

## **Geochemistry and petrogenesis of the volcanic rocks from Bagh complex, northern Balochistan, Pakistan**

**M. Ishaq Kakar<sup>1</sup>, Khalid Mahmood<sup>1</sup>, Andrew C. Kerr<sup>2</sup>, Alan S. Collins<sup>3</sup>, Mehrab Khan<sup>4</sup>, and Aimal Khan Kasi<sup>1</sup>**

<sup>1</sup>Centre of Excellence in Mineralogy, University of Balochistan, Quetta, Pakistan

<sup>2</sup>School of Earth and Ocean Sciences, Cardiff University, Main Building, Park Place, Cardiff, Wales, CF10 3YE, UK

<sup>3</sup>Tectonics, Resources and Exploration (TRaX), School of Earth and Environmental Sciences, University of Adelaide, SA 5005, Australia

<sup>4</sup>Department of Geology, University of Balochistan, Quetta, Pakistan

### **Abstract**

The Bagh complex is an assemblage of igneous and sedimentary rocks containing many lithologic units which are bounded by layered parallel thrusts. The volcanic rocks from basalt-chert unit (Bbc) and hyaloclastite-mudstone unit (Bhm) are comprised of pillowed and bedded basalt, hyaloclastite and reworked sediments. Petrography and geochemistry of the basalt from Bbc shows that these rocks are basaltic trachy-andesite, trachy-andesite and foidite with tholeiitic character. While those from Bhm are tephrite-basanite, basalt and picro-basalt having alkaline nature.

N-MORB-normalized diagram of the tholeiitic rocks have flat pattern of HFS-elements. In contrast enrichment of LIL-elements with the REE having almost flat pattern between 10X and 20X chondritic which are typical of N-MORB. The enrichment of LIL-elements, especially Th and depletion of Nb relative to other incompatible elements are depicting the addition of subduction zone component to a depleted mantle source. The multi element normalised plots of the volcanic rocks from Bhm show a similar pattern to that of OIB. These show a marked enrichment in the LIL-elements, depletion in some of the HFS-elements enrichments in LREEs and a marked depletion in the HREEs as compared to NMORB.

The geochemical features on tectonic discrimination diagram of tholeiite from Bbc and alkaline rocks from Bhm suggest supra-subduction zone and oceanic-island arc tectonic settings respectively. These rocks were possibly erupted during Cretaceous period in the area which extends from the continental margin of the Indian subcontinent over the Neo-Tethys Ocean floor, and then were obducted with the Muslim Bagh ophiolite over the Indian subcontinent.

*Keywords:* Bagh complex; Melange; volcanic rocks; Tholeiite; Alkaline; Petrogenesis

### **1. Introduction**

In the Muslim Bagh area, the suture zone is occupied by the Muslim Bagh ophiolite and Bagh complex. The Muslim Bagh ophiolite shows a nearly complete ophiolite sequence (Penrose conference, 1972) in which thick residual mantle is underlain by comparatively less developed crustal section. The crustal section comprises of a thick ultramafic to mafic cumulate section at the base grades to a less developed mafic cumulate or gabbros, having an immature sheeted dyke complex at the top. The upper most basaltic unit

with pelagic sediments is missing. The Bagh complex was earlier called as tectonic mélangé (Ahmad and Abbas, 1979). According to Mengal et al. (1994), the Bagh complex is an igneous-sedimentary assemblage containing various types of lithologic units, with each unit forming an individual thrust sheet. The Bagh complex is distributed around both the Jang Tor Ghar Massif (JTGM) and Saplai Tor Ghar Massif (STGM) and is in thrust contact with the overlying Muslim Bagh ophiolite (Fig. 1). This thrust contact is commonly marked by a serpentinite and mudstone mélangé (Fig.1). Mengal et al. (1994) divided the

Bagh complex into seven lithologic units. He and Sawada et al. (1992) also identified the volcanic rocks in various lithologic units. Following his divisions, this paper describes the petrogenesis and tectonic setting of these volcanic rocks on the basis of their field features, petrography and geochemistry.

## 2. Bagh complex

The Bagh complex comprises the following sub-units: mélangé unit (Bm), ultramafic-mafic rock unit (Bum), basalt-chert unit (Bbc), hyaloclastite-mudstone Unit (Bhm), and sedimentary rocks unit (Bs) (Fig.1).

### 2.1. Mélangé unit (Bm)

It crops out along the basal ophiolite thrust between localities Karimabad to the Bagh and west of the Bagh village near the Wazo Sakal Ghar (Fig.1). It consists of both the serpentinite mélangé (Fig. 2a) near the thrust contact with ophiolite and the mudstone mélangé in faulted contact with the serpentinite mélangé. The serpentinite mélangé includes various types of blocks of ultramafic-mafic rocks, metamorphic rocks; such as amphibolites, greenschist, intercalating basalt, and sedimentary rocks like;

chert, limestone and shale in scaly serpentinite matrix. Judging from the lithologies, it is estimated that ultramafic-mafic rocks may be derived from the Muslim Bagh ophiolite and basalt and sedimentary rocks from the Bagh complex. The mudstone mélangé includes various types of blocks surrounded by scaly mudstone. These blocks consist of basalt, radiolarian chert, limestone, and shale. Basalt, chert and limestone are correlative to those of the basalt-chert unit and interbedded limestone and shale is similar in lithology to Triassic-Jurassic sedimentary rocks in the Bagh complex.

### 2.2. Ultramafic-mafic rock unit (Bum)

This unit is distributed near the Sra Salwata, Kazhabayana village and the two small outcrops in the north-east of the Bagh complex. It is in faulted contact with underlying rock units (Fig. 1 and Fig. 2b) and consists of ultramafics; harzburgite, dunite and mafic; gabbroic rocks forming higher ridges than the other units in the Bagh complex. The margins of these slices are commonly marked by the mélangé. The lithology and occurrence of this unit suggest that it is a tectonic slice derived from the Muslim Bagh ophiolite. Other characteristics of these rocks are similar with those of Muslim Bagh ophiolite (Siddiqui et al., 1996).

