High-grade metasedimentary rocks (Gilgit Formation) in the vicinity of Gilgit, Kohistan, northern Pakistan

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A thick succession of metasedimentary and metavolcanic rocks has been reported for the first time in the Gilgit area. This succession (the Jaglot Group) comprises from bottom to top 1) the Gilgit Formation, 2) the Gashu-Confluence Volcanics, and 3) the Thelichi Formation. The Gilgit Formation consists of thick turbiditic sediments interstratified with amphibolites and calc-silicates. The lower contact of the formation is not exposed, but presumably underplated by the Chilas Complex, and the upper contact is conformable with the Gashu-Confluence Volcanics. The Gilgit Formation contains more than 80% paragneisses and schists showing metamorphism up to the sillimanite grade. The paragneisses are strongly deformed and at places migmatized.

The paragneisses of the Gilgit Formation are quartz rich, but also contain biotite, garnet, staurolite, kyanite, sillimanite, graphite, together with pyrite and magnetite. Petrographical and geochemical data show that they are metapelites, semi-metapelites and semi-metapsammities. Using geothermometry and geobarometry on garnet-biotite pairs, the estimated maximum temperature and pressure conditions are 640°C and 6.7 kbar, respectively. We assume that igneous intrusions, both the Chilas Complex and the Kohistan Batholith and crustal thickening accompanying arc accretion to the Karakoram plate might have ensued metamorphism in the Gilgit Formation and other lithological units of the Jaglot Group. As depicted by the chemical zonation profiles of garnets in two samples from Jutial, the grade of metamorphism in the metasediments of the Gilgit Formation seems to increase from top to bottom in a normal sequence. The field and laboratory studies show almandine amphibolite subfacies and sillimanite-almandine amphibolite subfacies metamorphic conditions for the Gilgit Formation, and ocean basin of a back-arc affinity for its deposition.

Keywords: Gilgit Formation, Jaglot Group, Kohistan terrane, Geothermometry, Grade of metamorphism, Back-arc basin

1. Introduction

The Kohistan terrane covers an area of about 40,000 km² in northern Pakistan. It consists of volcanic, plutonic, and sedimentary rocks variably deformed and metamorphosed. The Kohistan terrane is considered to represent an intra-oceanic island arc that developed in response to the northward subduction of Neotethyan oceanic lithosphere during Late Juras-

sic and Cretaceous times (Tahirkheli and Jan, 1979; Honegger *et al.*, 1982; Searle *et al.*, 1987). Karakoram-Asian and Indian plates bound this terrane in the north and south, respectively (Fig. 1). The two boundaries are thus marked by suture zones, namely the Main Karakoram Thrust (MKT) or Shyok suture and Main Mantle Thrust (MMT) or Indus suture, respectively (Tahirkheli and Jan, 1979; Coward *et al.*, 1986). Both the sutures are character-

Fig. 1. Sketch map of the Indian plate, Asian plate and their margins, and the tectonic position of the Kohistan and Ladakh terranes.

ized by the association of ophiolitic melanges and, in the case of MMT, blueschists and high-pressure granulites (Jan and Howie, 1981; Jan, 1991). The MKT has a closing age of 85 to 102 Ma (Petterson and Windley, 1985; Treloar *et al.*, 1989), whereas the Indus suture about 55 Ma (Powell, 1979; Klootwijk *et al.*, 1992). In the vicinity of Gilgit there are paragneisses, schists, metavolcanic rocks and calc-silicates. Here named as the Gilgit Formation, these rocks have not been paid much attention in the past. The occurrence of high-grade metasedimentary rocks in island arc terrane is intriguing and merits detailed description. It appears that these rocks are of considerable lateral extent.

This manuscript deals with the petrology, whole-rock and mineral chemistry of the paragneisses of the Gilgit Formation. Based on this study, an attempt has been made to discuss the origin and grade of metamorphism of the

formation.

II. Local geology and stratigraphy

A succession of metasedimentary and metavolcanic rocks occurs in the central part of the mapped area, west of Jaglot (Fig. 2). This succession is called as the Jaglot Group and has already been described in detail (see, Khan *et al.*, 1994, 1996; Takahashi *et al.*, 1996). The Jaglot Group of metasedimentary and metavolcanic rocks is divided into three stratigraphic units; from bottom to top: 1) the Gilgit Formation, 2) the Gashu-Confluence Volcanics, and 3) the Thelichi Formation (Fig. 3).

