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Field and minerological constraints of the Dir metavolcanic sequence, Kohistan Arc terrane, northern Pakistan

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ABSTRACT: *The Dir metavolcanic sequence, a part of the Dir group, constitutes a NE-SW trending belt within the northwestern portion of the Kohistan island arc in the western Himalayas of northern Pakistan. This sequence is dominantly composed of basaltic-andesite and andesite with subordinate basalt, dacite, rhyolite, and pyroclastic breccia. These rocks are foliated and sheared along local faults and also have small intrusions at places.*

Porphyritic textures are dominant, with less common aphyric and seriate textures. Plagioclase (An_{10-42}) is ubiquitous in all the members of the sequence and occurs as phenocrysts and in groundmass. K-feldspar and quartz predominate both as phenocrysts of the dacites and rhyolites. Chlorite, epidote, and actinolite are the most common metamorphic phases; hornblende, muscovite, biotite, kaolinite, sericite, carbonate, and opaques occur rarely. Phase assemblages and chemistry suggest predominant greenschist facies metamorphism with epidote-amphibolite facies conditions attained locally.

INTRODUCTION

The Dir metavolcanic sequence is a part of the Dir-Utror volcanic belt within the Kohistan arc. This belt stretches from Kalam through Dir and Bajaur to the border of Afghanistan (Fig. 1). It is oriented NE-SW more or less parallel to the subduction zone along the Main Mantle Thrust (MMT). The area of study is located in the vicinity of the Dir town in north western part of Pakistan. It covers an area of about 50 Km^2 between latitude 35° 9′ 48″ to 35° 11′ 48″ and longitude 71° 48′ 30″ to 72° 2′ on the toposheet Nos 38M/16, 38M/15 and 43A/3 (Fig.1). All the members of the sequence are metamorphosed. For simplicity the term "meta" will mostly be omitted from rock names in the text.

The rocks of the area were briefly described by Hyden (1915). Volcanic rocks, west of the study area were described by Khan (1979) in Barual valley and by Kaker et al., (1979) in Jandul. The westward extension of these volcanics along the border of Afghanistan in Mohmand-Bajaur agency has been reported by Badshah (1979). Tahirkheli (1979, 1982) described the Dir-Utror volcanics and associated metasediments as members of the Dir group and suggested the middle Jurassic to Cretaceous age for the metasediments. A late Paleocene to early Eocene age has been assigned to the Dir group on the basis of palaeontalogy and radiometric studies (Kakar et al., 1971; Khan, 1979; Treloar et al, 1989). Hamidullah and Onstot (1992) have however, assigned a 70 Ma age to Dir volcanics on the basis of $^{40}Ar/^{39}Ar$ data of primary hornblende obtained from a hornblende andesite north-east of Dir proper. The Dir volcanics have attained greater importance due to the associated copper mineralization, which is mainly restricted to these metavolcanics. The petrologic and geochemical studies of the rocks from Dir-Utror volcanic rocks of the Dir group are discussed by various workers (see Majid & Paracha, 1980; Majid et al. 1981; Fletcher, 1985; Hamidullah et al., 1990; Shah, 1991; Sullivan, 1992; Shah et al., 1993; Hamidullah & Shah, 1993).

This paper deals with the detailed field, petrographic and mineralogic features of the Dir metavolcanic sequence with emphasis on metamorphism.

FIELD ASPECTS

The Dir metavolcanic sequence is widely exposed in the study area and has a thickness of > 2 Km along the main Dir-Chitral road. It is mainly composed of basaltic-andesite, andesite with subordinate amount of basalt, dacites, rhyolite and pyroclastic breccia. The sequence is intruded by tonalitic, granodioritic and dioritic stocks. In general the volcanics have their upper northern contact with the Lowari pluton but in the studied area the upper thrust contact of the sequence lies against the Panakot meta-arkosic sandstone (Fig.1).

Mafic-metavolcanic rocks

Mafic metavolcanic rocks of the Dir metavolcanic sequence include (meta-) basalt, basaltic-andesite, and andesite. No distinction can be made between these rock types in the field,

