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Investigation for gold and base metals mineralization and petrochemical characteristics of the rocks of upper parts of Bagrot valley, Gilgit-Baltistan, Pakistan

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Abstract

Occurrence of placer gold has been reported in the stream sediments of the Gilgit-Baltistan for long time. Recent geochemical surveys in this region identified some areas with high concentration of gold. Bagrot valley (the study area), is one of these anomalous catchments situated in northeast of Gilgit, the capital city, of Gilgit-Baltistan province of Pakistan. The study area consists of rocks of Cretaceous Chalt Volcanic Group (CVG) and gabbroic-diorites of Kohistan batholiths (KB) belonging to the Kohistan island arc. The rocks of the CVG are mainly composed of porphyritic (basalts) and non-porphyritic (basalts to basaltic-andesite) volcanics. The porphyritic volcanics are hypersthenes normative with high plagioclase (Ab+An) normative composition whereas the non-porphyritic volcanics have greater amount of normative pyroxene (Hy+Di) relative to plagioclase (Ab+An). These are strongly deformed, highly tectonized and are metamorphosed mainly to greenschist facies and lesser extent to epidote-amphibolite facies. Numerous sulfide-baring altered/sheared zones are prominent along local faults within the rocks of CVG. These zones contain, pyrite, chalcopyrite and limonite and hydrothermal alteration products such as chlorite, epidote, sericite, kaolinite and trimolite/sctinolite.

The hydrothermally altered zones and the host rocks are the focus of this study for possible gold, silver and base metal mineralization and their petrochemical characteristics. The enrichment and depletion factors of various metals such as Au, Ag, Cu, Pb, Zn, Ni and Cr in the sulfide-bearing altered/sheared zone suggest the enrichment of Au, Ag and Pb while rest of the metals are depleted. This can be attributed to the immobile nature of Au, Ag and Pb and mobile nature of other metals during hydrothermal alteration. The multi-element spidergrams of both porphyritic and non-porphyitic volcanics of the CVG and the gabbroic-diorites show enrichment of LILE relative to HFSE with negative anomaly of Nb. The whole rock geochemistry of the studied non-porphyritic volcanics of CVG and the gabbroic-diorites of KB are of typical calc-alkaline character showing close affinities to subduction zone geochemical component. The porphyritic volcanics of the CVG exhibit tholeiitic character but are also consistent with the island arc tectonic setting.

Keywords: Gold and base metals; Petrochemistry; Chalt volcanic group; Bagrot valley; Gilgit.

1. Introduction

The association of gold mineralization with volcanic and geothermal activity and resultant hydrothermal alteration has long been recognized by prospectors and geologists. Therefore, hydrothermal alteration is generally used as a guide in searching for gold and base metals mineralization all over the world. On the basis of occurrence and genesis of gold, various types of gold deposits have been reported worldwide. Important among these are porphyry gold deposits of Lepanto Far South, Philippines (Sillitoe, 1991), Carlin type sediment hosted gold deposit of Nevada (Berger and Bagby, 1991), Skarn type gold deposits of Fortitude Nevada (Meinert, 1989), greenstone-hosted vein type gold deposits of California (Knopf, 1929), breccia pipe gold deposits of Kidstone, Australia (Sillitoe, 1991), carbonate replacement gold deposit of Ruby Hill, Nevada (Sillitoe, 1991), Archean banded-iron formation gold deposits of South Dakota (Caddy et al., 1991), epithermal gold deposits of goldfield, Nevada (Heald et al., 1987) and placer gold deposits of South Africa (Minter, 1991).

Northern areas of Pakistan are well known for the placer gold occurrences (Tahirkheli, 1974; Austromineral, 1976; 1978; PMDC, 2001). Detailed panned concentrate and stream sediments geochemical exploration for gold and other metals in the Chitral and Gilgit-Baltistan regions of the northern areas of Pakistan have been carried out by the Sarhad Development Authority (SDA) and Pakistan Mineral Development Corporation (PMDC) under the auspicious of the Australian Agency for International Development (AIDAB) from 1992-1997 in a project named as Gold Exploration and Mineral Analysis Project (GEMAP) (Sweatman et al., 1995). During this study, various geochemical base maps were prepared for most parts of the Gilgit-Baltistan and Chitral regions in the perspective of gold and base metals (Sweatman et al., 1995). They have identified more than 150 anomalies of gold in the northern areas of Pakistan (PMDC, 2001).

The study area is mainly lying in the upper parts of the Bagrot valley. This valley is mainly comprised of the rocks of the Cretaceous Chalt volcanic group of Petterson and Windley (1991), Khan (1994), Khan et al. (1994), and Petterson and Treloar (2004). These rocks are intruded by the gabbroic-diorites of Kohistan batholith in the southern part of the study area (Fig. 1). The rocks of the CVG are highly tectonized and metamorphosed to mainly greenschist and epidote-amphibolite facies and have the development of altered/sheared zones along local faults within these rocks.

The Bagrot valley is one of the anomalous gold bearing catchment areas (PMDC, 2001; Shah and Khan, 2004). It is mainly comprised of the rocks of the Chalt volcanic group (CVG) and Kohistan batholith belonging to Kohistan island arc (Fig. 1A&B). These rocks are hosting sulfide-bearing altered/sheared zones. These zones are identified through remote sensing and confirmed on the ground during field work. These sulfide-bearing altered/sheared zones can be considered as possible source for contributing placer gold in the sediments of Bagrot valley reported by PMDC (2001) and Shah and Khan (2004). In order to understand the geology and the genesis of the rocks of the study area in the context of gold and base metals mineralization, the petrochemical investigations were conducted to know the geochemical characteristics for possible gold and other base metal mineralization in the altered/sheared zones and to understand the paleo-tectonic settings of the studied rocks.

2. Methodology

Field Work: Representative samples were collected, from the various types of rocks and sulfide-bearing altered/sheared zones exposed in the study area, for both petrographic and geochemical analyses. Comprehensive studies in relation to mineral assemblages, identifiable in the field, and nature of the host rocks in terms of composition and texture were carried out carefully. Remote sensing techniques have been used for identification of sulfide-bearing altered/sheared zones and were confirmed on the ground before taking the samples. Each sample location was taken with the help of GPS. The contacts between different rock units and other geological features were recorded in detail. Two types of samples (bulk and grab) were collected. The bulk samples (>10 kg) from each spot were grabbed from the sulfide-bearing altered/sheared zones (Fig. 1B) and the host rocks for the determination of gold, silver and base metals whereas grab samples (<1 kg each) were collected from various types of fresh/less altered rocks for petrochemical analysis.

Laboratory Work: The selected samples were processed by using various laboratory techniques. Both polished and unpolished thin sections were prepared in the thin section preparation laboratory for their petrographic studies. The samples were crushed in jaw crusher to a small size (<1 cm) and the representative portions of the samples were obtained after passing through splitter and further quartering and coning. These crushed samples were then pulverized to 200 mesh size by ball mill. About 2 grams of each bulk powdered sample were digested with aqua-regia ($3HCl:1HNO_3$) and hydrofluoric acid (HF) for the analysis of Cu, Pb, Zn, Ni, Cr, Co and Ag by the methods of Macalalad et al. (1988) and Jeffery and Hutchison (1986) and gold, after extraction in methyle isobutyle ketone (MIBK) (Hubert and Chao, 1985) using Perkin Elmer-700 graphite furnace atomic absorption spectrometer (AAS) in the geochemistry laboratory of the National Centre of Excellence in Geology, University of Peshawar, Pakistan. The major and trace elements in the representative samples of fresh rocks were determined by using Bruker S4 Pioneer x-ray fluorescence machine at the Ellington & Associates, Houston, USA. Eighty one standards were used for the calibration of the instrument. Spectroscopic studies on the chip samples of the various rocks were also carried out on ASD spectrometer at the University of Houston, Houston USA. The loss on ignition (LOI) was determined by heating the powdered samples at 950ºC in the muffle furnace for about four hours. The analytical research grade reagents and chemicals were used and the standardization of the methods was validated with the use of certified rock standards such AGV-1, G-2, W-1. The accuracy and precision were found within 90% confidence limit.

