Geol. Bull. Univ. Peshawar, Vol. 26, pp. 59–73, 1993

Mineralogical constraints of the Shergarh Sar amphibolites, Allai Kohistan, northern Pakistan

M. TAHIR SHAH & M. QASIM JAN

NCE in Geology University of Peshawar, Pakistan

ABSTRACT: *Shergarh Sar amphibolites, a part of the southern amphibolite belt, are widely exposed in the area around Bana in Allai Kohistan. Epidote-amphibolite is the main unit with scattered patches of garnet-bearing variety. Amphibole, epidote and ,in some, garnet are the main phases with minor amount of quartz, plagioclase, clinopyroxene, opaque oxides and rutile. Amphiboles range in composition from tchermakitic-hornblende to actinolite with magnesio-hornblende as an intermediate phase. This transition is marked by decrease in* ^{iv}*Al Ti, alkalies and* Fe^{2+}/Mg *ratio and increase in Si. Epidote occurs as large crystals (both zoned and unzoned) with low Ps contents (9-15) and as small granular aggregates with high Ps contents (17-27). Garnet occurs sporadically in the form of porphyroblasts and is found in association with leucocretic veins. It is chemically unzoned and is predominantly made up of almandine-grossular-pyrope solid solution. Plagioclase ranges from* An_{27} *to pure albite and clinopyroxene is chemically homogeneous diopside.*

Petrographic observations and thermobarometry suggest that the rocks were initially equilibrated under amphibolite facies with overprinting of greenschist facies assemblage. This retrogression may have been facilitated by shearing during the obduction (uplift-cooling) of the rocks along the Indus suture following their Eocene collesion with the Indian plate.

INTRODUCTION

Amphibolites are the most voluminous rocks in the Shergarh Sar area north of Bana town in Allai Kohistan (Fig.1). These amphibolites are considered to be a part of the southern (Kamila) amphibolite belt of Kohistan (Jan, 1988). This belt of possibly late Jurassic to early Cretaceous age is composed mainly of volcanic and plutonic precursors with rare siliceous and calcareous metasediments (see Jan, 1979). It overlies ultramafic rocks and tectonic melange of the Indus suture zone, but in some places it thrusts over rocks of the Indian plate.

The Shergarh Sar amphibolites (Fig. 1) are massive to banded and mostly epidote-bearing, with scattered patches of garnet epidote-amphibolites (Shah, 1986; Shah et al., 1992). These are characterized by dark-green to light-gray colour with linear fabrics defined by segregations of felsic and mafic minerals. The epidote-amphibolites are medium- to coarse-grained rocks having inequigranular porphyroblastic to subidioblastic texture. Their major mineral constituents are hornblende, epidote, and quartz. Chlorite, actinolite and ores occur as minor constituents, while rutile apatite and calcite as accessories. Small amounts of plagioclase and clinopyroxene occur rarely in these rocks. Mineralogically, the garnet-bearing epidote-amphibolites are similar to epidote-amphibolites except for the presence of garnet.

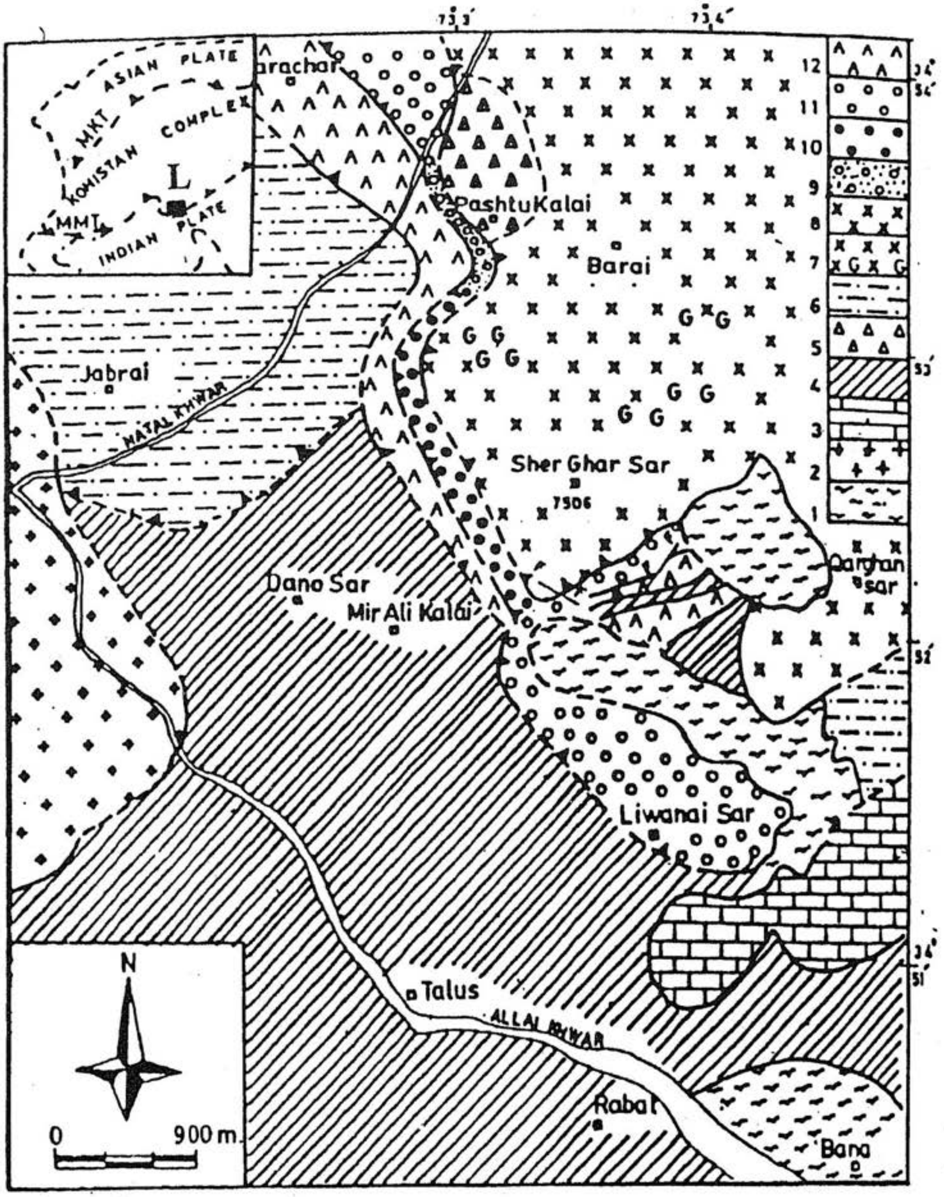

Fig. 1 Geological map of Shergarh Sar area, Allai Kohistan (after Shah, 1985). 1. Granite gneiss, 2. Limestone, 3. Schists, 4. Brecciated zone, 5. Greenschist, 6. Garnet epidote-amphibolites, 7. Epidote-amphibolites, 8. Serpentinite, 9. Peridotite, 10. Clinopyroxenite, 11. Lavas, 12. Overburden. MMT = Main Mantle Thrust; MKT = Main Karakoram Thrust. L = location of the area. Solid lines are thrust contacts, dashed where inferred.