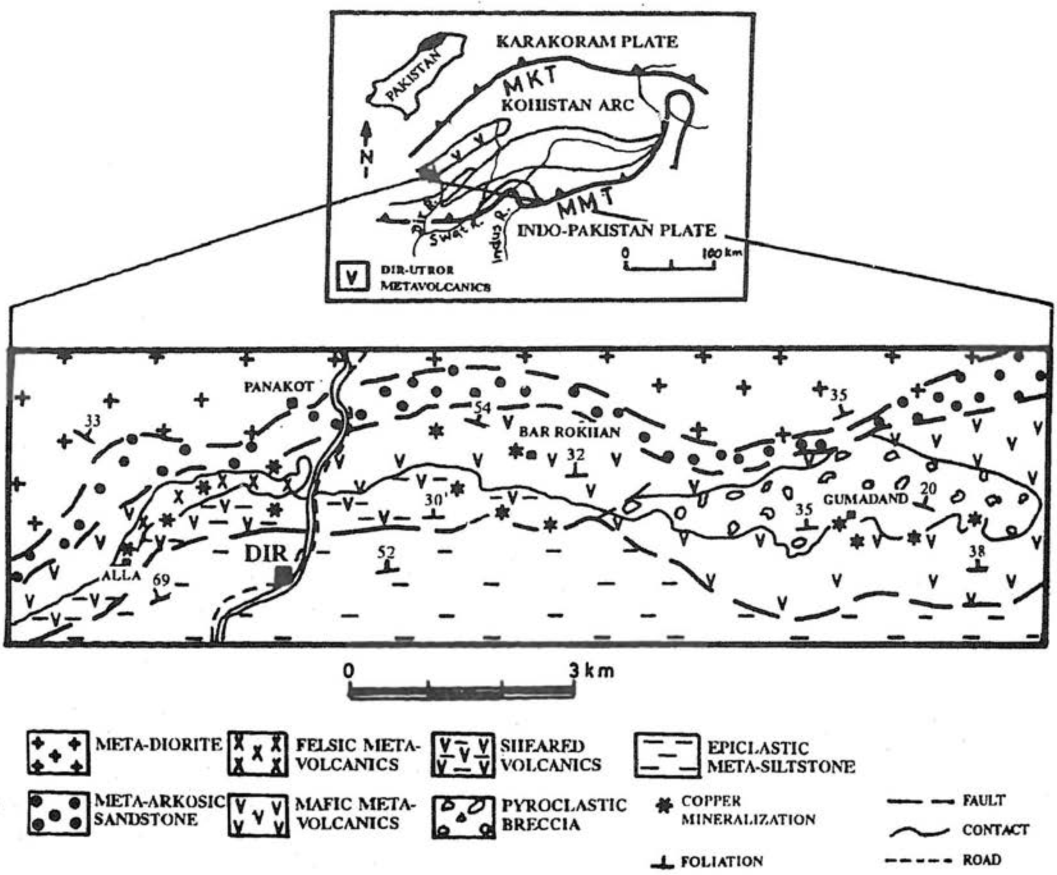

Fig. 1. Geological map of the area around Dir, northern Pakistan.

therefore, all mafic metavolcanic rocks are mapped as a single unit.

Mafic metavolcanic rocks are the most voluminous rock types exposed in the area (Fig.1). They commonly occur as porphyritic flows with elongated plagioclase phenocrysts (<5mm), partially altered to kaoline and epidote, oriented subparallel to foliation.

Mafic metavolcanic rocks are generally compact and hard, however, shearing and schistosity is found along local faults. Copper mineralization in these rocks is associated with the shear zones (<5m thick). These zones contain fracture filled quartz and carbonate veins. The foliation generally strike NE and dips NW but faulting and folding cause local variations in the trend. These rocks have upper and lower faulted contact with the meta-arkosic sandstone and epiclastic siltstone, respectively (Fig. 1).

Sheared metavolcanics

The sheared metavolcanics are considered to be same as the mafic metavolcanics, and the difference in the field can be observed only due to the severity of deformation in the proximity of the thrust fault between epiclastic siltstone and mafic metavolcanics. This deformation can be attributed to the south-west vergent thrusting of the metavolcanics over epiclastic siltstone unit. The sheared metavolcanics have probably been subjected to two phases of deformation. The first phase (D_1) produced the S_1 foliation which generally strikes NE and dip NW. The D_2 deformation is responsible for the crenulation lineation (S_2) produced by microfolding of the foliation planes.

The rock is generally greenish-gray to green in color, occasionally shows color banding with alternate bands of dark gray to green color. Epidotization and quartz veining is the common feature of these rocks. The quartz veins generally follow the fabric direction, however, veins which cross-cut the general fabric have also been observed. Occasionally, microveins of quartz + muscovite, carbonates and epidote may form network within these rocks.

Felsic metavolcanic rocks

Felsic metavolcanic rocks of the Dir metavolcanic sequence include both (meta-) dacite and rhyolite. They are light-gray in color on fresh surfaces with maroon to brownish-gray weathered surfaces. The felsic metavolcanics are generally fine-grained, compact and foliated but in places exhibit severe shearing and fracturing due to local faulting which has resulted in the development of crenulations, lineations and microfolds. Rhyolite dikes (2m thick) intruded within the basaltic-andesite and andesite have been observed along the stream section near Bikarai village.

The felsic metavolcanic rocks confirmably overly the mafic metavolcanics and the sheared metavolcanics. Their upper contact with the overlying Panakot meta-arkosic sandstone is faulted. These rocks have been intruded by a small (=200m across) stock-like body of granodiorite east of Bikarai village (Fig. 1).

