Journal of Himalayan Earth Sciences Volume 47, No. 2, 2014, pp. 15-27

Investigation for gold and base metals mineralization and petrochemical characteristics of the rocks of Golo Das and surrounding areas, District Ghizar, Gilgit-Baltistan, Pakistan

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Abstract

Panning of stream sediments for gold along Indus River and its tributaries in the northern areas of Pakistan is being carried out for decades but the source rocks for gold are still unknown in the region. The interpretation of geochemical exploration data obtained by various geological organizations and the Remote Sensing studies conducted in the region have identified five areas for follow-up studies for gold mineralization in the Gilgit-Baltisatn region. Among these, Golo Das and surrounding areas have been investigated for gold mineralization along sulfide-bearing sheared / alteration zones during this study. The rocks exposed in the study area are highly deformed and include basalt-andesite sheet dominant volcanics and un-deformed volcanic rocks of Ishkoman Volcanic Center / Teru Volcanic Formation of Ghizar Formation and diorites of the Kohistan batholith. These rocks in Golo Das and surrounding areas are explored for their petrochemical characteristics and productive nature for gold, silver and base metals mineralization associated with sulfide-bearing sheared / alteration zones. Results of this work confirm enrichment of copper, cobalt, gold and silver in these alteration zones by hydrothermal processes but not in high concentrations to be of economic level. On the basis of major and trace element chemistry and the enrichment in large ion lithophile elements relative to high field strength element with well-defined negative Nb anomaly the rocks of the study area are comparable to the subduction related calc-alkaline rocks of island arc type setting. These rocks are, therefore, displaying subduction related signature and are considered a part of the Cretaceous Kohistan island arc.

Keywords: Gold and base metals; Petro-chemistry; Volcanic and plutonic rocks; Golo Das; Gilgit.

1. Introduction

The northern areas of Pakistan are known for the occurrence of placer gold along the river beds for decades. Although small amount of gold is panned out of stream sediments for decades in Gilgit, Chitral, Hunza and along Indus River in northern Pakistan, but no host rock is known for gold mineralization. So in search of gold mineralization in northern areas of Pakistan, Pakistan Mineral Development Corporation (PMDC) in collaboration with Sarhad Development Authority (SDA) conducted a detailed geochemical survey in the northern areas of Pakistan. Results of this project were published in several reports (Austromineral, 1976; 1978; MINORCO, 1997; PMDC, 2001). Recently, University of Peshawar in collaboration with University of Houston started a new project to search for gold source rocks on the basis of previous studies. This project was funded as part of the Pakistan-United States Joint Science and Technology Program Phase-IV 2009-14.Through this project all of the previous datasets including that of PMDC (2001) and MINORCO (1997) reports were digitized and their GIS database was created. Using GIS spatial tools, five target areas were identified in northern areas of Pakistan that may hold potential for gold mineralization. These areas are Golo Das, Bargot, Machulu, Shagari Bala and Ranthuk.

1.1. Geology of the area

Golo Das area is located close to Shyok suture zone that separates Kohistan paleo-arc from Karakoram block. The rocks of the Karakoram block are mainly composed of meta-sediments, and consist of garnet-muscovite-schist, biotiteschist, graphitic-schist, staurolite-schist, calc-schist, quratz-schist, chlorite-schist and conglomerate with para-gneisses. The Shyok suture zone in this area mainly contains slates with interbedded conglomerate and sandstone. It also contains chaiotic bodies of volcanics, serpentinites, limestone, red shale and quartzites. While the rocks of Kohistan paleo-arc in the study area are the volcanic rocks of the Chalt Volcanic Group (CVG), the meta-sediments of the Yasin Group and the diorites of Kohistan batholith. The contact between the Chalt Volcanic Group and the overlying Yasin Group is sheared and tightly folded.

Searle et al. (1996) mapped the volcanic rocks of the southern part of the study area as Shamran volcanics of Sullivan et al. (1993). These volcanics were later on renamed as Teru volcanic Formation (TVF) by Danishwar et al. (2001). However, Petterson and Treloar (2004) have named the volcanic rocks of the study area as part of the Ghizar Formation (GF) of CVG. The Ghizar Formation has been classified as 1) basalt-andesite sheet dominant (BASD) (highly deformed) and 2) Ishkoman Volcanic Centre (IVC) (less deformed/un-deformed) volcanics. The BASD volcanics are exposed in the northern part of the study area while the volcanic rocks of the IVC are covering most of the central and southern part of the study area. These volcanics are intruded by the diorites of Kohistan batholiths (Fig. 1). On the basis of field features and un-deformed nature, the rocks of the IVC of Petterson and Treloar (2004) in the study area can be correlated with the Teru volcanic Formation (TVF) of Danishwar et al. (2001) which are exposed in the west of the study area. Therefore, in order to avoid the confusion in adopting different nomenclatures for the rocks of the Chalt volcanic Group, the nomenclature used by Petterson and Treloar (2004) has been modified by naming the rock of the IVC as Ishkoman Volcanic Centre / Teru volcanic Formation for this study.

This paper presents results of detailed work carried out in the Golo Das and surrounding areas of Gilgit-Baltistan region. The main goal of this study was to confirm and locate gold mineralization and carry out petrochemical studies of host rocks to understand processes of mineralization in this region. For this purpose satellite remote sensing data were used to identify mineralization zones that were followed by field work. Finally petrographic and geochemical analyses were carried out on rock samples collected from mineralization zones as well from host rocks.

2. Methodology

Various sulfide-bearing altered zones and host rocks have been identified and mapped using remote sensing and field observations. Multispectral Landsat-8 satellite data were utilized for this study. The Landsat-8 was launched on February 11, 2013 and includes two sensors, the Operational Land Imager (OLI) and Thermal Infrared Sensor (TIRS). The OLI collects data from nine spectral bands in the visible, near infrared, and shortwave infrared wavelength regions in 30 meters resolution, the TIRS, on the other hand, collects data from two bands in the thermal infrared wavelength region at 100 m resolution but revamped to 30 m (Landsat Science, 2014).

Representative rock samples in the form of bulk (> 10 kg) and grab (1 kg) samples were collected during field. Bulk samples were collected from the sulfide-bearing altered zones for the investigation of gold, silver and other base metals while grab samples were collected from fresh surfaces of the host rocks for understanding petrographic and geochemical characteristics of the host rocks and mineralization.