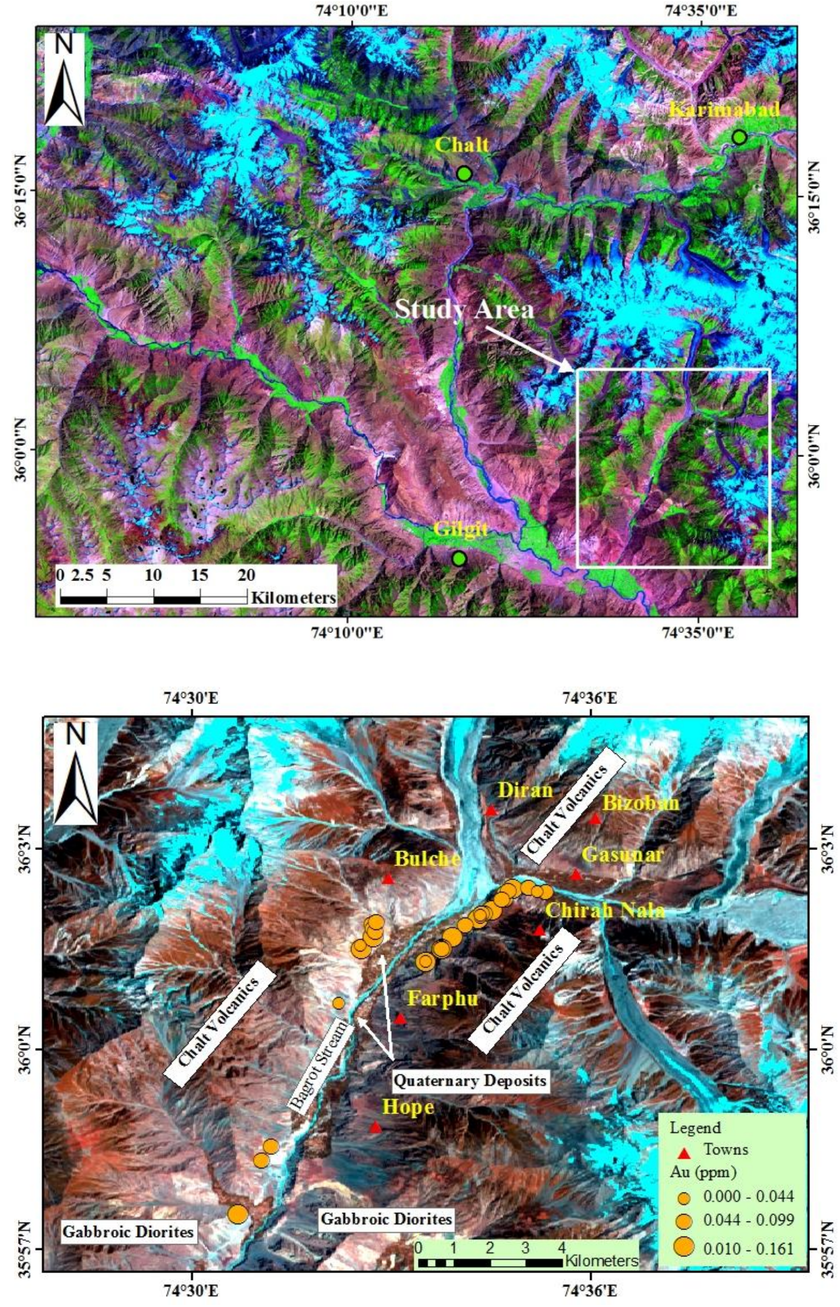


Fig. 1 (A) Landsat image of Gilgit and surrounding areas showing location of Bagrot valley,
(B) Landsat (LDCM) band ratio image with 4/3-6/3-7/5 displayed as red-green-blue, showing various lithologies and the concentration of gold from this study.

3. Results and Discussion

3.1. Remote sensing and field observation

This work used Landsat 8 Continuity Mission (LDCM) data. Landsat LDCM was launched on February 11, 2013 and acquires data in nine (9) spectral bands in visible, near-infrared and short-wave infrared spectrum. Several image processing techniques were used for identification of sulfide-bearing alteration/sheared zones. First the data were calibrated using Log residual technique then true and false color composites were generated followed by principal component analysis and minimum noise fraction. But the best results were obtained from 632 band combination. Figure 1B shows image as red, green and blue color combination. This image clearly discriminate different litholigcal units such as Chalt volcanics, gabbroic-diorites, Quaternary deposits and especially sulfide-bearing alteration/sheared zones from where the bulk samples for gold have been collected (Fig. 1B).

Numerous sulfide-bearing altered/sheared zones of variable thickness (< 1 m to > 10 m) and length (< 10 m to > 100 m) are present within the rocks of the CVG of the Bagrot valley (Fig. 2a, b, c, d). Local shearing along the faults are very common and well recognized due to the staining of yellowish-brown color formed by the oxidation of chalcopyrite and pyrite to limonite (Fig. 2b). With closer observation, the intensive alteration of the primary mineral phases to chlorite and epidote is also clearly visible. The traversing of quartz veins of variable thickness (<1 cm to > 1 m) along these altered/sheared zones are very common, which are deformed due to local or regional deformation. The schistosity and boudenaged structure of quartz vein along these zones are the examples of such deformation. Similar sulfide-bearing alteration/sheared zones are noticed in the gabbroic-diorites of the area.

The rocks of CVG are mainly covering the western and eastern parts of the Bagrot river (Fig. 1) where the terraces of glacio-fluvial and fluvial sediments are present on both sides of the river. The rocks of the CVG in the study area are generally greenish-gray on fresh surface and yellowish brown on weather surface. The gray to green colored steeply dipping volcanic sheets, mainly basalt or basaltic-andesite in character, with intercalations of meta-tuffs, meta-rhyolite and meta-graywacke are exposed in the study area. These are generally deformed and exhibit greenschist facies metamorphism with the development of epidotes-amphibolite facies metamorphism at places. However, greenish-gray colored compact rocks with low degree of deformation/metamorphism are also not uncommon. The greenschist rocks are foliated with the development of chlorite and epidotes along with other felsic phases (mainly feldspar) oriented in the fabric direction whereas, the epidotes-amphibolite rocks show development of hornblende in addition to above mentioned phases. These rocks are generally fine-grained non-porphyritic, but porphyritic rock are also not uncommon.

The gabbroic-diorites belonging to the Kohistan batholiths are exposed in the south-western part of the study area and are having intrusive contact with the rocks of the Chalt Volcanic Group (Fig. 1). These rocks usually display gray to dark-gray color on the fresh surface and yellowish-brown color on the weather surface due to leaching of sulfides. In hand specimen, plagioclase, hornblende, biotite and epidote can be clearly recognized. Pyrite grains are also found in dissemination. The leaching of pyrites and staining of yellowish-brown color on the weathered surface is very common. Relatively dark colored gabbroic-diorites have high proportion of hornblende and micaceous minerals (mainly biotite). The intrusion of quartz veins and alteration (mainly epidotization) and leaching of sulfides are common in host rocks along these veins.