Shah (1986) and Shah et al. (1992) described the geochemical characteristics of the Shergarh Sar amphibolites and suggested that these are derived from basic igneous rocks of tholeiitic character. These workers further suggested that plagioclase, clinopyroxene, and olivine fractionation played a major role in the evolution of igneous crystallization trend of

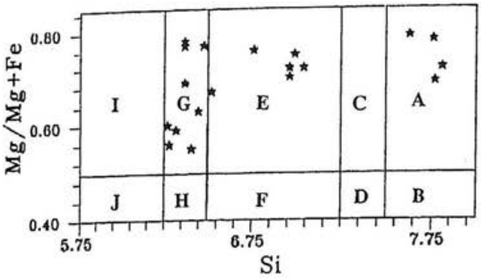

Fig. 2 Amphiboles from the amphibolites of Shergarh sar area on Mg/Mg+Fe vs Si diagram. Nomenclature is according to the International Mineralogical Association (Leake, 1978). A = actinolite, B = ferro-actinolite, C = actinolitic-hornblende, D = ferro-actinolitic-hornblende, E = magnesio-hornblende, F = ferro-hornblende, G = tchermakitic-hornblende, H = ferro-tchermakitic-hornblende, I = tchermakite, and J = ferro-tchermakite.

these amphibolites. Zahid (1991) and Hamidullah et al. (1991) presented mineralogical constraints of similar amphibolites from Gantar area, further eastward of the studied amphibolites. This paper presents the results of mineral-chemical investigations of the Shergarh Sar amphibolites; the main objective is to define the metamorphic history and its effect on the chemical and optical properties of index minerals.

MINERAL CHEMISTRY

The mineral phases in the amphibolites of the Shergar Sar area have been analyzed using the Cameca SX-50 electron microprobe at the University of South Carolina, Columbia. 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. Three main mineral phases (i.e., amphibole, epidote and garnet) along with minor phases (i.e., plagioclase and pyroxene) were analyzed in selected samples in order to find out the variation in element abundance and change in color caused by metamorphic changes.

Amphiboles

On the basis of colour and pleochroism, the amphiboles are distinguishable into three varieties: (1) green to dark green, (2) blue-green to green, and (3) colorless to green. These have the following disposition in different rocks: entire grain made up either of (1), (2) or, rarely (3); zoned grains with cores of (1) and margins of (2), cores of (2) and margins of (3), and cores of (1), middle zone of (2) and margins of (3). At places the amphiboles are also rimed around the clinopyroxene. Textural evidence suggests that the dark green (locally olive) type has formed at peak metamorphic conditions, and the colourless to green variety during retrograde greenschist facies metamorphism with the transitional bluish green type probably during waning stages of epidote amphibolite facies metamorphism. Similar textural features are also observed further east of Shergarh Sar by Zahid (1991), Hamidullah et al. (1991) in the amphibolites of Gantar area.

Microprobe analyses of ten grains in six representative amphibolites are listed in Table 1. Total iron, determined as FeO, was partitioned into Fe_2O_3 and FeO, assuming the total number of cations (Ca+Na+K) = 13, on 23 (O) basis (Laired & Albee, 1981). All the analyses are calcic with Ca atoms in excess of 1.5 in half unit cell. According to IMA nomenclature (Leake, 1978), the dark green amphibole classifies as tchermakitic-hornblende, the bluish green as magnesio-horblende, and the colorless to green pleochroic as actinolite. The transition from tchermakitic hornblende to actinolite is marked, in addition to fall in ^{iv}Al and increase in Si, by decrease in ^{vi}Al, Ti, alkalies, A-site occupancy and Fe^{2+}/ Mg ratios. These changes are suggestive of lowering temperature (Liou et al., 1974; Laird & Albee, 1981;

TABLE 1. CHEMICAL ANALYSES AND STRUCTURAL FORMULAE OF AMPHIBOLES FROM SHERGARH SAR AMPHIBOLITES .

Sample No	Alk46A		Alk40		Alk33		Alk21		Alk33		Alk 8		Alk 92A		Alk 92A		Alk33		Alk40
Grain No	1		2		3		4		5		6		7		8		9		10
	Core	Rim	Core	Rim	Core	Rim	Core	Rim	Core	Rim	Core	Rim	Core	Rim	Core	Rim	Core	Rim	Core
SiO_2	44.61	44.66	44.74	44.01	42.86	42.76	43.32	43.39	45.69	47.50	43.86	48.70	48.54	47.78	49.12	54.67	53.78	53.22	54.17
TiO_2	0.33	0.31	1.08	0.99	0.70	0.51	0.94	0.61	0.62	0.56	0.63	0.43	0.67	0.57	0.54	0.03	0.01	0.04	0.07
Al_2O_3	14.97	14.83	12.21	12.88	16.30	16.18	15.21	15.39	14.21	11.50	14.47	9.22	9.81	10.02	9.02	2.31	1.54	1.32	2.40
FeO	12.37	12.84	15.15	16.09	15.63	15.64	15.89	15.12	10.64	11.43	14.51	11.94	12.62	12.15	12.69	13.26	12.73	15.64	13.79
MnO	0.06	0.12	0.17	0.13	0.23	0.32	0.20	0.33	0.20	0.26	0.13	0.06	0.06	0.08	0.04	0.25	0.30	0.30	0.25
MgO	12.13	12.03	11.00	10.17	8.63	8.80	9.15	8.77	13.22	13.50	10.69	13.40	13.08	12.75	13.75	14.98	15.85	14.01	14.34
CaO	10.96	11.07	11.20	11.28	10.71	10.59	10.95	11.04	12.62	12.15	10.78	11.78	11.63	11.53	11.73	11.51	11.41	11.39	11.39
Na_2O	1.96	2.02	1.35	1.37	2.27	2.13	1.84	1.79	0.91	0.90	2.08	1.06	1.06	1.15	1.00	0.49	0.42	0.42	0.61
K_2O	0.02	0.04	0.28	0.25	0.27	0.22	0.24	0.22	0.07	0.06	0.07	0.00	0.01	0.02	0.01	0.03	0.02	0.00	0.00
Cl	0.00	0.00	0.02	0.00	0.06	0.04	0.07	0.01	0.04	0.01	0.01	0.02	0.03	0.16	0.02	0.00	0.00	0.00	0.00
TOTAL	97.41	97.92	97.20	97.17	97.66	97.19	97.81	96.67	98.22	97.87	97.23	96.61	97.51	96.21	97.92	97.53	96.06	96.34	97.02