Bulk and grab samples were crushed through jaw crusher into small size chips (<1 cm). Representative portion of each sample was obtained after proper splitting through splitter. This portion was then pulverized to -200 mesh size using tungsten carbide ring mill. A representative portion of each powder sample was then collected by quartering and conning for further digestion and geochemical analysis. The bulk and grab samples were analyzed for Cu, Pb, Zn, Ni, Cr, Co, Cd, Ag and Au using the facilities at the National Center of Excellence in Geology, University of Peshawar. Gold was determined by extraction in methyle isobutyle kotone (MIBK) after the sample digestion in aqua regia (Hubert and Chao, 1985) and the other elements by simple digestion through aqua regia and hydrofluoric acid (Macalalad et al., 1988; Jeffery and Hutchison, 1986) using Perkin Elmer 700 series atomic absorption spectrometer. The grab samples of fresh volcanics and diorites were analyzed for major and trace elements using Bruker S4 Pioneer x-ray fluorescence machine at the Ellington & Associates Houston, USA. 81 standards were used in the calibration. The loss on ignition (LOI) was determined by igniting the powder samples at 950 ºC for more than 4 hours. Methods were validated by using the chemicals of analytical grade and certified reference material. The precision and accuracy for all the elements was found 90-95% confidence limit.

3. Results and Discussion

3.1. Remote sensing and field observations

Landsat 8 data were calibrated and processed using Log residual technique which has identified all the major lithologies in this region and revealed several mineralized zones. Figure 1 shows rocks of Karakoram block in dark greyish or bluish tones in top right of the image. Rocks of the Karakoram block are separated by Shyok suture zone (maroon to violet tone) from the Chalt volcanics/BASD volcanics (light-yellowish to reddish tone) of Ghizar Formation of CVG and metasediments (off-white tone) can be seen in the upper parts of the image running northwest to southeast. The volcanic rocks of IVC / TVF and plutonic rocks of Kohistan batholiths can also be clearly discriminated in the central and bottom part of the image respectively. Several rock alteration zones can be seen in volcanic rocks of BASD and IVC / TVF and in diorites of the Kohistan batholith from where the bulk samples for Au have been collected (Fig.1).

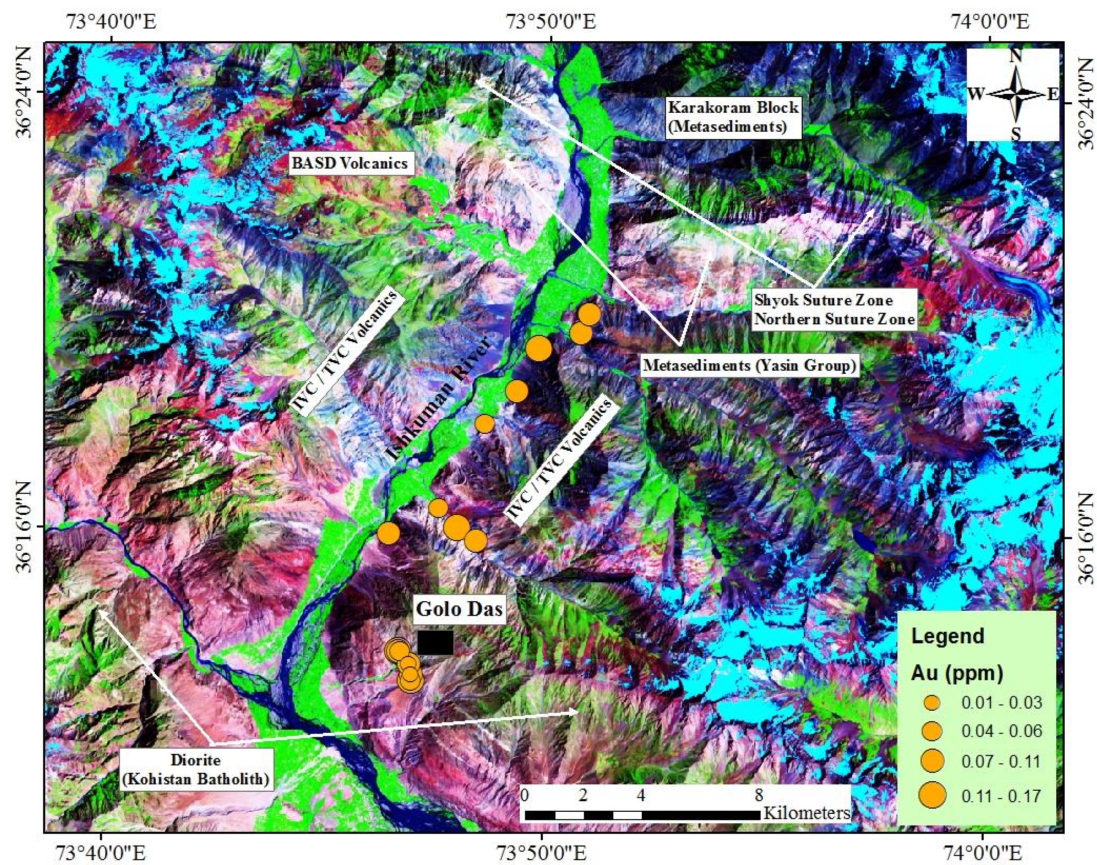

Fig. 1. Landsat 8 bands 7, 5 and 4 displayed as red, green and blue showing major geological units for Golo das and surrounding areas. The concentrations of gold in the bulk rock samples collected from the sulfide-bearing alteration / sheared zones at different locations within the IVC / TVF are also shown.

The rocks of BASD volcanics are mainly basalt, andesite and rhyolite flows, which are highly deformed and metamorphosed, the metamorphism ranges from greenschist to amphibolite facies. These volcanics are cleaved, foliated, thinly bedded to thickly laminated, and displaying green and greyish-green color on fresh surfaces and brown color on weathered surfaces. These rocks are characterized by chlorite, epidote, amphibole, plagioclase, quartz-mica, carbonates and iron oxides. Quartz veining along shear zones is common in these rocks.