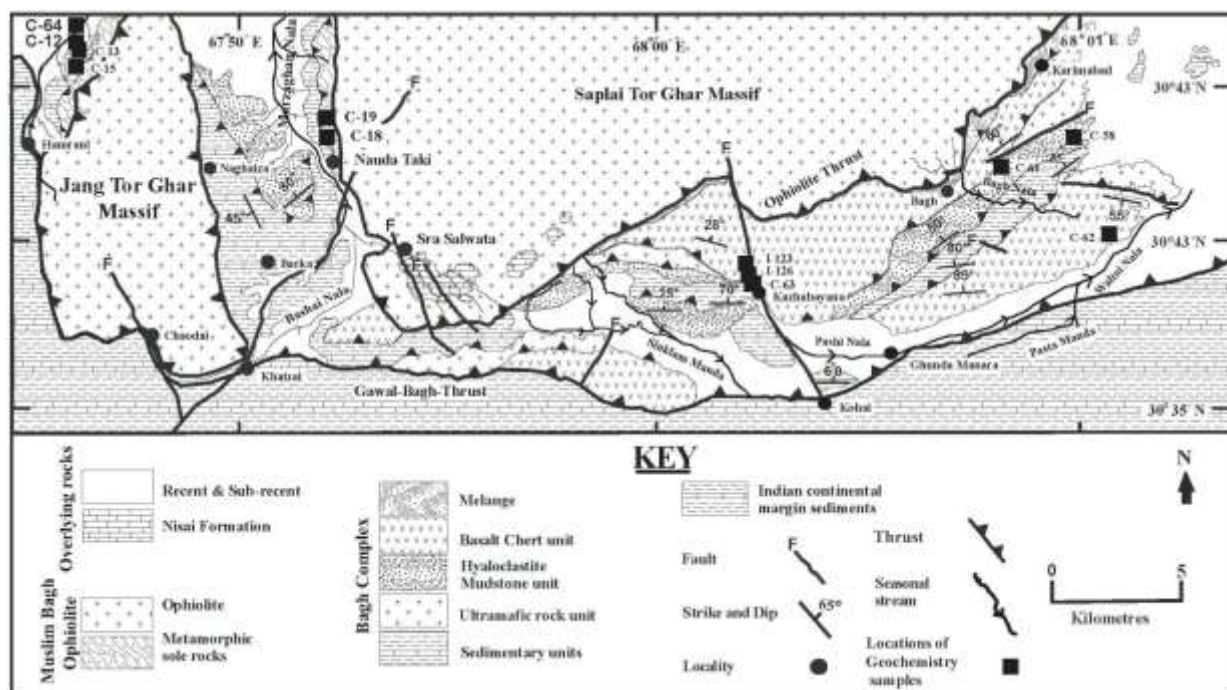


Fig.1. Geological map of the Bagh complex (modified after Mengal et al., 1994).

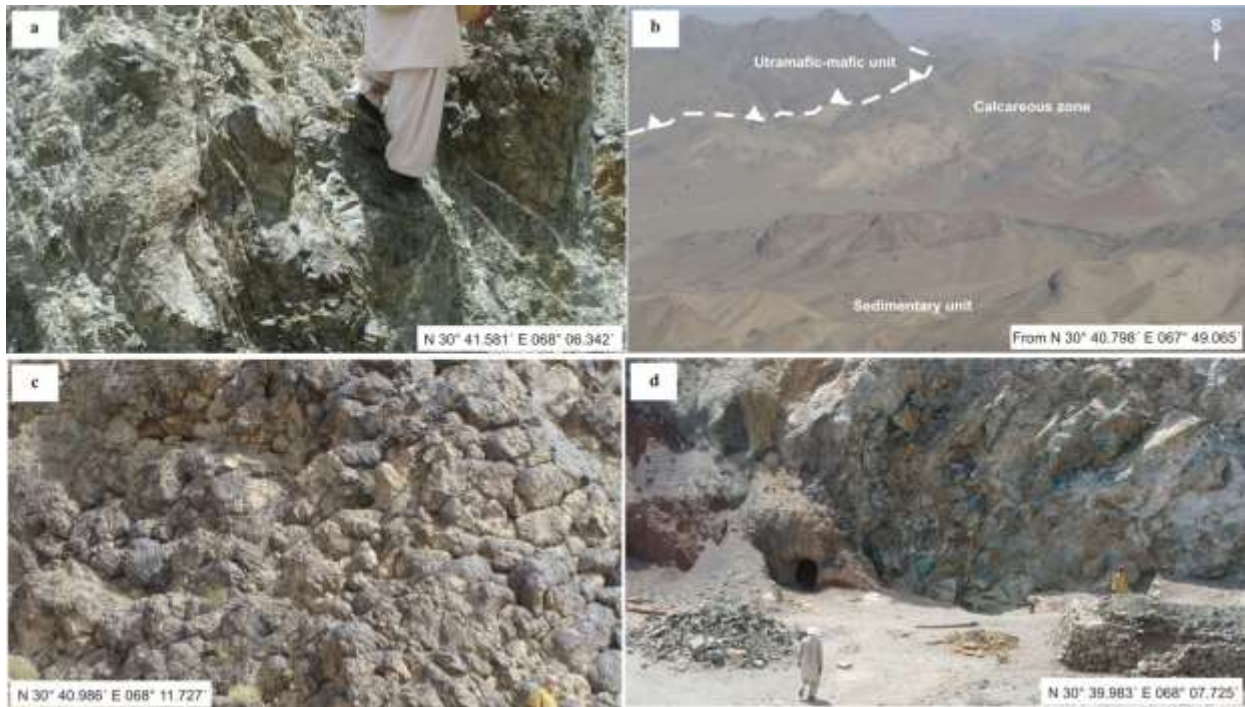


Fig. 2. a) Blocks of various types of rocks in serpentinite matrix in the mélangé unit of Bagh complex near the Bagh village, b) field photograph showing sedimentary unit in the foreground, ultramafic-mafic unit in the far left and the sediments of the Calcareous zone in the far right near Sra Salwata, c) pillow basalt of the basalt-chert unit near the dam on Chingin road, GhundaManra and d) Copper mine in basalt-chert unit, Bagh complex.

### 2.3. Basalt chert unit (*Bbc*)

It is one of the biggest units in the Bagh complex, which is distributed from Karimabad village through Bagh village up to the Kazhabayana village. It also occurs along and north of the Waltoi Nala and south of the Sinklam Manda with a small outcrop near Sra Salwata (Fig. 1). It is characterized by thick basaltic rocks with bedded chert, micritic limestone and hemipelagic mudstone. The basaltic rocks occur dominantly as pillow lavas with minor massive lavas and volcanic breccias. The pillow lavas consist of well formed, closely-packed pillows, ranging in diameter from a few centimeters to one metre (Fig. 2c), with intercalations of limestone and chert. The petrography and geochemistry of these basalts are described in the section follows. The bedded chert is reddish brown in color and is rich in radiolarian fossils of Early Cretaceous to Turonian in age (Kojima et al., 1994). It is forming alternating beds of 2 to 15 cm thick chert layers and fine mudstone layers of up to 10 cm thick.

This unit is faulted and sheared in some places and as a result the original sedimentary sequence is quite disturbed. Mengal et al. (1994) reconstructed the original stratigraphy of the basalt-chert unit as basaltic rocks in the lower part are overlain by limestone-chert and silicious shale which is about 2 to 10 m thick.

Minor traces of Copper, Manganese, Iron and other economic minerals were found within this unit (Fig. 2d and Fig. 3a). The chert-limestone from *Bbc* yield radiolarian age from Early Cretaceous to Turonian (Kojima et al., 1994).

### 2.4. Hyaloclastite mudstone unit (*Bhm*)

In the Bagh complex, this unit is distributed near the localities like Bagh village, Kazhabayana village, and between the JTGM and STGM (Fig. 1). This unit consists of thick outcrops of basaltic volcanic rocks interbedded with siliceous mudstone and limestone in the upper part with volcanic rocks, intercalated with small amounts of limestone and shale in the middle part and



siliceous mudstone with micritic limestone intruded by basalt and dolerite.