Pyroclastic breccia

Pyroclastic breccia is widely exposed in Gumadand area (Fig.1). On the basis of proportion of clasts and matrix, the pyroclastic breccia is divided into: (1) matrix supported breccia and (2) clast supported breccia.

The matrix supported breccia is the dominant, maroon-colored, polymict rock. This type of breccia is mainly composed of subangular to subrounded clasts (2 to 20cm across in diameter) and blocks (up to one meter) across of basalt and basaltic-andesite all set in more than 50% fine-grained matrix of maroon to maroon gray color. Clasts within the matrix supported breccia have coherent igneous textures similar to those seen in basalts and basaltic-andesites of the mafic metavolcanic. The breccia occasionally exhibits multiple sequences of normally graded bedding having alternate beds (1/2m thick) of fine-grained maroon-colored matrix with clasts of <1cm to 4cm in diameter and beds (1m thick) having big clasts (2 to 24cm across in diameter) embedded in the same kind of fine-grained matrix. In some cases the clasts are deformed to an elliptical shape with their long axis aligned parallel to the fabric.

The matrix supported breccia is probably fragmental basalt and basaltic-andesite debris supplied from the volcanic vent. The debris occurs as coarse volcanic breccia and lava flows piled around filled volcanic vent. The pyroclastic flows were probably emplaced at high temperature as is evidenced by the thermal oxidation of iron phase (magnetite) to hematite producing the pink to maroon color (see Cas & Wright, 1987).

The clast supported breccia is commonly monomict breccia (clast to matrix ratio is 3:1) and is mainly comprised of subangular to subrounded mafic volcanic clasts of over two meter across in a sparse maroon colored matrix. The clasts have similar igneous texture as that of the mafic volcanics. This rock lacks any kind of bedding. The clast supported breccia was probably produced by the gravitational collapse of lava flow or caldera which may have contributed clast supported breccia to the pyroclastic flow deposits.

PETROGRAPHY

The least altered samples, having no copper mineralization, were selected for petrogrphic and geochemical studies in order to decipher the original mineralogical and chemical history of these rocks. Over 120 thin sections were studied petrographically.

Mafic metavolcanic rocks

These rocks are characterized by common porphyritic texture, with less common aphyric, seriate texture. Plagioclase is the main phenocryst, and occurs as well in the groundmass. Chlorite, epidote, actinolite, kaolin, sericite, carbonates, and more rarely hornblende and opaques form the groundmass.

Plagioclase phenocrysts vary in size from <0.5mm to more than 3mm enclosed in fine-grained groundmass and exhibit partial alteration to epidote, kaoline and carbonates. Pseudomorphs after plagioclase and less commonly after ferromagnesian minerals (probably pyroxene and olivine), have been noticed. Plagioclase is completely replaced by epidote, carbonates and sericite while pyroxene and olivine are replaced by chlorite and actinolite. Occasionally these rocks contain amygdules filled with chlorite along with small amount of epidote and calcite. The amygdules may reach to 2mm across in maximum diameter.

In groundmass laths and crystallites of albite are set in dark patches probably derived from the devitrification of once glassy matrix. These patches are re-crystallized mainly to chlorite, clay minerals, carbonates, magnetite and hematite occasionally oriented along the fabric direction.

Sheared volcanics

Rocks of the sheared volcanic unit are dominantly composed of pseudomorphs after feldspar phenocrysts within a chlorite-rich groundmass. The texture of the rock is generally schistose to gneissose. Feldspar phenocrysts (<1mm to 2.5mm) are mortared, fractured and corroded along margins. These phenocrysts show partial or complete alteration to epidote, muscovite, sericite, carbonates and kaolin. The phenocrysts generally occur as augens with undulose extinction and are oriented parallel to the fabric direction. The groundmass is mainly composed of chlorite, muscovite, epidote and hornblende. Post-deformational microveins of carbonates are conspicuously developed in these rocks.

The original texture of these rocks has been completely destroyed by the extensive shearing. This shearing has resulted in the development of schistose and gneissose foliations and epidote + chlorite + amphibole assemblage.

Felsic metavolcanic rocks

The felsic metavolcanic rocks (rhyolite, dacite) consist of plagioclase, orthoclase, and rare quartz phenocrysts embedded in a fine-grained, cryptocrystalline groundmas.; Aphyric varieties occur as well. The plagioclase and orthoclase phenocrysts (>1.5mm across in diameter) are highly fractured and exhibit partial alteration to epidote and clay minerals. These phenocrysts have undulose extinction. The fine-grained groundmass is mostly composed of felsic phases (quartz and feldspar) along with secondary phases i.e., epidote, muscovite, sericite, kaolin, biotite, rare chlorite, calcite and opaques. Zircon occurs as inclusions within quartz and feldspar. Recrystallized quartz also occur as microveins and patches. Biotite occurs as minute flakes along with muscovite. Biotite exhibits greater absorption of color and greater size wherever found adjacent to the opaque phases.

