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COMPREHENSIVE PETROGRAPHIC AND GEOCHEMICAL CHARACTERIZATION OF DIORITES, HORNBLENDITES AND AMPHIBOLITES FROM THE KOHISTAN ISLANAD ARC SEQUENCE NEAR TIMERGARA, DIR (LOWER), PAKISTAN

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Abstract
Well exposed outcrops of the Kohistan Island Arc (KIA) sequence are located along the hanging wall of Main Mantle Thrust (MMT) in Dir (Lower). Among the KIA sequence the most abundant rock unit is Southern Kamila Amphibolites, diorites and hornblendites. Detail field investigation was carried it in the proposed study area and observed that the area has undergone through severe tectonic deformations. The examined rock unit possess multiple shear zone and are cross cutted by variable veins. Shearing reflects the activeness of MMT, and rooted veins demonstrates crustal thickening and crustal anatexis. The inspected amphibolites are banded as well massive in nature represents variable protoliths for their genesis. Massive amphibolites are intruded and cross cutted by leucogranite pegmatites veins. The unmetamorphosed nature of these pegmatites exhibits its post collisional origin as a result of crustal thickening. Petrographic study reveals that examined rock has experienced medium grade metamorphism, evident from the development of hornblende and Ca-rich plagioclase. Analytical data interpretation suggests that protolith for the investigated rock unit was tholeiitic basalt, that has been metamorphosed under regional dynamo-thermal amphibolite grade metamorphosed during collisional phase of Himalayan orogeny. Petrographically the amphibolites are mainly composed of hornblende and plagioclase with subordinate amount of quartz and alkali feldspar. Biotite, muscovite, chlorite, epidote and opaque occur as accessory mineral constituents. Diorites are dominantly composed of plagioclase with variable proportion of quartz and alkali feldspar. The other minor constituents observed in the representative samples of diorites include biotite, hornblende, muscovite, and apatite, zircon, garnet and opaque. Hornblendites of the investigated complex are essentially composed of hornblende (with variable amounts of plagioclase and pyroxene), and minor amount of opaque minerals, mostly magnetite and, locally, apatite, rutile, quartz, sphene, chlorite, epidote and carbonate. Paragenetic

interpretation of some of the observed minerals exhibits as a product of alteration such as chlorite, epidote and carbonate.

INTRODUCTION

The Earth's crust is primarily formed by different processes e.g., plate convergence, subduction, and arc-magmatism, which play an essential role in the formation of island arcs, suture zones and associated metamorphic and metasomatic terranes, and are critical to understanding the tectonic evolution of convergent margins (Bignold, Treloar & Petford, 2006). In intra-oceanic island arcs, the intrusion of mafic and ultramafic cumulates and basaltic to intermediate volcanism in the arc crust is often preserved as metamorphosed greenschist to amphibolite facies units (Yoshino et al., 1998). The resulting litho-tectonic assemblages provide valuable insights into evolution of arc, magma and crust interaction, and crustal growth (Searle et al., 1999). From a global viewpoint, amphibolite facies belts within arc settings have been studied as records of deep arc processes and crustal thickening (Yoshino et al., 1998).

In the northern region of Pakistan, the Kohistan Island Arc (KIA) represents a well exposed example of a Cretaceous intra oceanic arc, sandwiched between the Indian Plate to the south and the Eurasian plate to the north. The KIA is bounded by two major suture zones: the Main Karakoram Thrust (MKT) in the north and the Main Mantle Thrust (MMT) in the south (Searle et al., 1999). The Kohistan Island Arc comprises a complex lithostratigraphy including mafic and ultramafic cumulates (e.g., the Jijal Complex), amphibolite belts (e.g., the Northern and Southern Kamila Amphibolite Belt) and granitoid intrusions (Khan et al., 1996). Within this tectonic framework, the Kamila Amphibolite represents a key unit, predominantly metamorphosed to amphibolite facies and capturing an intra-oceanic arc basement environment (Kausar et al., 2008; Khan et al., 1998).

The study area, located in the southwestern part of the Kohistan Island Arc near Timergara, consists mainly of amphibolite rocks intruded by diorites and hornblendites, situated close to the Main Mantle Thrust (MMT). Previous geological work in the district includes early mapping by Hyden (1915) in District Dir. Khan & Saleemi (1972) and Arbab & Khan (1973) carried out preliminary geological work in various areas of District Dir; they also reported uneconomical copper mineralization in Barwa, Kambat and Ushiri areas. Corundum-bearing and related rocks around Timergara have also been reported (Khan et al., 1969). Geology of Timergara and surrounding areas of Dir district has been described by Chaudhary et al. (1974), Butt et al. (1980), Jan & Tahirkheli (1990), and Shah & Sarwar (1998) who carried out stream-sediment geochemical surveys in Timergara and Jandul valley. Dir and surrounding areas have been geologically investigated in more detail by Tahirkheli (1979, 1982, 1983), Hamidullah et al. (1990), Shah & Hamidullah (1993), and Shah et al. (1994) and Sullivan et al. (1993). Much geochemical data have been published from rock suites throughout the accessible regions of Kohistan (Jan and Howie, 1981, Petterson and Windley, 1985, Jan, 1988, Treloar et al., 1989, Jan and Windley, 1990, Petterson and Windley, 1991, Petterson and Windley, 1992, Sullivan, 1992, George et al., 1993, Khan et al., 1993, Petterson et al., 1993, Sullivan et al., 1993, Khan et al., 1996, Khan et al., 1997, Bignold and Treloar, 2003). However, despite these investigations, there remains a distinct lack of detailed petrographic and whole rock geochemical studies (utilising XRF techniques) focused on the Kamila Amphibolite and associated intrusive units within this southwestern Kohistan section.

Despite extensive regional investigations, little work has been directed toward the petrographic and rock geochemical characterization of the Kamila Amphibolite near Timergara. The aim of the present study is (1) petrography of different rock units of the Kamila Amphibolite Complex, and (2) to demarcate the whole rock geochemistry of selected samples using XRF analysis. These objectives aim to fill the study gap and provide new data on the lithology, alteration and mineralization potential of this under the studied area of the Kohistan Island arc.