The volcanic rocks comprise of pillowed (Fig. 3b) and massive basanite, alkali-basalt, and trachy-basalt and also occur as hyaloclastite and reworked volcanic breccias (Fig. 3c). They are characterized by the development of vesicles and the existence of phenocrysts of pyroxene several mm to 2 cm in diameter (see the petrography and geochemistry in the section follows). The upper part of the hyaloclastite unit is comprised of siliceous shale with subordinate limestone.

The radiolarian assemblages collected from siliceous material in the lower part of this unit yield an Early Cretaceous age (Kojima et al., 1994). K–Ar ages on hornblende and biotite collected from volcanic rocks range from 81 to 68Ma (Sawada et al., 1995) and most likely reflect a later thermal event.

### 2.5. Sedimentary rock unit (Bs)

Mengal et al. (1994), divided this unit into

two subunits; upper sedimentary and lower sedimentary rocks unit while Naka et al. (1996), further divided it into three subunits; upper sedimentary, lower sedimentary unit and undivided sedimentary unit. By comparing the lithology with immediate contact rocks of the Indian continental margin sediments, we propose that these rocks are part of the Jurassic-Triassic system of the Sulaiman belt found within the Bagh complex. We combined all the three units of Naka et al. (1996) into one unit and describe this as sedimentary rock unit.

The rocks of sedimentary unit are distributed between the JTGM and STGM, along the Pashi Nala from the locality Kazhabayana to Ghunda Manra, along part of the Bagh Nala and some small outcrops in the northeastern corner of the mapped area (Fig. 1). The rocks of this unit consists of limestone with alternating beds of mudstone, siliceous mudstone, sandstone, and conglomerate (Fig. 3d). The limestones are well-bedded and mostly micritic, and is characterized by the sedimentary structures like current marks and deformational structures like folds (Fig. 4a).

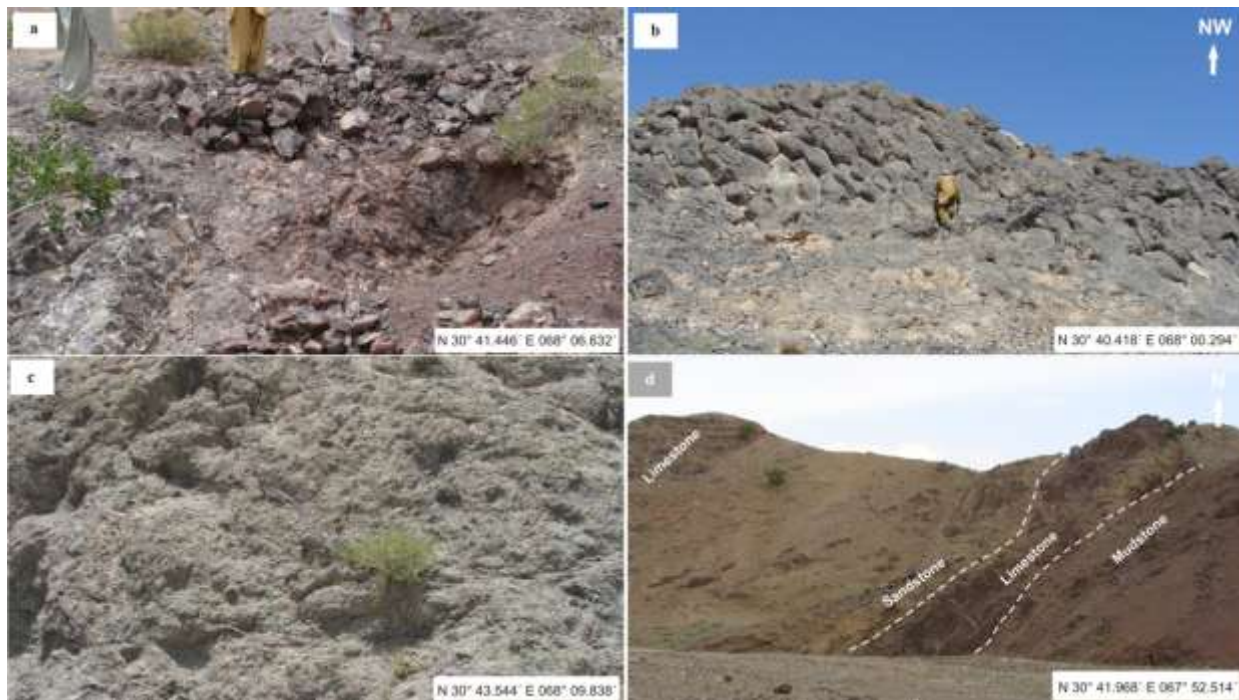


Fig. 3. a) Manganese deposits in Basalt-Chert unit, near the Bagh village. b) pillow basalt of the hyaloclastite unit near Kazabayana village, c) hyaloclastite and reworked volcanic breccias in the hyaloclastite unit and d) alternating beds of lime stone, mudstone, sandstone and conglomerate in the sedimentary unit near Nauda Taki village.