Table 1 continued

Cations on 23 (O) basis																			
Si	6.37	6.37	6.52	6.45	6.28	6.27	6.32	6.41	6.48	6.76	6.37	7.04	6.96	6.96	6.99	7.81	7.76	7.77	7.63
Al	1.63	1.63	1.48	1.55	1.72	1.73	1.68	1.59	1.52	1.24	1.64	0.96	1.04	1.04	1.01	0.19	0.24	0.23	0.38
Site C																			
Al	0.90	0.86	0.62	0.68	1.10	1.07	0.94	1.09	0.86	0.69	0.84	0.61	0.61	0.68	0.51	0.20	0.02	0.00	0.11
Ti	0.04	0.03	0.12	0.11	0.08	0.06	0.10	0.07	0.07	0.06	0.07	0.05	0.07	0.06	0.06	0.00	0.00	0.00	0.00
Fe^{3+}	0.72	0.78	1.16	1.30	1.50	1.26	1.40	1.56	0.82	0.92	1.06	1.14	1.09	1.17	0.99	1.26	0.96	1.37	0.91
Fe^{2+}	0.76	0.75	0.68	0.67	0.41	0.66	0.54	0.31	0.44	0.47	0.70	0.30	0.42	0.31	0.53	0.33	0.57	0.54	0.52
Mn	0.00	0.01	0.02	0.02	0.00	0.04	0.03	0.04	0.02	0.00	0.02	0.00	0.00	0.01	0.00	0.03	0.04	0.04	0.04
Mg	2.58	2.56	2.39	2.22	1.88	1.92	1.99	1.93	2.79	2.86	2.31	2.89	2.79	2.77	2.92	3.19	3.41	3.05	3.42
Site B																			
Ca	1.68	1.69	1.75	1.77	1.68	1.66	1.71	1.75	1.92	1.85	1.68	1.83	1.79	1.80	1.79	1.76	1.76	1.78	1.78
Na	0.32	0.31	0.25	0.23	0.32	0.34	0.29	0.25	0.08	0.15	0.32	0.18	0.21	0.20	0.21	0.14	0.12	0.12	0.17
Site A																			
Na	0.22	0.25	0.13	0.16	0.33	0.19	0.23	0.26	0.17	0.10	0.26	0.12	0.08	0.12	0.07	0.00	0.00	0.00	0.00
K	0.00	0.00	0.05	0.05	0.05	0.05	0.05	0.04	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fe/Mg	0.28	0.31	0.49	0.59	0.80	0.65	0.70	0.81	0.30	0.32	0.46	0.40	0.39	0.42	0.34	0.39	0.28	0.45	0.26
Mg/Mg+Fe	0.78	0.77	0.67	0.63	0.56	0.60	0.59	0.55	0.77	0.76	0.69	0.72	0.72	0.70	0.75	0.72	0.78	0.69	0.79
Mg#	63.61	62.55	56.41	52.98	49.60	50.07	50.65	50.83	68.89	67.80	56.77	66.67	64.88	65.16	65.89	66.82	68.94	61.49	64.96

1-4 = Unzoned green to dark green hornblende with brownish tint.

5&6 = Zoned hornblende having green core and bluish green rim.

7 = Unzoned bluish green hornblende.

8 = Zoned bluish green hornblende with marginal actinolite.

9&10 = Actinolites.

Spear, 1981; Jan & Howie, 1982) and confirm the petrographic observations.

Complex substitutions in the composition of the amphiboles were studied graphically by plotting the analyses in various ways. Figure 3 shows the position of several amphibole end members on ^{iv}Al vs ^{vi}Al + 2Ti + Fe^{3+} diagram. The amphibole analyses plot along a well-defined trend and clearly show substantial tchermakite and subordinate glaucophane substitution from actinolite to tchermakitic-hornblende. A similar picture emerges when the analyses are plotted on (Na)$_B$ vs Al + 2Ti +Fe^{3+} diagram (Fig. 3). In Figure 4 the analyses are plotted in terms of A-site vacancy-Al^{iv}-Al^{vi} components. Again a substantial tchermakitic substitution and minor edenitic substitution from actinolite to tchermakitic-horblende, resulting in a trend towards pargasite, are observed.

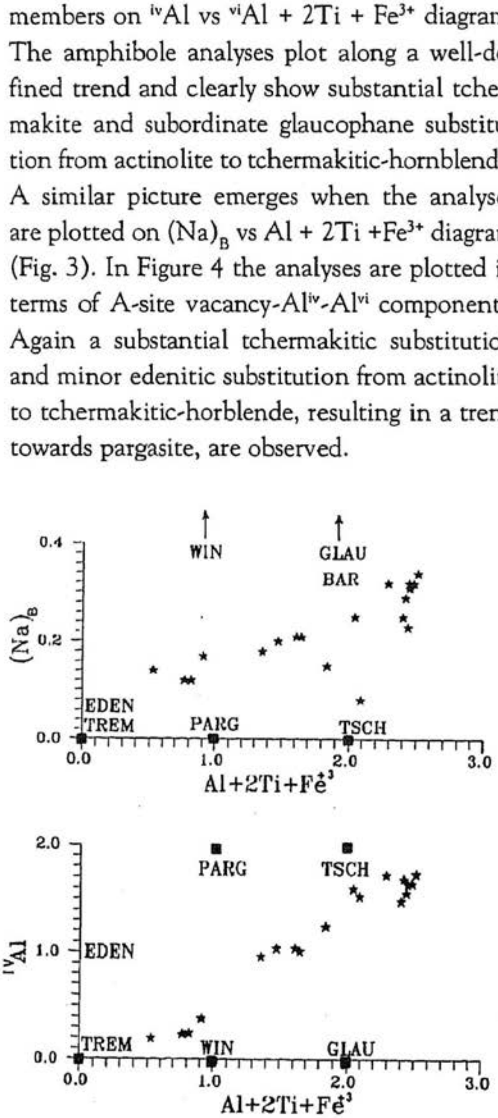

Fig. 3 Plots of ^{iv}Al and Na$_B$ vs ^{vi}Al + 2Ti + Fe^{3+} for analysed amphiboles, together with the positions of some amphibole end members.