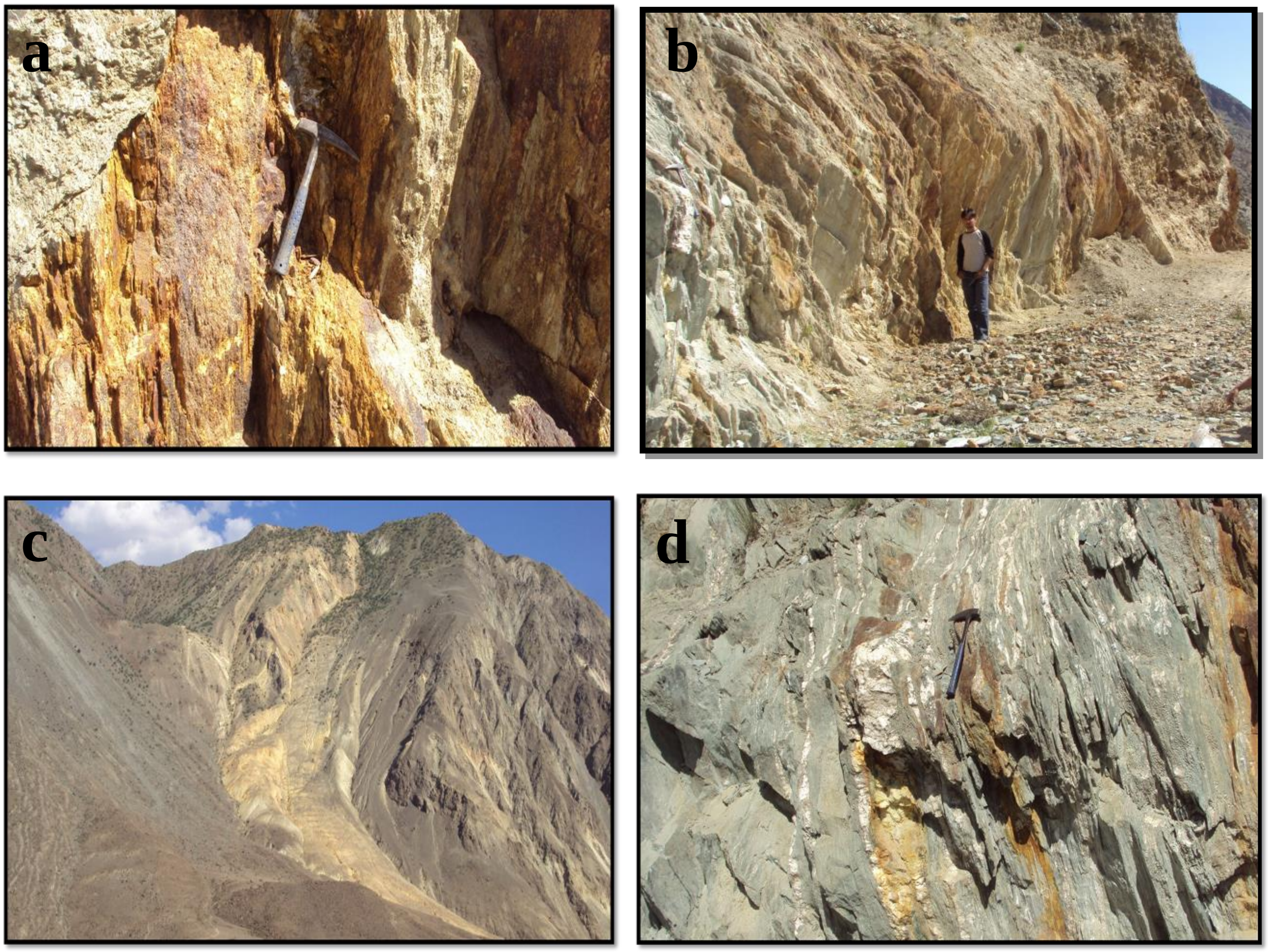


Fig. 2. Photographs showing the sulfide-bearing alteration / sheared zones in the study area. Photographs a, b and c are showing the oxidation of various sulfide phases along sheared zones. Photograph d is displaying the occurrence of quartz veins along fabric direction within altered / sheared zones.

3.2. Petrographic and spectroscopic characteristics

3.2.1. Sulfide-bearing altered/sheared zones

Primary mineral phases such as plagioclase, pyroxene and hornblende have been completely altered as indicated by the presence of relics and pseudomorphs of these minerals. In most cases the plagioclase is altered to epidote and hornblende. In some cases, these rocks show banded appearance due to the metamorphic segregation of alternate mafic and felsic phases. This could be due to shearing as in greenschist grades metamorphic segregation. The alteration phases are generally chlorite, epidote, and lesser amount of sericite, tremolite/actinolite and calcite ± muscovite. Apatite ± zircon ± titanite ± rutile occurs as accessory phases. The opaque ores are pyrite, magnetite ± ilmenite ± chalcopyrite.

Spectral reflectance of four selected samples from sulfide-bearing altered/sheared zone is presented in Figure 3a. The hematite/magnetite, kaolinite and OH^- have distinctive absorption feature on reflectance curve. These graphs demonstrate absorption features in all samples at 0.55 µm, suggesting the presence of iron (Fe^{+2}). Absorption features at 1.45 µm represent presence of OH^-, 2.05-2.30 µm indicating clay minerals and 2.35 µm to show absorption of calcite (Petrovic et al., 2012).

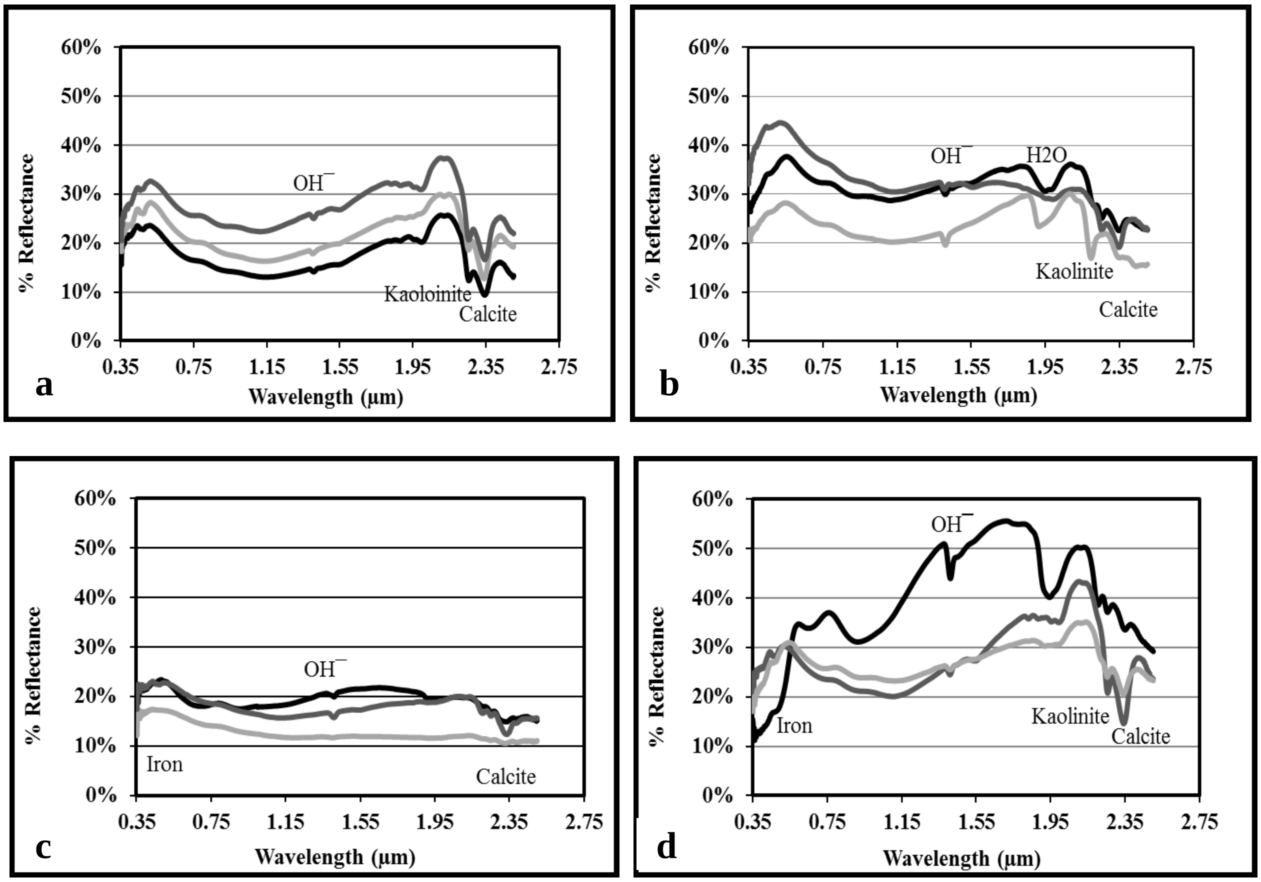


Fig. 3. Spectral reflectance curves of representative samples of (a) porphyritic volcanics, (b) non-porphyritic volcanics of Chalt Volcanic Group, (c) gabbroic-diorites and (d) sulfide-bearing altered/sheared zones of the study area.

3.2.2. Chalt Volcanic Group

In the non-porphyritic volcanics, the phenocrysts of plagioclase and hornblende are either absent or present in lesser amount (<15 vol. %) whereas the groundmass is generally cryptocrystalline and felsophyric, having mainly feldspar. The alteration phases such as epidotes, chlorite, biotite, sericite, calcite, muscovite ± tremolite/actinolite and accessory minerals such as apatite ± zircon ± titanite and opaque ores are present in variable amounts. The porphyritic rocks consist mainly of phenocysts of plagioclase, hornblende, and or pyroxene whereas the groundmass contains felsic material, chlorite, epidote ± biotite ± muscovite ± calcite and ± tremolite/actinolite. Epidotes, sericite, chlorite and tremolite/actinolite are the alteration products of phenocrysts and ground mass phases during greenschist facies metamorphism. The accessory phases such as apatite, zircon and titanite are present in traces. Magnetite is found in dissemination.

Reflectance curves of both porphyritic (Fig. 3b) and non-porphyritic volcanics (Fig. 3c) indicate that there are strong and deep absorption features of Fe^{+2}, OH^{-}, H_2O, kaolinite and calcite at 0.35-0.65 µm, 1.38 µm, 1.95 µm, 2.05-2.32 µm and at 2.35 µm for non-porphyritic volcanics whereas in porphyritic volcanics, low absorption depth of iron at 0.55 µm, OH^{-} at 1.45 µm is present and also absorption feature of H_2O from 2.05 µm wavelength and kaolinite at 2.05-2.30 µm.