More than 80% of the Gilgit Formation consists of paragneisses and schists. These paragneisses and schists include both semi-sammites, semi-pelites and pelites. In several places, it appears that they have gradational relationship with each other.

Fig. 2. Geological map of part of the Kohistan terrane exposed between Chilas and Gilgit, northern Pakistan (after Khan *et al.*, 1994).

Other lithologies in the formation include amphibolites and calc-silicates. The amphibolites are more abundant and form laterally continuous horizons (Khan *et al.*, 1994). The calc-silicate horizons are common in the upper part of the formation above the amphibolite horizon. The contact of the Gilgit Formation with the overlying volcanic rocks seems to be conformable.

The Gashu-Confluence Volcanics are exposed on the roadside between Thelichi and Jaglot. They comprise tuffs and flows. The volcanics and associated rocks are metamorphosed to lower amphibolite facies of regional metamorphism. The upper contact of these rocks with the Thelichi Formation is sheared. We consider the possibility of an unconformity at this contact. This speculation is based on a distinct break in the grade of regional

metamorphism between the Gashu-Confluence Volcanics and the Thelichi Formation; the former is lower amphibolite/upper greenschist and the latter hardly approaches lower greenschist facies.

The Thelichi Formation comprises a sequence of slate, marble and metavolcanic rocks. The chemistry of the metavolcanic rocks is consistent with the back-arc basin basalts (Khan *et al.*, 1994, 1996). They are fine-grained and schistose to massive, presumably comprising volcanoclastic sediments and flows. The rest of the formation comprises predominantly of interbedded slate, sandstone and siltstone of turbidite origin, and marble in the middle part of the formation. The marble unit is laterally persistent and serves as a useful marker horizon. The upper contact of the Thelichi Formation is not exposed.

Fig. 3. Stratigraphic correlation of the rocks in the Kohistan terrane exposed between Chilas and Gilgit. (1) Chileli Gah, (2) Shinghai Gah, (3) Sai Nala, and (4) Thelichi-Jaglot section. F, Fault.

The southern part of the mapped area comprises the Chilas Complex (Jan *et al.*, 1984; Khan *et al.*, 1989). It contains gabbro, gabbro-norite, quartz diorite and ultramafite. The complex has intruded the Jaglot Group rocks, and itself is intruded by the Kohistan Batholith. At the northern margin of the Chilas Complex, xenoliths of amphibolite and metasediments are incorporated. In the south of the mapped area (northeast of Raikot bridge) the complex has faulted and sheared contact with the Kamila Amphibolites.

A major part of the investigated area is occupied by the Kohistan Batholith. The batho-

lith comprises plutons of different ages (for detailed description, see Jan *et al.*, 1981; Jan and Asif, 1983; Petterson and Windley, 1985; Khan *et al.*, 1994). Mafic dykes, which are subordinate in amount, intrude the rocks of the Chilas Complex and the Kohistan Batholith (Jan *et al.*, 1984; Khan *et al.*, 1992; Sawada *et al.*, 1993). Recent deposits (including alluvium, colluvium and glaciofluvium) are mainly concentrated at the snouts and in the upper reaches of the valleys between Chilas and Gilgit.

Due to overturned, isoclinal and tight upright folding and faulting in the Kohistan terrane, the true thickness of the rock units is

difficult to estimate. However, a possible litho-stratigraphic construction of the Jaglot Group has been made and presented in Fig. 3. For structural details see Coward *et al.* (1987) and Khan *et al.* (1994).

III. Regional stratigraphic correlation

The Gilgit Formation occurs in three NW-SE trending belts. The main belt (15 × 40 km) is located probably in the core of a large antiform (Coward *et al.*, 1987). The other two belts each 500 m broad occupy the two limbs of the Jaglot syncline to enclose the overlying Gashu-Confluence Volcanics and the Thelichi Formation. The stratigraphic position of Yasin Group rocks above the Chalt Volcanics (Pettersen *et al.*, 1990) is similar to that of the Thelichi Formation above the Gashu-Confluence Volcanics. Lithological similarities together with structural arguments suggest that the Gashu-Confluence Volcanics and the Thelichi Formation are the equivalents of the Chalt Volcanics and the Yasin Group of Pudsey (1986).