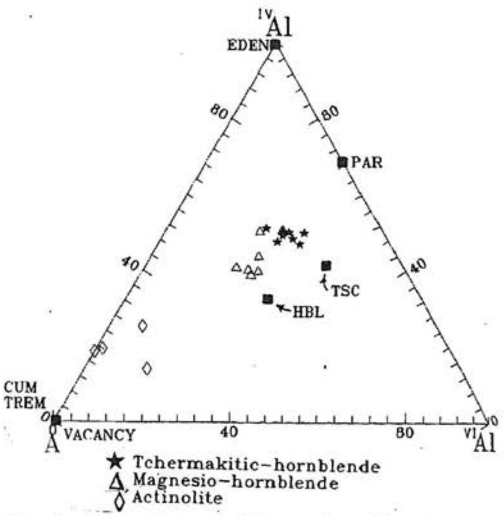

Fig. 4 Composition of the analysed amphiboles in terms of ^{vi}Al, ^{iv}Al and A site vacancy (adapted from Blundy and Holland, 1990).

Epidote

Epidote occurs in two habits: (a) as long subhedral to anhedral grains up to 4x2 mm in size, and (b) as small granular aggregates with bright interference colors. The type "a" epidote crystals are weakly zoned with cores displaying an anomalous bluish gray interference color and margins showing normal gray to yellow interference color. In some cases an additional highly birefringent rim of type "b" epidote surrounds the type "a" epidote. The type "a" epidote occurs in close association with hornblende and both minerals are commonly intergrown. In the banded epidote-amphibolites, the dark bands consist of type "a" epidote and hornblende, whereas the white bands generally contain quartz and feldspar. In such rocks, the type "a" epidote may occur as "augen porphyroblasts" surrounded by relatively finer grains of prismatic hornblende.

Chemical composition of both the varieties of epidote are given in Table 2. It is clear from this table that the change in interference colour reflects the change in chemistry (especially iron contents) in these epidotes. The bluish gray cores of the type "a" epidotes are

TABLE 2. CHEMICAL COMPOSITION AND STRUCTURAL FORMULAE OF TYPE "A" AND TYPE "B" EPIDOTES FROM SHERGARH SAR AMPHIBOLITES.

Sample Nos	Alk46A		Alk92A		Alk33		Alk8		Alk33	Alk8	Alk46A	Alk37
Grain Nos	1		2		3		4		5	6	7	8
	Core(B)	Rim(Y)	Core(B)	Rim(B)	Core(Y)	Rim(Y)	Core(Y)	Rim(Y)	B1	B2	B3	B4
SiO_2	38.52	37.64	38.20	37.56	38.22	38.03	36.71	36.69	36.48	38.25	37.59	35.17
TiO_2	0.09	0.17	0.04	0.26	0.18	0.15	0.19	0.30	0.22	0.11	0.01	0.07
Al_2O_3	29.85	27.85	29.97	27.12	28.29	28.27	26.96	26.27	25.26	27.39	25.16	25.27
Fe_2O_3	5.02	7.94	4.99	8.00	7.56	7.70	8.78	8.99	10.00	8.71	10.70	14.21
MnO	0.02	0.07	0.11	0.03	0.20	0.30	0.16	0.17	0.21	0.29	0.18	0.26
CaO	23.84	23.31	23.61	23.24	22.43	22.06	23.02	22.84	23.05	23.23	23.71	22.02
TOTAL	97.34	96.98	96.92	96.21	96.88	96.51	95.82	95.26	95.22	97.98	97.35	97.00
Cation on 13 (O,OH) basis												
Si	3.11	3.08	3.10	3.10	3.12	3.11	3.06	3.08	3.08	3.11	3.10	2.95
^{iv}Al	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05
^{vi}Al	2.84	2.68	2.86	2.64	2.72	2.73	2.65	2.60	2.51	2.62	2.45	2.45
Ti	0.01	0.01	0.00	0.02	0.01	0.01	0.01	0.02	0.01	0.01	0.00	0.00
Fe	0.30	0.49	0.30	0.49	0.46	0.47	0.55	0.57	0.63	0.53	0.67	0.90
Mn	0.00	0.00	0.0	0.00	0.01	0.02	0.01	0.01	0.01	0.02	0.01	0.02
Ca	2.06	2.04	2.05	2.06	1.96	1.93	2.05	2.05	2.09	2.02	2.10	1.97
PS	9.55	15.45	9.49	15.65	14.47	14.69	16.93	17.20	20.06	16.83	21.47	26.86

1&2 = Zoned type "a" epidote.
3&4 = Unzoned type "a" epidote.
5,6,7&8 = Type "b" epidote.
Ps = Pistacite contents.
B = Blue, Y = Yellow in crossed polars

compositionally Al-epidotes (Holdaways, 1972) with pistacite contents [Ps = 100 $Fe^{3+}/(Fe^{3+}+Al)$] of 9.5 to 14.5. These epidotes are considered to be stable at epidote-amphibolite/amphibolite facies conditions attained by the host rock. The rims are yellow in color with epidote compositions having a Ps content greater than 15. This zoning can be attributed to retrogressive metamorphism (see Miyashiro & Seki, 1958) and is observed only in the large crystals (2-4 mm in size) of type "a" epidote. The smaller type "a" epidote grains (<2mm in size) are unzoned and match well the rims of the zoned epidotes in interference colour and composition. The type "b" epidotes occur as fine-grained granular aggregates. They have greater iron contents (Ps = 17-27) and range from Al-epidotes to Fe-epidotes. Such compositions are typical of greenschist metamorphism (Holdaway, 1966; Cooper, 1972) and are considered here to imply lower equilibration temperatures than the type "a" epidote. The type "b" epidotes also have higher contents of MnO than the type "a" epidotes.

