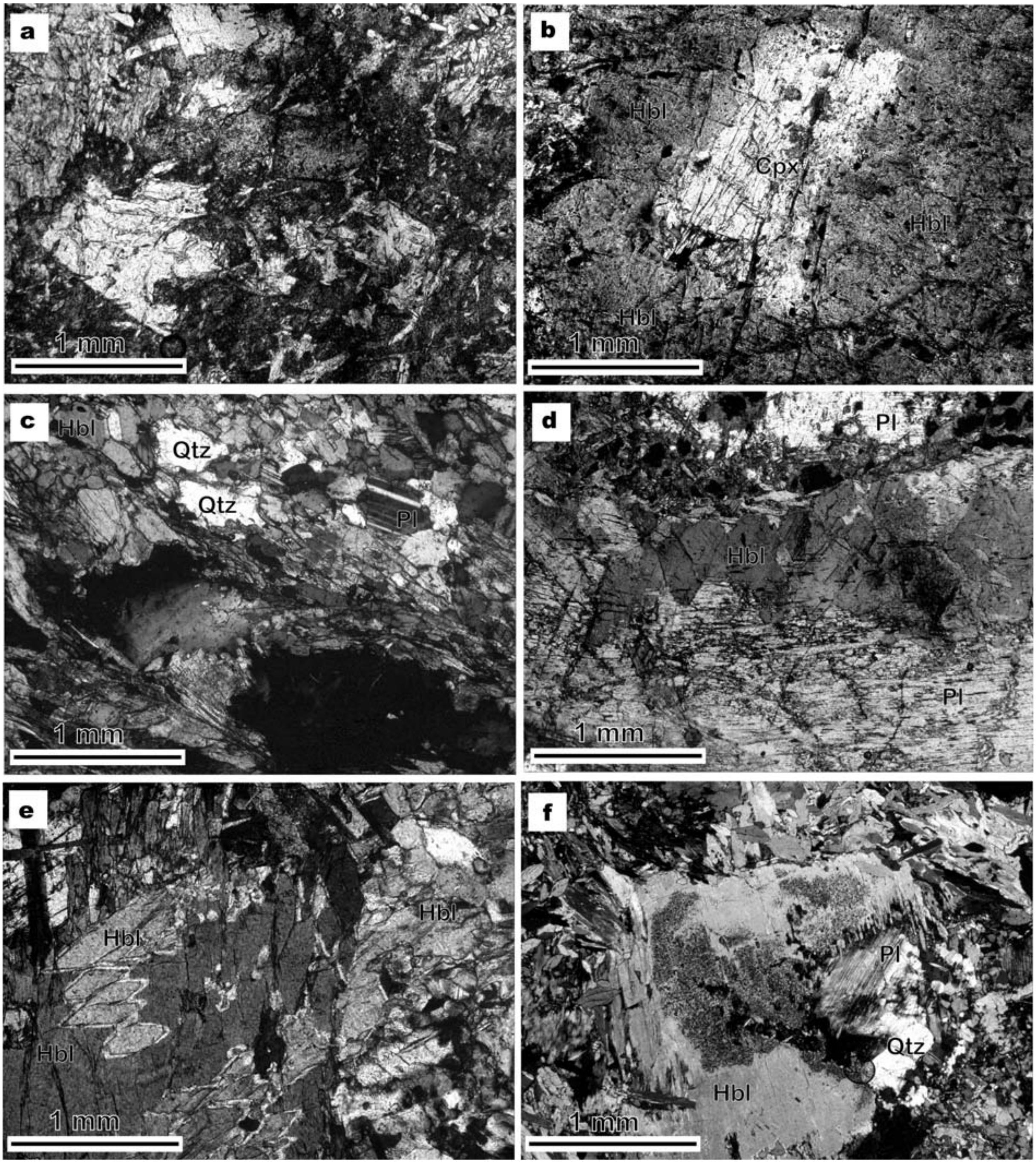

Figure 5- Photomicrographs of the studied amphibolites with their mineralogical and textural features. a: Relict doleritic texture in amphibolite. b: Relict clinopyroxene within hornblende. c: Amphibolite sample made mainly of hornblende with subordinate amount of plagioclase. d: Porphyroblastic amphibolite with relatively large hornblende. e: large plagioclase crystals in amphibolite. f: fine-grained amphibolite which is more likely formed by metamorphism of extrusive rocks. All photos in cross polarized light.

samples have TiO_2 contents more than 1 wt% (all less than 1.5 wt%). According to the TiO_2 contents and considering that TiO_2 is immobile during alteration and metamorphism up to amphibolite facies, an EMORB tholeiite can be proposed considering the chemical features, as the magma from which the mafic protolith of the Qushchi amphibolites were crystallized.