2. Geology and Tectonics

2.1 Regional Geological Setting

The northern areas of Pakistan consist of three parts: the Eurasian plate in the north, the Kohistan Island Arc (KIA) in the middle, and the Indian plate in the south. This Cretaceous intra-oceanic island arc begins with the Indian plate northward drifting (Hu, Haoyui et al., 2020). The KIA represents the different tectonic stratigraphic units from south to north, including Jijal Complex, Kamila Amphibolite, Chilas Complex, Kohistan Batholith, Gilgit Gneisses, Chalt Volcanics and Yasin Group (Naseem et al., 2023). Dir Group is a 120 km long and 15-20 km wide belt that runs through Dir Swat valley in western Kohistan. The Dir Group is further divided into the Barawal Banda Slate Formation and Utror Volcanic Formation. The thickness of the Barawal Banda Slate is about 3 km. The lower part of the Barawal Banda Slate contains conglomerates, breccia, and pebbly sandstone, while the upper part is composed of thin-bedded sandstone, siltstone, and mudstone (Rashid et al., 2019). Rare interbedded limestone in Barawal Banda slate contains the marine faunas of the Late Paleocene age (Rashid et al., 2019). The Dir Utror Formation consists of basalt, basaltic andesite, dacite, rhyolite, pyroclastic breccia and tuff of calc-alkaline nature. The study area is the southern section of Kamila amphibolite extended to Afghanistan (Ullah et al., 2025). This southern extension exposes a representative section of the Kamila Amphibolite, offering key insights into the metamorphic evolution and intrusive relationships along the Main Mantle Thrust.

2.2 Local Geology of the Study Area

The Kamila amphibolite exposed in Dir Lower is dominantly composed of amphibolite, having the inclusion of granite, granodiorite, hornblendite, diorite, quartz diorite, porphyry quartz monzonite and gabbronorite (Ullah et al., 2025). This geological framework forms the basis for the subsequent petrographic and geochemical analyses aimed at interpreting the petrogenesis and tectonic evolution of the Kamila Amphibolite and associated intrusive units. The rocks of the area are distinguished into three main lithological units: amphibolites, meta-diorites/meta-granodiorites and hornblendite. Hornblendite occupies the southern part of the studied area while meta-diorite/granodiorites and amphibolites are exposed in the northern part of the area. Amphibolites and diorite rock units have intrusive contact and exhibit local faulting and shearing. The amphibolites are generally massive but also exhibit banding at places; these amphibolites are intruded by quartz and quartzo-feldspathic veins especially in areas where the shearing and faulting are intense. The amphibolites are also intruded by the meta-diorite/granodiorite in the form of small plugs. The meta-diorites/granodiorites are medium to coarse-grained, massive in character and have xenoliths of amphibolites. The Hornblendite of the Torra Tigga mafic ultramafic complex occurs along the MMT (the westward extension of Indus suture zone). The hornblendite has been emplaced in a thick sequence of amphibolites along the MMT whose trace was probably followed by the Jandul Rud in the south of the complex (Jan et al., 1983). Copper mineralization in the form of disseminated grains of tetrahedrite and chalcopyrite and supergene enrichment in the form of malachite and azurite occur within quartz veins in limited areas (Jan et al., 1983; Chaudhary et al., 1974; Butt et al., 1981; Shah & Sarwar, 1998).

These lithological and structural characteristics suggest a complex history of arc magmatism, metamorphism, and localized hydrothermal alteration, warranting detailed petrographic and geochemical investigation

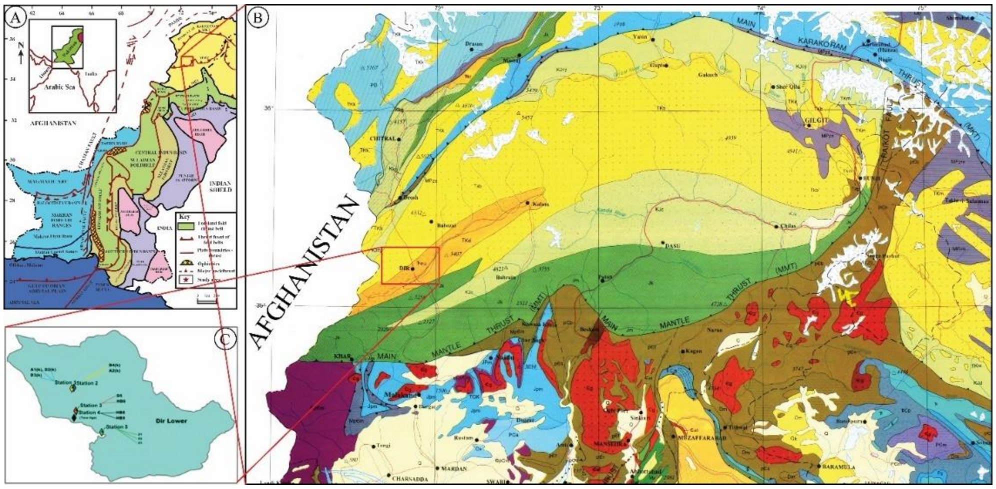

Figure 1. (A) Geological map of the Pakistan representing major geological provinces of Pakistan. (B) Geological map of Northern Pakistan exhibiting location of the study area (Red rectangle); also demonstrates geological address of the investigated area bounded by major tectonic elements such as Main Karakoram Thrust (MKT), Main Mantle Thrust (MMT), Main Boundary Thrust (MBT), and Salt Range Thrust (SRT (C) Sampling location map of study area.