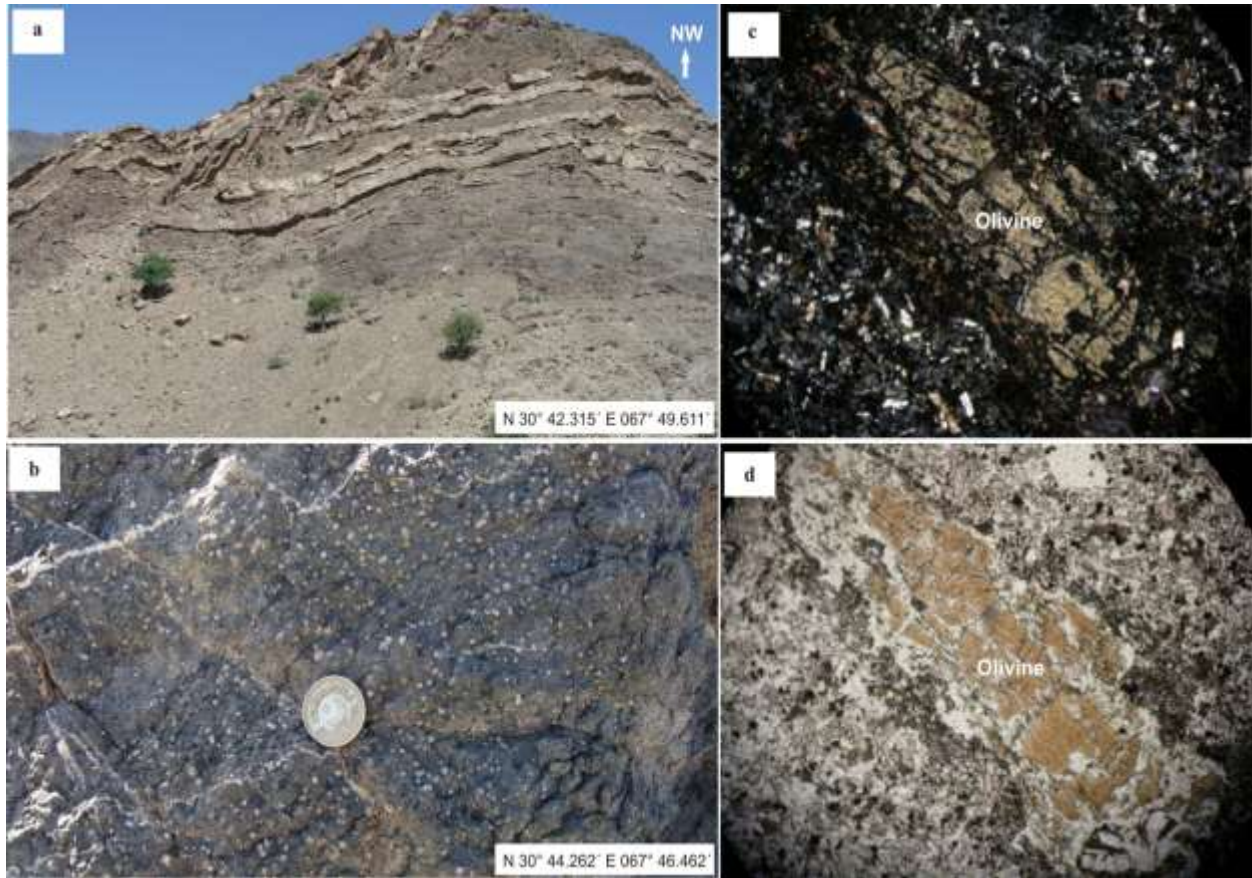


Fig. 4. a) large recumbent fold in sedimentary unit, Yay Shakh Nala, JTGm, b) outcrop of amygdulid basalt from the basalt-chert unit of Bagh complex, c) a phenocryst of olivine embedded in fine grained groundmass of altered pyroxene, plagioclase and opaque (XPL x 10), d) PPL x 10.

Some of limestones are massive and oolitic. The conglomerate is composed of heterogeneous rocks material of varying size. Shallow marine fossils including ammonites, Halobia, and bivalves are found in the unit. These fossil data show that the age of sedimentary unit range from Triassic to Jurassic, and Permian to Triassic (Kojima et al., 1994; Naka et al., 1996).

### 3. Volcanic rocks of Bagh complex

#### 3.1. Petrography

The basalts from Bbc are hypocrySTALLINE, subporphyritic and sub-interstitial in texture. Mineralogically these rocks comprise of plagioclase, and clinopyroxene (augite), with minor chlorite and accessory epidote, ilmenite and

secondary actinolite. The volcanic rocks contain amygduals (Fig. 4b) and are traversed by irregular fractures filled with secondary minerals like calcite, chlorite and zeolites. In some thin sections the rocks have olivine as phenocryst, opaque and devitrified glass in the groundmass (Fig. 4c and d). The volcanics in Bhm where least altered are petrographically basanite and alkali-basalt contain phenocrysts of olivine and augite with a groundmass consisting of plagioclase, pargasite, phlogopite and opaque and glassy material.

In tephrite and trachybasalt the phenocryst of plagioclase, augite, olivine, pargasite and phlogopite are embedded in the groundmass of plagioclase, Ti-augite, pargasite, phlogopite, apatite, opaque minerals (ilmenite) and devitrified glass (Sawada et al., 1992).

## 3.2. Geochemistry

### 3.2.1. Analytical method

Twelve samples of basalts were analysed for major and trace elements and four samples were analysed for rare earth elements (REE). The samples were crushed in a jaw crusher, the weathered surfaces were removed then powdered using a tungsten carbide mill to the size of < 200 mesh. The required number of grams of the powder of each sample was then heated in a porcelain crucible to 900°C for 2 hours to determine the loss on ignition.

For major elements, the sample powder was thoroughly mixed with lithium tetra-borate (flux) with a 1:5 sample flux ratio and the glass beads were formed. Then the fused beads were analysed for major elements composition using a Philips Wave Dispersive X-Ray Fluorescence (WD/XRF) at the Geoscience Research Laboratories, Geological Survey of Pakistan, Islamabad, Pakistan.

For trace elements powdered pellets of all the samples were prepared by putting 5–7 grams powdered sample (< 200 mesh) in an Aluminum cup and compressed between two tungsten carbide plates (within circular briquettes) at about 20 ton per square inch pressure, in a hydraulic press. Then these pellets were analysed for trace elements composition using a Philips WD/XRF at the National Centre of Excellence in Geology, University of Peshawar, Pakistan.

For REE study the powder was dissolved in 30 ml of 10 % HNO<sub>3</sub> and 20 ml of de-ionised water. The samples were prepared by a standard Teflon vial acid digestion method using a mixture of HF ± HClO<sub>4</sub>–HNO<sub>3</sub>. All samples were spiked to 50 ng/ ml with Indium to serve as an internal standard. REE analyses for this study were calibrated against a set of multi-element working standard solutions. All the solutions were introduced via a peristaltic pump, and analyses were performed by using a Perkin-Elmer ELAN

6100 Inductively Coupled Plasma Mass Spectrometer (ICP-MS) at the Amdel Laboratories, Pvt. limited, Adelaide, Australia.

### 3.2.2. Major and trace elements

The geochemical composition of the major oxides from the volcanic rocks of Bbc are; SiO<sub>2</sub> = 38.45 – 56.9 wt %; TiO<sub>2</sub> = 0.88 – 3.45 wt %; Al<sub>2</sub>O<sub>3</sub> = 12.56 – 16.68; Fe<sub>2</sub>O<sub>3</sub> 8.46 – 11.39 MgO = 2.4 – 8.21 wt%; CaO 4.4 – 13.67; Na<sub>2</sub>O = 2.49 – 6.94; K<sub>2</sub>O = 0.05 – 0.58 wt %; P<sub>2</sub>O<sub>5</sub> = 0.06 – 0.19 wt %. The geochemical data is reported in table 1.

The rocks were classified by plotting on the total alkali versus silica (TAS) diagram of Le Bas et al. (1986). Four samples plot in the basalt field and one in the basaltic trachy-andesite and one each in the trachy-andesite and in the foidite fields (Fig. 5a). To check the remobilization of alkalis due to alteration the samples were plotted on Zr/Ti versus Nb/Y diagram of Pearce, (1996) all the samples fall in the basalt field confirming their basaltic nature (Fig. 5b). All the samples were also plotted on the P<sub>2</sub>O<sub>5</sub> versus Zr diagram of Winchester and Floyd (1976) (Fig. 5c, which shows that the rocks are tholeiitic in nature.

On an N-MORB-normalized plot of Sun and McDonough (1989), the high field strength (HFS)-elements (P, Zr, Sm, Ti, and Y) have a flat pattern parallel to NMORB. In contrast the large ion lithophile (LIL)-elements (Cs, Ba, Th, K, and Sr) are relatively more enriched than N- MORB (Fig. 6a). The chondrite-normalised REE patterns of these rocks are depleted in most of LREE (i.e., between 10x and 18x chondritic) and have flat HREE pattern (Fig. 6b), typical of NMORB.