In order to find out the paleotectonic setting of the protoliths of the Qushchi amphibolites, discriminant diagrams for different tectonic settings of mafic rocks

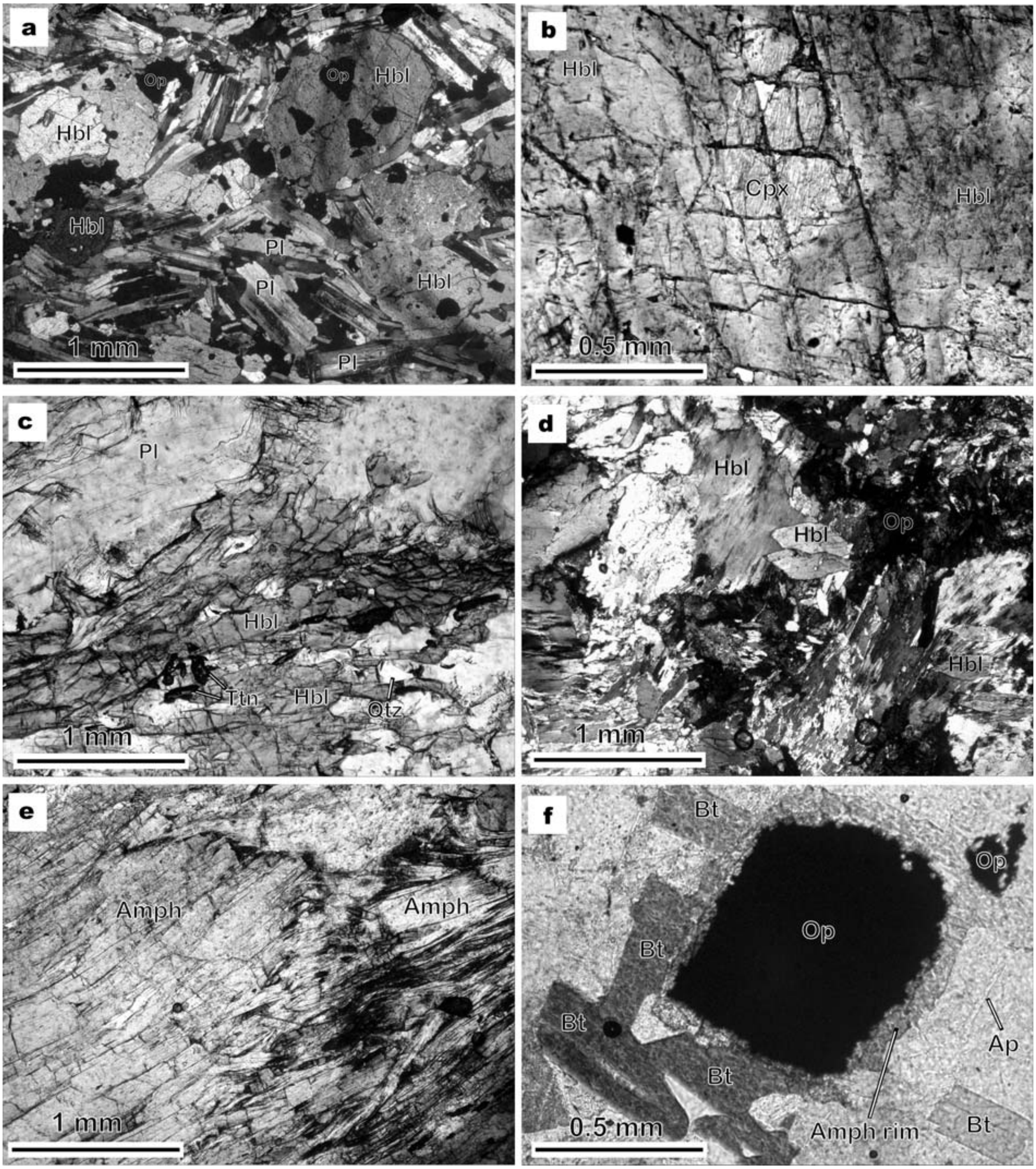

Figure 6- Photomicrographs of western Qushchi amphibolites (continued). a: amphibolite with relatively high quartz content with a quartz diorite protolith. b: idioblastic small hornblende grown on larger hornblende. c: numerous apatite needles in amphibolite. d and e: relict igneous clinopyroxene enveloped by amphibole and is not in direct contact with other minerals in the rock. f: opaque minerals surrounded by amphibole. a and d are in cross polarized light and all other images are in plain polarized light.