3. Methodology

3.1 Field Methodology

3.1.1 Collection of rock samples

Extensive fieldwork activity was conducted to collect field data and rock samples and mark the inspected area on a map. After an extensive field visit, a total of 15 water samples were collected weight of normally (2-4 kg) from the rock exposures in the field. Samples were also collected from veins and contact zone. Fresh rock samples were collected in different sample bags. These samples were properly numbered in the field and brought to the laboratory for further analyses. Some observations were recorded for each sample site/station during the field e.g., sample number, sampling interval, prospect/location, GPS data and photography.

3.2 Laboratory methods

3.2.1 Petrography

The selected samples have been treated with various laboratory techniques to get the desired result. A total 15 collected samples were analyzed and among them 10 samples were selected for detail mineral analysis (petrographic study) and sent to Geoscience lab Islamabad for thin section preparation to show the mineralogical and textural features on polarize microscope. The rock chips of about (5 x 3 cm) were cut by a rock cutting machine and then one side of each chip was ground and polished to make a plane surface. This polished plane surface of chip was then mounted on a glass slide of same size with an epoxy. Before mounting the rock chip on the glass slide, it was heated above 100°C on a hotplate. After mounting the rock chip on the glass slide, it is again cut on the rock cutting machine to minimize the thickness of the chip for further process, the chip was then further ground to minimum thickness of 0.03 mm by using various sizes of the silicon carbide powder. For petrographic studies, these thin sections were then covered with cover slips using Canada Balsom. For mineral chemistry, the thin sections were not covered with cover slips but these were further polished by using various size abrasive cloths on automatic polisher.

3.2.2 XRF (X-ray fluorescence)

After thin section study, the desired samples were sent to the Geoscience lab Islamabad for whole rock Geochemistry to know the major, minor and trace elements contents. A total of 7 samples were pulverized for the whole-rock chemical analysis in Geosciences lab Islamabad. Except for silica, the contents of the major, minor and trace elements were determined through X-ray fluorescence spectrometry. The silica concentration was determined by UV spectrophotometer. The XRF analyses were carried out on fused disks called as glass beads. A small amount of each sample (4-5gm) was dried overnight at 110°C to remove the absorbed moisture, if any. After cooling in desiccators. 0.7gm of each of the samples was mixed with 7gm of flux (mixture of lithium meta-borate and lithium tetraborate). Two-three drops of releasing agent (lithium iodide) were added to the mixture. The resulting sample-flux mixture was fused in platinum (95%)-gold (5%) crucible at 1100°C for 10-15 minutes. During this period the crucible was periodically swirled over a burner to eliminate the gas bubbles and ensure the thorough mixing and homogeneity of the melt. The melt was cast in platinum mold having a diameter of 30mm. Each bead was analyzed for SiO_2, TiO, AlO, FeO3, MnO, MgO, CaO, Na_2O, K_2O and P_20_5. The analyses were performed through a PAN analytical PW4400/24 spectrometer equipped with a rhodium anode X-ray tube. International standards namely, WROXI-1. WROXI-2, WROXI-3. DT-N. SDC-1, PG-I, G-2 were alternately run with each batch of five samples to Monitor the precision and accuracy of the machine

4. Results

4.1 Petrography

4.1.1 Diorite

Diorites are dominantly composed of plagioclase with variable proportion of quartz and alkali feldspar. The other minor constituents observed in the representative samples of diorites include biotite, hornblende, muscovite, and apatite, zircon, garnet and opaque. Plagioclase is the most common mineral series present in the observed thin sections, ranging from 50 to 65%. The plagioclase content is 50% in D1, 60% in D2 and 65% in D5. The amount of orthoclase in D1, D2 and D3 is 25%, 20% and 15% respectively. The Quartz is 11% (D1), 10% (D2) and 12% (D3) in the examined rock sample. The Hornblende is about 5% in D1, 5% in D2 and 4% in D3. While there is small amount of magnetite 2% (D1), 1% (D2) and 2% (D3), muscovite 4% (D1), 3% (D2), 2% (D3) and 1% (D1) of chlorite observed in the inspected rock sample (Table 2).

4.1.2 Hornblendite

Hornblendites are essentially composed of hornblende (with variable amounts of plagioclase and pyroxene), and minor amount of opaque minerals, mostly magnetite and, locally, apatite, rutile, quartz, sphene, chlorite, epidote and carbonate in the investigated rock. Hornblende is ranging from 75% to 99% with 2% to 25% of plagioclase (Table 3).

4.1.3 Amphibolite

Petrographically the amphibolites are mainly composed of hornblende and plagioclase with minor amount of quartz and alkali feldspar. Other accessory mineral constituents are biotite, muscovite, chlorite, epidote and opaque. About 70% of the grains in the examined thin sections is of amphibole. The hornblende in the examined thin section is 40% (Z1), 45% (Z2) and 60% (Z3). The plagioclase content is 50% (Z1), 40% (Z2) and 30% (Z3). Orthoclase is 2% in Z1, 5% in Z2 and 5% in Z3. While the amount of quartz is 5 (Z1), and 3% in Z3. About 10% of chlorite in Z2 while tremolite content is 3% in Z1 and 2% in Z3 (Table 4).

