Petrography, Geochemistry and Tectonic Setting of Mafic Rocks of Southern Bela Ophiolite, Balochistan

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Abstract: Petrogpaphical and geochemical studies of the mafic rocks of southern part of Bela Ophiolite (BO) is made to infer tectonic setting of the area. The BO is the largest (~450km) and most complete ophiolite in Pakistan, linked with Neotethyan ophiolitic belt which extend from European Alps to Asia. Petrographically, the majority of mafic rocks appeared as amygdaloidal and vesicular porphyritic basalt. Large phenocryst of feldspar, olivine, ortho- and clinopyroxene are present with in fine-grained groundmass of nearly similar composition. Numerous small needles of black opaque minerals are dispersed in the fine groundmass. The petrographic study revealed two stages of crystallization. In the first step, phenocrysts are formed while in the second step, pillow basalt at MORB setting were fractionate during the rapid cooling in cold seawater. Based on TAS diagram, the rocks of the study area appear as basalts. These rocks displayed tholeiitic characteristics and showed relevancy with metaluminous type of rocks. Trace element assemblage of the studied rocks plots on various discrimination diagrams as ocean floor tholeiite, initially formed at Mid-ocean Ridge setting. The subsequent subduction phase generates SSZ ophiolite, forming Island-Arc Tholeiite (IAT) and Back-Arc Basin Basalts (BAB).

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Key words: mafic rocks, petrography, geochemistry, tectonic setting, Bela Ophiolite

1. Introduction

In the recent past, considerable attention have focused to study petrography, geochemistry and genesis of Neotethyan ophiolites of Late Cretaceous age especially in Cyprus, Iran, Turkey, Oman and Pakistan (Moghadam et al., 2010, Dilek and Thy, 2009, Sheth, 2008 and Xiong et al., 2008). The ophiolitic rock association helps to insight the processes and conditions of magmatic differentiation in perspective of tectonics prevailed in a region. Thus, they provide excellent opportunities to reconstruct the tectonic history of a region, as these units indicate the presence of sutures and the closure of ancient oceanic basins (Ghazi et al., 2010).

The Bela Ophiolite (BO) is the largest (~450km) and most complete ophiolite in Pakistan, striking NS. The BO is linked with Alpine-Himalayan Mesozoic Ophiolite Belt, which stretches from European Alps to Asia. Gnos et al. (1998) divided BO into upper (northern) and lower (southern) units. A lot of work has been carried out on the northern part (Ahmed and Ernst, 1999 and Gnos et al., 1998) but very little attention has been paid on the southern part. The study area lies in the southern part of BO and situated between Winder and Uthal towns of Balochistan (Figure 1). Varieties of igneous rocks along with sedimentary rocks are exposed in an N-S trending belt (Figure 1). The zone is termed as Accretionary wedge (Gnos et al., 1998) and consists of mélange in which agglomerate and other segments of ophiolite are present (Gansser, 1979). The mafic suite consists of pillow basalt, amygdaloidal basalt, porphyritic basalt, and olivine gabbro. Numerous dykes and sills bisected Sembar Formation of Early Cretaceous age are also present. The volcanogenic sedimentary Mn deposits and massive volcanic sulphides (MVS) are hosted within the mafic rocks (pillow), increasing the economic importance of the rocks (Kearey et al., 2009). Present studies help to evaluate petrographical and geochemical characteristics of the mafic rocks of BO and the related tectonics is construed from discrimination diagrams.

2. Sampling and analytical methods

Samples of mafic rocks of BO were collected from different locations. The pulverized rock samples were fused with lithium metaborate in a platinum crucible. Silica (SiO_2) was estimated gravimetrically using hydrofluoric (HF) acid. The chemical composition of major and trace elements were determined by an atomic absorption spectrophotometer (Hitachi Model, Z 5000). Thin sections of relatively fresh mafic rocks were studied using Laborlus Pols microscope and photographed on Leica Microsystem (DFC 280).