are used. In Cr versus Y diagram (Figure 8a) the studied samples plot in the mid-oceanic basalt (MORB), within plate basalt (WPB) and volcanic arc basalt (VAB) fields. Although most of the samples plot in the VAB field, it is not possible to make a clear decision on tectonic setting of the studied rocks. On TiO_2 versus Zr diagram (Figure 8b) most of the samples plot in the volcanic arc filed, although a few samples plot in the MORB and WPB fields. This is the case for the Nb/Y versus Ti/Y diagram as well (Figure 8c). Al_2O_3/TiO_2 versus CaO/TiO_2 diagram of figure 8d clearly indicates a volcanic arc setting for

Table 1- Whole rock composition of the amphibolite samples from the Qushchi area, NW Iran.

Sample	TSL10	TSL1B	TSL1E	TSL2B	TSL2G	TSL2L	TSL2M	TSL3B	TSL3A	TSL6A	TSL6B	TSL8B	TSL8A	TSL9A	TSL9B	TSL9E
Major oxides, wt%																
SiO_2	47.02	51.58	49.10	48.05	49.73	47.99	48.22	48.22	48.97	51.10	51.73	49.79	49.54	50.21	48.61	49.57
TiO_2	1.37	0.36	0.26	0.14	0.56	0.15	0.18	1.19	1.10	0.45	0.86	0.78	0.74	0.56	0.23	0.44
Al_2O_3	15.96	17.56	16.79	18.60	16.18	17.76	16.92	15.70	15.23	16.66	18.09	16.62	15.78	15.36	15.89	16.20
$Fe_2O^*_3$	10.60	6.26	5.77	4.11	8.13	4.17	4.47	10.19	9.83	7.45	7.66	7.41	8.33	8.40	5.63	5.90
MnO	0.18	0.13	0.10	0.08	0.12	0.08	0.09	0.17	0.16	0.14	0.13	0.14	0.15	0.14	0.11	0.12
MgO	8.18	6.78	10.35	10.53	8.11	10.92	11.61	8.04	8.00	7.09	5.47	10.09	9.77	9.51	11.69	9.17
CaO	9.69	11.60	13.89	14.67	13.01	15.43	15.54	10.67	10.39	10.67	9.38	8.99	10.52	10.52	11.87	13.89
Na_2O	2.45	3.42	1.84	1.34	2.39	0.97	0.90	2.28	2.38	2.84	3.28	3.78	3.20	3.58	2.85	2.14
K_2O	1.34	0.10	0.11	0.02	0.27	0.02	0.02	0.61	0.86	1.44	0.90	0.17	0.11	0.14	0.23	0.23
P_2O_5	0.15	0.04	0.03	0.01	0.05	0.01	0.02	0.12	0.11	0.03	0.18	0.09	0.07	0.08	0.04	0.03
LOI	2.67	2.01	1.54	2.13	1.18	2.14	1.71	2.53	2.66	1.84	2.12	1.80	1.46	1.29	2.47	1.92
Total	99.60	99.80	99.80	99.70	99.70	99.60	99.70	99.70	99.70	99.70	99.80	99.70	99.70	99.80	99.60	99.60
Trace elements, ppm																
Ba	205	43	201	21	23	20	21	181	170	172	147	25	40	78	141	105
Cr	296	28	275	1281	356	1142	1110	264	466	130	63	413	426	136	514	395
Ga	19	13	8	12	13	11	12	18	18	19	20	14	15	14	13	14
Nb	4	3	2	3	3	2	2	2	4	2	3	2	3	2	2	2
Ni	104	79	137	222	131	239	240	79	58	52	29	170	156	147	220	131
Rb	9	10	10	9	9	11	9	10	13	36	21	9	11	9	9	10
Sr	178	174	150	116	138	112	99	171	230	282	340	138	140	192	254	172
V	231	181	135	100	212	101	129	239	228	162	214	213	229	253	146	206
Y	28	12	8	5	16	3	8	26	25	19	14	19	19	15	8	13
Zn	120	39	32	20	60	21	19	84	77	63	65	49	49	42	30	34
Zr	71	22	23	11	38	10	10	93	92	40	46	54	46	33	18	23

Table 2- Representative analyses of relict igneous clinopyroxene in Qushchi amphibolites. Formula unit on the basis of 6 oxygen atoms.