MINERAL CHEMISTRY

Mineral phases in rocks of the Dir metavolcanic sequence have been analyzed by using the Cameca SX-50 electron microprobe at the University of South Carolina. The operation conditions were 15 Kv accelerating potential and beam current of 25 nA. Natural and synthetic standards were used, with counting times of 20-30 seconds for each element.

Amphiboles

Amphiboles occur as fibrous to prismatic grains which vary in color from colorless to light-green or bluish-green to green. The actinolites are the early phases as these are replaced along the margins by bluish-green hornblende. In some cases the actinolites have been completely replaced by prismatic hornblende. Occasionally the colourless to light green variety overprints chlorite in the groundmass.

Cores and margins of the amphiboles are analyzed by electron microprobe and the results are presented in Table 1. The Fe^{3+} contents were determined following the method of Laird and Albee (1981). The Leake (1978) classification scheme was adopted to classify these amphiboles (Fig. 2). These amphiboles are considered to be calcic, with Ca + Na >1.34 and Na <0.67 atoms per formula unit on the basis of 23 oxygens. They variously plot in the fields shown for actinolite, actinolitic hornblende, magnesio-hornblende and tchermakitic hornblende. Three of the analyzed amphiboles plot in the ferro-hornblende and one along the boundary of tschermakite and ferrotchermakite (Fig. 2).

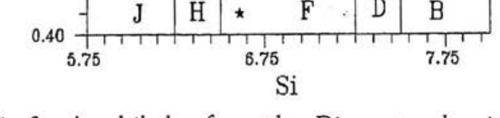

Fig. 2. Amphiboles from the Dir metavolcanic sequence plotted on Mg/Mg+Fe vs Si diagram. Nomenclature is that of the International Mineralogical Association (Leak, 1978). A = actinolite, B = ferro-actinolite, C = actinolitic hornblende, D = ferro-actinolitic hornblende, E = magnesio-hornblende, F = ferro-hornblende, G = tchermakitic hornblede, H = ferro-tchermakitic hornblende, I = tchermakite, J = ferro-tchermakite.

TABLE 1. REPRESENTATIVE CHEMICAL ANALYSES AND STRUCTURAL FORMULAE OF AMPHIBOLE, EPIDOTE, PLAGIOCLASE, CHLORITE, BIOTITE AND MUSCOVITE IN THE DIR METAVOLCANIC SEQUENCE.

AMPHIBOLES

S.No	DR133		DR63		DR263	DR316	
Grians	GR1		GRI		GRI	GRI	
	core	rim	core	rim		core	rim
SiO_2	45.62	44.70	45.32	45.69	40.75	51.97	51.65
TiO_2	0.40	0.52	1.33	1.24	0.08	0.15	0.07
Al_2O_3	9.03	9.22	7.47	7.47	16.39	3.74	3.75
FeO	18.73	18.80	20.62	20.38	18.44	13.04	13.40
MnO	1.00	0.89	0.59	0.467	0.36	0.52	0.44
MgO	9.99	9.82	8.9	9.02	7.31	14.77	14.69
CaO	11.54	11.45	11.35	11.3	11.49	12.30	12.59
Na_2O	1.11	1.08	1.31	1.17	1.27	0.27	0.24
K_2O	0.32	0.15	0.88	0.81	0.37	0.07	0.11
Total	97.74	96.64	96.03	97.55	96.46	96.83	96.94
23(O) basis							
Si	6.76	6.65	6.82	6.86	6.12	7.50	7.49
Al	1.24	1.35	1.18	1.14	1.88	0.50	0.51
Site C							
Al	0.35	0.28	0.19	0.19	1.03	0.15	0.13
Ti	0.04	0.08	0.15	0.15	0.00	0.00	0.00
Fe^{+3}	0.67	0.82	0.48	0.48	0.71	0.44	0.39
Fe^{+2}	1.63	1.52	2.1	2.1	1.6	1.15	1.24
Mn	0.11	0.11	0.08	0.08	0.04	0.08	0.04
Mg	2.19	2.19	2.01	2.01	1.63	3.18	3.19
Site B							
Ca	1.88	1.88	1.84	1.84	1.84	1.92	1.95
Na	0.12	0.12	0.16	0.16	0.16	0.09	0.05
Site A							
Na	0.18	0.18	0.22	0.18	0.22	0.00	0.03
K	0.08	0.04	0.15	0.15	0.08	0.00	0.00
Mg/Mg+Fe	0.57	0.59	0.49	0.49	0.5	0.73	0.72