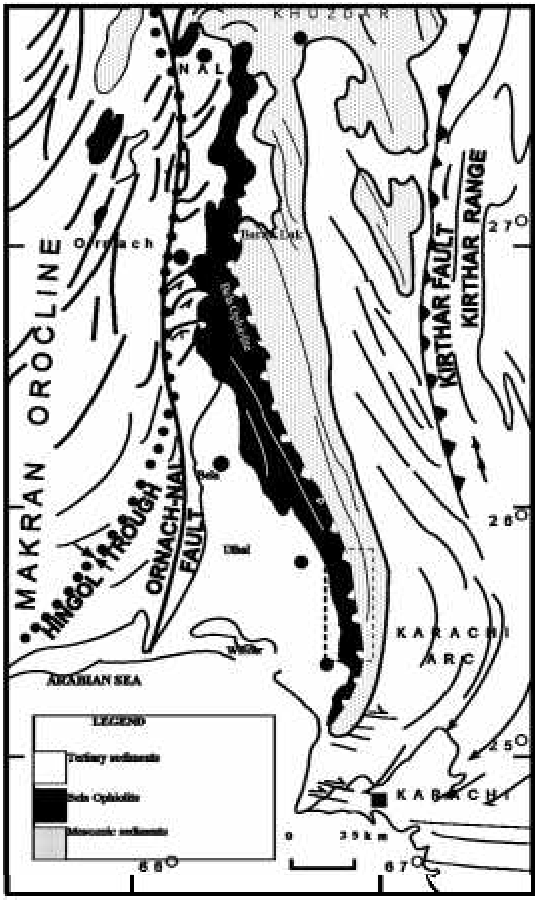


Fig. 1 Map of Bela Ophiolite; Study area is enclosed by broken lines.

3. General Geology

The study area lies within the Western Fold Belt of Pakistan forming the western margin of the Indian plate. The belt comprises of BO and sedimentary rocks ranging in age from Jurassic to Tertiary. On the basis of thick crustal sequence, absence of dolerite dykes in the mantle sequence, presence of cumulate gabbros and large quantities of podiform chromite, the BO exhibits relevance with HOT-type ophiolite of Nicolas (1989). Gnos et al. (1998) divided BO into upper (northern) and lower (southern) units on the basis of age difference and emplacement style. Upper unit of BO is presented by true ophiolitic sequence, carries typical island arc lithologies including low-Ti mafic rocks (Sheth, 2008). The lower unit comprises of tectonic accretionary wedge of older back-arc basin lithologies, including high-Ti mafic rocks.

Xiong et al. (2009), on the basis of Ar^{40}/Ar^{39} dating, suggest ~110Ma age for lower unit and 60-65Ma for upper unit. Yaliniz et al. (1996) have divided the ophiolites of the region into two groups; western MOR Jurassic and eastern suprasubduction (SSZ) Cretaceous ophiolites. The SSZ features often comparable with younger back-arc basins worldwide (Pearce et al., 1994). Neotethyan SSZ ophiolites that developed along the periphery of the Mesozoic Gondwanaland represent the remnants of an anomalous oceanic crust produced in a proto-forearc setting (Dilek and Thy, 2009). The BO is originated from obduction of Neotethyan oceanic plate on the rifted western margin of Indian plate (MOR), obducted floor of a back-arc basin (SSZ) and an associated island arc originated in a large oceanic fracture zone (Xiong et al., 2008 and Sheth, 2008). Xiong et al. (2011) based on the remote-sensing data, suggest two episodes of obduction. Initially, the upper unit was obducted onto the lower unit and then the two units combinedly obducted as a single body onto the western margin of Indian plate.

4. Results and Discussion

a. Petrography

In the study area, the mafic volcanic rocks display aphyric or phyric texture and consist of pillow, amygdaloidal and porphyritic basalt, with one exception of olivine gabbro.