The Gilgit Formation resembles the Katzarah Formation in lithology and stratigraphic position (Hanson, 1989) in part of the Kohistan terrane extending to the east into the Baltistan region (not shown in the map). Here the formation consists of metasediments, regionally metamorphosed to garnet and sillimanite grades, overlain by volcanoclastic sedimentary and metavolcanic rocks similar to the Gashu-Confluence Volcanics. Similar rocks are also reported from west of the mapped area in Swat as Karandukai schists (Tahirkheli, 1982)?

IV. Field features and petrography

The paragneisses of the Gilgit Formation trend in NW-SE direction with steep dips either towards south or north. In Sai Nala, which is the type locality, the paragneisses consist main-

ly of semi-metapsammites and metapelites with subordinate semi-metapelites. A brief description of each of the rock units is presented in the following.

1. Metapelites and semi-metapelites

They occur in Sai Nala, to the west of Hurkus, near Bar Kas (not shown in the map) and the junction of Gashu Gah and Sai Nala. The rocks trend N60°W and dip 85°SW. The metapelites weathered brownish gray and semi-metapelites grayish brown. The two can thus be generally distinguished by the colour contrast and their quartz content (present in them). Garnet and other aluminous minerals are abundant in the more pelitic rocks. At Urkiki (Sai Nala), the metapelites/semi-metapelites trend N30°W and dip 70°SW. These rocks contain quartz, biotite, muscovite, plagioclase, garnet ± kyanite (kyanite is recorded only at this locality). Garnet forms porphyroblasts of two types: (i) red-coloured, transparent and deformed, and (ii) dark brown-coloured, translucent and less deformed. The garnet porphyroblasts cut the schistosity planes and the crenulations in these rocks. Calcite and quartz veins traversing them are folded and boudinaged.

Petrographic studies have been conducted on 18 rock samples collected in Sai Nala (ST), Jutial Gah, Jutial (JP), and Jaglot, along the Karakoram Highway (JT). The metapelites and semi-metapelites are fine to medium-grained, nematoblastic and porphyroblastic. Subpoikloblastic and symplectitic textures are noticed in quartz-sillimanite-garnet-biotite-muscovite-staurolite (ST21) and quartz-biotite-muscovite gneisses (ST16) are also found. Epidote, garnet, staurolite, sillimanite, graphite, magnetite and pyrite are present locally. Quartz grains are abundant in the groundmass and also as tiny inclusions in garnet and at places in sillimanite. Quartz grains are anhedral, strained and fractured, and sub-

Fig. 4. Photomicrograph showing garnet porphyroblast, fibrolite (sillimanite), quartz and biotite (ST21). The peripheries of the garnet are partly consumed and/or invaded by quartz, fibrolite and biotite matrix minerals. The photomicrograph also shows margins of garnet free from fibrolite, but the rest of the grain is occupied. This feature may indicate zoning in the garnet porphyroblast. The garnet seems to be developed before deformation which is displayed by the elongation of garnet along the schistosity, but the present position may be considered as syn-kinematic. Crossed polars.

Symbols: Grt, Garnet; Sil, Sillimanite.

rectangular. Biotite and muscovite impart schistosity to the rocks, but some of the muscovite flakes cross-cut the schistosity planes. In some of the rocks, the two micas are bent due to deformation. Garnet occurs as anhedral and subhedral porphyroblasts. At the margins, garnets are corroded and possibly replaced by biotite and fibrolite. In sample ST21, fibrolite occurs in the middle part of the garnet whereas cores and margins are free (Fig. 4). This type of feature indicates a two-stage garnet growth and alteration into fibrolite during the syn-kinematic metamorphic process. Some garnet porphyroblasts have sharp boundaries with biotite, indicating equilibrium conditions. Sillimanite occurs mainly as fibrolites and rods cutting the foliation planes of the rocks. Epidote occurs as intergranular grains and contains vermicular quartz. Plagioclase

(An₃₈) grains are subhedral and fresh.

Garnet and fibrolite are developed in abundance in the metapelitic rocks. These rocks depict strong deformation as evident by the rotation in garnets and bending in mica. The mineral assemblages generally found in the metapelites and semi-metapelites include quartz—biotite—muscovite; quartz—biotite—sillimanite; quartz—biotite—muscovite—garnet—sillimanite—staurolite; quartz—sillimanite—garnet—biotite—muscovite—staurolite; quartz—sillimanite—biotite—staurolite; quartz—biotite—kyanite—plagioclase—garnet; and quartz—sillimanite—biotite—muscovite—plagioclase—garnet. This wide variation in the mineral assemblages indicates heterogeneity in the source composition of the rocks, grade of metamorphism and the degree of deformation.