EPIDOTE

S.No	DR133	DR398	DR509
Grains	GR1	GR1	GR1
SiO_2	37.51	37.69	38.82
TiO_2	0.01	0.03	0.00
Al_2O_3	21.02	22.21	23.61
FeO	15.38	13.76	11.76
MnO	0.17	0.56	0.24
MgO	0.00	0.03	0.00
CaO	23.07	22.65	22.10
Na_2O	0.01	0.00	0.26
K_2O	0.02	0.00	0.04
Total	97.19	96.93	96.84
12.5(O) basis			
Si	3.12	3.10	3.17
Al	0.00	0.00	0.00
Σz	3.12	3.10	3.17
Al	2.04	2.17	2.27
Ti	0.00	0.00	0.00
Fe	1.08	0.96	0.79
Mn	0.02	0.04	0.02
Σy	3.15	3.17	3.08
Mg	0.00	0.00	0.00
Ca	2.06	2.02	1.94
Na	0.00	0.00	0.04
K	0.00	0.00	0.00
Σw	2.06	2.02	1.98
Ps	34.67	30.67	25.85

PLAGIOCLASES

S.No	DR216		DR70		DR263	
Grains	GR1		GR1		GR1	
	core	rim	core	rim	core	rim
SiO_2	69.05	68.73	66.94	66.95	60.62	59.64
TiO_2	0.00	0.00	0.02	0.00	0.00	0.01
Al_2O_3	20.07	20.27	21.99	21.69	24.83	25.59
FeO	0.03	0.03	0.21	0.43	0.09	0.22
MnO	0.00	0.00	0.06	0.00	0.00	0.00
MgO	0.00	0.00	0.00	0.00	0.01	0.00
CaO	0.29	0.36	2.13	1.84	5.74	6.65
Na_2O	10.27	10.40	9.36	9.66	7.42	7.10
K_2O	0.09	0.08	0.17	0.12	0.04	0.13
Total	99.80	99.90	100.88	100.71	98.74	99.34
8(O) basis						
Si	3.00	2.99	2.89	2.90	2.04	2.00
Al	1.03	1.04	1.12	1.10	0.98	1.01
Ti	0.00	0.00	0.00	0.00	0.00	0.00
Fe	0.00	0.00	0.01	0.01	0.00	0.01
Mn	0.00	0.00	0.00	0.00	0.00	0.00
Mg	0.00	0.00	0.00	0.00	0.00	0.00
Ca	0.01	0.01	0.09	0.08	0.21	0.23
Na	0.87	0.88	0.79	0.81	0.48	0.46
K	0.00	0.00	0.01	0.00	0.00	0.01
Ab	98.48	98.51	88.06	91.04	69.57	65.71
An	0.01	0.01	10.45	8.96	30.43	32.86
Or	0.00	0.00	1.49	0.00	0.00	1.43

BIOTITE				
S.No Grains	DR263 GR1 core	rim	DR216 GR2 core	rim
SiO_2	37.18	37.11	35.71	35.36
TiO_2	1.77	1.86	2.49	2.57
Al_2O_3	17.85	17.81	17.30	17.21
FeO	15.09	14.62	18.67	18.64
MnO	0.55	0.66	0.26	0.34
MgO	13.06	13.02	10.40	10.27
CaO	0.00	0.00	0.00	0.00
Na_2O	0.07	0.07	0.10	0.14
K_2O	9.95	10.10	9.36	9.43
Total	95.55	95.30	94.30	93.95
22(O) basis				
Tet.Si	5.54	5.54	5.51	5.51
Al	2.46	2.46	2.50	2.50
Oct.Al	0.66	0.70	0.62	0.62
Ti	0.18	0.22	0.29	0.29
Fe	1.87	1.84	2.39	2.42
Mn	0.07	0.07	0.04	0.04
Mg	2.90	2.90	2.39	2.39
Oct.total	5.69	5.73	5.73	5.76
Ca	0.00	0.00	0.00	0.00
Na	0.04	0.04	0.04	0.04
K	1.91	1.95	1.84	1.87
Int.total	1.95	1.98	1.87	1.91
Fe/Fe+Mg	0.39	0.39	0.50	0.50