Sample UH_2 is a fine grained basaltic rock. The groundmass is composed of mixture of pyroxenes and plagioclase feldspars. Randomly oriented microlites of feldspars are common, indicating formation of tiny crystals of feldspars in fine to glassy matrix (Ross, 1962). Similar observations were also made by Ozsoy et al. (2010) while studying ophiolitic rocks of Eskisehir, Turkey. The shape and size of plagioclase feldspars is the function of composition and rate of cooling, which ultimately control the nucleation and crystal growth rate (Hefferan and O'Brien, 2010). According to Lofgren (1983 & 1980), tabular to skeletal shape of crystals illustrate relatively high rate of under cooling and Na-rich albite composition. Phenocrysts and glomerocryst of olivine are visible. Such type of texture is referred as glomeroporphyritic (Xu et al., 2009) and the rock is termed as olivine phyric basalt. Some basalt contain two generation of phenocryst (phenocryst and microphenocryst) as well as groundmass, indicating two stages of crystallization during ascent prior to eruption (Gill, 2010). Phenocrysts are initially formed by the crystallization of high temperature minerals (olivine-pyroxene) at slow rate of cooling, before the lava reached the surface. The presence of plagioclase and clinopyroxene phenocrysts, with some megacrysts suggest to possible magma mixing. Petrographical heterogeneity is the most significant character of MORB, as it was noted by Einaudi et al. (2000), while working on one of the famous Semail

Ophiolite, Oman. Numerous small needles of black opaque minerals (ilmenite, chromite, magnetite, etc.) are dispersed in the fine groundmass but absent in the microlites (Figure 2A). The restriction of Fe-Ti oxides in the groundmass designates late stage crystallization in the MORB sequence. Some of the feldspars (albite) are relatively large size as phenocryst (Figure 2A). The crystal has many cris-cross microfractures indicating intense tectonism in the area.

The rock GM_1 appears as tholeiitic basalt having felty texture. Matrix composed of a crowded mass of microlites, generally of feldspar, interwoven in irregular fashion. Possibly, the texture is indicative of rapid underwater cooling, during the formation of pillow basalt. Abundant black grains of oxide minerals are also common (Figure 2B), which is also verified from the high content of Fe, Ti, Cr in the rock (Table 1). Microphneocrysts of olivines are evenly distributed in the fine-grained matrix. The matrix mainly composed of fine olivines and plagioclase set in an intergranular matrix of plagioclase and granular pyroxene.

The samples (PU_1 and PU_2) collected from north of Winder town are amygdaloidal basalt. Vesicles are formed when dissolved magmatic gases are released during the extrusion of magma due to pressure drop forming gas bubbles (the cavities) in the magma. Later, these vesicles are filled due to precipitation of calcite from seawater. The cavities are perfect rounded in shape and are 1-5mm in size. The rest mass is fine-grained in which olivine-pyroxene-feldspar is present (Figure 2C). Few euhedral clinopyroxene phenocryst are also visible (Figure 2D). Olivine is subhedral (hypidiomorphic) while clinopyroxene is euhedral (idiomorphic) in shapes exhibiting schiller structure. Both these samples have high amount of tiny opaque crystals of ilmenite and magnetite, evenly distributed in the fine groundmass. Possibly, pillow basalt at MORB setting were fractionate during the rapid quenching in cold seawater.

Only one sample of gabbro (DA_1) was found from the study area. Probably, it is representative of gabbroic segment of BO, present within the accreted mass as mélange. The mineralogy suggests it as olivine gabbro having ophitic texture (Figure 2E). Randomly oriented plagioclase laths are enclosed by the matrix of intercumulate olivine and pyroxene. Few medium sized (2x2mm) opaque grains (ilmenite) are present within the fine ferromagnesian minerals.

Another sample of same locality (DA_2) is an olivine basalt in which groundmass is consists of more olivine and less clinopyroxene. Feldspar is present as microlite but comparing to previous slide, the content is less (Figure 2F). Probably, the presence of plagioclase microlite is the common feature of Tethyan ophiolites, as it was observed from one of the Turkish ophiolite (Ozsoy et al., 2010). Patches of olivine are also present. Opaque grains are less frequent than the other rocks. Void spaces are filled with carbonate minerals.

The sample MT_1 is fine grained basalt and shows aphanitic texture. The less number of olivine phenocryst suggest either the melt has ascended directly from its source without being detained in the magma chamber or phenocryst were settled down during subsequent ascent (Gill, 2010). The rock has less opaque grains and most of them are present within clinopyroxene and form array around calcite grain. All void spaces are filled with calcite. Few microcracks are visible, which are filled with limonite and hematite.