SiO_2	54.80	54.71	54.29	54.52	54.36	54.43	54.16	54.29
TiO_2	0.04	0.03	0.03	0.02	0.11	0.07	0.05	0.09
Al_2O_3	1.06	0.71	1.13	0.94	1.30	1.42	1.16	1.25
Cr_2O_3	0.02	0.00	0.00	0.00	0.00	0.01	0.05	0.17
FeO	5.14	4.73	5.16	4.88	5.22	5.38	5.47	5.60
MnO	0.13	0.16	0.09	0.13	0.15	0.13	0.16	0.13
MgO	15.75	15.91	15.49	15.76	15.35	15.31	15.47	15.14
CaO	25.00	25.19	24.98	25.00	24.89	24.83	24.71	24.95
Na_2O	0.31	0.21	0.37	0.30	0.34	0.40	0.35	0.39
K_2O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	102.25	101.65	101.56	101.57	101.71	101.97	101.57	102.01
Si	1.97	1.98	1.96	1.97	1.96	1.96	1.96	1.96
Ti	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Al	0.04	0.03	0.05	0.04	0.06	0.06	0.05	0.05
Cr	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fe^{+3}	0.04	0.03	0.05	0.04	0.03	0.04	0.05	0.04
Fe^{+2}	0.12	0.11	0.11	0.11	0.13	0.12	0.12	0.12
Mn	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00
Mg	0.84	0.86	0.84	0.85	0.83	0.82	0.83	0.81
Ca	0.96	0.97	0.97	0.97	0.96	0.96	0.96	0.96
Na	0.02	0.01	0.03	0.02	0.02	0.03	0.02	0.03
K	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00
$Mg/(Mg+Fe^{2+})$	0.88	0.88	0.89	0.89	0.87	0.87	0.88	0.87
$Fe^{2+}/(Fe\text{-}total)$	0.76	0.78	0.68	0.73	0.79	0.75	0.70	0.74
$Al/(Al+Fe^{3+}+Cr)$	0.54	0.49	0.49	0.50	0.63	0.60	0.49	0.52

the protolith of the amphibolites. To separate the rocks formed at volcanic arc setting and back arc basin, Ti/Zr versus Zr diagram is used (Figure 8e). Most of the samples are plotted in the volcanic arc setting. Therefore more likely the protolith of the Qushchi amphibolites were formed at a volcanic arc setting.

The mineral chemistry of the relict igneous clinopyroxenes in the studied rocks, is used to confirm the tectonic setting for the protolith. This is an accepted practice for igneous rocks (Nisbet and Pearce, 1977). Relict igneous clinopyroxenes from the Qushchi area, define a sub-alkaline magma type for the protoliths on Leterrier et al. (1982) diagrams (Figures 9). The low Na_2O content in the clinopyroxenes confirms the sub-alkaline nature for the magma and a relatively low pressure for clinopyroxene crystallization (Bonev and Stampfli, 2009). Also Ti content in Qushchi samples is low. This may reflect a depleted mantle nature for the source materials (Pearce and Norry, 1979).

Clinopyroxene composition is used to confirm volcanic arc setting for the magmas from which the protolith of the Qushchi amphibolites are crystallized. Considering Ti versus Ca diagram of Leterrier et al. (1982), the protolith of the amphibolites is formed at an orogenic environment (Figure 9a). In order to find the tectonic setting more precisely, F1 versus F2 diagram of Nisbet and Pearce (1977) and Ti+Cr versus Ca diagram of Leterrier et al. (1982) are used (Figure 9b and 9c). These diagrams indicate volcanic arc-oceanic floor basalt and volcanic arc setting.