MUSCOVITE				
S.No Grains	DR263 GR1 core	rim	DR216 GR1 core	rim
SiO_2	47.32	47.57	47.60	46.47
TiO_2	0.47	0.49	0.44	0.51
Al_2O_3	30.08	31.07	30.81	30.43
FeO	5.71	5.43	4.99	5.19
MnO	0.06	0.00	0.02	0.02
MgO	1.88	1.55	1.76	1.70
CaO	0.00	0.00	0.01	0.00
Na_2O	0.14	0.20	0.23	0.02
K_2O	10.70	10.58	10.24	10.68
Total	96.36	96.89	96.09	95.21
22(O) basis				
Tet.Si	6.40	6.26	6.40	6.37
Al	1.60	1.74	1.60	1.63
Oct.Al	3.19	3.30	3.26	3.26
Ti	0.04	0.04	0.04	0.04
Fe	0.66	0.63	0.55	0.59
Mn	0.00	0.00	0.00	0.00
Mg	0.37	0.29	0.37	0.33
Oct.total	4.25	4.25	4.22	4.22
Ca	0.00	0.00	0.00	0.00
Na	0.04	0.07	0.07	0.07
K	1.84	1.84	1.77	1.88
Int.total	1.88	1.91	1.84	1.95
Fe/Fe+Mg	0.64	0.68	0.60	0.64

CHLORITE			
S.No Grains	DR133 GR1	DR398 GR1	DR70 GR1
SiO_2	22.32	25.32	27.53
TiO_2	0.00	0.04	0.09
Al_2O_3	20.22	21.11	17.23
FeO	33.66	26.34	23.94
MnO	2.02	1.16	0.39
MgO	7.14	13.92	17.09
CaO	0.02	0.00	0.08
Na_2O	0.09	0.01	0.00
K_2O	0.02	0.00	0.03
Total	85.52	87.90	86.39
28(O) basis			
Tet.Si	5.19	5.38	5.90
Al	2.81	2.62	2.10
Oct.Al	2.72	2.67	2.25
Ti	0.00	0.00	0.00
Fe	6.51	4.68	4.26
Mn	0.37	0.19	0.05
Mg	2.48	4.40	5.43
Int.Ca	0.00	0.00	0.00
Na	0.05	0.00	0.00
K	0.00	0.00	0.00
Oct.total	12.08	11.94	11.98
Fe/Fe+Mg	0.72	0.52	0.44

A number of differences can be observed between actinolite and hornblende compositions. The Ti content of hornblendes are higher than in actinolites which is most probably a function of metamorphic temperature rather than bulk rock chemistry (see Shah et al., 1993; see also Cooper & Lovering 1970; Raase, 1974; Kuniyoshi & Liou, 1976; Hutchison, 1978). Amphiboles with lower Ti contents generally have a bluish tint, whereas green amphiboles are generallly richer in Ti. Similar change in color with change in Ti contents has also been reported by Binns (1965) and Raase (1972).

Plagioclase

Plagioclase is ubiquitous in all the members of the metavolcanic sequence. It occurs both as phenocrysts and in the groundmass. Occasionally, the plagioclase has a turbid appearance with weak twinning, and is peppered with inclusions of secondary epidote. In some samples, plagioclases phenocrysts are completely pseudomorphed by epidote and other metamorphic phases.

Representative analyses of these plagioclase are presented in Table 1. Plagioclase compositions range from albite to andesine. No calcium rich plagioclase (An>50) has been observed in these rocks. The plagioclases were analyzed at the cores and margins. No zoning has been observed in the analyzed plagioclases suggesting the homogeneous nature of these grains.

Epidote

Epidotes occur as fine-grained granular aggregates, pseudomorphically replacing the plagioclase, irregular patches in the groundmass and locally very abundantly in veins. These epidote grains are highly birefringent and devoid of any zoning.

Representative analyses of epidote are given in Table 1. All the epidotes are iron-rich, with pestacite (Ps) = Fe/(Fe+Al)*100, ranging from 24.00 to 38.82 mole %. This is indicative of low grade (greenschist facies) metamorphic conditions for the studied sequence (see Holdaway, 1966; Cooper, 1972). The analyzed epidotes contain MnO ranging from 0.00 to 0.98 wt. % and negligible amount of TiO_2, Na_2O, MgO and K_2O. No significant Fe^{2+} substitution for Ca has been observed in the W site of these epidotes indicating relatively reducing conditions (Liou, 1973; Coombs et al., 1977). Also the data do not show any significant core to margin variation in composition reflecting these epidotes to be homogeneous.

Chlorite

Chlorite is the most abundant metamorphic mineral in basic to intermediate members of the sequence. It occurs typically in four parageneses: (1) as groundmass replacement mineral, (2) as pseudomorphs after primary igneous ferromagnesian minerals, (3) as irregular inclusions within altered feldspars phenochrysts and (4) as veins (millimeter scale) and vugs in all members, especially in sheared rocks.

Representative microprobe analyses and structural formula of chlorite are presented in Table 1. The chlorite varies in composition between ripidolite to brunsvigite according to the classification scheme of Foster (1962) in Figure 3. The chemical analyses show that chlorite compositions are relatively 'pure' and have very low or negligible concentration of Ca, Na and K, typical of interstratified chlorite associated with smectite component (see Evarts & Schiffman, 1983; Bettison & Schiffman, 1988).