The volcanic rocks from Bhm have geochemical composition of major oxides ranges as; SiO<sub>2</sub> = 41.57– 44.48 wt %; TiO<sub>2</sub> = 2.37– 4.17 wt %; Al<sub>2</sub>O<sub>3</sub> = 10.25 – 14.53; Fe<sub>2</sub>O<sub>3</sub> 10.21–13.4 MgO = 6.68 – 10.86 wt%; CaO 9.68 – 14.78; Na<sub>2</sub>O = 0.93 – 4.35; K<sub>2</sub>O = 0.26 – 1.63 wt %; P<sub>2</sub>O<sub>5</sub> = 0.44 – 0.7 wt % (Table 1).

Table 1. Major oxides (wt%), trace and REE elements (ppm) of the volcanic rocks from the Bagh complex

Sample No.	C-12	C-13	C-15	C-18	C-19	C-58	C-61	C-62	C-63	C-64	I-123	I-126
Rock type	Basalt	Basalt	Basalt	Basalt	Basalt	Hyaloc	Hyaloc	Basalt	Basalt	Hyaloc	Basalt	Basalt
SiO <sub>2</sub>	51.01	38.45	44.48	46.96	48.25	46.08	41.57	56.9	47.87	42.21	50.58	42.27
TiO <sub>2</sub>	1.02	3.45	2.37	0.88	0.91	3.42	3.41	1.19	1.06	3.21	0.89	4.17
Al <sub>2</sub> O <sub>3</sub>	16.68	12.56	10.25	14.55	14.33	10.71	11.13	15.72	15.45	12.36	15.68	14.53
Fe <sub>2</sub> O <sub>3</sub>	8.54	11.39	10.21	9.05	9.38	13.4	11.8	9.05	9.35	11.48	8.46	12.07
MnO	0.26	0.23	0.12	0.2	0.19	0.1	0.18	0.18	0.24	0.15	0.25	0.21
MgO	6.48	8.2	6.68	7.28	7.67	8.23	10.86	2.4	8.21	7.84	7.48	7.41
CaO	4.4	13.67	14.78	11.92	10.78	10.19	12.68	4.89	9.94	14.23	9.41	9.68
Na <sub>2</sub> O	6.94	2.49	3.59	4	4.1	4.35	1.57	7.64	3.28	2.43	4.38	0.93
K <sub>2</sub> O	0.06	8.03	0.37	0.05	0.06	0.86	1.59	0.1	0.58	1.41	0.21	4.63
P <sub>2</sub> O <sub>5</sub>	0.08	0.13	0.44	0.06	0.06	0.53	0.7	0.19	0.08	0.65	0.06	0.58
LOI	4.45	1.2	6.71	5.04	4.26	2.72	4.59	1.68	3.94	4.05	2.6	3.51
Total	99.92	99.8	100	99.99	99.99	100.59	100.08	99.94	100	100.02	100	99.99
Sc	35.7	25.8	18.8	36.3	35.6	22.5	18.6	23.5	34.4	21.2	37.1	16.2
V	173.7	231.6	272.0	233.9	227.9	261.1	231.5	311.2	252.0	224.5	224.9	241.3
Cr	463.5	43.1	506.3	296.7	305.7	785.6	433.8	11.2	369.1	342.5	392.8	134.6
Co	54.8	48.7	55.9	46.0	51.7	76.0	63.9	39.7	51.6	56.5	61.0	54.0
Ni	130.0	30.2	292.4	80.5	107.3	443.5	260.7	8.1	124.6	188.5	102.7	106.2
Cu	157.5	80.7	55.7	51.6	89.9	104.0	74.1	146.4	74.1	48.8	65.0	44.6
Zn	85.4	49.0	50.4	52.7	62.1	110.0	125.0	76.2	75.0	84.2	75.0	105.9
Ga	26.1	28.5	26.0	23.8	26.6	26.9	31.9	27.9	26.8	30.7	23.0	34.4
As	4.8	0.1	1.4	2.6	2.6	1.0		3.0	2.6	4.3	14.5	2.6
Br	1.4	3.2	2.6	3.3	3.0	2.6	2.2	2.3	2.1	2.9	2.9	1.8
Rb	0.4	5.1	3.9			2.6	20.6		7.8	27.1	2.5	75.9
Sr	314.5	170.0	325.4	98.7	134.6	244.1	488.6	93.9	166.5	522.8	264.5	1146.7
Y	16.7	21.6	19.2	19.8	20.0	23.3	25.3	27.8	23.1	25.3	18.7	29.7
Zr	55.5	58.1	168.5	41.5	45.2	222.3	271.9	77.5	55.6	266.6	50.6	300.0
Nb	0.7	2.1	32.3	1.3	1.6	47.9	58.2	3.5	2.2	63.1	0.9	52.3
Mo	2.6		1.4	0.1		1.9	2.5	0.3	0.2	2.8		3.0
Ag	20	18.1	19.7	21.0	19.0	20.6	15.8	15.6	13.4	21.6	17.9	22.7
Cd	9.8	8.0	7.8	5.7	10.2	11.4	10.7	10.1	5.9	9.8	10.7	11.0
Sn	15.8	11.4	11.9	12.5	11.2	12.3	14.5	14	10.9	13.3	14.2	15.5
Sb			5.3	1.1		1.3	1.2	1	2.7	7.1		1.7
Cs						0.2	0.9		0.2			2.7
Ba	202.5	66.5	391.8	52.9	46.1	498.2	1008.8	78.0	60.4	475.8	50.6	1273.8
La	13.4	7.1	13.0	11.2	6.8	12.0	10.0	15.2	1.8	58.1	2.0	64.4
Ce	43.4	21.6	16.3	32.5	29.9	9.2	14.4	29.8	4.7	15.3	6.1	18.0
Nd	20.6	9.0	42.3	15.3	11.9	40.0	55.0	12.1	6.5	5.5	10.2	8.9
Sm					4.9	8.5	10.5	3.8	2.4	2.0		
Yb	3.8		19.8		2.3	1.65	2.0		2.8	11.6	2.3	
Hf	20.0	20.5	27.3	25.0	29.1	30.5	42.6	25.7	27.8	22.6	32.2	36.9
Ta		0.2	1.8	4.3		13.1	11.2		1.0			5.2
Pb						3.0	3.5		3.5	0.2		
Bi	12.3	14.7	16.9	16.7	13.6	15.2	17.2	17.0	15.2	17.9	15.2	15.5
Th	25.6	28.3	30.5	29.0	29.4	9.6	8.0	29.5	10.0	31.7	9.0	26.2
Tm						0.25	0.3		0.4		0.35	
Tb						1.05	1.15		0.6		0.5	
Pr						10.0	13.5		1.2		1.05	
Lu									0.18			
Ho						0.9	1.0		0.88		0.72	
Gd						7	8.5		2.8		2.4	
Eu						2.8	3.2		0.88		0.84	
Er						2.3	2.6		2.8		2.3	
Dy						6	6.5		4.4		3.7	

Note: LOI = Loss on ignition at 1000°C, Fe<sub>2</sub>O<sub>3</sub> = Total Iron, Hyaloc = Hyaloclastite