2. Semi-metapsammites and meta-psammites

They are locally distributed. The semi-metapsammites exposed at Jagot (a locality inside Sai Nala) contain quartz, mica, garnet and hornblende. Hornblende occurs as radiating crystals up to 4 cm in length. The garnet forms porphyroblasts about 1 cm across, and occurs in the pelitic parts of the rocks. Locally these metapsammites retain graded bedding. The rocks are medium-grained, porphyroblastic and granoblastic, and at places banded. Quartz, biotite, garnet±sillimanite±epidote, graphite, magnetite and pyrite are the minerals found in these rocks. Garnet occurs as anhedral and subhedral porphyroblasts some of which contain quartz and biotite inclusions. These are polygonal in shape, but at places the peripheral parts of the garnet are corroded and surrounded by quartz inclusion (Fig. 5), and the peripheries are consumed probably due to pressure solution activity (Barker, 1990) under relatively high stress conditions (Durney, 1972; Vernon, 1978; Karanth, 1985). Garnet shows

Fig. 5. Photomicrograph showing rotated garnet (Grt) porphyroblasts (ST36). The peripheral parts of garnets are occupied by quartz grains which developed due to pressure solution. The matrix is composed of quartz and biotite. Shearing planes occupied by biotite are also noticeable. The gray porphyroblast is sillimanite. Crossed polars. Symbols as in Fig. 4.

Fig. 6. Photomicrograph showing sillimanite porphyroblast (Sil) containing staurolite (St) (ST58). The sillimanite is surrounded by biotite and muscovite. Sillimanite seems to have grown at the expense of muscovite and the staurolite seems to have grown before sillimanite. Crossed polars. Symbols: Bt, Biotite; Sil, Sillimanite; St, Staurolite; Ms, Muscovite.

syn-kinematic development. It is subhedral and replaced by biotite. Sillimanite is fibrolitic, but coarse-grained prismatic sillimanite also occurs in one of the rocks (ST58). In sample ST58, quartz occurs as equigranular, locally strained, grains with subrectangular shapes and occupy the matrix as well as pressure shadows. The pressure shadows are asymmetrical and developed during syn-tectonic crystallization. The staurolite in ST58 contains quartz inclusions and may itself occur in sillimanite porphyroblasts (Fig. 6). Graphite is abundantly sprinkled in this rock. Plagioclase occurs in minor amounts in these psammitic rocks, depending upon the bulk chemical composition. Epidote occurs as intergranular grains. Calcite is a secondary mineral noticed in a few rocks. Apatite and zircon are the accessory minerals. Opaque oxides are mainly magnetite $\pm$ ilmenite. Green hornblende is developed in a few rocks. Common mineral assemblages in this group include quartz—epidote—biotite—hornblende—plagioclase—garnet; quartz—biotite—hornblende

—epidote—garnet—plagioclase; quartz—biotite—muscovite—garnet—staurolite—plagioclase; quartz—hornblende—garnet—biotite—epidote—plagioclase and quartz—biotite—plagioclase—muscovite—epidote—garnet.

V. Whole-rock chemistry

Whole-rock analyses were carried out on pressed-powder pellets by using Rigaku system 3370 X-ray fluorescence spectrometer (XRF) in the Geoscience Laboratory, Geological Survey of Pakistan, Islamabad. Twelve standard reference samples provided by the Geological Survey of Japan were used for the calibration of the instrument. The results of the analyses were compared to the recommended values of USGS standard samples. The results were normalized on a volatile free basis with total iron expressed as Fe_2O_3 .

Eight rock samples were analyzed for major and trace elements (Table 1). Sample ST58 is distinctive in that it contains >75 (wt.%) SiO_2 , <14% Al_2O_3 , <1% Fe_2O_3 , <1%

Table 1. Major and trace element analyses (wt.% and ppm) of paragneisses of the Gilgit Formation