The ophiolitic rock samples collected from NE of Winder Town are amygdaloidal (TW_1) and vesicular porphyritic basalt (TW_2). In the rock (TW_1) large calcite amygdaloid (9x12mm) along with numerous calcite veins are present (Figure 2G). Hydrothermal circulation during burial of lava leads to the deposition of calcite in the vesicles.

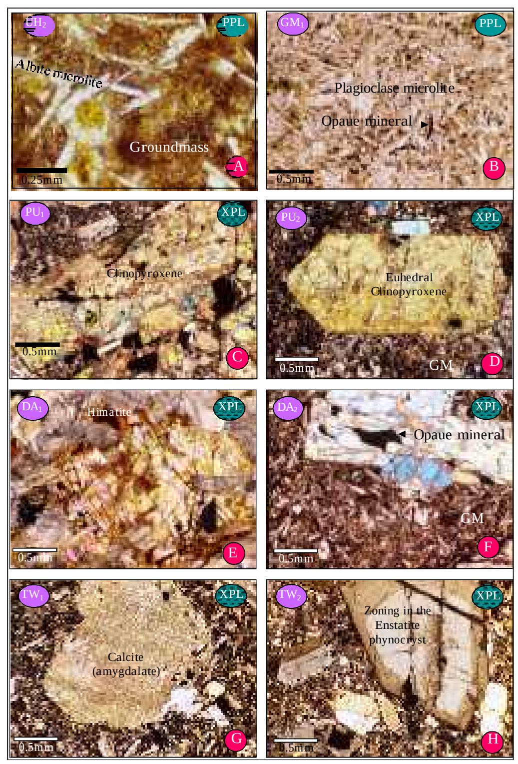


Fig. 2 Photomicrographs of mafic igneous rocks of the Winder area. Sample numbers are marked on top left and status of nicols on top right.

Table 1. Composition of mafic rocks of Winder area. Major oxides are in weight %, while trace elements are in mg/kg.

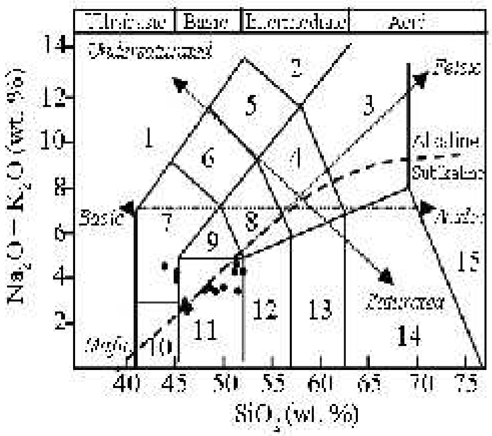
Samples	UR_1	UH_2	GM_1	PU_1	PU_2	DA_1	DA_2	AT_1	MT_1	TW_1	TW_2	TW_6
SiO_2	49.72	51.58	48.76	44.00	45.14	46.45	45.54	51.23	52.08	48.26	49.08	51.55
TiO_2	2.91	1.85	3.21	2.29	2.94	1.02	4.09	3.14	1.31	4.12	3.71	1.82
Al_2O_3	13.24	16.12	11.01	10.34	12.54	13.70	10.08	12.32	10.85	10.62	10.52	10.64
Fe_2O_3	1.60	0.78	1.91	0.70	1.25	1.27	1.92	1.04	0.85	1.09	0.96	0.56
FeO	7.34	5.78	8.53	5.34	6.12	4.98	6.81	5.85	6.33	8.65	6.22	12.05
MnO	0.35	0.68	0.54	0.40	0.87	0.79	0.66	0.88	0.75	1.04	0.68	0.68
MgO	13.05	10.45	14.18	7.45	6.89	17.56	12.91	12.26	12.84	13.78	14.02	10.02
CaO	6.81	7.23	6.92	17.01	14.95	10.34	9.82	7.45	9.35	8.51	11.23	8.23
Na_2O	3.37	4.45	3.23	4.35	3.85	2.48	4.11	4.12	4.23	3.03	2.69	2.85
K_2O	0.10	0.06	0.16	0.05	0.05	0.06	0.06	0.22	0.12	0.30	0.41	0.39
P_2O_5	0.35	0.26	0.11	0.75	0.68	0.25	0.11	0.12	0.18	0.26	0.46	0.43
CO_2	1.10	0.65	1.01	7.09	4.72	0.05	3.65	1.24	0.36	0.08	0.07	0.04
$+H_2O$	0.21	0.35	0.28	0.15	0.45	0.21	0.31	0.35	0.49	0.41	0.29	0.52
DI	29.11	38.00	28.28	35.86	32.88	19.34	35.47	36.16	36.50	27.41	25.18	26.42
ASI	0.73	0.78	0.61	0.27	0.37	0.59	0.41	0.60	0.45	0.51	0.41	0.53
Cu	211	12	177	137	165	390	148	409	166	356	390	330
Zn	123	10	110	82	98	116	79	98	73	67	98	72
Cr	402	126	482	510	1141	385	481	335	283	603	1265	326
Co	64	73	63	33	62	57	57	53	36	81	99	52
Ni	791	11	854	797	969	797	825	775	748	342	561	199
Pb	95	33	83	85	90	01	97	77	83	45	19	01
Ba	4696	7380	3882	5510	5374	2528	4612	2228	5230	4988	6096	5115
V	4816	4562	5234	5620	6104	2930	5954	5254	4110	3172	3664	3350