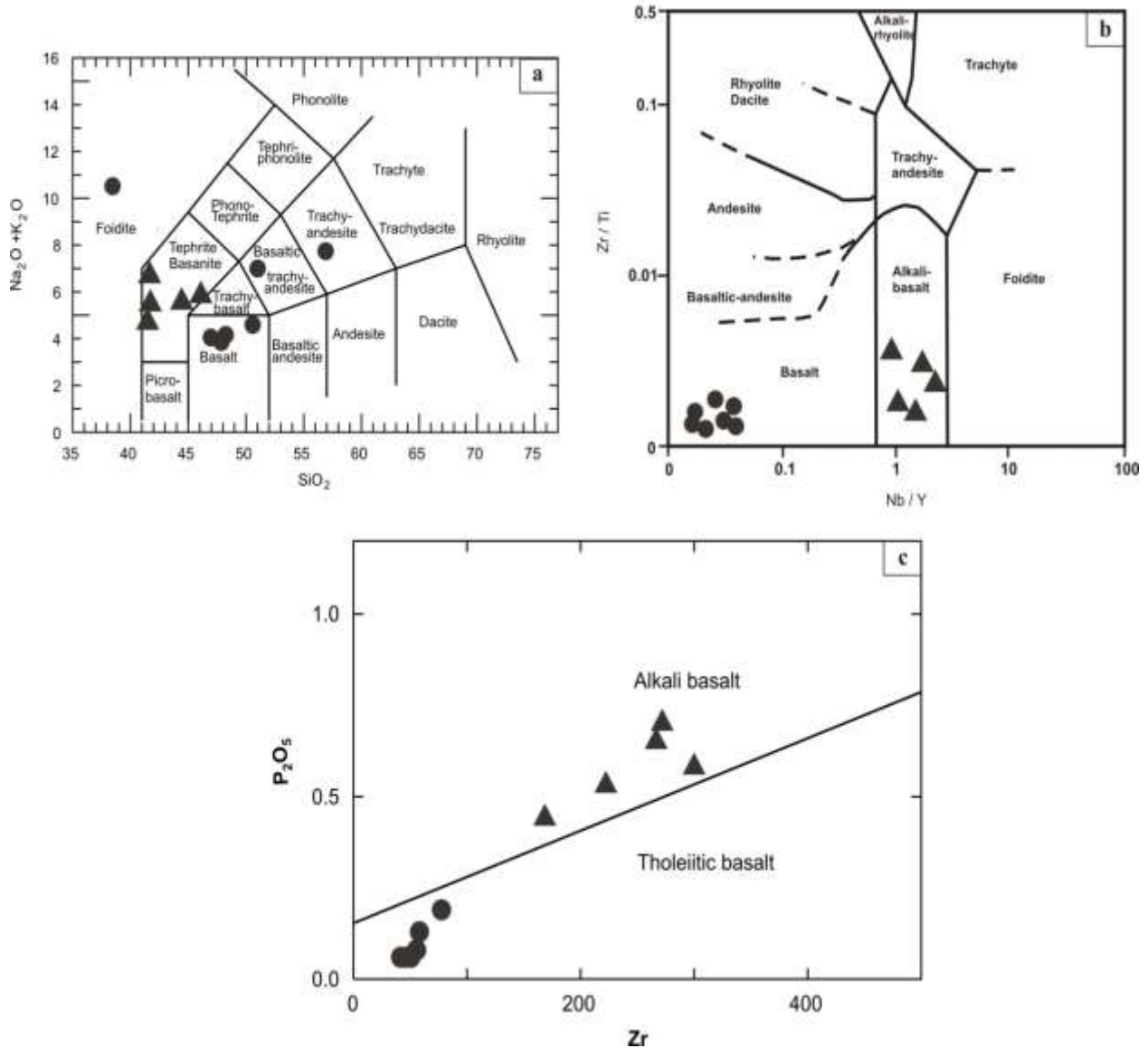


Fig. 5. a) Total alkali versus  $\text{SiO}_2$  plot (after LeBas et al., 1986), b)  $\text{Zr}/\text{Ti}$  versus  $\text{Nb}/\text{Y}$  plot (after Pearce, 1996) and c)  $\text{P}_2\text{O}_5$  versus  $\text{Zr}$  plot (after Winchester and Floyd, 1976) of the volcanic rocks from the basalt chert unit (filled circles) and hyaloclastite-mudstone unit (filled triangles) of the Bagh complex.

The rocks have been classified using the total alkali–silica (TAS) diagram (Le Bas et al., 1986), which shows that three samples plot in the tephrite-basanite field and one each in the basalt and in the picro-basalt fields (Fig. 5a). On  $\text{Zr}/\text{Ti}$  versus  $\text{Nb}/\text{Y}$  diagram of Pearce (1996), the entire samples plot in the field of alkali basalt (Fig. 5b). This has also been confirmed by plotting the samples in the  $\text{P}_2\text{O}_5$  versus  $\text{Zr}$  diagram (Fig. 5c) of Winchester and Floyd (1976).

The multi-element N-MORB and chondrite normalised (Sun and McDonough, 1989) diagrams (Fig. 6c-d) show an enrichment in the LIL-elements and depletion in some of the HFS-elements (Fig. 6a). The chondrite normalised REE plot shows a marked depletion in the HREE as compared to NMORB (Fig. 6d). Both these diagrams show that the volcanic rocks from the hyaloclastite mudstone unit have trace element normalised patterns similar to those of Oceanic Island Basalt (OIB) (Fig. 6c-d).