	ST58	JT1	ST28	STA2	ST17	ST19	JP1	JP3
SiO ₂	77.99	61.48	59.76	58.15	53.31	54.02	62.94	63.90
TiO ₂	0.06	0.81	0.73	0.78	0.87	0.80	0.76	0.77
Al ₂ O ₃	13.23	17.77	18.41	20.63	18.01	20.81	17.04	16.94
Fe ₂ O ₃	0.78	6.69	7.34	6.61	11.47	9.54	6.29	6.82
MnO	0.02	0.09	0.19	0.07	0.10	0.11	0.09	0.12
MgO	0.05	2.86	3.00	2.63	6.86	3.46	2.57	2.70
CaO	0.78	3.93	3.50	2.56	2.62	4.54	4.83	4.30
Na ₂ O	2.99	2.21	1.63	1.64	3.08	0.87	1.54	0.75
K ₂ O	5.05	3.29	4.17	5.00	1.79	1.41	2.95	2.92
P ₂ O ₅	0.01	0.13	0.14	0.25	0.07	0.11	0.14	0.14
Total	100.96	99.26	98.87	97.54	98.18	95.67	99.11	99.36
V	4	145	152	129	271	243	133	121
Co	35	38	22	20	24	24	39	41
Y	27	32	26	34	17	24	30	31
Zr	61	187	159	182	73	98	190	190
Nb	12	15	13	15	3	4	14	14
Th	*	14	13	17	BDL	BDL	14	14
Nd	*	25	21	34	BDL	10	BDL	BDL
Rb	187	136	169	178	47	39	136	132
Sr	27	207	208	153	115	213	176	158
Ba	51	565	823	581	341	230	346	285
Ce	*	57	50	90	BDL	BDL	79	52
K ₂ O/Na ₂ O	1.69	1.49	2.56	3.05	0.58	1.62	1.92	3.89

Key: ST=Sai Nala; STA=Sai Nala; JT=Jaglot; JP=Jutial Gah
 ST58=Semi-metapsammite; JT1, JP1 and JP3=Semi-metapelites; STA2 to ST 19=Metapelites. Total iron expressed as Fe₂O₃. BDL=Below detection limit. Trace and rare earth elements (V to Ce) were determined by XRF using pressed powder pellets. Detection limits for V, Co, Y, Zr, Nb, Th, Nd, Rb, Sr, Ba and Ce are (7, 1, 1, 1, 10, 10, 1, 1, 24 and 30 ppm, respectively). * = Not determined.

CaO, and <3% Na₂O (semi-metapsammite). The rest of the rocks (semi-metapelite and metapelites) overlap in most major and trace element distributions. For instance, SiO₂ (wt.%) in metapelites ranges from 53.31 to 59.76 and in the semi-metapelite and semi-metapsammite from 61.48 to 77.9. The metapelites, however, tend to be higher in Al₂O₃, Fe₂O₃, MgO and CaO (>2.62%). Samples JP1 and JP3 have nearly similar major and trace elements geochemistry except that JP3 shows higher K₂O/Na₂O ratio, i. e., 3.89 compared to 1.92 in JP1. The higher ratio in the JP3 is also reflected by the relatively higher SiO₂ and

lower Al₂O₃ contents. A weak to moderate correlation of Ti, Fe, Ni, Co and Sc to Al₂O₃ in the paragneisses may suggest that these elements resided originally in the clays. Trace elements signatures in all the rock samples are similar (Table 1) except ST58 (semi-metapsammite) and ST17 and ST19 (metapelites).

Sediments in general are transported from their tectonic setting of origin into a sedimentary basin in a different tectonic environment (McLennan *et al.*, 1990). According to Rollinson (1993), the plate tectonic processes impart a distinctive geochemical signature in two separate ways, i) different tectonic environments

Fig. 7. Discrimination diagrams for the paragneisses of the Gilgit Formation based upon (a) a bivariate plot of TiO_2 versus $(\text{Fe}_2\text{O}_3 + \text{MgO})$ and (b) a bivariate plot of $\text{Al}_2\text{O}_3/\text{SiO}_2$ versus $(\text{Fe}_2\text{O}_3 + \text{MgO})$. The fields are A, oceanic-island arc; B, continental island-arc; C, active continental margin, and D, passive margin (after Bhatia, 1983).