3.2.3. Gabbroic-diorites

These rocks are medium- to coarse-grained, equigranular to inequigranular, anhedral to euhedral with xenomorphic to idiomorphic granular texture. The principal constituent minerals are plagioclase, orthoclase, hornblende, biotite and quartz. Plagioclase (An_{40-55}) is euhedral to subhedral and is commonly fresh looking and exhibit polysynthetic albite twinning and normal compositional zoning. Green to dark green hornblende occurs as prismatic grains. Epidote, ± chlorite ± muscovite, calcite and kaolinite occur as alteration products whereas ± titanite ± apatite ±zircon and opaque minerals occur as accessories.

Spectral reflectance of three representative samples of gabbroic-diorites is presented in Figure 3d. There are two intervals where changes can be observed on the reflectance curve. In this figure, all the samples show spectral absorption at around 1.45 µm indicating presence of OH^-. These samples also show absorption for calcite at around 2.35 µm.

It is evident from the spectral data that all the studied rock types have unique curves with specific absorption and reflectance behavior. This suggests the different mineralogical characteristics of each rock type as has also been noticed during field and petrographic studies. The greater concentration of clay minerals and the Fe-bearing phases in the sulfide-bearing altered/sheared zone also confirm the greater alteration due to hydrothermal solution within the sulfide-bearing altered/sheared zone as has also been noticed in petrographic studies.

3.3. Geochemistry

3.3.1. Gold, silver and base metals in the sulfides-bearing altered/sheared zones

The quartz veining and the pervasive alteration along these zones suggest the involvement of hydrothermal fluid in the alteration and precipitation of base metal sulfides, gold and silver. As the occurrence of anomalous gold in the stream sediments of the Bagrot valley has been reported by the previous workers (PMDC, 2001; Shah and Khan, 2004), the rocks of the area, especially the sulfides-bearing along altered/sheared zones, attained main focus of this study regarding gold, silver and base metal mineralization in the area. In order to identify the source bed rocks contributing anomalous gold, silver and base metals in the stream sediments, the rocks and the sulfides-bearing altered/sheared zones of the CVG have been investigated geochemically.

In this respect, the bulk samples (~10 Kg) were collected from rocks and sulfides-bearing altered/sheared zones in the Bagrot valley for the analysis of Au, Ag and base metals such as Cu, Pb, Zn, Ni, and Cr. The concentration of Au, Ag and base metals in the sulfides-bearing altered/sheared zones and fresh/less altered rocks of CVG are given in Table 1 and their average values are graphically presented in Figure 4. In the samples of these zones, the concentration of Cu ranges from 5-96 ppm with average value of 50 ppm, Pb from 2-38 ppm with average value of 9 ppm, Zn from 4-199 ppm with average value of 42, Ni from 2-39 ppm with average value of 14 ppm and Cr ranges from 6-79 ppm with average value of 37 ppm. In these sample, the precious metals such as Au ranges from <0.05-0.161 ppm with average value of 0.083 ppm and Ag from <0.05-11.30 ppm with average value of 0.64 ppm. The average amount of Au, Ag and base metals of the samples of fresh/less altered and sulfides-bearing altered/sheared zones have been used to calculate the enrichment and depletion factors [(altered-fresh)/fresh)*100)] and presented graphically in Figure 4 to understand the gain and loss due to hydrothermal alteration in the sulfides-bearing altered/sheared zones. It is clear from Figure 4 that there is enrichment of Au, Ag and Pb whereas Cu, Zn, Ni and Cr show depletion in the sulfides-bearing altered/sheared zones as compared to the fresh/less altered rocks of CVG.

It is generally understood through earlier studies that hydrothermal solutions are usually enriched in sulfides, gold and silver which precipitate these metals at low temperature along fractures and other weak zones. The effects of hydrothermal solution within the sulfides-bearing altered/sheared zones of the study area and the extensive oxidation of sulfides in these zones suggest that the base metal sulfides along with gold and silver may have been precipitated along these altered/sheared zones. However, the enrichment of Au, Ag and Pb and the depletion of the Cu, Zn, Cr, and Ni in these zones can be attributed to the surface weathering and variable mobility of these metals. The base metal sulfides are easily dissolved during chemical weathering and hence the base metals, especially Cu and Zn have been easily leached out due to their mobile nature whereas Au, Ag and Pb, due to their immobile nature have been least affected during the chemical weathering and leaching processes.

Data of this study suggests that the studied sulfides-bearing altered/sheared zones are not of economic importance as far as the concentrations of gold in the surface samples are concerned. However, drilling along these zones and collection of samples at depth may reveal promising anomalies.

3.3.2. Whole rock geochemistry

Ten representative samples including four from non-porphyritic and three each from porphyritic volcanics of the CVG and the gabbroic-diorites of the Kohistan batholith were analyzed for the major and trace elements.

3.3.2.1. Chalt Volcanic Group

The whole rock geochemical data including major and trace elements and CIPW norms are presented in the Table 2.

Major-elements: The porphyritic rocks of the CVG of the Bagrot area are classified as basalt and the non-porphyritic rocks as basalt and basaltic-andesites. Data in Table 2 show that in porphyritic volcanic rocks concentration of SiO_2 varies from 49.56 to 50.13 wt%, Al_2O_3 from 11.68 to 11.84 wt%, TiO_2 from 0.50 to 0.59 wt%, Fe_2O_3t from 10.41 to 11.42 wt%, MnO from 0.16 to 0.17 wt%, MgO from 6.84 to 7.01 wt%, CaO from 10.78 to 11.54 wt%, Na_2O from 1.41 to 2.01 wt%, K_2O from 0.42 to 0.48 wt% and P_2O_5 from 0.10 to 0.16 wt% . The non-porphyritic rocks have SiO_2 in the range of 47.89-54.78 wt%, Al_2O_3: 16.98-17.89 wt%, TiO_2: 0.47-0.62 wt%, Fe_2O_3t: 6.49-10.56 wt%, MnO: 0.07-0.26 wt%, MgO: 2.43-4.48 wt%, CaO: 5.89-9.67 wt%, Na_2O: 1.38-3.77 wt%, K_2O: 1.10-2.49 wt% and P_2O_5: 0.05-0.16 wt% (Table 2). The loss on ignition in both the volcanic types is <5 wt%. The Mg# [$100*MgO/(Mg+Fe_2O_3t)$] is low (<40) but the porphyritic volcanics have little more Mg# as compared to the non-porphyritic volcanics. The major element oxides are plotted in the Harker diagrams (not shown), suggest vaguely defined trends for most of the major oxides. The data further suggest that both the varieties have different entities and are, therefore, not comagmatic.

The CIPW norms (calculated on anhydrous basis) indicate that these volcanics are generally quartz normative whereas one sample of non-porphyritic volcanics is olivine normative. These are hypersthenes normative with high plagioclase (Ab+An) normative composition. However, the porphyritic volcanics in comparison to non-porphyritic volcanics have greater amount of normative pyroxene (Hy+Di) relative to plagioclase (Ab+An) (Table 2). Two samples of non-porphyritic volcanics have normative corundum whereas the normative phases such as orthoclase, magnetite, ilmenite and apatite are present in variable amount (Table 2)

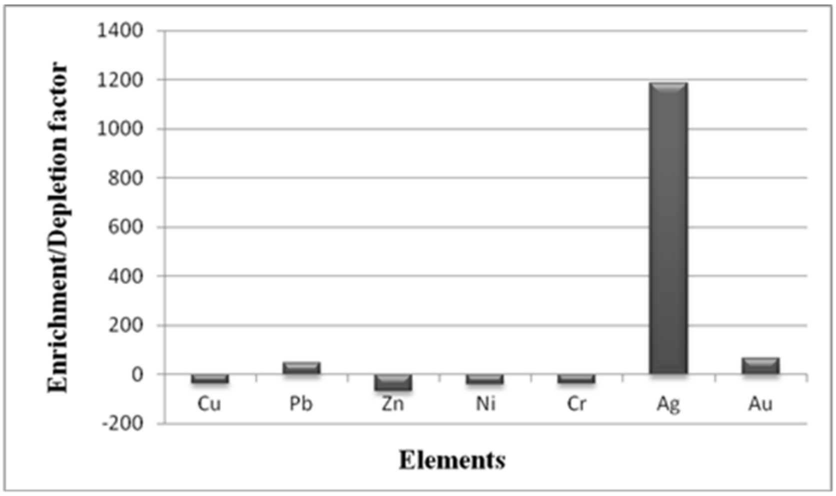


Fig. 4. Diagram showing the enrichment and depleted concentrations of gold, silver and base metals in the sulfide-bearing altered / sheared zones and fresh rocks of the area study.

Table 1. Concentrations of gold, silver and base metals in the samples of sulfide-bearing altered/sheared zones of the study area.