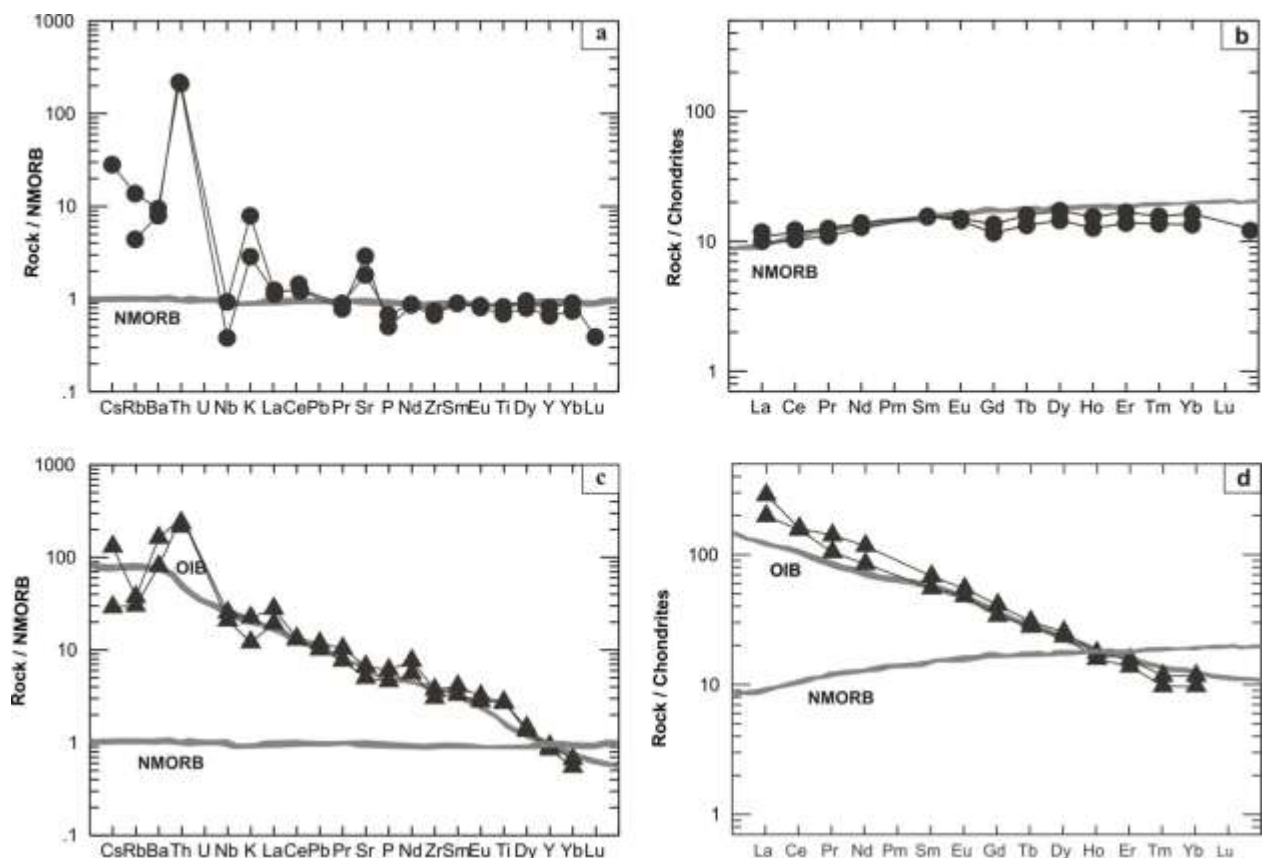


Fig. 6. Multi-element spider diagram of the volcanic rocks, of Bagh complex, a & b) from the Basalt-chert unit, c & d) from the hyaloclastite-mudstone unit.

#### 4. Discussion

The Bagh complex consist of various lithologic units, with each unit forming an individual thrust sheet. The mélangé is characterized by various types of blocks in serpentinite matrix and are found along the margins of the Muslim Bagh ophiolite. The characteristic features of these blocks indicate that they are possibly derived from the surrounding rock units such as the Muslim Bagh ophiolite and the coherent lithologic units of the Bagh complex. The above mentioned occurrence and the development of serpentinite scaly fabric of the mélangé suggest that they were formed by shearing in association with the emplacement of Muslim Bagh ophiolite.

The basalt-chert unit is composed of hemipelagic mudstone and pelagic radiolarian chert with pillowed and bedded tholeiite. Ahmad and Abbas (1979) and Otsuki et al. (1989) regarded the

basalt-chert unit as an upper member of the Muslim Bagh ophiolite. The reconstructed stratigraphy of the basalt-chert unit (Mengal et al., 1994) shows that basalts are overlain by Early Cretaceous to Turonian pelagic radiolarian bedded chert, followed by the deposition of younger hemipelagic mudstone. In contrast the new U-Pb age produced in this study on plagiogranite from the Muslim Bagh ophiolite yields an age of  $80.2 \pm 1.5$  Ma. The age difference clearly indicates that the basalt-chert unit is not a member of the Muslim Bagh ophiolite as also proposed by Mengal et al. (1994).

The hyaloclastite-mudstone unit consists of alkaline rocks interbedded with radiolarian siliceous shale and micritic limestone. The association of sediments and alkaline igneous rocks shows that alkaline rocks were erupted in a hemipelagic environment (Mengal et al., 1994). This unit is dated as Cretaceous based on radiolarian fossils by Kojima et al. (1994) and K-Ar ages by Sawada et al. (1992). The sedimentary rocks unit is characterized by more

abundant hemipelagic sediments and rare shallow-marine sediment than the calcareous sediment on the Indian subcontinent to the south. These features show that sedimentary rock units of the Bagh complex were deposited in the more distal part of the Indian subcontinent (Mengal et al., 1994; Kojima et al., 1994).

#### 4.1. Petrogenesis and tectonic setting of volcanic rocks

The petrography and geochemistry of the volcanic rocks of basalt-chert unit shows that these rocks are basaltic trachy-andesite, trachy-andesite and foidite (Fig. 5a) while those of the hyaloclastite mudstone unit are tephrite-basanite, basalt and picro-basalt (Fig. 5a). The  $P_2O_5$  versus Zr plot of Winchester and Floyd (1976) revealed that rocks of the basalt-chert unit are tholeiitic while those of the hyaloclastite mudstone unit are alkaline in nature (Fig. 5c).

The tholeiitic rocks have a major element chemistry with high  $Al_2O_3$  (12.56 – 16.68 wt %), low  $TiO_2$  (0.88 – 3.45 wt %),  $MgO$  (2.4 – 8.21 wt %) and  $K_2O$  (0.05 – 0.58 wt %) typical of mid ocean ridge basalt as compared to the alkaline rocks which have relatively low  $Al_2O_3$  (10.25 – 14.53 wt %), high  $TiO_2$  (2.37– 4.17 wt %),  $MgO$  (6.68 – 10.86 wt %) and  $K_2O$  (0.26 – 1.63 wt %) typical of ocean island basalt.

The enrichment in LIL-elements in the volcanic rocks of Bbc can be due to modification of the depleted mantle by a subducted slab component or may be due to variable degree of mobilization during the alteration processes. However the enrichment of Th and depletion of Nb (Fig 8.12a) relative to other incompatible elements are considered to represent the addition of subduction zone component (e.g., Wood, 1980).

The multi element and REE normalised (Sun and McDonough, 1989) plots of the volcanic rocks in the hyaloclastite-mudstone unit shows a similar pattern to that of OIB (Fig. 6c-d). The alkaline rocks show a marked enrichment in the LIL-elements with depletion in some of the HFS-elements (Fig. 6a) and enrichments in LREEs and a marked depletion in the HREEs as compared to NMORB.

Tectonic settings of the volcanic rocks of both

the units i.e. basalt-chert unit and hyaloclastite unit were determined using discrimination diagram based on HFS-elements. The ternary plot of  $Zr - Ti/100 - Y*3$  (Fig. 7a) of Pearce and Cann (1973), differentiates between NMORB, VAB, WPB and Calc alkali basalt (CAB). The samples of the basalt-chert unit show transitional characters and plotted in the overlapping fields of NMORB and VAB and those of the hyaloclastite mudstone unit plotted in WPB field (Fig. 7a). Ti/Y versus Nb/Y diagram (Pearce, 1982) and Zr/Y versus Zr diagram (Pearce and Norry, 1979) differentiates between NMORB, VAB and WPB. The samples from the basalt-chert unit fall in the overlapping fields of NMORB and VAB and those of the hyaloclastite mudstone unit fall clearly in WPB fields (Fig. 7b & c). The transitional characteristics between NMORB and IAT of the samples from the basalt-chert unit and the WPB tectonic setting of the samples from the hyaloclastite unit was further confirmed when plotted on Cr versus Y diagram (Fig. 7d) of Pearce (1982). It plotted the samples of the basalt-chert unit in the overlapping field of NMORB and IAT and those of the hyaloclastite mudstone unit fall in WPB field (Fig. 7d).