The abundant epidote in the Shergarh Sar amphibolites appears to reflect the calcium-rich nature of the parent rock. Its occurrence is attributed to the release of Ca (mainly from calcic- plagioclase) during the regional metamorphism of epidote-amphibolite facies conditions, which is supported by the presence of albite in the rock. The attainment of the large size of these epidote grains may suggest the prevalence of these conditions for a considerable time or rapid reaction velocities.

Garnet

The occurrence of garnet in the epidote-amphibolites of the area is sporadic. It is generally confined to those places where leucocratic veins and bands are prominent. The garnet commonly forms porphyroblasts up to 6 cm across. It is colourless to pinkish in thin section, and usually found along the contact of hornblende and type "a" epidote. These features suggest that the garnet may have formed at the expense of hornblende and type "a" epidote. Quartz surrounding garnet crystals and occupying microveins, diverging from reaction spots, is especially common.

Five grains in different samples were analyzed from core to rim and the analyses are presented in Table 3. The structural formulae, recalculated on the basis of 24 oxygens, closely correspond to the ideal formula $X^{2+}_{3}Y^{3+}_{2}Z_{3}O_{12}$. No distinct variation in chemical composition is present from core to margin in single grain analyses. However, different grains display noticeable variation in Fe, Mg, Mn, and Ca within a thin section. The lack of zoning in garnet in these rocks suggests that it may have escaped retrogressive metamorphism, however, variation from grain to grain within the domain of a thin section suggests local equilibration. The garnet is predominantly made up of almandine component with substantial pyrope and grossular solid-solution (Alm_{44-60} Pyr_{14-39} $Gros_{13-26}$). These compositions are broadly within the range of previous analyses from amphibolite belt discussed by Jan and Howie (1987), except for the rather low grossular + andradite contents of the analyses in sample Alk 49A. The average CaO (8wt.%) is within the range of garnet from metabasites of medium to high pressure (Miyashiro, 1973).

All the analyses (core to rim) have been plotted on the pyrope-(almandine + spessertine)-(grossular + andradite) triangular diagram (Fig. 5) of Dobretsov et al. (1972). Four of the analyses plot within the overlapping field of eclogite and granulites while the rest of the analyses plot in the amphibolite garnet field. No analysis falls in the field of garnet from epidote-amphibolites.

The development of sporadic garnet in amphibolites has been attributed to variation

TABLE 3. CHEMICAL COMPOSITION AND STRUCTURAL FORMULAE OF GARNET FROM SHERGARH SAR AMPHIBOLITES

Sample No.	Alk8		Alk8		Alk9		Alk92A		Alk49A	
Grain N	1		2		3		4		5	
	Core	Rim	Core	Rim	Core	Rim	Core	Rim	Core	Rim
SIO_2	38.25	38.52	38.71	38.80	39.00	38.65	38.13	38.14	39.59	39.79
TiO_2	0.05	0.19	0.06	0.08	0.05	0.03	0.04	0.32	0.01	0.00
Al_2O_3	21.25	21.38	21.80	21.87	22.06	21.94	21.03	21.60	22.42	22.65
CrO_3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fe_2O_3	0.55	0.43	0.32	0.19	0.14	0.12	0.69	0.00	0.00	0.00
FeO	26.66	26.14	22.39	23.53	24.20	24.45	26.93	27.75	21.66	20.84
MnO	1.51	1.47	0.46	0.54	0.85	0.45	0.92	0.99	1.15	1.35
MgO	3.97	4.24	6.46	5.77	6.84	6.17	3.52	4.04	10.27	10.15
CaO	8.17	8.37	9.78	9.72	7.97	8.62	9.00	9.01	4.81	5.49
TOTAL	100.41	100.71	99.98	100.50	100.84	100.43	100.35	100.85	99.91	100.27
Cations on the 24 (O) basis										
Si	6.00	6.00	5.97	5.98	5.97	5.96	5.99	5.96	6.00	6.00
Al	0.00	0.00	0.03	0.02	0.03	0.04	0.01	0.04	0.00	0.00
Al	3.93	3.93	3.96	3.95	3.95	3.95	3.90	3.94	4.00	4.02
Ti	0.00	0.02	0.01	0.01	0.00	0.00	0.00	0.04	0.00	0.00
Cr	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fe^{3+}	0.06	0.05	0.04	0.02	0.01	0.01	0.08	0.00	0.00	0.00
Fe^{2+}	3.50	3.41	2.89	3.03	3.10	3.15	3.54	3.63	2.74	2.63
Mn	0.20	0.19	0.06	0.07	0.07	0.06	0.12	0.13	0.15	0.17
Mg	0.93	0.99	1.48	1.33	1.56	1.42	0.82	0.94	2.32	2.28
Ca	1.37	1.40	1.62	1.60	1.31	1.43	1.52	1.34	0.78	0.88
AL	58.35	57.03	47.78	50.31	51.32	52.09	58.99	60.28	45.80	44.40
PY	15.47	16.51	24.57	21.99	25.85	23.45	13.74	15.62	38.73	38.21
GR	21.13	21.67	25.65	25.84	21.08	23.09	23.12	21.33	13.00	14.85
SP	3.34	3.25	0.98	1.17	1.24	0.97	2.04	2.18	2.46	2.89
AD	1.71	1.54	1.02	0.69	0.49	0.40	2.10	0.57	0.02	0.00
Mg/Fe	0.27	0.29	0.51	0.44	0.50	0.45	0.23	0.26	0.85	0.87

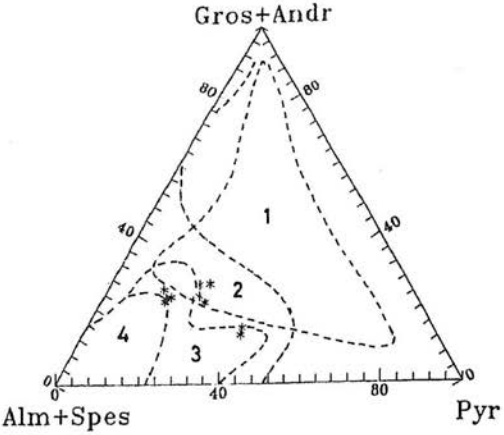

Fig. 5 Garnet of the garnet epidote-amphibolites from Shergarh Sar area on Pyrope-(Grossular + Andredite)-(Almandine + Spesertine) triangle showing the fields of garnet from (1) eclogites, (2) granulites, (3) amphibolites, and (4) epidote-amphibolites (after Dobretsove et al., 1972).