S. No.	Cu (ppm)	Pb (ppm)	Zn (ppm)	Ni (ppm)	Cr (ppm)	Co (ppm)	Ag (ppm)	Au (ppm)
BG-B1	6.8	0.55	0.35	0.145	0.3	40.7	0.35	0.1075
BG-B2	38.85	2.35	3.5	0.183	0.413	69.1	0.05	0.0355
BG-B3	55.45	<0.02	46.1	0.175	0.696	41.85	0.05	0.064
BG-B4	50.75	0.02	27.25	0.322	1.254	55.1	0.05	0.08333
BG-B5a	66.2	2.75	53.8	0.209	1.519	56.55	0.05	0.048
BG-B5b	82.4	0.02	23.6	0.17	0.824	48.55	0.05	0.09267
BG-B6	73.15	2.1	11.75	0.135	1.461	48.55	0.05	0.067
BG-B7	30.25	0.02	29.85	0.031	0.611	39.35	0.05	0.161
BG-B8	42	0.02	19.75	0.163	1.129	48.6	0.05	0.132
BG-B9	31.85	0.02	16.9	0.193	0.656	33.25	1.45	0.041
BG-B10	13.3	0.02	15.95	0.136	0.781	47.2	0.35	0.076
BG-B11	96	0.02	26.45	0.19	0.26	52.25	0.05	0.072
BG-B12	43.4	0.02	6.85	0.366	0.151	47.4	0.2	0.041
BG-B13	23.225	9.575	12.3	39.2	11.55	17.125	0.3	0.0545
BG-B14	44.65	0.02	108.2	0.302	0.505	24.85	0.05	0.157
BG-B15	71.1	0.02	154.7	0.203	0.908	22.35	0.05	0.05467
BG-B16	61.5	0.65	43	0.184	0.685	32.9	0.05	0.15025
BG-B17	87.85	0.02	43.95	0.305	1.014	30.5	0.05	0.04967
BG-B18	65.15	0.02	0.05	0.193	0.985	38.95	0.05	0.063
BG-B19	17.1	0.02	0.05	0.116	0.919	52.9	0.05	0.05433
BG-B20	87.85	0.02	37.5	0.163	1.377	40.3	0.05	0.04
BG-B21	77.55	0.02	109.5	0.181	0.356	42.8	0.05	0.108
BG-B22	46.25	0.02	84.85	0.043	1.089	37.5	11.3	0.055
BG-B23	54.25	0.02	17.95	0.225	0.395	54.35	3.8	0.099
BG-B24	78.95	0.02	14.35	0.402	0.539	71.9	0.05	0.091
BG-B25	89.3	0.02	31.1	0.46	0.007	35.2	0.05	0.07
BG-B26	77.5	0.02	46.75	0.631	0.883	47.35	0.05	0.12833
BG-B27	24.65	0.02	70.05	0.249	0.151	32.7	0.05	0.0415
BG-B28	24	0.02	56	0.316	0.565	54.55	0.05	0.1325
BG-B29	31.85	0.02	0.05	0.422	0.792	37.15	0.35	0.0435
BG-B30	67.9	0.02	198.9	0.723	1.572	53.95	0.6	0.093
BG-B31	46.05	0.02	34.25	0.487	0.65	42.9	0.75	0.0865
BG-B32	5.3	0.02	22.85	0.621	0.763	68.6	0.65	0.15375
Average	51.8902	0.56106	41.4682	1.44982	1.08364	44.4629	0.64242	0.08323
STd	25.8924	1.76355	45.2209	6.77884	1.92143	12.747	2.03493	0.03856
Minimum	5.3	<0.02	<0.05	0.031	0.007	17.125	<0.05	<0.05
Maximum	96	9.975	198.9	39.2	11.55	71.9	11.3	0.161

Table. 2. Whole rock geochemical data (major oxides in wt% and trace elements in ppm) of the porphyritic and non-porphyritic volcanics of Chalt Volcanic Group of the study area.

	Chalt Volcanic Group (CVG)						
	Porphyritic volcanics			Non-porphyritic volcanics			
Sample	**BG-G15**	**BG-G20**	**BG-G28**	**BG-14**	**BG-22**	**BG-23**	**BG-G17**
SiO_2	49.56	50.13	49.98	50.68	51.45	54.78	47.89
Al_2O_3	11.84	11.68	11.80	17.70	17.67	16.98	17.89
TiO_2	0.50	0.59	0.52	0.62	0.61	0.47	0.59
Fe_2O_3	11.42	10.41	10.78	10.56	9.29	6.49	10.34
MnO	0.16	0.17	0.16	0.18	0.26	0.07	0.19
MgO	7.01	6.84	6.92	4.25	4.34	2.43	4.48
CaO	10.78	11.54	10.93	6.78	5.89	7.49	9.67
Na_2O	1.41	2.01	1.85	1.38	2.84	3.77	2.95
K_2O	0.42	0.48	0.44	2.49	1.53	1.37	1.10
P_2O_5	0.10	0.16	0.14	0.05	0.15	0.16	0.14
L.O.I	4.60	4.32	4.52	4.34	4.43	4.56	4.89
Total	**98.04**	**98.91**	**98.04**	**98.22**	**98.46**	**98.58**	**98.69**
Trace elements							
As	7	7	6	3	5	4	5
Sc	34	33	33	45	29	17	20
V	371	293	343	389	329	162	234
Co	48	42	46	5	11	4	21
Cr	48	81	67	56	50	52	53
Ni	25	38	30	18	18	17	19
Cu	89	103	95	104	42	19	98
Pb	4	7	5	9	6	4	3
Zn	93	93	90	252	180	42	109
Sr	244	457	332	240	178	388	345
Rb	12	20	16	44	27	50	16
Ba	117	188	142	617	589	238	223
Th	1	2	1	1	2	3	2
U	1	1	1	1	1	1	1
Nb	1	2	1	1	1	1	2
Y	17	19	17	23	25	22	24
Zr	23	47	28	82	99	94	87
Hf	1	3	2	1	4	4	2
Au	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Ag	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Mg#	38.04	39.64	39.40	28.70	31.83	27.28	30.23

C.I.P.W. norms

Q	6.78	4.29	5.31	7.12	5.74	7.82	-
C	-	-	-	0.54	1.04	-	-
Or	2.69	3.04	2.8	15.69	9.71	8.68	6.86
Ab	12.91	18.28	16.9	12.47	25.77	34.12	26.48
An	26.81	22.98	24.38	35.53	30.33	27.1	34.23
Di	25.03	30.57	27.5	-	-	9.55	12.99
Hy	21.58	16.52	19.24	24.59	23.38	9.67	6.61
Ol	-	-	-	-	-	-	8.68
Mt	2.85	2.61	2.7	2.64	2.38	1.64	2.57
Il	1.02	1.21	1.07	1.27	1.25	0.96	1.19
Ap	0.22	0.37	0.33	0.11	0.33	0.4	0.31

Trace-elements: The trace element data of porphyritic volcanic rocks in Table 2 indicate that the large ion lithophile elements (LILE) such as Sr (244-457 ppm), Rb (12-20 ppm), Ba (117-188 ppm) and high field strength elements (HFSE) such as Th (1-2 ppm), U (up to 1 ppm), Nb (1-2 ppm), Zr (23-47 ppm), Hf (1-3 ppm) and Y (17-19 ppm) have less variation in concentration. The transitional metal (TMs) such as Cr, Ni, Cu, Pb, Zn, Co and V are found in the range of 48-81 ppm, 25-38 ppm, 89-103 ppm, 4-7 ppm, 90-93 ppm, 42-48 ppm and 293-371 ppm respectively (Table 2). However, precious metals such as Au and Ag are present below the detection limit (<0.05 ppm) (Table 2).

The trace element data of the non-porphyritic rocks in Table 2 exhibit that the LILE such as Sr ranges from 178 to 388 ppm, Rb from 16 to 50 ppm, Ba from 223 to 617 ppm; and the HFSE such as Th ranges from 1 to 3 ppm, Nb from 1 to 2 ppm, Zr from 82 to 99 ppm, Hf from 1to 4 ppm and Y from 22 to 25 ppm whereas the transition metals are ranging as: Cr from 50 to 56 ppm, Ni from 17 to 19 ppm, Cu from 19 to 104 ppm, Zn from 42 to 252 ppm, Co from 4 to 21 ppm and V from 162-389 ppm. The gold and silver are present below the detection limit (<0.05).

The analyzed data of LILE and HFSE are normalized to primitive mantle, chondrite and MORB by using the normalization factors of Taylor and McLennan (1985), Sun and McDonough (1989) and Pearce (1983) respectively and plotted in spidergrams (not all are shown here). In these diagrams, the trace element slopes toward right showing increasing trend from HFSE to LILE and suggest enrichment of LILE relative to HFSE with negative anomaly of Nb (Fig. 5a). These patterns are consistent with calc-alkaline rocks formed in subduction related environment. In an island arc volcanics, the enrichment of LILE is usually due to metasomatism of sub arc mantle source caused by aqueous fluids generated from subduction crust whereas depletion of HFSE are particularly due to high degree of partial melting and also stabilized mantle source (Arculus and Powel, 1986; Green, 1982; Pearce and Norry, 1979).