The petrographic relationship between parent rock and calcite signify secondary origin. On microscopic level, randomly oriented, fine to medium sized microlites are also common. Small phenocryst of clinopyroxene is also evidenced. The phenocrysts are not opaque, indicating that during fractional crystallization, oxides of Fe-Ti entered in the late phase with rapid cooling of lava. The hypabyssal rock (TW_2) shows porphyritic texture. Members of orthopyroxene family as phenocryst are widely distributed in the groundmass of clinopyroxenes. Lath of orthopyroxene is visible in the photomicrograph, while some phenocryst of orthopyroxene exhibiting zoning (Figure 2H) is also noted. There are abundant Fe-Ti oxides, in the groundmass and as well as along the cracks. It is a sign that the plutonic stage of crystallization has been sufficiently prolonged for significant evolution in melt composition to take place (Gill, 2010).

b. Geochemistry

Major and trace element composition of the mafic rocks of the study area is presented in Table 1, reflecting their nature. The Total Alkali Silica (TAS) diagram is used to classify many common types of fine-grained volcanic rocks (Le Bas et al., 1986), because the study of fine grained rocks through petrography is difficult due to intense alteration. It is based upon the relationships between the combined alkali content (Na_2O+K_2O) and the silica (SiO_2) on anhydrous basis. The mafic rocks of the study area on TAS diagram are confined in the basalt zone; however few of them are plotted as tephrite/basanite (Figure 3). The TAS diagram also illustrates the boundaries of silica saturation and thus it reflects certain tectonic regimes, as described by Streckeisen et al. (2002). The plots of rocks illustrate that pillow basalts are undersaturated tholeiitic mafic rocks.

In the study area, igneous rocks contain appreciable amount of feldspars, thus, the concept of alumina saturation index (ASI) is based on whether or not there is an excess or lack of Al to make up the feldspars. Oxide of Al is assessed versus oxides of Na+K+Ca to evaluate type of magma. Three possible conditions exist, depending upon the content of Al versus Na, K & Ca (Table 1). The peraluminous types have more Al (ASI>1), necessary to make feldspars. The rocks with ASI<1 are termed metaluminous, when molar Na+K<Al, and are peralkaline when molecular Na+K>Al (Frost and Frost, 2008). The calculated ASI of the mafic rocks of the study area varies 0.27 to 0.78 (Table 1), indicating metaluminous nature having feldspars and pyroxenes.



Legend

1:Foidite, 2:Phonolite, 3:Trachyte/trachydacite, 4:Trachy-andesite, 5:Tephriphonolite, 6:Phonotephrite, 7:Tephrite/basanite, 8: Basaltic trachy-andesite, 9:Trachy-basalt, 10:Picro-basalt, 11:Basalt, 12:Basaltic andesite, 13:Andesite, 14:Dacite, 15:Rhyolite

Fig. 3 Classification of mafic igneous rocks of Winder area on Total alkali-silica diagram (Le Bas et al., 1986).