in bulk chemistry and/or changes in temperature and pressure (Engel & Engel, 1962; Leake, 1963; Buddington, 1966; Dewaard, 1967; Manna & Sen, 1974; Jan, 1988). There can be various causes of garnet growth in amphibolites currently studied: (1) low Mg/Fe^{2+} ratio (see also Jan, 1988), (2) low Fe_2O_3/FeO ratio and (3) local increase in temperature due to the intrusion of leucocretic veins.

Plagioclase

Plagioclase is generally sparse, having been replaced almost completely by type "a" epidote. When present, it is cloudy due to subsequent alteration. Analyses of two grains in two different samples are unzoned (Table 4). In one of these, the plagioclase is pure albite (An_1) while in the other it is more calcic (An_{27}) and is closely associated with bluish-green amphibole. It is possible that the former has grown in greenschist facies retrogression and the latter during epidote-amphibolite facies condition.

Clinopyroxene

Found only in a few rocks, the clinopyroxene varies from minor in amount up to 30% in rare cases. It most commonly occurs as cores within large blue-green hornblende, but is also found as small interstitial grains, along with quartz, magnetite and rutile.

Analyses of four clinopyroxenes presented in Table 5 show that they are diopsidic (Wo_{48-56} En_{37-40} Fs_{3-14}). The core to rim analyses suggest that they are very homogeneous in nature. The clinopyroxene can be divided into two groups. Those of sample Alk40 and Alk92A are normal diopsides whilst those in Alk33 are strongly aluminous (Al_2O_3 up to 7.07%) and enriched in Ca. The former have lower TiO_2 and higher FeO, MnO, and Na_2O. Several workers (e.g. Jan, 1988) have shown that the growth of clinopyroxene in amphibolites can be controlled by bulk composition (notably high CaO) and temperature. In Shergarh Sar area, there does not appear any compositional control on its growth. It is likely that the clinopyroxene grow locally in response to high temperature.

DISCUSSION

Petrographic observation, supplemented by mineral chemistry suggest that the Shergarh sar amphibolites passed through a thermal history of amphibolite to greenschist facies metamorphism. The paragenesis representing the peak metamorphic conditions realised in the area is well-preserved and abundant in most of the rocks. This consists of green tchermakitic hornblende and Al-epidote , with or without garnet and clinopyroxene. Garnet-hornblende geothermometry (estimates for average composition in three samples) suggests temperatures of 600 to 650°C following the model of Perchuk (1967) and 685 to 715°C following Powell (1985). A clinopyroxene-hornblende pair gives a temperature of 670°C (Perchuk, 1967). Maximum temperature in excess of 650°C are consistent with the presence of local granitic bands and veins which may be a partial

TABLE 4. CHEMICAL ANALYSES AND STRUCTURAL FORMULAE OF FELDSPAR FROM SHERGARH SAR AMPHIBOLITES

Sample No	Alk21		Alk92A	
	Core	Rim	Core	Rim
SiO_2	67.39	65.82	63.17	61.84
A_2O_3	21.12	21.36	25.13	24.72
MgO	0.01	0.04	0.00	0.00
CaO	0.30	0.68	5.18	5.20
MnO	0.00	0.02	0.01	0.00
FeO	0.29	0.92	0.03	0.02
BaO	0.00	0.00	0.02	0.00
Na_2O	9.76	10.20	7.52	7.79
K_2O	0.05	0.02	0.03	0.03
TOTAL	98.92	99.06	101.09	99.60
Cation on 8 (O) basis				
Si	2.96	2.91	2.75	2.74
Al	1.09	1.11	1.29	1.29
Fe	0.01	0.03	0.00	0.00
Mg	0.00	0.00	0.00	0.00
Mn	0.00	0.00	0.00	0.00
Ca	0.01	0.03	0.24	0.25
Ba	0.00	0.00	0.00	0.00
Na	0.83	0.87	0.64	0.67
K	0.00	0.00	0.00	0.00
Or	0.00	0.00	0.00	0.00
Ab	99.00	97.00	73.00	73.00
An	1.00	3.00	27.00	27.00

TABLE 5. CHEMICAL ANALYSES AND STRUCTURAL FORMULAE OF PYROXENE FROM SHERGARH SAR AMPHIBOLITES.

S. No	Alk40		Alk92A		Alk33		Alk33	
	Core	Rim	Core	Rim	Core	Rim	Core	Rim
SiO_2	50.75	49.69	50.46	50.17	47.68	47.56	47.08	47.33
TiO_2	0.25	0.35	0.23	0.31	0.50	0.51	0.59	0.60
Al_2O_3	3.58	3.75	3.41	3.63	6.85	6.66	7.07	6.87
Cr_2O_3	0.06	0.04	0.04	0.00	0.02	0.01	0.00	0.03
Fe_2O_3	2.90	3.24	2.62	2.91	3.66	4.18	4.45	3.90
FeO	7.22	7.06	7.70	7.41	2.53	2.11	2.08	2.57
MnO	0.24	0.29	0.32	0.30	0.08	0.06	0.08	0.08
MgO	12.22	12.07	12.26	12.07	12.86	12.91	12.70	12.76
CaO	22.45	21.74	21.55	21.90	24.73	24.90	24.81	24.55
Na_2O	0.62	0.65	0.66	0.64	0.05	0.05	0.06	0.06
TOTAL	100.29	98.88	99.25	99.34	98.96	98.95	98.92	98.74
Cations on 6 (O) basis								
Si	1.90	1.88	1.90	1.90	1.78	1.78	1.77	1.78
Al	0.10	0.12	0.10	0.10	0.22	0.22	0.23	0.22
Al	0.06	0.05	0.05	0.06	0.08	0.07	0.08	0.08
Ti	0.00	0.01	0.00	0.01	0.01	0.01	0.02	0.02
Fe	0.08	0.09	0.07	0.08	0.10	0.11	0.13	0.11
Fe	0.22	0.22	0.24	0.23	0.08	0.06	0.06	0.08
Mn	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.00
Mg	0.68	0.68	0.69	0.67	0.72	0.72	0.71	0.71
Ca	0.89	0.88	0.87	0.88	0.99	0.99	0.99	0.99
Na	0.04	0.05	0.05	0.05	0.00	0.00	0.00	0.00
WO	47.34	46.81	46.28	47.06	52.38	2.66	52.38	52.38
EN	36.17	36.17	36.70	35.83	38.10	38.30	37.57	37.57
FS	16.49	17.02	17.02	17.11	9.52	9.04	10.05	10.05