3.3.2.2. Gabbroic-diorites

Major elements: These rocks represent variable concentration of SiO_2 (53.56-54.12 wt%), TiO_2 (0.70-0.75 wt%), Fe_2O_3t (8.24-9.22 wt%), MgO (4.56-5.18 wt%), CaO (9.34-11.58 wt%), Na_2O (2.64-3.54 wt%), K_2O (0.22-1.45 wt%) and very low variations of Al_2O_3 (16.45-16.80 wt%), MnO (0.12-0.17 wt%) and P_2O_5 (0.32-0.36 wt%) (Table 3) The loss on ignition (1.50-1.23 wt%) and Mg # (35.05 to 37.51 wt%) are also low in these rocks. These rocks are quartz normative (3.7-5.68%) with dominant plagioclase (54.53-57.80%) and lesser orthoclase (1.31-8.69%) as normative feldspar phase. Normative diopside and hypersthenes are in the range of 13.29-18.14 % and 13.75-15.43% respectively. The other normative phases are magnetite (2.02-2.06%), ilmenite (1.36-1.42%) and apatite (0.70-0.81%).

Trace elements: The trace element data in Table 3 show that the LILE such as Sr ranges from 493 to 679 ppm, Rb from 13 to 34 ppm and Ba from 167 to 234 ppm whereas the HFSE such as Th is ranging from 2 to 3 ppm, Nb from 7 to 8 ppm, Zr from 78 to 81 ppm, Hf from 2-6 ppm and Y from

21-24 ppm. The transition metal such as Cr varies from 62-68 ppm, Ni from 38-51 ppm, Cu from 47-84 ppm, Pb from 4-7 ppm, Zn from 76-91 ppm and Co from 37-42 ppm. Gold and silver are found below the detection limit (<0.05) in these rocks (Table 3)

The LILE and HFSE values have been normalized to primodial mantle and plotted in spidergram (Fig. 5b). This diagrams shows that the data generally slope from left to right showing high values of LILE with respect to HFSE indicating the characteristic of calc-alkaline rocks.

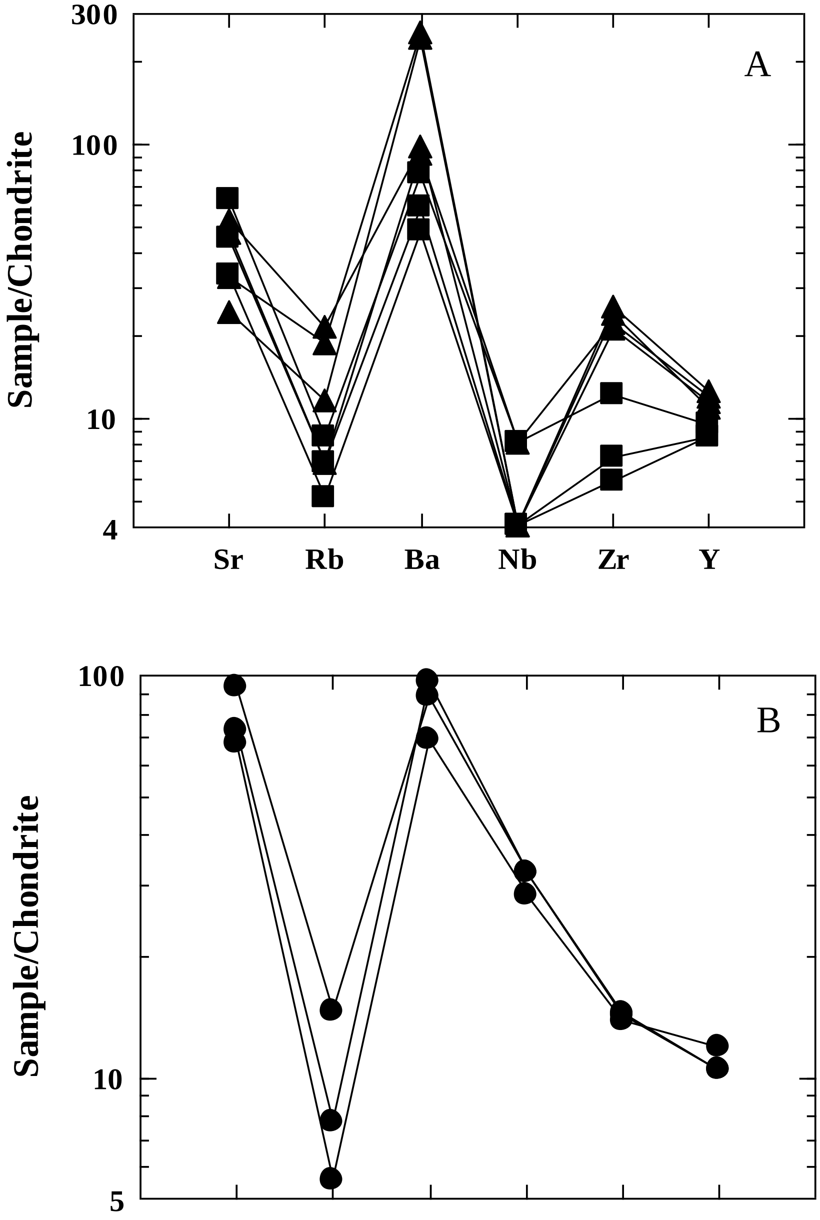


Fig. 5. Chondrite normalized spiderdiagrams for the (a) the rocks of the Chalt Volcanics Group and (b) gabbroic-diorites of the Kohistan batholiths of the study area. The symbols used are as: ■ = porphyritic volcanics, ▲= non-porphyritic volcanics and ●= gabbroic-diorites

3.4. *Tectonic affinity and magma generation*

To understand the magma formed at different tectonic settings on the basis of their chemical characteristics, various major and trace elements of immobile nature have been evaluated by various workers after the pioneer work of Pearce and Cann (1973). The major and trace elements data of the rocks of CVG and gabbroic-diorites of Kohistan batholiths of the Bagrot valley have been plotted in various tectonomagmatic discrimination diagrams such as FeO_t-Na_2O+K_2O-Mgo (Irvine and Barager, 1971), MnO-P_2O_5-TiO_2 (Mullen, 1983), Nb-Zr-Y (Meschede, 1986), Th-Hf-Nb (Wood, 1980), MgO-FeOt-Al_2O_3 (Pearce et al., 1977), T-Zr-Y (Pearce and Cann, 1973), Ti-Zr-Sr (Pearce and Cann, 1973), Ti-Si-Sr (Vermeesch, 2006) and Nb-Na-Sr (Vermeesch, 2006). Among these, the Hf-Th-Nb (Fig. 6), Ti-Zr-Si (Fig. 7) and Nb-Na-Sr (Fig. 8) diagrams are shown here. These diagrams are used to understand the parental magmas and their formation in the specific tectonic setting for the rocks of Chalt Volcanic Group and Kohistan batholith of the study area. These diagrams clearly suggest that the porphyritic volcanics of CVG are tholeiitic and the non-porphyretic volcanics of CVG and gabbroic-diorites of Kohistan batholiths are of calc-alkaline formed in island arc setting. The geochemical data involving both major and trace elements have been utilized to describe the petrology and tectonic setup of the area. The Chalt volcanics show different petrological characteristic of both calc-alkaline and tholeiitic volcanics which may be closely associated with the mélange zone. Thus calc-alkaline and tholeiitic volcanics occur together in Chalt Volcanic Group (e.g., Petterson and Windley, 1985).

The enrichment of LILE relative to the HFSE and the Nb anomaly in the studied rock samples of Chalt Volcanic Group and the Kohistan batholith can be referred to as subduction zone geochemical component which may reflect the crustal contamination and or production of magma in a mantle wedge that are usually enriched in the LILE and light REE during the dehydration of descending plate (Condie, 1989). This is in consistent with the formation of Teru/Shamran volcanics (Khan et al., 2004), and the volcanic rocks of the Chalt Volcanic Group in this region (Peterson and Windley, 1991, 2010; Sheikh, 2013; Sheikh et al., 2014) and the Kohistan batholith (Petterson and Windley, 1991; Sheikh, 2013; Sheikh et al., 2014).