The chlorites have Mn content ranging from 0.05 to 0.37 atoms per formula unit and have positive correlation with Fe and ^{vi}Al and negative correlation with Mg indicate Fe(+Mn)

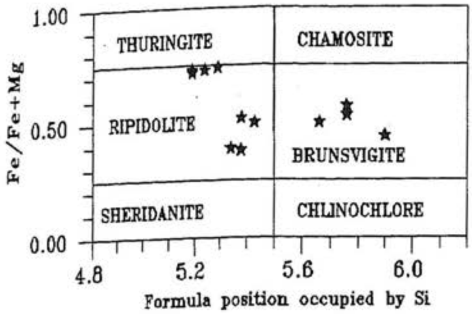

Fig. 3. Classification of chlorites from the Dir metavolcanic sequence.

= Mg type of substitution (Table 1). The total octahedral occupancies in the studied chlorites ranges from 11.66 to 12.12 which are close to the theoretical values of 12 atoms per formula unit for trioctahedral chlorite.

Biotite

Biotite occurs as small to large flakes in the chlorite-sericite groundmass of andesites, dacites and rhyolites. Textural features show that these biotites formed at the expense of chlorite, muscovite and iron ore (magnetite).

Representative analyses of biotite, from cores to margins are reported in Table 1. These biotites are the Mg-rich variety.

On the ^{vi}Al vs ^{iv}Al diagram (Fig. 4) all the biotite analyses plot above the line labeled $^{vi}Al = {}^{iv}Al-2$, showing that ^{vi}Al is not balanced by

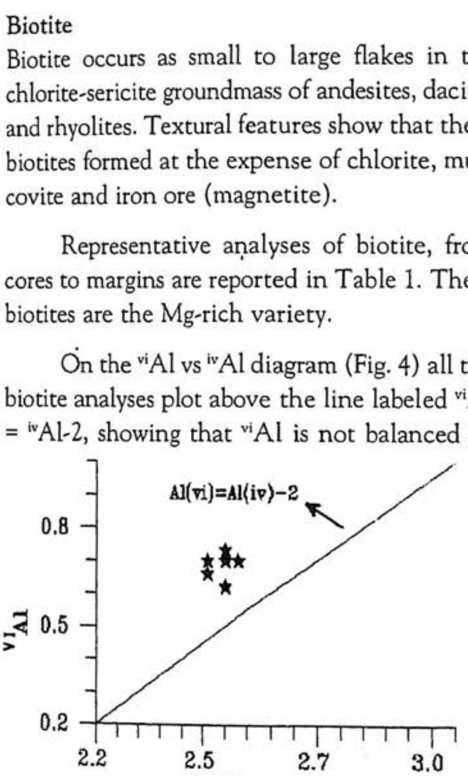

Fig. 4. ^{vi}Al vs ^{iv}Al plot of biotite from the Dir metavolcanic sequence.

^{iv}Al according to the Al-tchermak's substitution $(R^{2+})+(Si^{4+}) = (Al^{3+})^{vi}+(Al^{3+})^{iv}$ (Dymek, 1983). In all these biotites, the sum of the octahedral site is <6 atoms per formula unit and have a range of 5.69 to 5.80. Theoretically, biotite has two atoms per formula unit (sum of Ca, Na and K) in the interlayer site. The sum of inte rlayer cations in the studied biotite range from 1.87 to 1.98 i.e. less than the theoretical values, indicating possible vacancies. Similar vacancies in the interlayer sites have also been reported by earlier workers (i.e. Foster, 1960; Deer et al, 1962; Craw et al, 1962; AlDahan & Morad, 1986; AlDahan et al., 1988).

Muscovite

Muscovite occurs as scattered flakes in the groundmass of altered mafic and felsic metavolcanics.. Representative analyses are shown in Table 1. These muscovites have ^{vi}Al ranges from 2.93 to 3.44, and Mg and Fe range from 0.25 to 0.55 and 0.40 to 0.92, respectively. The total octahedral cations in the studied muscovite vary between 4.22 to 4.55. The K (1.77 to 1.88 atoms per formula unit) is the dominant interlayer cation with Na ranging from .04 to 0.07 atoms per formula unit. The amount of Ca at this position is negligible.

DISCUSSION

Metamorphic assemblages of the Dir metavolcanic sequence have been divided in to two groups: (1) albite + oligoclase + epidote + chlorite + actinolite in mafic to felsic metavolcanics and (2) albite + oligoclase + andesine + epidote + hornblende in the vicinities of shear zone. The former assemblage corresponds to the greenschist facies, while the latter corresponds to the epidote amphibolite facies. The Dir metavolcanic sequence is conspicuously foliated, but original textural features are commonly preserved except where shearing is pervasive. Under lower greenschist facies conditions, the glass and much of the cryptocrystalline groundmass has turned into chlorite. Psedumorphs of mafic phases like clinopyroxenes and hornblende occure (see Hamidullah & Shah, 1993; Hamidullah et al., 1990). Calcic-plagioclase is replaced by (oligoclase-andesine and/or albite) + epidote assemblage. Though primary magnetite/titanomagnetite has been observed but its transformation to ilmenite is most common.