6. Discussion and Conclusions

Amphibolites from the east of Qushchi in west Azerbaijan province of Iran mineralogically (high hornblende and plagioclase and low quartz content)

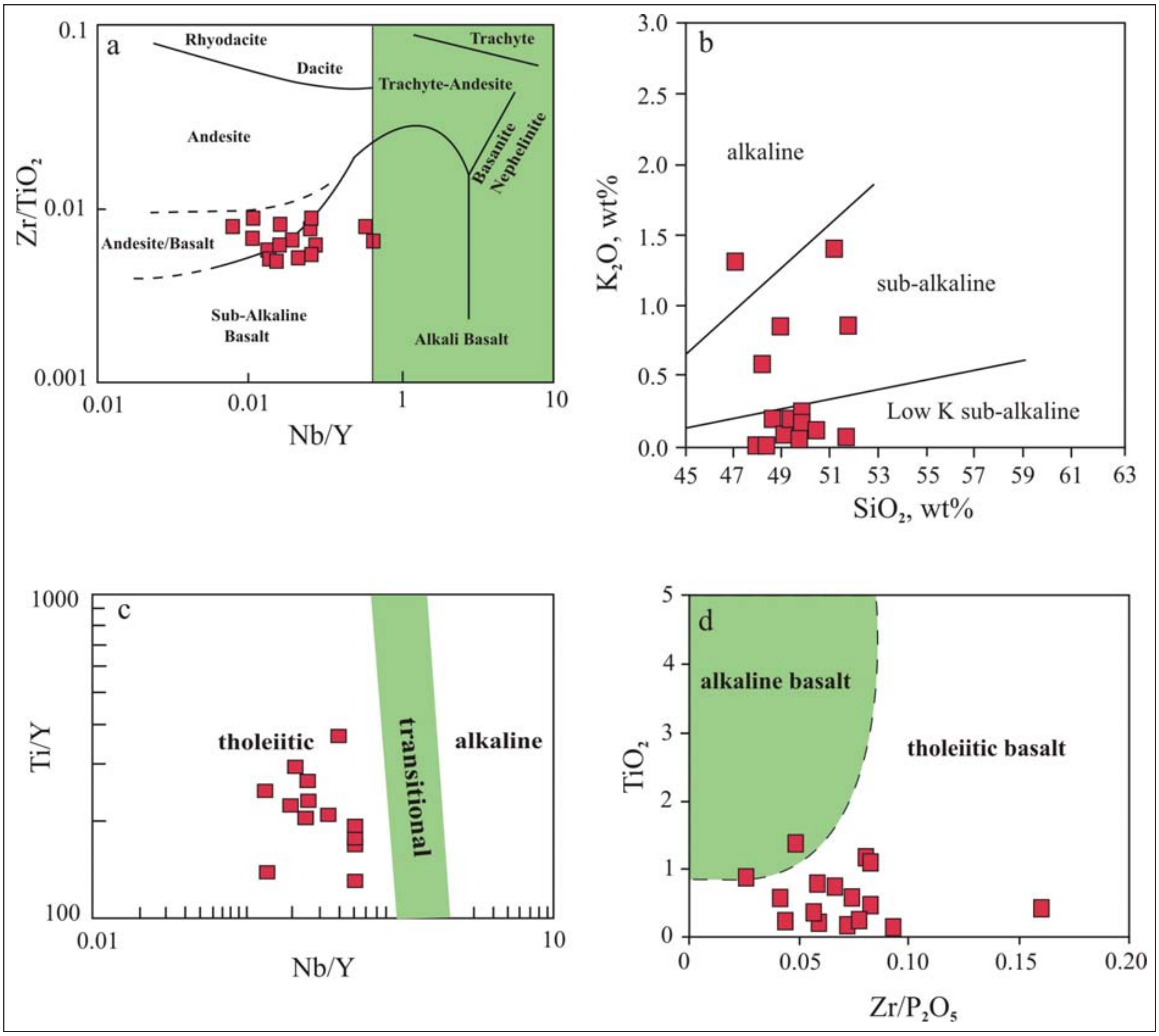

Figure 7- Diagrams used to identify the protolith nature of the Qushchi amphibolites. The protolith was andesite basalt and the original magma was sub alkaline tholeiite. Diagrams a and d from Winchester and Floyd (1977), diagram b from Middlemost (1975) and diagram c from Pearce (1982).