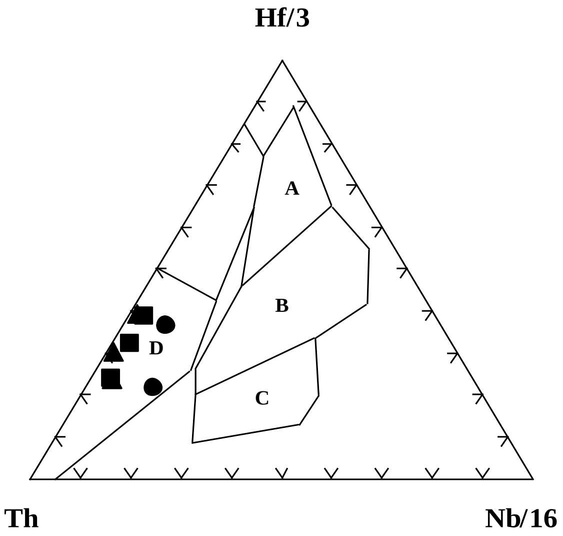


Fig. 6. Th-Hf-Nb ternary diagram of Wood (1980) for studied samples. A = N-type MORB, B = E-type MORB and within-plate tholeiites, C = alkaline within-plate basalts, D = destructive plate-margin basalts. Symbols used as for Figure 5.

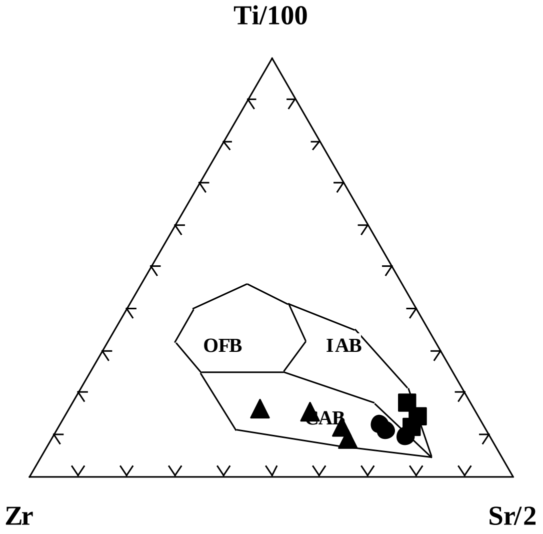


Fig. 7. Ti-Zr-Sr discrimination ternary diagram of Pearce and Cann (1973) with data from this study. OFB = ocean floor basalts, IAB = island arc basalts, CAB = calc-alkaline basalts. Symbols used as for Figure 5.

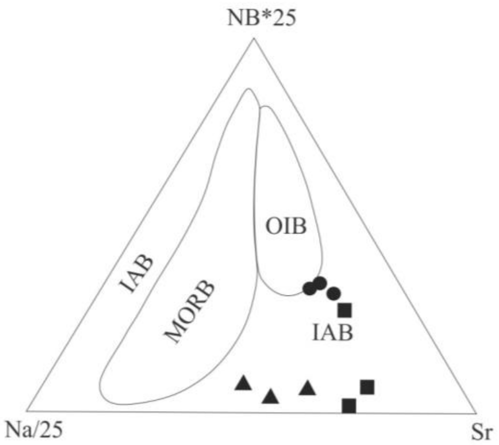


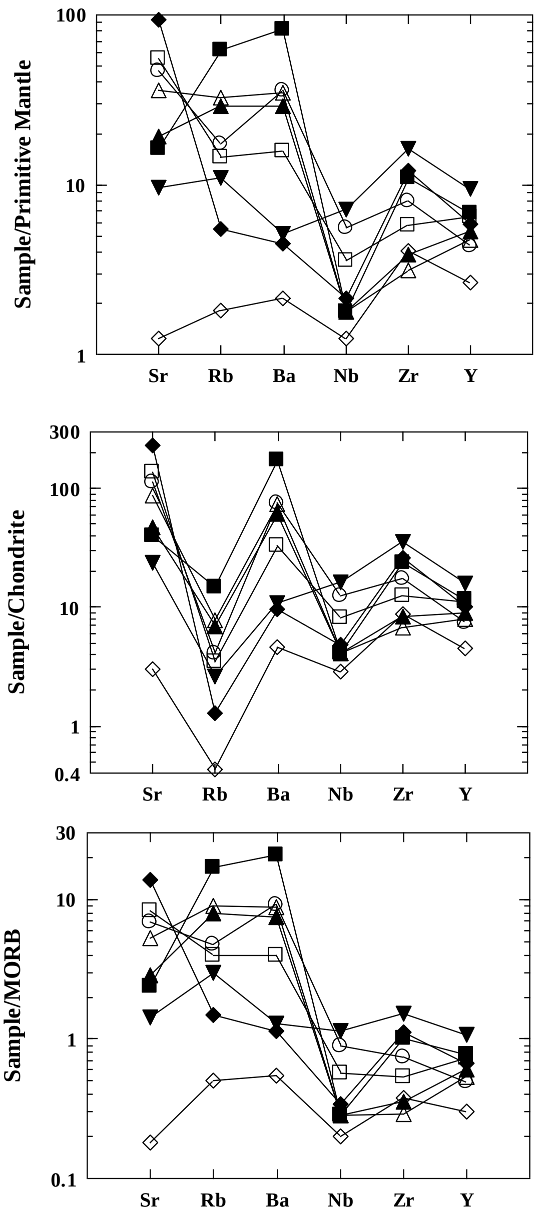
Fig. 8. The trace elements NB*25-Na/25-Sr ternary diagram of Vermeesch, (2006) for the studied samples. OIB = ocean island basalts, IAB = island arc basalts, MORB = mid-oceanic ridge basalts. Symbols used as for Figure 5.

Various geochemical studies have been conducted on the volcanics and plutonic rocks along the northern margin of the Kohistan Island arc (i.e., Petterson et al., 1990; Petterson and Windley, 1991, 1992, 2010; Petterson and Treloar, 2004; Sullivan et al., 1993; Khan, 1994; Khan et al., 2004; Sheikh, 2013). Petterson and Windley (1991) have studied the rocks of Chalt Volcanic Group in detail and have divided this group into 1) the high Mg-tholeiites (MgO 6-15%), exposed in the Hunza valley and 2) the low-intermediate MgO (MgO < 6%) calc-alkaline volcanics exposed in the western parts of Gilgit. The first one was named as Hunza Formation and the second one was named as Ghizer Formation by Petterson and Treloar (2004).

The Ghizer formation was further divided into 1) basalt-andesite sheet dominant (BASD), 2) Ishkoman volcanic centre (IVC) and the tuff dominant volcanics (TDV). However, Sheikh et al. (2014) have considered volcanic rocks of IVC of Ghizar formation equivalent to those of Teru volcanic Formation of Danishwar et al. (2001). Petterson and Treloar (2004) have included the volcanic rocks of the study area (Bagrot valley) into high-Mg tholeiites of the Chalt Volcanic Group. However, the geochemical composition of the volcanic rocks of the Bagrot valley during this study is not consistent with the earlier observations of Petterson and Treloar (2004).

In order to correlate the volcanic rocks of the present study with those exposed in the northern margin of the Kohistan Island arc, the average major and trace element data of the studied volcanics are compared with the calc-alkaline volcanics of CVG of Petterson and Windley (1991), Sheikh (2013) and Sheikh et al., 2014), Teru volcanics of Khan et al. (2004), high-Mg tholeiites of CVG of Petterson and Windley (1991) and tholeiitic volcanics of CVG of Khan (1994) in tables 4a & b and Figure 9. The studied porphyritic rocks of the tholeiitic character are correlated with the tholeiitic volcanics of Khan (1994) while the studied non-porphyritic volcanics are best correlated with the BASD volcanics of the Ghizer Formation. This study, therefore, suggests that the rocks of the Ghizer Formation which according to Petterson and Treloar (2004) are exposed in the western part of Gilgit are also exposed in the Bagrot valley located in the eastern part of Gilgit and hence this formation of the CVG covers relatively more area as compared to Hunza formation in the region.

It has already been established through the spidergrams and the tectonic discrimination diagrams that the gabbroic-diorites of the study area, belonging to Kohistan batholith, have been originated in the island arc type of environment with strong component of subduction. The rocks of Kohistan batholith have been divided into stage-1, 2 and 3 on the basis of their ages and the fabric development (Petterson and Windley, 1986, 1991). The stage-1 deformed plutons are 102 ± 12 Ma, stage-2 undeformed plutons are of 85-40 Ma and stage-3 intrusions are of 30 Ma. Among these the geochemical characteristics of stage-1 and stage-2 plutons are related to subduction zone calc-alkaline magmatism whereas, the stage-3 intrusions are considered as of post-collisional crustal melt (Petterson and Wndley, 1991). The trace elements of the studied gabbroic-diorite are compared with stage-1, 2 and 3 plutons in spidergrams (Fig. 10). This indicates the studied gabbroic-diorites are not comparable with stage-1 and stage-3 plutons, however, it can be comparable to some extent with stage-2 diorites of Petterson and Windley (1991). As these gabbroic–diorites are undeformed and are younger than Chalt Volcanic Group as of having intrusive contact with the CVG, these gabbroic-diorites can be correlated with stage-2 diorites.