have distinctive provenance characteristics, and ii) they are characterized by distinctive sedimentary processes. Sedimentary basins, according to Bhatia and Crook (1986) may be assigned to the oceanic island arc (fore-arc or back-arc basins, adjacent to a volcanic arc developed on oceanic or thin continental crust),

continental island arc (inter-arc, fore-arc or back-arc basins, adjacent to a volcanic arc developed on a thick continental crust or thin continental margin), active continental margin, passive continental margin, collisional and rift settings. An attempt has been made to discriminate the metasedimentary rocks of the Gilgit Formation (Figs. 7a and 7b) using bivariate plots of TiO_2 versus $(\text{Fe}_2\text{O}_3 + \text{MgO})$ and $\text{Al}_2\text{O}_3/\text{SiO}_2$ versus $(\text{Fe}_2\text{O}_3 + \text{MgO})$, respectively. Rock samples plot in the oceanic island arc domain close to the continental arc. Two of the samples ST19 and ST28 plot outside the fields (Fig. 7a) whereas in Fig. 7b also, samples STA2 and ST19 plot outside the discriminating fields. Rock sample ST58, which is semi-metapsammite, plots close to the passive continental margin. The trace elements chemistry of the metapelites is consistent with arc-derived volcanic rocks. Semi-metapelites show trace elements chemistry consistent with intermediate to acidic volcanic and/or plutonic rocks. We assume that the sediments of the Gilgit Formation might have derived from an oceanic island arc and deposited in a back-arc basin.

VI. Mineral chemistry

Electron probe microanalyzer (EPMA), Shimadzu 8705 Q-II system, was used to analyze minerals in some of the selected samples for major elements chemistry. These elements include Si, Ti, Al, Fe, Mn, Mg, Ca, Na, K, and P. The Asitmex and Taylor standard samples used include TiO_2 , SiO_2 , MgO , CaSiO_3 , Cr_2O_3 , Fe_2O_3 , MnSiO_3 , Al_2O_3 , $\text{NaAlSi}_3\text{O}_8$ and $\text{NaAlSi}_3\text{O}_8$. ZAF procedure was used for the correction. The sample current was kept at 5.000 ± 0.005 nA, accelerating current at 15 kv and a counting time at 10 seconds for peak and back-ground intensities. Two rock samples out of six have been analyzed in the Department of Earth and Planetary Systems Science,

Table 2. Microprobe analyses of garnet and biotite in the paragneisses of the Gilgit Formation

Samples	ST21		ST41		ST36		ST58		JP1*		JP3*	
Minerals	Grt(r)	Bt(r)	Grt(c)	Grt(r)	Bt(r)	Grt(c)	Grt(r)	Bt(r)	Grt(r)	Bt(r)	Grt	Bt
SiO ₂	35.07	36.18	37.52	38.24	37.67	38.42	37.29	36.12	36.99	37.45	37.68	37.29
TiO ₂	0.16	2.30		0.05	2.63		0.07	2.78		1.73		3.56
Al ₂ O ₃	22.39	19.40	23.34	21.95	19.76	20.80	22.35	21.30	23.97	21.61	20.98	18.64
Cr ₂ O ₃	0.07			0.11				0.04	0.09	0.07		
FeO	37.55	19.44	28.81	26.16	18.01	33.25	31.97	18.65	33.02	14.87	28.49	20.86
MnO	0.30		4.69	6.44	0.07	3.75	5.44		1.95	0.07	7.74	0.25
MgO	3.95	9.48	2.18	2.51	9.70	2.44	2.68	10.24	2.20	15.63	2.14	8.55
CaO	1.07	0.02	6.64	6.10	0.06	2.82	2.49	0.03	2.13	0.02	2.97	0.02
Na ₂ O	0.06	0.45		0.07	0.17		0.03	0.17		0.44		0.07
K ₂ O	0.01	9.22		0.01	9.37		0.02	10.66		7.95		10.46
Total	100.63	96.56	103.18	101.65	97.44	101.46	102.34	99.99	102.35	99.84	100.00	99.71
Si	5.65	5.42	5.82	5.99	5.52	6.10	5.92	5.53	5.75	5.25	6.06	5.43
Al	4.26	3.44	4.27	4.04	3.41	3.89	4.13	3.63	4.39	3.57	3.98	3.36
Cr	0.01			0.01					0.01	0.01		
Ti	0.02	0.26		0.01	0.29		0.01	0.30		0.02		0.27
Mg	0.95	2.11	0.50	0.59	2.12	0.58	0.63	2.21	0.98	3.26	0.51	2.11
Fe ⁺²	5.07	2.43	3.74	3.43	2.21	4.41	4.19	2.26	4.30	1.74	3.83	2.51
Mn	0.04		0.67	0.85	0.03	0.50	0.72		0.26	0.01	1.05	0.03
Ca	0.18	0.00	1.10	1.03	0.01	0.48	0.42	0.00	0.36		0.51	0.01
Na	0.02	0.02		0.02	0.05		0.01	0.47		0.12		0.04
K		1.76			1.57			1.97		1.14		1.89
X _{Mg}	0.16	0.16	0.10	0.02	0.49	0.11	0.11	0.50	0.18	0.65	0.10	0.37
Almandine	81.19		62.70	58.16		73.89	70.34		73.03		64.86	70.83
Grossular	2.95		18.51	17.39		8.02	7.02		6.03		8.68	8.05
Pyrope	15.22		8.45	9.96		9.66	10.52		16.57		8.66	9.29
Spessertine	0.67		10.35	14.49		8.43	12.12		4.37		17.83	11.78