and chemically (low K_2O) are ortho-amphibolites resulted from metamorphism of mafic igneous rocks. The protolith was a sub alkaline andesite basalt to basalt. The magma forming the protolith was of tholeiitic nature. Tectonic setting discriminant diagrams show that this magma was formed at a volcanic arc setting. The exact age of the amphibolites is not known, but Haghipour and Aghanabati (1989) proposed a Precambrian-Paleozoic age for them based on the fact that the associated Permian limestone of the area (with tectonic contact) is not metamorphosed. Azizi et al. (2011) reported Upper Paleozoic age (U–Pb zircon) for protolith and Upper Cretaceous-Lower Triassic (Rb–Sr mineral isochron) for metamorphism of the Khoy amphibolites to the north of the study area. Since the non-metamorphosed Permian limestone is in tectonic contact with the studied amphibolites, it is not easy to conclude about the age of metamorphism in the Qushchi area. The ophiolitic mélange in the Salmas area is Upper Cretaceous-Paleocene in age. The studied amphibolite can be considered as tectonic slivers of this ophiolitic mélange.

If these rocks are Late Cretaceous- Paleocene in age, they might have been formed as parts of a volcanic arc in the Neotethyan oceanic crust. In this case, the ophiolitic complex and the volcanic arc rocks all are metamorphosed at amphibolite facies following the Neotethys ocean closure and the