The volcanic rocks of IVC / TVF are compact, less deformed / un-deformed and un-metamorphosed dark-gray to greenish-grey in color. These rocks include basaltic-andesitic lavas, volcanoclastic and pyroclastic rocks. The lavas generally have porphyritic texture with phenocrysts of plagioclase, hornblende and pyroxene present in the greenish color chlorite mass. The volcanoclastic and pyroclastic rocks are generally matrix supported and containing angular volcanic clasts and bombs which represent proximity to sub-areal to subaqueous volcanic eruption centre.

The dioritic intrusions in the study area are considered as part of the Kohistan batholith. These are medium to coarse-grained, having dark-gray color on fresh surface and brownish-gray color on weathered surface having intrusive contact with the volcanic rocks of IVC / TVF. The rocks are fresh looking, no fabrics observed, however, local faults and fractures are present. These are dominantly containing mica (biotite) with variable amount of amphibole along with essential minerals such as plagioclase, easily distinguished in hand specimen. Due to the undeformed nature, these diorites can be correlated with the stage 2 diorites of Petterson and Windley (1985, 1991).

There are numerous sulfides-bearing alteration zones found in the study area, which are generally present along shear zones formed by local faulting (Fig. 2a). Quartz veins are ubiquitous along these shear zones. The leaching of sulfides, mainly chalcopyrite and pyrite, in the form of malachite, azurite, hematite and limonite are common along these shear zones (Fig. 2b). Epidotization along fractures and shear zones is also common. All the above mentioned weathering and alteration characteristics of IVC / TVF volcanics can be well noticed in the Golo Das area. Here the discontinuous beds of calcareous rocks are present as more than 10 m thick and 100-200 m long beds. These are hosting the iron ore, containing magnetite, hematite, specularite and ilmenite (Fig. 2c). The iron ore occurs as pods (>30 m long and >2 m thick) within the calcareous rock. These beds show sulfides alteration / skarnification with the development of yellowish-brown surface weathering (Fig. 2d).

3.2. *Gold, silver and base metals in the altered sulfide zones*

During the field work, in the Golo Das and surrounding area, numerous sulfide-bearing alteration zones are identified. A major zone of alteration at a high altitude in Golo Das is associated with the calcareous rocks. It is the area of interest in regard to precious metals (i.e., Au and Ag) and base metal (i.e., Cu, Pb, Zn, Ni, Cr, Co and Cd) mineralization for this study. However, small scale sulfides leaching zones have also been identified in surrounding areas. Bulk samples (>10 kg) from the major alteration zone at Golo Das and the other such zones in the surrounding areas were collected for the geochemical concentration of Au, Ag and base metals. The concentration of precious metals such as Au and Ag and the base metals such as Cu, Pb, Zn, Ni, Cr, Co and Cd in the samples from the sulfide-bearing altered zones are reported in Table 1. Among the base metals, Cu concentration varies from 1-3496 ppm with an average amount of 424 ppm, Pb varies from 0.02-6.70 ppm with an average concentration of 3.45 ppm, Zn varies from <0.02-52.30 ppm with an average concentration of 30.27 ppm, Ni varies from <0.02-47.95 ppm with an average concentration of 10.43 ppm, Cr varies from <0.04-181.8 ppm with an average concentration of 48.81 ppm, Co varies from 2.8-44.6 ppm with an average concentration of 23.80 ppm and Cd varies from 1.2-5.55 ppm with an average concentration of 2.68 ppm (Table 1). Among the precious metals analyzed, Au is ranging from 0.012-0.166 ppm with an average amount of 0.083ppm and Ag is ranging from <0.02-2.90 ppm with an average amount of 1.57 ppm.

Table 1. Gold, silver and base metals concentration (in ppm) in Golo Das and surrounding areas.

S.No	Cu	Pb	Zn	Ni	Cr	Co	Cd	Ag	Au
GDB-1	6.65	<0.02	34.90	19.75	50.55	19.30	2.60	1.75	0.084
GDB-2	1.30	4.20	21.00	22.20	64.05	33.55	3.50	2.90	0.097
GDB-3	73.00	3.85	12.90	<0.02	12.85	2.80	2.00	<0.05	0.112
GDB-4	60.50	<0.02	34.50	9.10	24.90	15.05	2.65	<0.05	0.103
GDB-5	72.75	5.75	49.80	6.80	49.05	29.70	2.80	<0.05	0.058
GDB-6	51.10	<0.02	34.95	5.75	52.40	24.90	1.20	<0.05	<0.05
GDB-7	2156	<0.02	43.20	3.95	40.55	23.60	3.20	<0.05	0.097
GDB-8	53.25	<0.02	34.15	10.95	59.20	29.80	1.70	<0.05	0.092
GDB-9	748.00	<0.02	4.90	<0.02	42.05	15.05	3.60	1.10	0.166
GDB-10	3496	<0.02	24.85	5.40	56.55	32.05	2.55	2.80	0.079
GDB-11	24.55	4.60	36.00	6.45	<0.02	27.75	3.95	1.00	0.031
GDB-12	8.35	4.00	<0.02	2.40	<0.02	3.80	2.55	1.60	0.082
GDB-13	11.55	0.55	<0.02	2.35	34.75	14.70	1.65	1.20	0.012
GDB-14	102.55	1.45	35.85	47.95	181.80	26.35	1.20	0.85	0.043
GDB-15	613.75	0.30	52.30	5.65	40.80	39.35	2.30	<0.05	0.111
GDB-16	14.85	6.45	<0.02	2.30	16.30	8.65	2.65	1.25	0.057
GDB-17	138.75	6.70	<0.02	8.80	21.30	44.60	5.55	1.20	0.112
GDB-18	4.85	0.20	4.60	7.20	33.90	37.45	2.50	<0.05	0.086
Average	424.34	3.45	30.27	10.43	48.81	23.80	2.67	1.56	0.083
Minimum	1.30	<0.02	<0.02	<0.02	<0.02	2.80	1.20	<0.05	0.012
Maximum	3496.25	6.70	52.30	47.95	181.80	44.60	5.55	2.90	0.166
Standard Deviation	927.32	2.45	14.91	11.50	38.62	11.99	1.049	0.726	0.036