Key : ST=Sai Nala ; JP=Jutial Gah ; X_{Mg}=Mg/(Mg+Fe⁺²+Mn) ; Oxygen number : garnet (24) and biotite (22) ; JP1* and JP3*=Analysis carried out in the Department of Earth and Planetary Systems Science, Faculty of Science, Hiroshima University, Japan.
Grt(r)=Garnet(rim) ; Grt(c)=Garnet(core) ; Bt=Biotite.

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The compositions of garnet-biotite pairs in six paragneisses (ST21, ST36, ST41, ST58, JP1 and JP3) are given in Table 2. The analyses were conducted on rims of adjacent mineral pairs and cores of the garnets. Following is a brief description of the analyzed minerals.

1. Garnet

Garnets from the paragneisses are characterized by abundant almandine molecule (58.15 to 81.19). It has been argued that chemical zoning in metamorphic garnet records P-T history (Spear, 1989a, b; Florence and Spear, 1991). A decrease in Mn content from core to rim, the so called normal zoning, has been interpreted as a result of continuous growth of garnet with increasing temperature (Spear, 1988).

Garnet analyses in two samples (ST36 and ST41) show a decrease of Fe and Ca and increase of Mg and Mn towards the rim, indicating a progressive fall of temperature (Fediukova', 1973). Two rock samples (JP1 and JP3) represent the Gilgit Formation from the Jutial Gah, Gilgit. In sample JP1, seventeen spots have been probed, and the average is shown in Table 2. Across the garnet, a weak compositional zoning pattern is noticed from margin to core (Fig. 8). Fe and Mg contents are enriched in the rim relative to the core. Mn and Ca contents are enriched in the core as compared to the rim. In sample JP3, five spots have been probed between the two margins of the garnet, and the average presented in Table 2. In the chemical zonation profile diagram (Fig. 9 ; JP3), Fe, Mn, Mg, and Ca show flat and

Fig. 8. Sketch and compositional zoning profile across a garnet porphyroblast (JP1). Symbols represent probed points. Vertical scale represents cation numbers of Fe, Mn, Mg and Ca on the basis of O=24. A-B line is 1.4 mm across.

Fig. 9. Sketch and compositional zoning profile across the garnet porphyroblast (JP3). Symbols and vertical scale are same as in Fig. 8. A-B line is 0.12 mm across.

horizontal patterns. At the margin (probe point No. 5), Fe shows slight enrichment. It is to be noted that sample JP3 as a whole is enriched in Fe and Mn contents. The garnet of

JP3 is homogenized and has grown under high-grade metamorphic conditions and complete intracrystalline diffusion (Barker, 1990).

2. Biotite

Biotite contains 1.73 to 3.56% TiO_2 and its $\text{Mg}/(\text{Mg}+\text{Fe})$ ratios range from 0.37 to 0.65. The Ti content of the biotite has been reported to increase with grade of metamorphism, mainly temperature (Best and Weiss, 1964; Zakrutkin and Grigorenko, 1968). Also, it is high in biotite adjacent to ilmenite or rutile. The $\text{Mg}/(\text{Mg}+\text{Fe})$ ratio increases in biotite at the contact with garnet due to Mg-Fe exchange. In the analyzed biotite, Ti increases with the increase in Mg.

In Moldanubian terrain, the TiO_2 content ranges from 3.3 to 5.5% in the biotite of granulites, 2.5 to 3.3% in those of cordierite migmatites, and is less than 2% in paragneiss (Suk, 1983). In paragneisses of the Gilgit Formation the TiO_2 content is similar to the paragneisses and cordierite migmatites studied by Suk (1983).