melting product of the amphibolite (cf. Whyllie, 1977). Such temperature have already been recorded from the amphibolite belt in Swat and adjacent Indus valley (Bard, 1983; Jan, 1988). However, a lower temperature range (500-530°C) is reported for the similar rocks at Gantar area of Allai Kohistan (see Hamidullah et al., 1991; Zahid, 1991).

The transition from amphibolite to greenschist facies metamorphic conditions in the rocks is documented by the overgrowths of bluish-green magnesio-hornblende on the tchermakitic hornblende and more ferric epidote around the Al-epidote. These appear to have grown at intermediate temperatures. The composition of a magnesio-hornblende and an adjacent calcic-oligoclase yield a temperature estimate of about 520 °C both by the model of Spear (1980) and Plyusnina (1982). Overprinted on these paragenesis in most rocks is typical greenschist facies assemblage consisting of actinolite, Fe-epidote, albite and local chlorite. The former two of these minerals occur in independent grains and as outer most zones around hornblende and Fe-poorer epidote, respectively.

Quantitative estimates of operating pressures during the metamorphic evolution of the rocks have not been obtained, however, there are indications that these may have been high. Laird and Albee (1981, Fig. 8) showed that amphiboles from low-, medium- and high-pressure metamorphic terrains plot in distinct fields on ^{iv}Al vs ^{vi}Al + Ti + Fe^{3+} diagram. The hornblendic amphiboles from the area fall in overlapping fields of medium and high-pressure fields. The plagioclase-hornblende thermobarometer of Plyusnina (1982) suggests a pressure of 5 kb for the one analysed pair referred to above. The ^{iv}Al vs ^{vi}Al plots of the hornblendic amphiboles (Fig. 6) suggest pressure in excess of 5 kb. The "garnet-epidote" thermobarometers of Dobretsov et al. (1972) gives rough estimates of 690°C and 6.2 kb for epidote with Ps contents of 15. Pressure in excess of 5 kb have already been suggested for peak metamorphism in the amphibolite belt (Bard, 1982; Jan, 1988, Treloar et al., 1989).

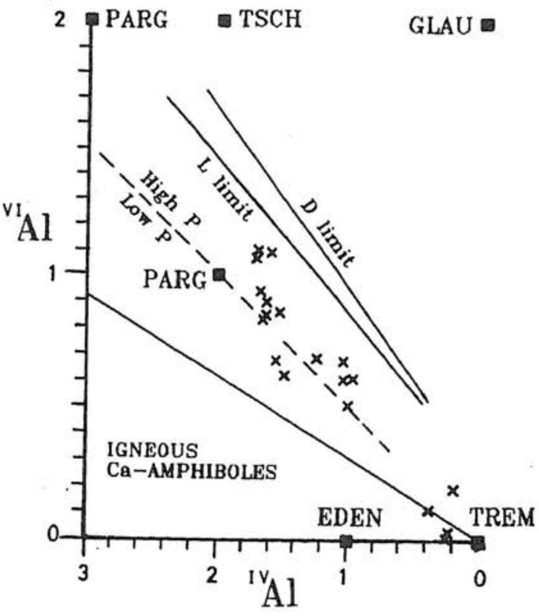

Fig. 6 Relationship of ^{vi}Al to ^{iv}Al in the analysed amphiboles. D limit is after Doolan et al. (1978) and L limit is after Leake, (1971). Fields of igneous Ca-amphiboles and the boundary of high and low pressure Ca-amphiboles are after Fleet and Barnett (1978).

Radiometric data suggest that metamorphism in southern Kohistan coincides with collision and overthrusting of Karakoram plate onto the Kohistan magmatic arc. The entire amphibolite belt is a major shear zone (Treloar et al., 1989, 1990). The amphibolite facies metamorphism, thus, occurred in response to thrust stacking and crustal thickning. The initial suturing (collision) of the Kohistan magmatic arc with the Indian plate is considered to have taken place during the Eoceine (Patriate & Achache, 1984; Treloar et al., 1989). The uplift and cooling of the amphibolite belt occurred, probably, during ensuring obduction of the

Kohistan arc and its emplacement onto the Indian plate. During this episode of uplift-cooling, overprinting of lower grade assemblages took place along grain boundaries. The process was enhanced along shear zones due to granulation and availability of fluids, mainly H_2O. The Shergarh Sar amphibolites nicely document these events. It would be fruitful to perform additional work on the mineral chemistry and radiometric ages to construct a P-T path for the rocks, beginning with their basaltic and gabbroic protoliths. Jan (1988) and Hamidullah et al. (1990, 1991) have reported several gabbroic relics in the amphibolites of Indus, Swat and Allai Kohistan valleys, and a careful search may also reveal such relics in the area under discussion.

REFERENCES

Bard, J. P., 1983. Metamorphic evolution of an obducted island arc: Example of the Kohistan sequence (Pakistan) in the Himalayan collided range. Geol. Bull. Univ. Peshawar., 16, 105-184.

Brown, E. H., 1977. The crossite content of Ca amphibole as a guide to pressure of metamorphism. Jour. Petrol., 18, 53-72.

Blundy, J. D. & Holland, J. B., 1990. Calcic amphibole equilibria and a new amphibole-plagioclase geothermometry. Contrib. Mineral. Petrol., 104, 208-224.

Buddington, A. F., 1966. The occurrence of garnet in the granulite facies terrane of the Andirondack Highlands. Jour. Petrol., 7, 331-335.

Cooper, A. F., 1972. Progressive metamorphism of metabasic rocks from the Haast schist group of southern New Zealand. Jour. Petrol., 13, 457-492.