The differentiation index (DI) is a measure of differentiation of magmatic evolution. It can be assessed by totaling the low temperature normative minerals: quartz, orthoclase, albite and their low silica equivalents (Allaby and Allaby, 1999).

DI = normative (Q + Or + Ab + Ne + Ks + Lc)

It is expressed in percentage, ranging from zero to 100%. Basalt generally have a low differentiation index (<25), whereas granites have indices exceeding 75. The assessed DI values of the studied rocks ranged 19.35 to 38.0%, with an average 30.88% (Table 1), that shows compatibility with the nature of basalts.

5. Tectonic Setting

Tectonic evaluation of an area is an essential step for the study of igneous rocks. Composition of igneous rocks is utilized for the tectonic appraisal through discrimination diagrams since long time (Pearce and Cann, 1973 and 1971). Rollinson (1993) summarized the use of major and trace elements to distinguish different tectonic environments.

Vermeesch (2006) has introduced the concept of classification tree in order to define tectonic environment of formation. Volcanism occurs at three different settings on the ocean floor. These settings are mid-ocean ridge (MORB), Ocean Island (OIB) and island arc (IAB). The classification tree utilized high field strength (HFS) element to discriminate basalts of MORB, OIB and IAB affinities that have undergone alteration. The mafic rock samples of the study area demonstrate all three types of rocks. Sample DA_1 shows affiliation with IAB, UH_2, MT_1 and TW_6 are in MORB, while rest of the samples is within the domain of OIB (Figure 4A). Similarly, Ti vs. V plots also signifies IAB, MORB and OIB affinities (Figure 4B). The presence of three suites was also identified by Ahmed and Ernst (1999), while working on the BO.

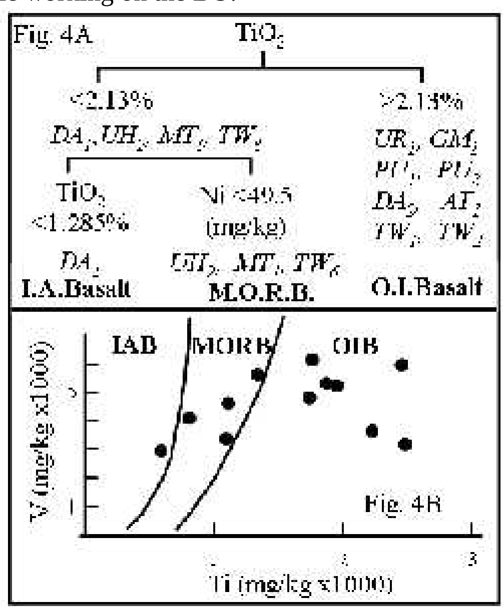


Fig. 4 Mafic volcanic rocks of Winder area, A) on tectonic classification tree, B) on Ti vs. V diagram (simplified after Vermeesch, 2006).

Samples were plotted on various geochemical diagrams to discriminate the tectonic settings of rocks. On Cr vs. Ti diagram (Figure 5A) all of the samples plot in the field of ocean floor tholeiite (OFT). Further, on Ni vs. Ti/Cr plot the mafic rocks of study area mainly confined in the field of OFT. Only one sample plots in the field of island arc tholeiite (Figure 5B). Probably, the high Ti bearing rock in the study area suggests formation of magma having N-MORB type composition and emplaced in the divergent tectonic setting (MOR), as it was noted by Srivastava et al. (2004), for Andaman ophiolite suite, India.

Water of crystallization (+H_2O) is also assists to evaluate the origin of basaltic rock (Gill, 2010 and Rollinson, 1993). The H_2O vs. K_2O diagram shows majority of the basalts of the Winder area were generated in back arc basin (BAB) and MORB settings; however three samples are in the domain of Ocean Island Basalt (Figure 5C).