VII. Grade of metamorphism and geothermometry

Field and laboratory studies suggest that the Gilgit Formation of the Jaglot Group shows metamorphism from almandine amphibolite subfacies to sillimanite—almandine amphibolite subfacies (Fyfe *et al.*, 1958; Fyfe and Turner, 1966). The change in the composition of garnets of paragneisses with increasing grade of metamorphism is shown in Fig. 10. In this diagram, the garnets containing higher $(\text{CaO}+\text{MnO})$ mole % occupy the field of garnet zone. The increase in metamorphic grade is also depicted by the decrease in $(\text{CaO}+\text{MnO})$, and increase of $(\text{FeO}+\text{MgO})$ mole %. This phenomenon is featured by the garnets of kyanite and sillimanite zones. The $K_d (X_{\text{Fe}})/(1-X_{\text{Fe}})^{\text{biotite}}/(X_{\text{Fe}})/(1-X_{\text{Fe}})^{\text{garnet}}$ values determined are quite different from each other where $X_{\text{Fe}}=(\text{Mg}+\text{Mn}+\text{Fe})$. For example the garnet-biotite pair from sample ST41 shows $K_d=0.43$, where ST36, ST21, ST58, JP1 and JP3

Fig. 10. Variation diagram showing changes in the composition of garnets with increasing grade of metamorphism in the paragneisses of the Gilgit Formation. This diagram also shows a negative trending slope with the increase in $(\text{FeO}+\text{MgO})$ mole%. The dividing lines between different garnet zones are after Nandi (1967). Data source is Table 2.

have the K_d values = 0.33, 0.22, 0.12, 0.48 and 0.29, respectively. The different K_d values found in the paragneisses suggest different temperature conditions (Gorbatshev, 1968). Using Ferry and Spear (1978) geothermometer, temperature estimates of 526°C, 570°C, 640°C, 530°C and 491°C are obtained for the paragneisses containing biotite—garnet—plagioclase; biotite—garnet—staurolite—sillimanite; biotite—garnet—sillimanite ± staurolite; biotite—muscovite—garnet—plagioclase + sillimanite and biotite—muscovite—garnet (plagioclase), respectively. The sillimanite-bearing rocks are closely associated (within a few metres) with the kyanite-bearing rocks both of which also contain biotite and garnet. It is to be noted that the sillimanite bearing rocks are intensely sheared and occur along fault zones. Chamberlain *et al.* (1989) studied some samples of the schists of the Jaglot Group and noted that garnet cores formed at higher pressure (9–9.5 kbar) than rims (7–7.5 kbar,

580°C). They thought that the rims of the garnet grew when the Kohistan terrain was thrust onto India along the Indus suture. In Skardu area the Katzarah Formation has been metamorphosed from biotite to sillimanite (K-feldspar zone). The metamorphism here is differently interpreted. Hanson (1989) showed regional metamorphic isograds cut by later plutons. Allen and Chamberlain (1991), on the other hand, noted that the rocks underwent a static low-P (2–4 kbar, 450–650°C) thermal metamorphism related to the intrusions of igneous plutons.

VIII. Conclusion

The Jaglot Group exposed in the central part of the Kohistan terrane is characterized by its intact stratigraphy (Khan *et al.*, 1994; 1996; Treloar *et al.*, 1996). Features such as intercalation between metapelites and semi-metapsammities and preservation of graded bedding relationships suggest that the Gilgit Formation has a turbidite protolith. Likewise, the sediments of the Thelichi Formation are characterized by the interbedded sandstone and predominantly mudstone successions (Bouma sequence) with common internal laminations, graded bedding and sole structures pointing towards turbidite nature. The back-arc basin affinities of Majne and Gashu-Confluence Volcanics (Khan *et al.*, 1996) and their intercalation in the turbidite successions suggest that the Jaglot Group was deposited in the ocean basin of a back-arc affinity rather than fore-arc basin as suggested by Petterson *et al.* (1990). The temperature and pressure estimates determined in the kyanite- and sillimanite-bearing gneisses of the Gilgit Formation reveal that the maximum operating conditions may have ranged from 570°C, 5.3 kbar to 640°C, 6.7 kbar, respectively. We assume that igneous intrusions, both the Chilas Complex and the Kohistan Batholith and crustal thickening accompanying arc accretion

to the Karakoram plate might have ensued metamorphism in the Gilgit Formation and other lithological units of the Jaglot Group. As depicted by the chemical zonation profiles of garnet of samples JP1 and JP3 (Jutial Gah, Jutial), the grade of metamorphism in the metasediments of the Gilgit Formation seems to increase for north to south, i.e., from top to bottom.

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