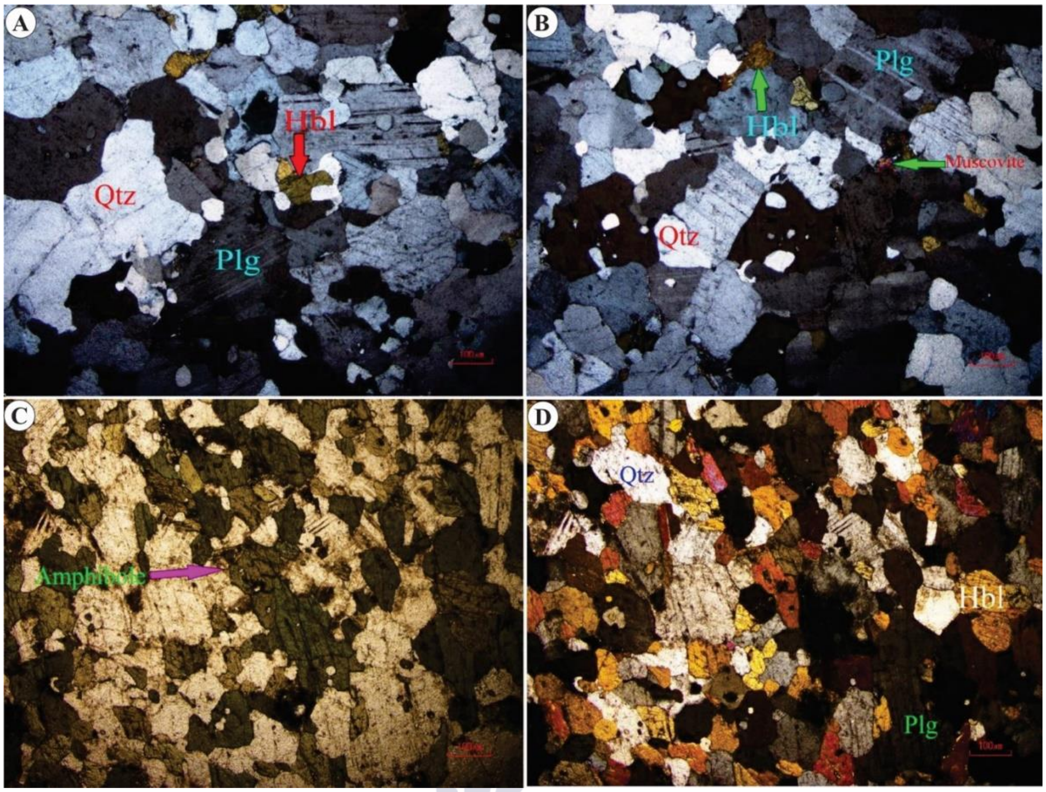

Figure 2. Plain and cross polarized light photomicrographs represent (A-B) Diorite rock exhibits medium to coarsely crystalline quartz grain with interlocking crystal mosaics. They exhibit light gray to gray color. Plagioclase display distinct twinning. Hornblende show brown color. (C-D) Plain and cross polarized light photomicrographs of Diorites display interlocking crystal mosaic of quartz and plagioclase. The rock is medium crystalline. Grains indicate equidimensional grains with abundance of amphibole minerals.

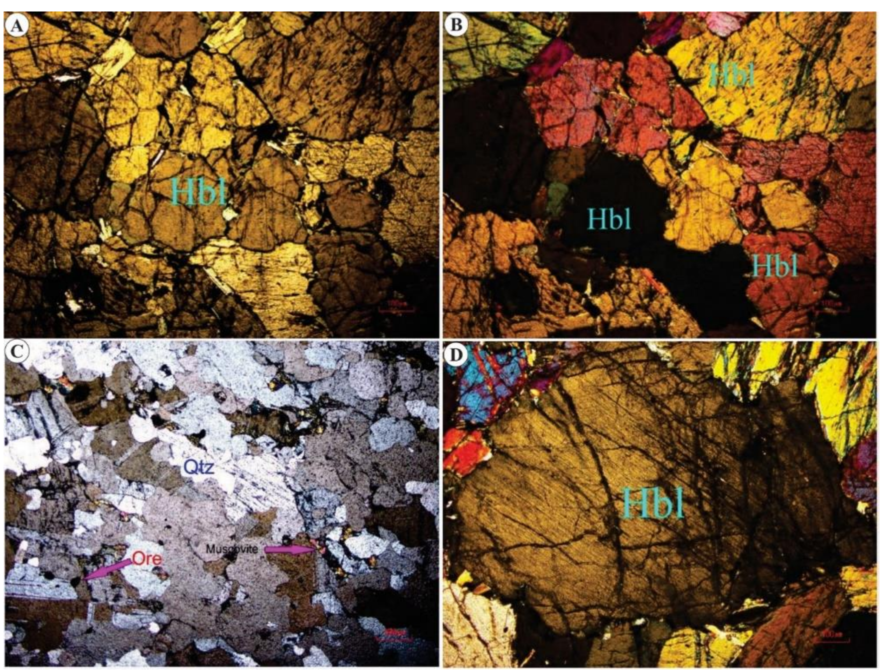

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Figure 3. Plain and cross polarized light photomicrographs represent (A-B) Plain and cross polarized light photomicrographs of Hornblendites, display interlocking crystal mosaic of Hornblende crystals. The rock is very coarsely crystalline. The rock is almost composed of monomineralic composition i.e., hornblende. Two set of cleavages and fractures are present in the crystals of hornblende. Display multi-interference colors. (C) exhibits medium to coarsely crystalline quartz grain with interlocking crystal mosaics with plagioclase and hornblende. They exhibit light gray to gray color. Plagioclase display distinct twinning. Hornblende show brown color. (D) cross polarized light photomicrographs of hornblendite display interlocking crystal mosaic of hornblende. The rock is coarsely crystalline. Grains indicate two set of cleavages/fractures and multi-interference color.