From the above discussion it is inferred that there are two types of volcanic rocks which had been formed in different tectonic settings. One type is tholeiite and the other is alkaline in nature. Tholeiitic rocks are represented by the basalt-chert unit while the alkaline one is represented by the hyaloclastite mudstone unit (Fig. 5c). Tholeiitic rocks have been interpreted as N-MORB by the previous workers (Siddiqui et al., 1996, Sawada et al., 1992 and Khan et al., 2007) but results from this study suggest that these are having characteristics transitional between NMORB and IAT. It is, therefore, suggested that these rocks were formed in an oceanic environment due to modification of the depleted mantle by a subducted slab component in Early Cretaceous (Kojima et al., 1994), during the break up of Gondwanaland. The presence of this subduction component is supported by the marked depletion of Nb and enrichment of Th. According to Wood (1980) and Pearce (1982), the Nb depletion and Th enrichment are indicative of a subduction component. The alkaline rocks probably represent hot spot derived magmatism formed during the Late Cretaceous (Campanian) period (Sawada et al., 1995).

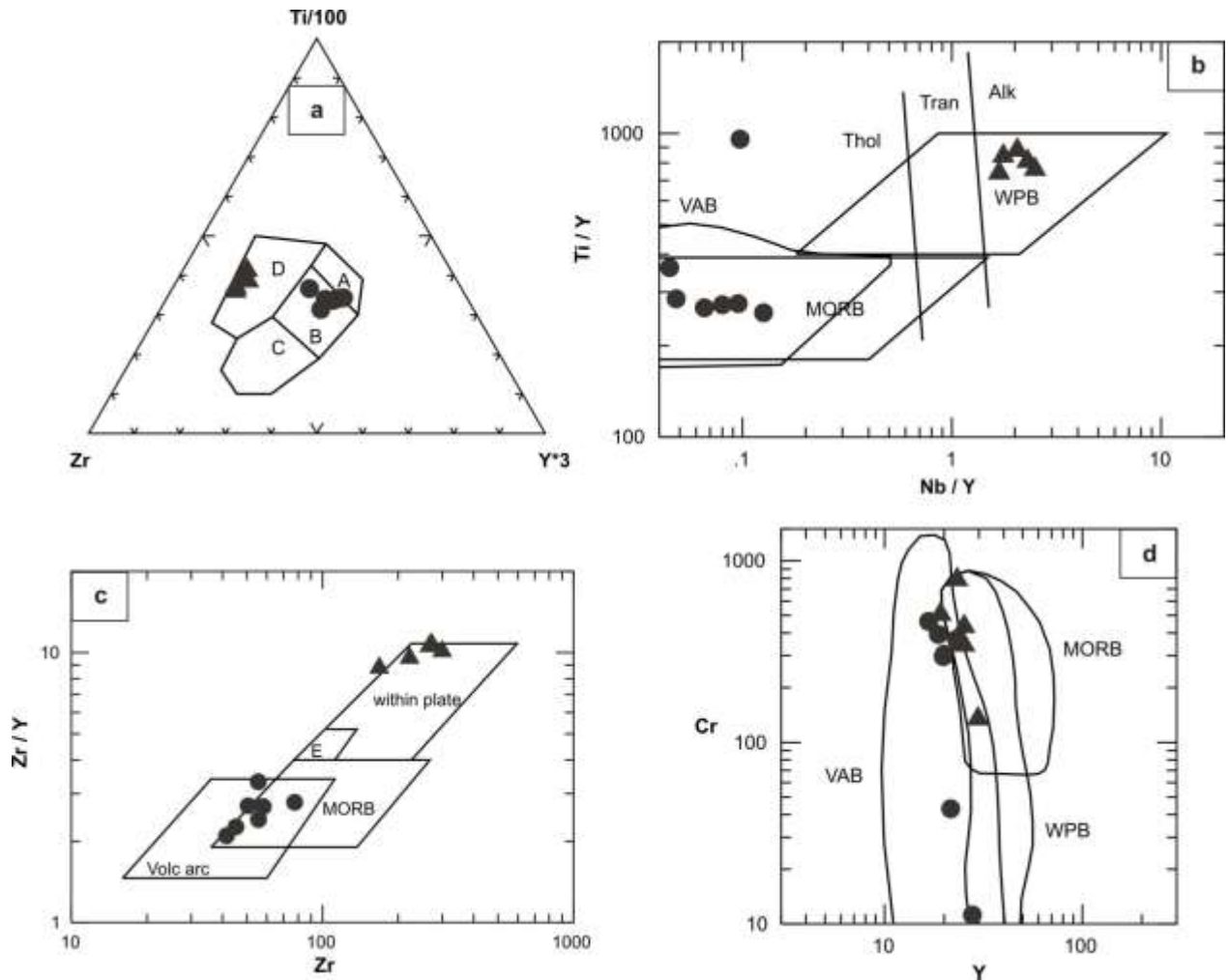


Fig. 7. tectonic discrimination diagram of the volcanic rocks from basalt-chert unit (filled circles), hyaloclastite-mudstone unit (filled triangles) of the Bagh complex, a) Ti/100–Zr–Y\*3 triangular plot (after Pearce and Cann, 1973). Key: AB = Island arc, B = Ocean floor, BC = Calc alkali and D = within plate, b) Ti/Y–Nb/Y plot (after Pearce, 1982), and c) Zr/Y versus Zr plot (after Pearce and Norry, 1979), E = MORB + within plate basalt, d) Cr–Y plot (after Pearce, 1982).

## 5. Conclusions

On the basis of above discussion the following conclusions are drawn:

1. The Bagh complex is an assemblage of igneous and sedimentary rocks contains various types of lithologic units. Each lithologic unit is bounded by a layered parallel thrust.
2. The volcanic rocks found in Bbc and Bhm is comprised of pillowed and bedded basalt and pillowed basalt with hyaloclastite and reworked sediments respectively.
3. Petrography and geochemistry of the basalt from Bbc show that these rocks are basaltic trachy-andesite, trachy-andesite and foidite and that these are oceanic tholeiite in nature. While those from Bhm are tephrite-basanite, basalt and picro-basalt and are alkaline in nature. Their associations with hemipelagic sediments show that alkaline rocks were erupted in a hemipelagic environment.
4. The geochemical features of Bbc and Bhm suggest their tectonic settings as supra-subduction zone and oceanic-island arc respectively.
5. The above mentioned characteristic features of the volcanic suites clearly distinguish them from the ophiolite suite in the north. These rocks were possibly erupted during Cretaceous period in the area which extends

from the continental margin of the Indian subcontinent over the Neo-Tethys ocean floor, and then were obducted with their respective units coupled with the Muslim Bagh ophiolite over the Indian subcontinent.

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