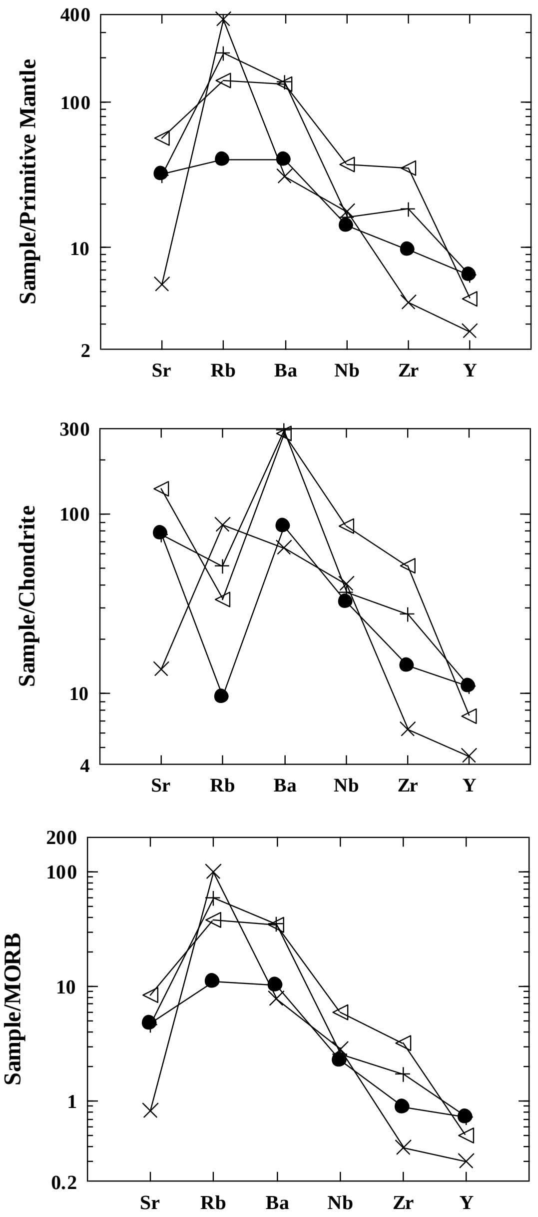


Fig. 9. Average trace elements data plotted as spidergrams for porphyritic and non-porphyritic volcanics of the Chalt Volcanics Group with the similar composition volcanics of BASD and IVC of Sheikh, 2013 and Sheikh et al., 2014, Teru volcanics of Khan et al., 2004, calc-alkaline and high-Mg tholeiites of Petterson and Windley, 1991 and Chalt Volcanic Group. The symbols used are as: ■ = porphyritic volcanics (this study) , ▲= non-porphyritic (this study), ☐ = BASD and △ = IVC, ○ = Khan et al. (2004), ♦ = Calc-alkaline of Petterson and Windley, (1991), ◇ = High Mg tholeiites and ▼= Chalt Volcanic group.

Fig. 10. Spidergrams for average compossition of diorites of this study showing comparison with the stages-1, 2 and stage-3 diorites of Petterson and Windley (1991). The symbols used are as: ● = Diorite (this study), ◁ = stage-1 diorite, + = stage-2 diorite and × = stage-3 diorite of Petterson and Windley (1991).

Table. 4a. Comparision of average major oxide data (in ppm) of the rocks of the Chalt Volcanic Group during this study with the other studies of the volcanic rocks in the region.

Sample	**Porphretic volcanics (This study)**	**Non-porphretic volcanics (This study)**	**BASD volcanics of CVG (Sheikh, 2013; Sheikh et al., 2014)**	**IVC / TVF volcanics of CVG (Sheikh, 2013; Sheikh et al., 2014)**	**Teru volcanics (Khan et al., 2004)**		**Calc-alkaline volcanics of CVG (Petterson and windley, 1991)**		**High-Mg tholeiitic volcanics of CVG (Petterson and Windley, 1991)**	**Tholeiitic volcanics of CVG (Khan, 1994)**
					42B	**7-4**	**IK679**	**K681**	**N146**	**ST33**
SiO_2	49.89	51.20	47.30	53.20	50.00	54.00	53.80	54.20	48.70	49.37
Al_2O_3	11.77	17.56	17.45	16.87	18.00	17.00	19.00	16.60	11.60	15.73
TiO_2	0.54	0.58	0.60	0.38	1.70	0.70	0.75	0.62	0.42	1.07
Fe_2O_3t	10.87	9.17	9.04	8.77	11.00	9.40	10.30	9.90	12.00	10.85
MnO	0.16	0.17	0.14	0.18	0.20	0.10	0.19	0.19	0.19	0.19
MgO	6.92	3.88	4.07	6.40	5.70	7.00	3.80	4.90	13.40	7.73
CaO	11.08	7.46	11.49	8.63	9.40	9.30	10.10	7.40	11.80	11.67
Na_2O	1.76	2.74	3.17	2.34	4.20	2.10	1.80	3.50	1.60	2.09
K_2O	0.45	1.62	0.41	0.86	0.60	1.00	0.12	2.01	0.25	0.22
P_2O_5	0.13	0.12	0.22	0.37	0.40	0.10	0.23	0.21	0.03	0.10
L.O.I	4.48	4.56	5.00	2.07	-	-	-	-	-	-
Total	98.33	98.49	98.89	100.10	100.00	101.00	100.10	99.53	99.99	100.72

Table. 4b. Comparision of the average trace elements data (in wt%) of the rocks of the Chalt Volcanic Group during this study with the other studies of the volcanic rocks in the region.

Sample	Porphretic volcanics (This study)	Non-porphretic volcanics (This study)	BASD volcanics of CVG (Sheikh, 2013; Sheikh et al., 2014)	IVC / TVF volcanics of CVG (Sheikh, 2013; Sheikh et al., 2014)	Teru volcanics (Khan et al., 2004)		Calc-alkaline volcanics (Petterson and windley, 1991)		High-Mg tholeiitic volcanics of CVG (Petterson and Windley, 1991)	Tholeiitic volcanics of CVG (Khan, 1994
					42B	7_4	IK679	K681	N146	ST33
Sc	28	33	22	26	-	-	-	-	-	-
V	279	336	215	230	-	-	197	293	189	270
Co	10	45	21	45	-	-	-	-	-	-
Cr	53	65	85	275	-	-	30	21	958	283
Ni	18	31	40	84	-	-	9	16	267	68
Cu	66	96	76	52	-	-	-	-	-	-
Pb	5	5	6	5	-	-	-	-	-	-
Zn	146	92	82	100	-	-	-	-	-	-
Sr	288	344	986	638	832	799	1657	698	22	170
Rb	34	16	8	18	9.5	184	3	27	1	6
Ba	417	149	80	177	182	388	23	411	11	26
Th	2	1	2	3						-
Nb	1	1	2	1	3.11	20	1.2	1.7	0.7	4
Y	23	18	22	16	14.7	43	20	15	9	32
Zr	91	32	48	26	66.8	175	100	53	34	136
Hf	3	2	7	5	1.9	4.8	-	-	-	-

4. Conclusions

The area of study mainly comprised of the rocks of the Chalt Volcanic Group intruded by the gabbroic-diorites of Kohistan batholiths. Numerous sulfides-bearing altered/sheared zones have been identified along local faults within the rocks of the CVG using remote sensing and field observations. These zones have typical yellowish-brown color due to leaching/oxidation of sulfides. The rocks of the CVG along shear zones are highly deformed and metamorphosed to greenschist and epidotes-amphibolite facies. Petrographically, the rocks of the CVG are fine-grained, foliated and are of both porphyritic and non-porphyritic character. Although this study couldn't find high concentration of gold in rock samples collected in Bagrot valley. But detailed study of sulfide alteration zones that are identified in this study may show potential economic deposits of gold, silver and other base metals.

The geochemical data suggest that the non-porphyritic volcanics of CVG and gabbroic-diorites of Kohistan batholiths exhibit calc-alkaline character with typical of subduction related component which can be correlated with the BASD volcanics of Ghizer formation while the porphyritic volcanics are of low-Mg tholeiites which can be correlated with other reported low-Mg tholeiitic volcanics of the region and not with the high-Mg tholeiites of Hunza valley. The gabbroic-diorites can be correlated with the stage-2 pluton of the Kohistan batholith.

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