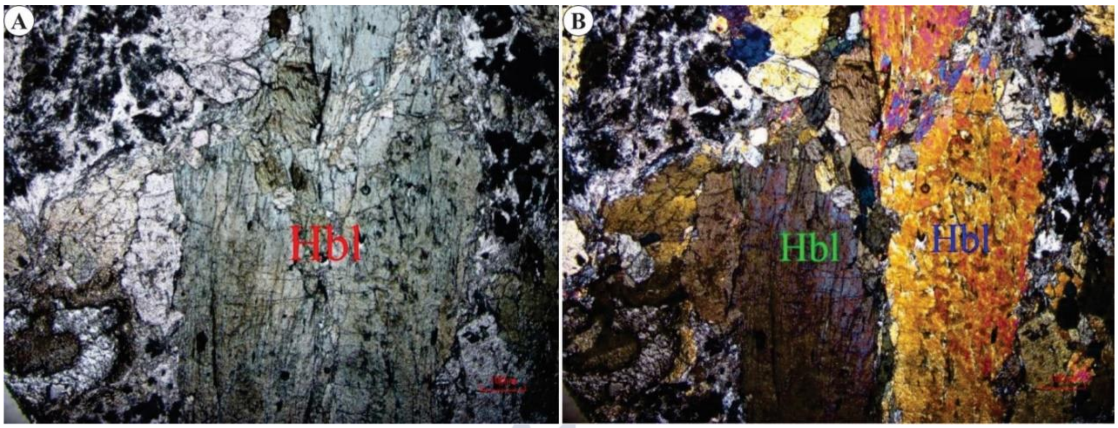

Figure 4. Plain and cross polarized light photomicrographs represent (A-B) Plain and cross polarized light photomicrographs of Amphiboles, display preferred alignments of amphibole grains. The rock is very coarsely crystalline. The rock is composed of amphibole, quartz, biotite and ore minerals. One set of cleavages and fractures are present in amphibole crystals and display multi-interference colors.

4.2 Geochemistry

After analyzing the petrography of rocks. Representative samples of Amphibolites, Diorites and Hornblendites were sent to Geoscience lab Islamabad for the whole rock Geochemistry to know the major and trace element contents by using x-ray florescence technique.

4.2.1 Diorites

Diorites having SiO2 between (51.97 - 65.79%), low TiO2 (0.05-2.69%), high A12O3 (17.1-18.77%). Fe2O3 ranges from 4.7 to 9.41%, MgO from 1.13 to 4.93%, CaO from 4.3 to 7.29%, Na2O from 3.34 to 4.51%, K2O from 1.77 to 2.3% and P2O5 from 0.3 to 0.64% and MnO from 0.8 to 0.17 (Table 1). Among the trace elements Nb 14 to 41 ppm, Zr from 117 to 268, Ni from 7.2 to 27 ppm, Pb from 3 to 28 ppm, Y from 29.8 to 43 ppm, Sr from 131 to 499 ppm, Cu from 5 to 22.8 ppm, Co from 2.3 to 31 ppm, Rb from 3 to 127 ppm, Ba from 414 to 619 ppm, Cr from 18.2 to 48 ppm as shown in table 1.

4.2.2 Hornblendites

Hornblendite having SiO2 up to 39.05%, low percentage of TiO_2 2.69%, high concentration of $A1_2O_3$ 19.28%, Fe_2O_3 up to 22.16%, MgO 8.48%, CaO 1.07%, Na2O 0.21%, K2O 6%, P2O5 0.61% and MnO 0.19% (Table 1). Among the trace elements Nb 16 ppm, Zr 97 ppm, Ni 61 ppm, Pb 21 ppm, Y 51 ppm, Sr 302 ppm, Cu 1 ppm, Co 5ppm, Rb 9 ppm, Ba 322 ppm, Cr 83 ppm as shown in table 1.

4.2.3 Amphibolites

The amphibolites have wide range of SiO2 ranging from 40.73 to 55.63%, low TiO_2 (2.09-2.27%), high $A1_2O_3$ (13.8-19.87%). Fe2O3 ranges from 12.02 to 22.16%, MgO from 3.53 to 9.14%, CaO from 1.21 to 7.29%, Na2O from 0.09 to 3.36%, K2O from

1.75 to 4.32% and P2O5 from 0.37 to 0.73% and MnO is from 0.18 to 0.26 (Table 1). Among the trace elements Nb 12 ppm, Zr lies in range of 86 to 175ppm, Ni is from 0 to 72 ppm, Pb ranges from 13 to 19 ppm, Y from 34 to 56 ppm, Sr from 293 to 324 ppm, Cu from 2 to 9 ppm, Co from 3 to 11 ppm, Rb from 7 to 45 ppm, Ba from 302 to 727 ppm, Cr from 27 to 91 ppm (Table 1).

Table 1. Major and trace element data of representative rocks from study area.

Sample No.	D-5	D-3	D-7	Z-1	Z-3	H-9	D-1
Major Oxides (Wt. %)							
SiO_2	54.66	51.97	53.94	55.63	40.73	39.05	65.79
TiO_2	1.08	1.27	1.01	2.27	2.09	2.69	0.05
Al_2O_3	18.77	17.99	18.31	13.8	19.87	19.28	17.1
Fe_2O_3	8.41	9.41	7.92	12.02	21.53	22.16	4.7
MgO	4.33	4.93	5.23	3.53	9.14	8.48	1.13
CaO	6.94	6.67	7.29	7.09	1.21	1.07	4.3
Na_2O	3.34	4.51	3.72	3.36	0.09	0.21	4.2
K_2O	1.77	2.09	1.69	1.75	4.32	6	2.3
P_2O_5	0.3	0.9	0.64	0.37	0.73	0.61	0.17
MnO	0.17	0.11	0.21	0.18	0.26	0.19	0.08
Total	**99.77**	**99.85**	**99.96**	**100**	**99.97**	**99.74**	**99.82**
Trace Element (PPM)							
Nb	26	39	41	12	12	16	14
Zr	135	117	99	175	86	97	268
Ni	27	19	36	0	72	61	7.2
Pb	3	11	7	13	19	21	28
Y	38	43	61	34	56	51	29.8
Sr	499	563	372	324	293	302	131
Cu	5	17	13	9	2	1	22.8
Co	31	21	43	11	3	5	2.3
Rb	3	7	16	45	7	9	127
Ba	464	414	516	727	302	322	619
Cr	48	57	29	27	91	83	18.2
Li	30	17	9	0	47	51	0
Sc	25	13	11	32	6	9	7.9
V	212	153	127	405	117	125	44
Zn	107	34	79	125	73	67	55.9
As	0	0	0	0	0	0	4
Th	1	0	2	9	6	3	20.3

5 Interpretation and Discussion

5.1 Petrographic Interpretation

5.1.1 Diorite

Based on optical properties, quartz is recognized as the most abundant mineral in the examined thin section. Quartz appears as light gray to white in color studied under plain and crossed polarized light microscopy. In the examined thin sections, quartz grains are euhedral to anhedral in shape and exhibits coarsely crystalline texture as well. Plagioclase crystals were identified as elongated grains showing polysynthetic twinning as its diagnostic optical property. Very coarsely crystalline hornblende grains were observed as main mineral constituent of the investigated rock unit. Hornblende display yellowish brown to light green color in plain and cross polarized light respectively. These grains possess one set cleavages and exhibit pleochroism (Fig. 2A-D). Petrographic study reveals that texture of the examined rock unit is granoblastic to hypidiomorphic-granular, in which the interlocking grains of anhedral to subhedral shape are mostly of same size. The dominant mineral composition suggests that the inspected rock unit is diorite, formed at considerable depth within the earth crust, which was later on exposed as a result of crustal exhumation.