The presence of quartz, albite-oligoclase, chlorite, actinolite, epidote and calcite in the studied rocks represents an assemblage typical of greenschist facies metabasites (Hart & Grahm, 1975; Will et al., 1990). However, where bluish-green to green pleochroic hornblende has developed at the expanse of epidote, actinolite, feldspar and opaque phases, points to the prevalence of further higher metamorphic conditions of lower epidote-amphibolite facies.

On the of ^{vi}Al vs ^{iv}Al plot most of the analyses occur below the assumed 5 kb line of Raase (1974) and within the low-pressure field of Fleet and Barnett (1978) (Fig. 4). This suggests formation of these amphiboles at pressures less than 5 kb. The three analyses of

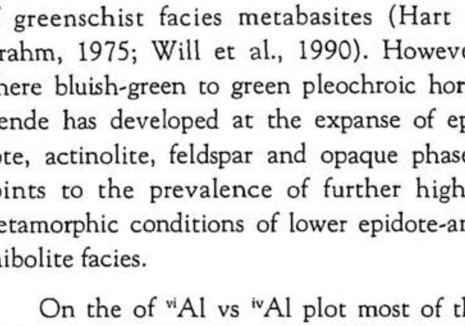

Fig. 5. Plot of ^{iv}Al vs ^{vi}Al for the amphiboles from the Dir metavolcanic sequence, showing the fields of (1) unaltered igneous calciferous amphibole, (2) low-pressure and (3) high-pressure metamorphic hornblende (after Fleet and Barrnett; 1978) and 5 Kb line of Raase (1974).

tchermakitic hornblende and tchermakite composition plot in the high-pressure field close to the 5 kb line. However, Na_B in these amphiboles is generally below 0.22 and is, therefore, indicative of a low-pressure origin (Brown, 1977). Some of the amphibole analyses plot within the field of igneous amphiboles. These amphibole grains, however, replace and follow the fabric direction of the rock indicating metamorphic growth.

The chlorites found in low grade rocks (having actinolite and actinolitic-hornblende) have higher Fe/Fe+Mg ratios as compared to higher grade rocks (having tchermakitic-hornblende and tchermakite) indicating high temperature metamorphic environment for the latter type as compared to the former (see Turnock, 1959; Cooper, 1972; Kurata & Banno, 1974; Ishizuka, 1985).

The presence of greenschist and epitode-amphibolite facies assemblages, the calcic amphiboles and their lower ^{vi}Al and the Na_B contents are indicative of low pressure metamorphism in the area (see Shido, 1958, Miyashiro, 1973, Raase, 1974, Brown, 1977, Maruyama et al., 1983; Ishizuka, 1985). The occurance of pure chlorite and actinolite in the studied rocks suggests that the temperature of metamorphism was higher than 300ºC (Evarts & Schiffman, 1983). Nitsch (1971) experimentally demonstrated that the assemblage actinolite + chlorite + albite + quartz is stable above 350ºC (at P_f=P_t=2 kb). Experimental work of Liou et al. (1974) suggest 475ºC as upper thermal boundary for the typical greenschist assemblage (albite + epidote + chlorite + actinolite) and 550ºC as lower thermal boundary for the amphibolite assemblage (calcic-plagioclase + hornblende) at P_f=P_t=2 kb and oxygen fugacity of quartz + fayalite-magnetite (QFM) buffer. The mineral assemblage transitional from greenschist to amphibolite facies (i.e. actinolite

+ plagioclase + chlorite) remained stable within the temperature interval between 475-550ºC during the same experiment of Liou et al. (1974). This transitional zone has further been divided by Maruyama et al. (1983) in to three subzones on the basis of plagioclase and amphiboles composition; (1) albite + oligoclase + actinolite + epidote + chlorite, (2) albite + oligoclase + hornblende + epidote + chlorite and (3) plagioclase + hornblende + epidote + chlorite.

The development of actinolitic-hornblende, plagioclase (albite-oligoclase), epidote, and chlorite in the Dir metavolcanic sequence corresponds to the second transition zone assemblage of Maruyama et al. (1983). The development of tchermakite, plagioclase (oligoclase-andesine) and epidote on the other hand correspond to the epidote-amphibolite facies metamorphism. Applying the experimental results of Nitsch (971) and Liou et al. (1974) along with other mineralogical constraints of the Dir metavolcanic sequence, It is suggested that the rocks of the sequence have undergone progressive metamorphism from greenschist facies to epidote-amphibolite facies in the temperature range of about 350 to 500ºC

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