In order to see the gain and loss of various metals in the alteration zones relative to the unaltered rocks, the enrichment and depletion factors [(altered rocks - unaltered rocks / altered rocks)×100] for the average composition of analyzed precious and base metals have been calculated and plotted in Figure 3. As the alteration zones are found along the local faults within the IVC / TVF volcanics, therefore, the calculations of enrichment and depletion factors are based on the assumption that the altered and unaltered rocks had identical composition prior to alteration. It is clear from Figure 3 that there is multifold increase in the concentration of Cu, Co, Ag and Au in the sulfides-bearing altered zones. While the Pb, Zn, Ni and Cr show depletion in the sulfide-bearing altered zones relative to the unaltered IVC / TVF volcanics. This is suggesting that the Cu-Fe sulfide phases such as chalcopyrite, pyrite have been precipitated along the shear zones by the hydrothermal solution which has altered the host rocks and also precipitated quartz veins along the shear zones. As no native gold and or gold and silver bearing phases have been observed in these altered rocks, therefore, it suggests that Au and Ag may have been incorporated in the sulfide phases. However, the depletion of Pb, Zn, Cr, and Ni suggest that these may have been leached out during alteration or may be the hydrothermal solution was devoid of these elements.

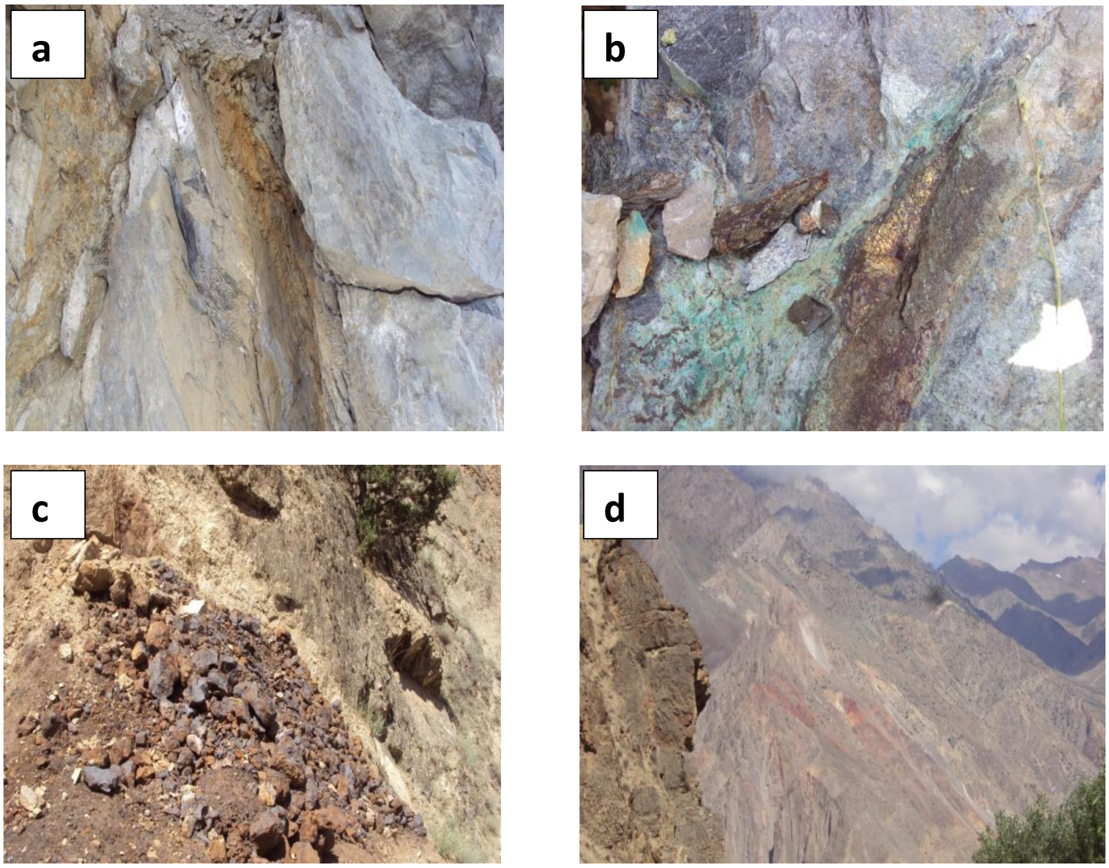

Fig. 2. Photographs showing: a) sulfide-bearing shear zone / alteration zone in yellowish-brown color due to weathering of sulfides (i.e., pyrite and chalcopyrite) can be observed, b) leaching of chalcopyrite to malachite and azurite, c) iron ore formed due to skarnification within the volcanics hosted calcareous rocks. The surface weathering to hematite, limonite and specularite can be seen and d) weathering of sulfide-bearing alteration zones clearly visible on the surface of the IVC / TVF volcanics.

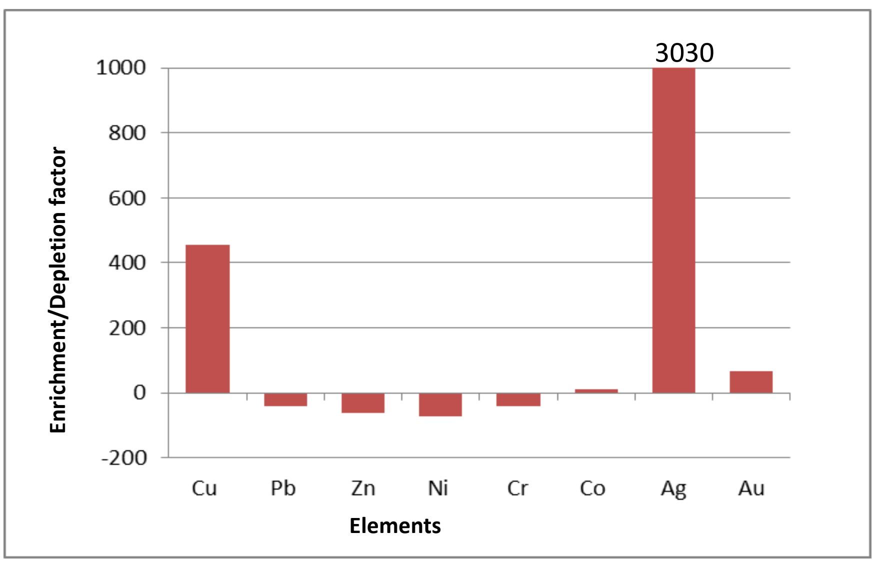

Fig. 3. Diagram showing the enrichment and depletion of various base and precious metals in the altered sulfide zones and unaltered rocks of the study area.