Dobretsov, L. N., Khlestov, V. V., Reverdatto, V. V. & Sobolev, V. S., 1972. The facies of metamorphism (transl. by D. A. Brown). Australian National University Press, Canberra.

De Waard, D., 1967. The occurrence of garnet in the granulite-facies terrane of the Andirondack Highlands and elsewhere, an amplication and a reply. Jour. Petrol., 8, 210-232.

Doolan, B.L., 1975. Evaluation of the quality of Ca-amphibole analyses and an estimate of "ideal hornblende". Trans. Amer. Geoph. Union., 56, 461.

Engel, A. E. J. & Engel, C. G., 1962. Progressive metamorphism of amphibolites, north-west Adirodack mountains, New York.In: Buddington Volume. Geol. Soc. Amer. Bull., 37- 82.

Fleet, M. E. & Barnet, R. L., 1978. $^{iv}Al/^{vi}Al$ partitioning in calciferous amphiboles from the Frood mine, Subury, Ontario. Canad. Mineral., 16, 527-532.

Hamidullah, S., Bangash, I. H. & Reuber, I., 1990. Petrology of the southern amphibolite belt rocks from Mahak and surrounding area, Kohistan arc, North Pakistan. Geol. Bull. Univ. Peshawar, 23, 27-43.

Hamidullah, S., Zahid, M. & Majid. M., 1991. Mineralogy and mineral chemistry of the amphibolite belt and Main Mantle Thrust rocks from Gantar area, Allai Kohistan, North pakistan. Geol. Bull. Univ. Peshawar, 24, 133-146.

Holdaway, M. J., 1966. Hydrothermal stability of clinozoisite plus quartz. Amer. Jour. sci., 267, 643-667.

Holdaways, M. J., 1972. Thermal stability of Al-Fe epidote as a function of fO_2 and Fe contents. Contrib. Mineral. Petrol., 37, 307-340.

Jan, M. Q., 1979. Petrology of the obducted mafic and ultramafic metamorphites from the southern part of the Kohistan island arc sequence. Geol. Bull. Univ. Peshawar., 13, 95-107.

Jan, M. Q., 1988. Geochemistry of amphibolites from the southern part of the Kohistan arc, N. Pakistan. Mineral. Mag., 52, 147-159.

Jan, M. Q. & Howie, R. A., 1987. Some garnets, epidotes, biotitic micas, and feldspars from the southern part of Kohistan, NW-Pakistan. Acta. Mineralogica Pakistanica, 3, 5-25.

Knopf, E. B., 1931. Retrogressive metamorphism and phyllonitization. Amer. Jour. Sci., 21, 1-27.

Laird, J. & Albee, A. L., 1981. Pressure temperature and time indicators in mafic schist: their application to reconstucting the polymetamorphic history of Vermont. Amer. Jour. Sci., 281, 127-175.

Leake, B. E., 1963. Origin of amphibolites from northern Adirondacks, New York. Geol. Soc. Amer. Bull., 74, 1193-1202.

Leake, B.E., 1971. On aluminous and edenitic hornblendes. Mineral. Mag., 38, 389-407.

Leake, B E., 1978. Nomenclature of amphibole. Canad. Mineral., 16, 501-520.

Liou, J. G., Kuniyoshi, S., & Ito, K., 1974. Experimental studies of the phase relations between greenschist and amphibolite in a basaltic system. Amer. Jour. Sci., 274, 613- 632.

Manna, S. S. & Sen, S. K., 1974. Origin of garnet in the basic granulites around Saltora W. Bengal, India. Contrib. Mineral. Petrol., 44, 195-218.

Miyashiro, A., 1973. Metamorphism and metamorphic belts. George Allen and Unwin, London.

Patriat P. & Achache, J., 1984. India-Eurasia collision chronology and its implication for crustal shortening and driving mechanism of plates. Nature., 311, 615-621.

Perchuk, L. L., 1967. Temperature dependence of the coefficient of distribution of calcium between coexisting amphibole and plagioclase. Geochemistry, Vol.?? 203-205.

Plyusnina, L.P., 1982. Geothermometry and geobarometry of plagioclase-hornblende bearing assemblages: Contrib. Mineral. Petrol., 80, 140-146.

Powell, R., 1985. Regression diagnostics and robust regression in geothermometer / geobarometer calibration: the garnet-clinopyroxene geothermometer revisited. Jour. Met. Geol., 3, 231-243.

Raase, P., 1974. Al and Ti contents of hornblende, indicators of pressure and temperature of regional metamorphism. Contrib. Mineral. Petrol., 45, 231-236 & 157-176.

Shah, M. T., 1986. Petrochemistry of the rocks from Shergarh Sar area, Allai Kohistan, Northern Pakistan. Unpubl. M.Phil Thesis, Univ. Peshawar.

Shah, M. T. & Majid, M., Hamidullah, S. & Shervais, J. W., 1992. Petrochemical characteristics of aphibolites from Shergarh sar area, Allai Kohistan, northern Pakistan Kashmir Jour. Geol., 10, 123-139.

Spear, F. S., 1980. NaSi=CaAl exchange equilibrium between plagioclase and amphibole. Contrib. Mineral. Petrol., 72, 33-41.

Spear, F. S., 1981. An experimental study of hornblende stability and compositional variability in amphibolite. Amer. Jour. Sci., 281, 697-734.

Spry, A., 1969. Metamorphic textures. Pergamon press, New York.

Takasu, A., 1984. Prograde and retrograde eclogites in the Sambagawa metamorphic belt, Besshi district, Japan. Jour. Petrol., 25, 619-643.

Treloar, P.J. & eight others., 1989. K-Ar and Ar-Ar geochronology of the Himalayan collision in NW Pakistan. Constraints on the timing of suturing, deformation, metamorphism and uplift. Tectonics., 8, 881-909.

Treloar, P.J. & seven others., 1990. The evolution of the Komila shear zone, Kohistan, Pakistan. In: Exposed Cross-Sections of the continental crust (M.H. Salisbury, & D.M. Fountain, eds.). Kluwer Acad. Press, Amsterdam., 175-214.

Zahid, M., 1991. Petrology and geochemistry of the melange zone and southern amphibolite belt rocks from Gantar area, Allai Kohistan, Hazara, N. Pakistan. Unpubl. M.Phil. Thesis, Univ. Peshawar.