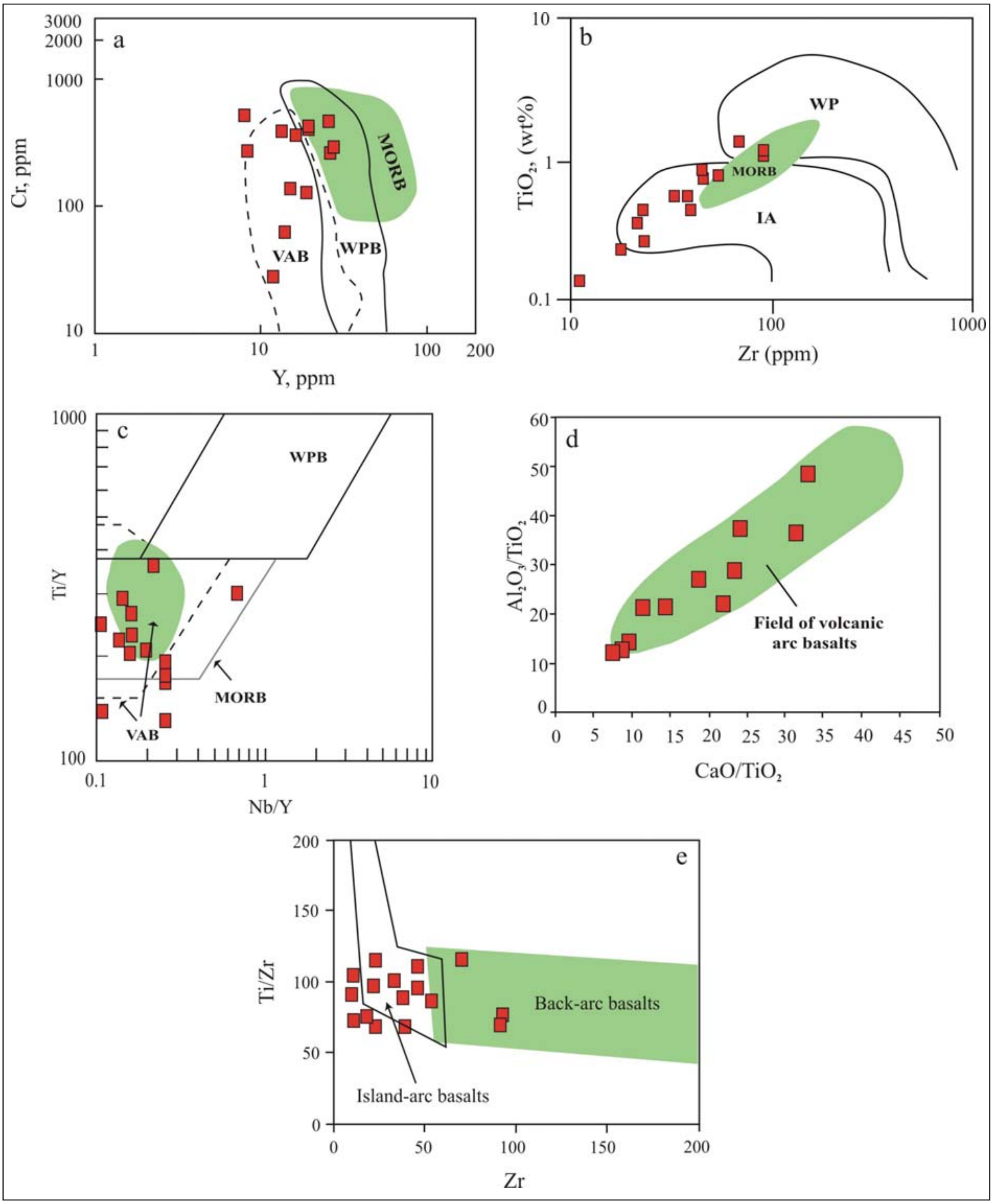

Figure 8- Tectonic discrimination diagrams to identify the tectonic environment of formation of the original magma of Qushchi amphibolites. See the text for explanations. Diagram a from Pearce et al. (1984), diagrams e, c, b from Pearce (1982) and diagram d from Sun and Nesbitt (1978).

continental collision. The alternative scenario is that the studied amphibolites are older than the ophiolitic mélange. In this case amphibolites from the Qushchi area are equivalents the similar amphibolites from the Khoy area, studied by Azizi et al. (2011) and they predate the closure of the Neotethys. However, considering that the serpentinites within the ophiolitic mélange lack the antigorite polymorph and are not

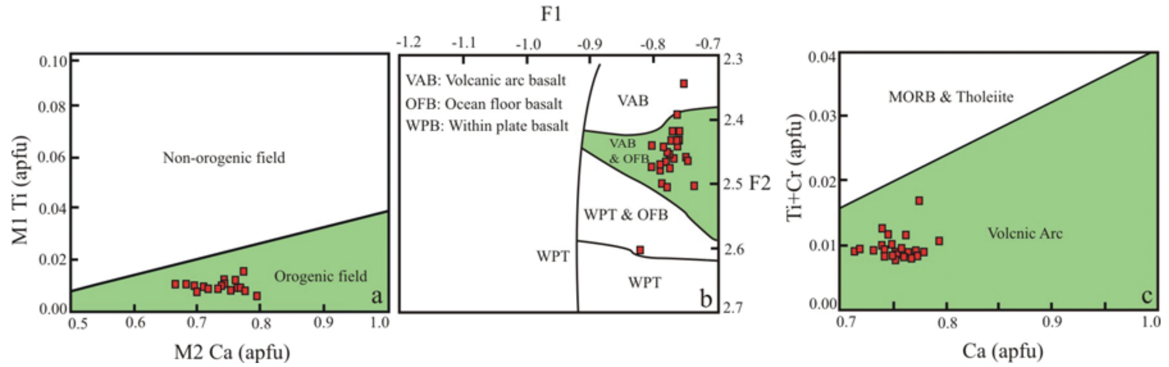

Figure 9- Relict igneous clinopyroxene composition in the amphibolites which indicate sub-alkaline type for the original magma. Diagram after Leterrier et al. (1982). a: The protolith of the amphibolites formed at an orogenic environment (diagram from Letterier et al., 1982). b: F1 versus F2 diagram of Nisbet and Pearce (1977) showing either volcanic arc basalt or ocean floor basalt for the protolith of the studied amphibolites. F1= -(0.012*SiO_2) - (0.0807*TiO_2) + (0.0026*Al_2O_3) - (0.0012*FeO) - (0.0026* MnO) + (0.0087 *MgO) - (0.0128*CaO) - (0.0419*Na_2O). F2= -(0.0469*SiO_2) - (0.0818*TiO_2) + (0.0212*Al_2O_3) - (0.0041*FeO) - (0.1435*MnO) + (0.0029*MgO) + (0.0085*CaO) + (0.016*Na_2O). c: Ti+Cr versus Ca diagram of Leterrier et al. (1982) clearly shows volcanic arc setting for the original magma of the Qushchi amphibolite protolith.

metamorphosed in amphibolite facies conditions, it is likely that the studied amphibolites are not part of the mélange. The third possibility is that the generation of protolith of the amphibolites was contemporaneous with ophiolite formation, but this protolith is metamorphosed within the accretionary prism but the obducted ophiolitic rocks (including serpentinite) are not metamorphosed. Radiometric age determinations from these amphibolites will help to solve this problem and to reconstruct their formation history.

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