Plagioclase is of (50 to 65%) which is in range of oligoclase to andesine .it is subhedral to anhedral. Plagioclase showing laminar twining showed in figure 2A. In some samples the plagioclase is generally fresh and have partial alteration along margins to sericite while in others it is severely altered. In some cases, the plagioclase grains exhibit alteration from core towards margin where the plagioclase rim is left unaltered. Alkali feldspar is of (15 to 20%). It is irregular to subhedral grains, mainly within the interstices of plagioclase. It usually shows undulose extinction. Quartz is of (10 to 12%). It is an interstitial phase and is generally irregular and strained. Ore mineral is magnetite is of (1 to 2%). It is irregular grain having black color showed in figure 3C. Hornblende is of (4 to 5%). It occurs as prismatic grains of red brownish color.

Table 2. Modal mineralogy (visual estimates) of Diorite from Jandul area District Dir (Lower).

Minerals	D1	D2	D5
Plagioclase	50	60	65
Orthoclase	25	20	15
Quartz	11	10	12
Epidote	-	-	-
Magnetite	2	1	2
Muscovite	4	3	2
Hornblende	5	5	4
Chlorite	1	-	--
Opaque	-	-	-

5.1.2 Hornblendite

The investigated rock unit is predominantly composed of hornblende. Petrographically hornblende crystals exhibits anhedral to subhedral shape with very coarsely crystalline texture as shown in Fig. 3A. Based on one set cleavage, pleochroism and exhibiting interference colors, hornblende was easily distinguished from other minerals during petrographic interpretation (Fig. 3A-D). The very larger crystals size of hornblende in the studied samples indicates very slow cooling of the parent magma at a very greater depth in the earth's crust. It has also been observed that grains contact in the studied samples are mostly interlocking, which is a diagnostic characteristic of plutonic igneous rocks. Abundance of hornblende with very negligible amount of quartz suggests that the investigated rock unit is hornblendite (Fig. 3A-D).

Analytical data interpretation suggests that monomineralic hornblendite cannot form directly from the crystallization of primary magma by following Bowen's Reaction series. The inspected monomineralic hornblendite is a product of secondary magma, originated in the lower crust by melting of the subducted oceanic lithosphere along the convergent plate boundaries. Kohistan Island Arc is a product of Intra-oceanic subduction, caused the subduction of oceanic lithosphere beneath oceanic lithosphere, give way to the origination of basic magma comprised of hornblende minerals only. In hand specimen the Hornblendites are generally in black color. The Hornblendites display grain-size heterogeneity. They are predominantly coarse-grained with up to a few centimeters' long crystals. However, they are locally medium- or even fine-grained. In thin section the rocks are essentially composed of hornblende (with variable amounts of plagioclase and pyroxene in some), and minor amount of opaque minerals mostly magnetite) and, locally, apatite, rutile, quartz, sphene, chlorite, epidote and carbonate, the last three or four minerals being the products of alteration.

Hornblende lies in range of 75 to 99%. Hornblende has green or brownish green color with thin margins of bluish green or greenish color. Twining, double sided cleavage was diagnostic feature of Hornblende. A few crystals show the characteristics shape and two cleavages at 120 degrees. The hornblende shows pleochroism from green to brown where the pleochroism of biotite is from dark brown to pale brown. Plagioclase varies 2 to 25%. Descriptions are givens in above sections.

Table 3. Modal analyses (visual estimates) of Hornblendites of Jandul District Dir (lower).

Minerals	HB9	Hor6
Hornblende	99	75
Plagioclase	2	25
Orthopyroxene	-	-
Clino-pyroxene	-	-
Olivene	-	-
Ore Minerals	1	

5.1.3 Amphibolites

Petrographically the representative thin sections are predominantly composed of amphibole, quartz, biotite and plagioclase as essential mineral constituents. Amphibole mineral exhibits multiple interference colors such as yellowish, brown and dark green, and display distinctive cleavage set as its diagnostic optical property. More than 70% of the grains in the examined thin sections were of amphibole. Light color anhedral to subhedral interlocking grains of quartz are also present in close association with amphibole. Quartz grains are mostly medium to coarsely crystalline in size, with irregular grain boundaries. The irregular grain boundaries with interlocking behavior are a diagnostic indicator of medium to high grade metamorphic rocks. Plagioclase were identified with the help of its distinct twinning and its moderate interference colors. It displays white to grayish color in plain and cross polarized light microscopy (Fig. 4A-B).

In hand specimens, the amphibolites are medium to coarse-grained with light green to grayish green in color. Hornblende, plagioclase, biotite and quartz can easily be recognized in hand specimen. All the minerals have preferred orientation along the fabric direction. While, in thin section the amphibolites are medium to coarse-grained, In-equigranular, hypidioblastic to sub-ideoblastic texture. Hornblende and plagioclase are the dominant while orthoclase and quartz are the minor constituents (Table. 4) Biotite, muscovite, chlorite, epidote, apatite, sphene, rutile, calcite and opaque occur as accessories. Hornblende is of (40 to 60%). It is generally light green to dark green in color; however, grains of bluish-green and light brown pleochroism are also observed. It is prismatic sub-hedral in shape and has well developed cleavages. Most of the hornblende grains enclose tine-grained rounded to sub-rounded quartz (Figure 2B). At places, chlorite and tremolite/actinolite occur as core material to hornblende which indicates that the former is replaced by the later. Sometime biotite is also enclosed within hornblende. In some cases, the hornblende grains are relatively small which are interlock and oriented along the fabric direction in such a way that it has developed schistosity in the rock. These types of rocks are common along the shear zones.