3.3. Host rocks petrography and geochemistry

3.3.1. Petrography

The BASD volcanics have plagioclase and hornblende as dominant phenocrysts whereas the groundmass is cryptocrystalline having chlorite, epidote, sericite, tremolite/actinolite and opaques. Plagioclase exhibits partial or complete alteration to saussurite. In some cases, the alteration is so intense that pseudomorphs after plagioclase are clearly seen. Plagioclase phenocrypts have developed preferred orientation along the fabric with laths of chlorite and tremolite/actinolite winding around these. Epidote and sericite, the alteration product of plagioclase, are well observed in the groundmass. Hornblende is the second abundant mineral phase which exhibits deformation and alteration to chlorite and epidote. Microveins of fine-grained quartz cross cutting the phenocryts are also common.

The volcanic rocks of IVC / TVF have well-developed porphyritic texture having phenocrysts of plagioclase, alkali-feldspar, clinopyroxenes and hornblende ranging from medium to coarse-grained, embedded in the fine-grained (cryptocrystalline) groundmass. These rocks have dominantly plagioclase with subordinate amount of clinopyroxene phenocrysts, set in a partially chloritized felsophyric matrix with scattered epidote and opaque phases. Euhedral to subhedral plagioclase and alkali-feldspar phenocrysts are generally fresh looking but partial alteration to epidote, carbonates and sericite is also noticed. Clinopyroxene phenocryts are mainly augite in composition. At places, clinopyroxene shows alteration to chlorite along micro-fractures. In some samples, phenocrysts of hornblende and quartz are also noticed.

The dioritic rocks of the study area can be divided into two groups: one group consists of major proportion of plagioclase, hornblende and biotite while the other group is having plagioclase, biotite and clinopyroxene (augite) in abundance. The minor amount of other minerals like quartz, alkali-feldspar and opaque minerals are present in all of these rocks, whereas zircon, apatite and garnet occur as accessory minerals. Texturally, these rocks are medium to coarse-grained, with inequigranular, hypidomorphic texture. These rocks are partially altered to sericite and epidote which are observed on the surface of plagioclase grains, while the greenish color chlorite is present in the vicinity of biotite, hornblende and opaque phases.

3.3.2. Geochemistry

The major and trace element data and CIPW norms composition of the volcanic rocks of BASD and IVC / TVF of the Ghizar Formation and diorites of the Kohistan batholiths in the study area are given in Table 2 and are graphically presented in Figures 4-6.

Major elements: The BASD volcanics are basaltic in composition in which SiO_2 (47.34-47.89 wt%), Al_2O_3 (17.34-17.56 wt%), CaO (11.10-11.82 wt%) and Na_2O (2.95-3.32 wt%) exhibit no greater variation while rest of the oxides have a relatively wide range as TiO_2 is ranging from 0.49 to 0.72 wt%, Fe_2O_3t from 8.31-10.05 wt%, MnO from 0.10 to 0.19 wt%, MgO from 3.11-5.77 wt%, K_2O from 0.10 to 0.71 wt% and P_2O_5 from 0.14 to 0.27 wt%. The loss on ignition (LOI) is ranging from 4.90 to 5.43 wt%. These rocks are olivine (0.94-3%) normative with high concentration of plagioclase (62.14-64.15%) and highly variable amount of diopside (8.57-22.22%) and hypersthene (1.29-19.1%). The Mg # [$100\times MgO/(MgO+Fe_2O_3t)$] of all the samples is low (27 to 36).

The volcanics of IVC / TVF are basaltic-andesite in composition having SiO_2 in the range of 52.67-53.78 wt%, Al_2O_3: 16.53-17.22 wt%, TiO_2: 0.31-0.45 wt%, Fe_2O_3t: 8.32-9.22 wt%, MnO: 0.13-0.22 wt%, MgO: 5.80-7.20 wt%, CaO: 8.13-9.34 wt%, Na_2O: 1.92-2.74 wt%, K_2O: 0.78-0.94 wt% and P_2O_5: 0.30-0.44 wt%. These volcanics are quartz normative (6.83-10.00%) with dominant normative plagioclase (43.88-56.41%) and sub-ordinate normative hypersthene (19.20-23.00%). The Mg # ofvaries from 41 to 44 (Table 2).

The major element oxides data of the studied diorites exhibit that SiO_2 is ranging from 59.78 to 61.70 wt%, Al_2O_3 from 15.98 to 16.89 wt%, TiO_2 from 0.49 to 0.65 wt%, MnO from 0.09 to 0.13 wt%, MgO from 2.54 to 2.94 wt%, CaO from 5.68 to 5.80 wt%, Na_2O from 3.42 to 3.89 wt%, K_2O from 2.81 to 3.32 wt% and P_2O_5 from 0.33 to 0.42 wt%. These diorites are quartz normative (10.20-13.30%). The plagioclase (50.50-51.84%) is a dominant normative phase with subordinate amount of orthoclase (16.72-18.60%) and hypersthene (7.91-11.30%). Mg # of these diorites is low ranging from 29 to 36.

Table 2. Whole rock geochemical data (major oxides in wt% and trace elements in ppm) of the study area.