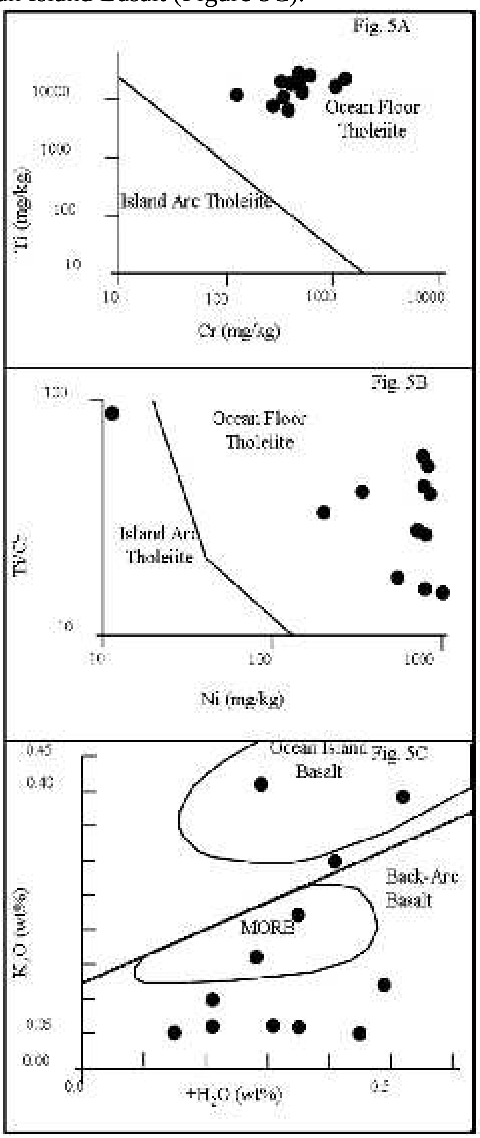


Fig. 5 Plots of mafic rocks of Winder area showing tectonic affiliation, A) Ti vs. Cr (after Pearce, 1975); B) Ni vs. Ti/Cr ratio (after Beccaluva et al., 1979); C) H_2O vs. K_2O (tectonic boundaries after Rollinson, 1993).

The all above hypothesis regarding the tectonics prevailed in the study area suggest that all three type of mafic rocks (IAB, MORB and OIB) were found in and around Winder Town. This assumption is also supported by different geoscientists worked on BO time to time, such as Sarwar (1992), Ahmed (1993), Gnos et al. (1998), Khan et al. (1998) and Sheth (2008).

6. Conclusions:

Petrographically, the mafic rocks are consists of fine grained basalt, olivine basalt, amygdaloidal and vesicular porphyritic basalt. In majority of the rocks, groundmass is composed of mixture of pyroxenes and plagioclase feldspars. The void spaces are mainly filled with calcite. Numerous small needles of black opaque minerals (ilmenite, chromite, magnetite, etc.) are also present. It is observe from the petrographic study that basaltic rocks of the study area faced two stages of crystallization. In the first step, phenocrysts (olivine-pyroxene) are formed while in the second step, pillow basalt at MORB setting were fractionate during the rapid quenching in cold seawater.

The rocks of the study area on TAS diagram appear as basalt with few tephrite/basanite and are undersaturated tholeiitic mafic rocks. The rocks of the study area on the basis of ASI show relevancy with metaluminous, representing igneous origin with dominant feldspars and pyroxenes. The differentiation index (DI) of the studied rocks varies 19.35 to 38.0%, with an average 30.88%, indicating basaltic nature.

The tectonics of the BO is complicated and faced by three different settings: Mid-ocean Ridge (MORB), Ocean Island (OIB) and Island Arc (IAB). On the basis of Ti and Ni content and Ti vs. V plots of the mafic rocks of the study area revealed IAB, MORB and OIB setting in the area. The oceanic character of the BO is also reflected from Cr vs. Ti and Ni vs. Ti/Cr plots, in which they appeared as ocean floor tholeiite (OFT). The high Ti bearing rocks in the study area suggest magma generation similar to N-MORB and emplaced in the mid-oceanic ridge tectonic setting. The sequence indicates their initial formation at MORB and characteristics of the supra-subduction zone (SSZ) were formed during the subduction of BO underneath the Indian Continental Plate. At the late stage, these rocks were intruded by hotspot-derived magmas.

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