Plagioclase is of (30 to 50%). it is in the range of oligoclase to andesine, however, some grains of albitic in composition are also observed. Plagioclase partially altered to sericite, and epidote. However, pseudomorphs and relics of plagioclase are also common due to more or less complete alteration, Sericitization and epidotization are the common features of these rocks. Plagioclase grains are also fractured and strained at places which are clearly evident by the bending and fracturing of elongated grains, of plagioclase. Alkali feldspar is of (2 to 5%) occurs as subhedral, medium-grained phase, which is partially or completely altered to kaolinite, sericite, muscovite etc. Quartz is present as inclusions within hornblende and also as anhedral individual grains within the interstices of plagioclase.

It is evident from the mineralogical and textural features of these amphibolites that these are formed from an igneous rock of gabbro or gabbro norite composition during prograde regional metamorphism. This rock has been subjected to greenschist facies metamorphism for considerable time, which is indicated by the presence of chlorite, tremolite/actinolite, epidote and plagioclase of oligoclase to andesine composition and then followed by the amphibolite facies condition during regional metamorphism as evident from the development of high proportion of hornblende and also progressive replacement of chlorite and tremolite/actinolite along the margins by hornblende. This whole paragenetic sequence suggests that the pyroxene, plagioclase and opaque phases within the protolith have played an important role in the development of existing mineralogy and texture of these amphibolites.

Table 4. Modal analysis (visual estimates) of Amphibolites of Jandul, District Dir (lower)

Minerals	Z1	Z2	Z3
Hornblende	40	45	60
Plagioclase	50	40	30
Orthoclase	2	5	5
Quartz	5	-	3
Chlorite	-	10	-
Tremolite	3	-	2
Actinolite	-	-	-
Muscovite	-	-	-

5.1 Geochemical Interpretation

The major elemental composition of seven representative samples collected from Kohistan Island Arc sequence is provided in the given Table 1. According to the chemical investigation, rocks of the KIA sequence show abundance of Hornblende and Amphibole minerals. Graphical representation of major oxides exhibits that Titanium Dioxide (TiO_2) exhibits a strong negative trend with silicon dioxide (SiO_2), while Aluminum oxide (Al_2O_3), Calcium Oxide (CaO) and Iron oxide (Fe_2O_3) shows a moderate positive trend with silicon dioxide (SiO_2).

The positive trend of Al_2O_3, Fe_2O_3, CaO and SiO_2 represent geochemical compatibility of these oxides in the examined rock samples. There is the negative correlation of K_2O, P_2O_5, MgO, and MnO with SiO_2 may indicate the extraction of biotite during metamorphic reactions. The negative tendency of MnO verses SiO_2 indicates the garnet will crystallize and segregate out of these metamorphic rocks during medium to high grade metamorphic rocks. The pronounced decline of MnO vs. Silica also favors garnet crystallization (Sajid, 2016). This strong negative correlation of K_2O and Fe_2O_3 with SiO_2 suggests the development of biotite during amphibolite grade metamorphism (Fig. 5-6).