	BASD Volcanics			**IVS Volcanics**			**Diorites**		
Sample	**GD-1**	**GD-2**	**GD-3**	**GD-13**	**GD-16**	**GD-18**	**GD-23**	**GD-21**	**GD-22**
SiO_2	46.70	47.30	47.89	52.67	53.78	53.10	59.78	60.23	61.70
Al_2O_3	17.60	17.30	17.56	17.22	16.53	16.90	16.89	16.34	15.98
TiO_2	0.59	0.72	0.49	0.45	0.31	0.39	0.65	0.56	0.49
Fe_2O_3	10.05	8.75	8.31	9.22	8.32	8.78	6.56	6.12	4.89
MnO	0.19	0.10	0.14	0.19	0.22	0.13	0.09	0.13	0.12
MgO	5.77	3.33	3.11	7.20	5.80	6.21	2.94	2.54	2.78
CaO	11.82	11.62	11.10	9.34	8.13	8.42	5.80	5.73	5.68
Na_2O	2.95	3.23	3.32	1.92	2.74	2.37	3.42	3.89	3.82
K_2O	0.10	0.71	0.42	0.78	0.94	0.85	2.81	3.12	3.32
P_2O_5	0.14	0.27	0.26	0.30	0.38	0.44	0.37	0.33	0.42
L.O.I	4.90	4.67	5.43	1.57	1.80	2.83	0.80	0.92	0.84
Total	100.81	98.00	98.03	100.86	98.95	100.42	100.11	99.91	100.04
C.I.P.W. Norms									
Q	-	-	0.59	6.83	7.82	10.00	12.25	10.2	13.30
Pg	63.70	62.14	64.15	43.88	54.70	56.4	51.84	51.40	50.50
Or	0.65	4.49	2.66	13.65	5.73	0.65	16.72	18.6	17.40
Di	8.57	22.22	20.80	6.67	6.53	3.08	2.42	6.94	6.60
Hy	19.10	1.29	5.63	22.90	19.20	23.00	11.30	7.91	7.01
Ol	0.94	3.00	-	-	-	-	-	-	-
Il	1.22	1.48	1.01	0.72	0.82	0.76	1.25	1.08	1.71
Mg	4.70	4.07	3.90	4.03	3.73	4.35	2.89	2.68	2.15
AP	0.35	0.65	0.65	0.70	0.90	1.04	0.86	0.76	0.97
Trace elements									
As	5	11	4	9	8	8	4	4	5
Sc	23	24	18	31	22	25	14	14	10
V	221	237	187	245	230	214	137	115	113
Co	32	17	15	50	50	36	18	16	23
Cr	45	164	45	402	226	198	65	79	55
Ni	23	76	20	110	82	61	39	35	15
Cu	85	17	127	18	66	71	100	145	138
Pb	3	9	6	6	4	6	14	14	11
Zn	96	71	78	105	116	79	81	89	58
Sr	356	1961	640	570	675	670	669	789	795
Rb	1	14	10	10	28	16	77	68	79
Ba	10	123	107	164	195	173	340	378	467
Th	2	3	1	4	3	3	10	9	12
U	1	1	2	2	1	1	1	1	2
Nb	2	4	1	1	1	1	8	7	6
Y	22	19	26	15	17	16	22	23	25
Zr	46	59	38	17	27	35	96	103	115
Hf	2	15	5	8	3	5	7	4	5
Ag	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Au	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Mg#	36	28	27	44	41	41	31	29	36

Trace elements: The trace element compositions of the BASD volcanics (Table 2) indicate that the large ion lithophile elements (LILEs) such as Sr (356-1961 ppm), Ba (10-123 ppm), Th (1-3 ppm) and Rb (1-14 ppm) and the High field strength elements (HFSEs) such as Nb (1-4 ppm), Pb (3-9 ppm), Cr (45-164 ppm), Zr (38-59 ppm) and Y (19-26 ppm) display a variable concentration. The LILEs and HFSEs are plotted on the chondrite-normalized spider diagram of Bevins et al. (1984) (Fig. 4a). The two samples of BASD volcanics in these diagrams generally show enrichment in LILE/HFSE ratios, therefore, have decreasing trend towards right while one sample exhibit very low Ba and Rb (may be due to alteration/leaching), due to which the trend is not well defined. These diagrams also display the negative Nb anomaly suggesting the role of calc-alkaline magmatism.

The trace elements concentrations in the volcanic rocks of IVC / TVF indicate that the LILEs such as Sr, Ba, Th and Rb are ranging from 570 to 675 ppm, 164 to 195 ppm, 3 to 4 ppm and 10 to 28 ppm respectively while the HFSEs such as Pb, Cr, Nb, Zr and Y varies from 4 to 6 ppm, 198 to 402 ppm, 1 ppm, 17 to 35 ppm and 15 to 17 ppm respectively. The chnodrite normalized spider diagram of LILEs and HFSEs (Fig. 4b) suggests that there is a decreasing trend from LILE to HFSE with the well-defined negative anomaly for Nb which can be attributed to the formation of these rocks in island arc type setup (Stolz et al., 1996).

The trace element data of the studied diorites show that among the LILE, Sr varies from 669 to 795 ppm, Ba from 340 to 467 ppm, Th from 9 to 12 ppm and Rb from 68 to 79 ppm. The HFSEs such as Nb, Pb, Cr, Zr and Y have a range of 6-8 ppm, 11- 14 ppm, 55-79 ppm, 96-115 ppm and 22-25 ppm. The LILE and HFSE data of the studied diorites are normalized to chondrite and plotted on the spider diagram (Fig. 4c). The trace element patterns indicate that there is a decreasing trend from left to right, showing the enrichment of LILE as compared to HFSE with negative anomaly for Nb and positive anomaly for Sr. This type of pattern is consistent with the calc-alkaline rocks originated in island type of environment (Stolz et al., 1996).

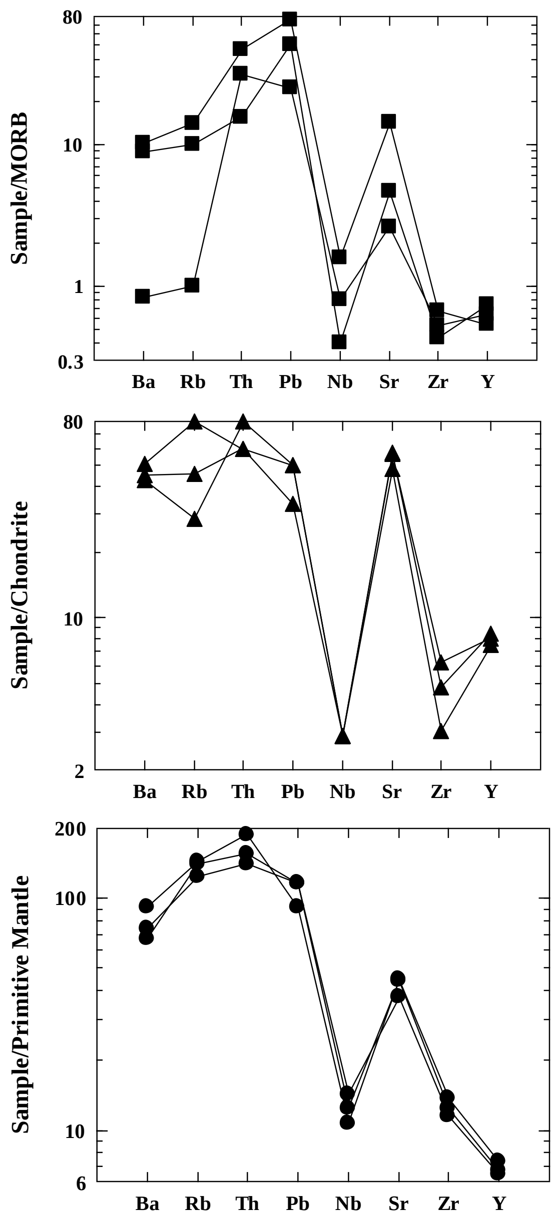

Fig. 4. Spider variation diagrams of a) BASD volcanics, b) IVC / TVF volcanics and c) diorites of the study area normalized to chondrite after Bevins et al. (1984) respectively.

3.4. Tectonic affinity

To find out the tectonic setting of magma generation for the rocks of the study area i.e., BASD volcanics, IVC / TVF volcanics and dioritic pluton, the analyzed rock samples, were collectively plotted in various tectonic discrimination diagrams of Vermeesch (2006), Meshede (1986), Mullen (1983), Wood (1980), which are generally used for finding the petrogenesis of magma in different tectonic settings. However, only two diagrams Figure 5 and Figure 6 of Vermeesch (2006) and Meshede (1986) respectively are presented here. These diagrams indicate that all the samples of BASD volcanics, IVC / TVF volcanics and dioritic pluton are akin to the field defined for calc-alkaline rocks of island arc settings, suggesting subduction related geotectonic environment for the formation of these rocks.

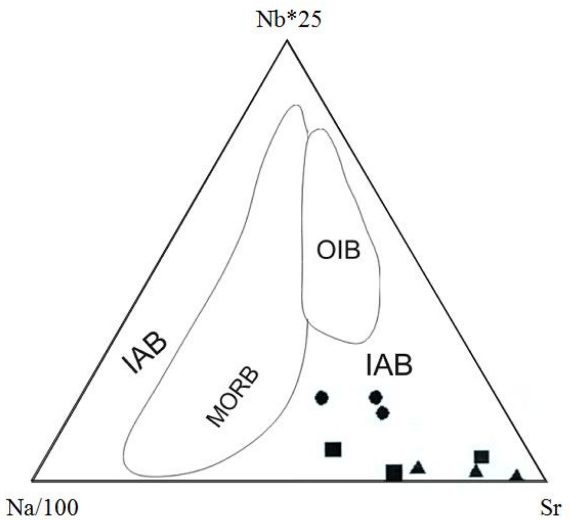

Fig. 5. Data of studied samples on the discrimination ternary diagram of trace elements showing different tectonic environments (after Vermeesch, 2006). IAB= island arc basalts, MORB= mid oceanic ridge basalts, OIB= ocean island basalts. ■ = Basalt-andesite sheet dominant volcanics ▲ = Rocks of Ishkoman Volcanic Center and ● = Diorites.

The geochemical data of the volcanics and diorites of the study area have been used to characterize the petrology and tectonic setting of these rocks. The volcanic rocks (both deformed BASD volcanics and less-deformed/undeformed IVC / TVF volcanics) are of calc-alkaline nature. The major and trace elements data suggest that the studied volcanic rocks were formed with a strong subduction component in an island type of environment. This is consistent with the findings of the earlier workers who worked on volcanic rocks (i.e., Ghizar Formation, Teru volcanic Formation and Shamran volcanics) in the northern most part of the Kohistan island arc (Petterson and Windley, 1991; Sullivan, 1993; Khan et al., 2004; Petterson and Treloar, 2004; Khan et al., 2009).

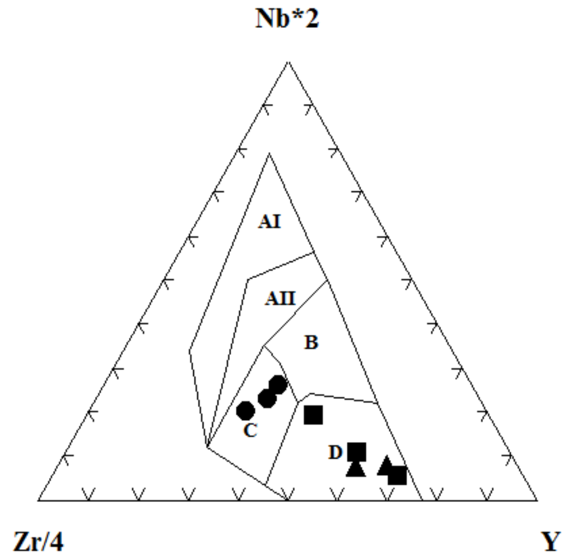

Fig. 6. Trace element data for rocks of the study area in the discrimination ternary diagram of Meschede (1986). AI = within-plate alkali basalt, AII = within-plate alkali basalt and within-plate tholeiites, B = E-type MORB, C = within-plate tholeiites and volcanic arc basalt, D = N-type MORB and volcanic arc basalt. Symbols are same as for Figure 5.

On the basis of chemical composition, especially MgO contents, Petterson and Windley (1991) divided the rocks of the Chalt volcanic Group into 1) High-Mg tholeiites and 2) low-intermediate MgO calc-alkaline volcanics. Later on, Petterson and Treloar (2004) renamed the second variety as Ghizar Formation. They further divided the Ghizar Formation into 1) Ishkoman Volcanic Centre, 2) basalt-andesite sheet dominant and 3) tuff dominant volcanics. In order to understand the geochemical behavior of the studied volcanics in the context of the similar volcanic rocks exposed in the western and eastern extension of the study area, the geochemistry of the studied volcanics have been correlated with those of the earlier workers such as Petterson and Windley (1990, 1991) and Khan et al. (2004). The Table 3 shows the comparison of the average major and trace elements data of the studied volcanics with the similar rocks of high-magnesia tholeiites (Hunza Formation) and low-intermediate MgO calc-alkaline volcanics (Ghizar Formation) of Petterson and Windley (1991) and Petterson and Treloar (2004) and the Teru volcanic Formation (previously known as Shamran volcanics by Pudsey et al., 1985 and Sullivan et al., 1993) of Danishwar et al. (2001) and Khan et al. (2004). It is clear from the Table 3 that the volcanic rocks of IVC / TVF of the study area have similar geochemical behavior as that of the low-intermediate MgO calc-akaline volcanics (Ghizar Formation) of Peterson and Windley (1991) and that of the Teru volcanic Formation of Danishwar et al. (2001). The calc-alkaline nature of the volcanic rocks of the Ghizar Formation as suggested by this study and also by Petterson and Windley (1991) can, therefore, be correlated with the calc-alkaline volcanics of Teru volcanic Formation of Danishwar et al. (2001) which is displaying a typical subduction zone signature for all these rocks. These rocks are, therefore, considered a part of the Cretaceous Kohistan island arc. The volcanic rocks of the Ghizar Formation of the studied area, especially the rocks of the Ishkoman Volcanic Center, having similar petrochemical behavior as that of the Teru volcanic Formation can be considered the eastern extension of the Teru volcanic Formation.