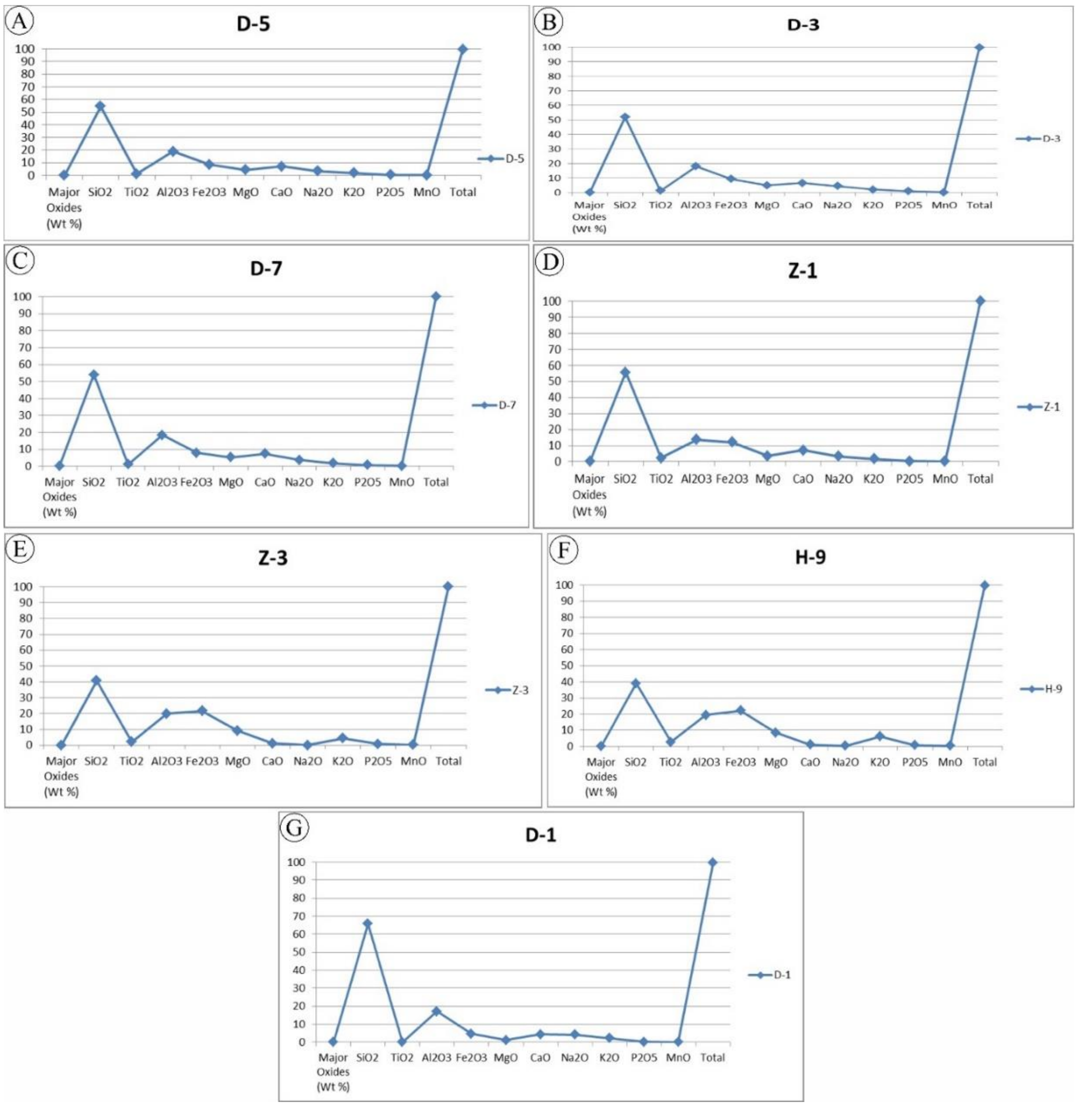

Figure 5. (A-E) Graphical representation of major oxides (Wt. %) detected in the representative samples of the investigated rock units of Kohistan Island Arc sequence. There is a clear positive trend in the concentration of SiO_2, Al_2O_3, Fe_2O_3 and CaO, while the rest exhibits negative trend.

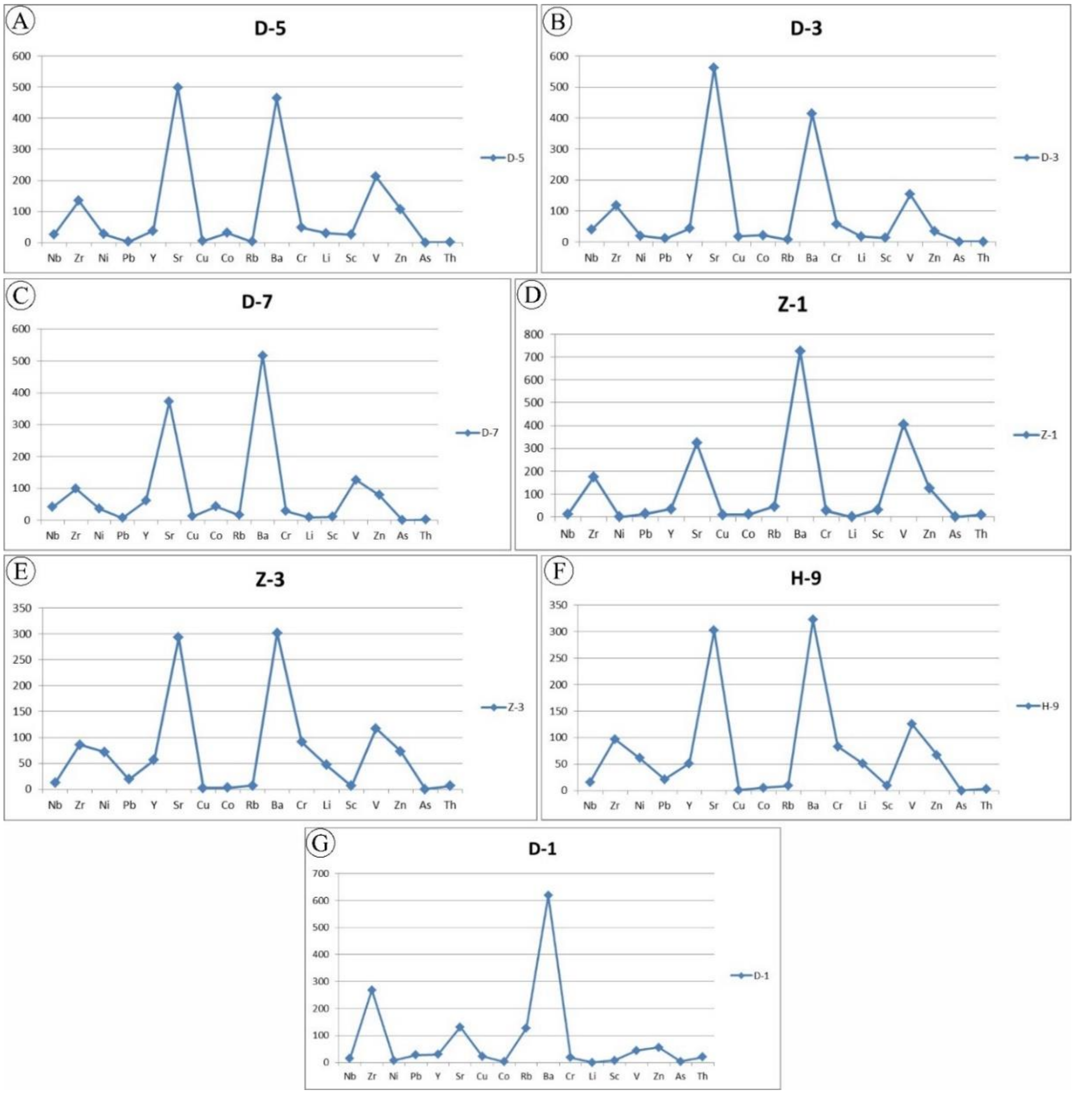

Figure 6. (A-E) Graphical representation of minor oxides (ppm) detected in the representative samples of the investigated rock units of Kohistan Island Arc sequence. There is a clear positive trend in the concentration of Sr, Ba, Zr and V, while Nb, Ni, Pb, Y, Cu, Co, Rb, Li, Sc, As and Th exhibits negative trend.

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