The diorites of the study area also show the calc-alkaline character and hence these rocks are also originated with a strong subduction component. Petterson and Windley (1991) have differentiated the Kohistan batholith in stage -1, stage-2 and stage-3 plutons. Among these the stage-2 plutons are of calc-alkaline character, having typical subdcution related calc-alkaline chemistry. The geochemical behavior of the studied diorites has, therefore, been compared with the stage-2 diorites of Petterson and Windley (1991) in Table 3. The average major and trace element data of the studied diorites (Table 3) are comparable with that of the stage-2 diorite of the Petterson and Windley (1991). In this regard the studied diorites can be correlated with the stage-2 pluton of Kohistan batholith of Petterson and Windley (1985; 1991) for which an age of 40-85 Ma has been assigned by Zeitler (1982) and Treloar et al. (1989). According to Petterson and Windley (1991), the typical mantle is the source region for stage-2 pluton which was metasomatised by subduction related processes.

Table 3. Comparision of major and trace elements data of the rocks of this study with Khan et al. (2004) and Petterson and Windley (1991).

Sample	**BASD volcanics (This study)**	**IVC volcanics (This study)**	**Diorites (This study)**	**Khan et al. 2004**		**Petterson and Windley (1991)**		**Petterson and Windley (1991) High-Mg tholeiitic volcanics**	**Petterson and Windley (1991) Stage-2 Diorites**
				42B	**7_4**	**IK679**	**K681**	**N146**	**A208**
SiO_2	47.30	53.20	60.54	50	54	53.8	54.2	48.7	59.68
Al_2O_3	17.45	16.87	16.39	18	17	19	16.6	11.6	16.99
TiO_2	0.60	0.38	0.57	1.7	0.7	0.75	0.62	0.42	0.73
Fe_2O_3	9.04	8.77	5.86	11	9.4	10.3	9.9	12	6.99
MnO	0.14	0.18	0.11	0.2	0.1	0.19	0.19	0.19	0.14
MgO	4.07	6.40	2.75	5.7	7	3.8	4.9	13.4	3.21
CaO	11.49	8.63	5.74	9.4	9.3	10.1	7.4	11.8	6.18
Na_2O	3.17	2.34	3.71	4.2	2.1	1.8	3.5	1.6	3.28
K_2O	0.41	0.86	3.08	0.6	1	0.12	2.01	0.25	3.74
P_2O_5	0.22	0.37	0.37	0.4	0.1	0.23	0.21	0.03	0.28
L.O.I	5.00	2.07	0.85	-	-	-	-	-	-
Total	98.89	100.10	100.14	100	101	100.1	99.53	99.99	101.22

Trace elements in ppm									
Sc	22	26	13	-	-	-	-	-	-
V	215	230	122	-	-	197	293	189	162
Co	21	45	19	-	-	-	-	-	-
Cr	85	275	66	-	-	30	21	958	24
Ni	40	84	30	-	-	9	16	267	18
Cu	76	52	128	-	-	-	-	-	-
Pb	6	5	13	-	-	-	-	-	-
Zn	82	100	76	-	-	-	-	-	-
Sr	986	638	751	832	799	1657	698	22	557
Rb	8	18	75	9.5	184	3	27	1	116
Ba	80	177	395	182	388	23	411	11	707
Th	2	3	10						
Nb	2	1	7	3.11	20	1.2	1.7	0.7	9.2
Y	22	16	23	14.7	43	20	15	9	22
Zr	48	26	105	66.8	175	100	53	34	154
Hf	7	5	5	1.9	4.8	-	-	-	-

4. Conclusions

Golo Das and surrounding areas contain rocks of the two entities, i.e., Kohistan island arc and Karakoram plate, separated by the northern suture zone. Most of this area is covered by the rocks such as the IVC / TVF and BASD volcanics and diorites of the Kohistan island arc. The BASD volcanics are highly deformed and metamorphosed while the IVC / TVF volcanics are un-deformed / less deformed. Sulfides-bearing sheared / alteration zones containing quartz veins are common along local faults in the volcanic rocks. The leaching of pyrite and chalcopyrite to malachite, azurite, hematite and limonite are ubiquitous along these zones while iron ores formed as a result of skarnification are commonly hosted by calcareous rocks within these volcanics. The enrichment of Cu, Co, Au and Ag and depletion of Pb, Zn, Ni and Cr in the sulfides-bearing sheared / alteration zones could be due to the hydrothermal alteration and leaching. However, concentrations of these metals, especially gold and silver are low in these hydrothermal alteration zones and may not be economic at this stage. Petrochemical studies suggest that the BASD volcanics are classified as olivine normative basalts and the IVC / TVF volcanics as quartz normative basaltic-andesites. The studied diorites are equivalent to the stage-2 diorites of Kohistan batholith. The major and trace element data of the volcanic rocks of IVC / TVF and BASD and diorites exhibit calc-alkaline character with enrichment in LILEs and strong negative anomaly for Nb positive amomaly for Th and Sr. This is suggesting the involvement of subduction related component in the formation of these rocks in the island type of environment.

Acknowledgement

We are very thankful to the Higher Education Commission and US-State Department for the financial support to conduct this research under the PAK-US Joint Science and Technology Phase-IV program. Mr. M. Tariq (Lab Technician) is highly acknowledged for his help during experimental work.

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