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New data on the metamorphism of the Nanga Parbat-Haramosh Massif, and the adjoining Ladakh island arc terrain, northern Pakistan

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ABSTRACT: *The Nanga Parbat-Haramosh Massif in northern Pakistan records the Tertiary metamorphism and dynamics of the Himalayan collision and subsequent overthrusting of the Asian plate onto the Indian plate. The massif consists of an intercalated sequence of paragneisses derived from the Precambrian Salkhala Series, of orthogneisses from Precambrian and early-Paleozoic granites, of minor metabsites and calc-silicate rocks, and of post-metamorphic pegmatite dikes. The adjacent part of the Ladakh arc consists of metasediments intruded by younger massive tonalites. The massif and the Ladakh arc are metamorphopsed under high pressure, upper amphibolite facies conditions. P-T estimates and P-T paths have been determined for the metapelitic samples from the massif and from the adjacent areas of the Ladakh arc along two cross-strike transects (Indus and Astore rivers) through the massif. Results show that the massif followed a compressional (counter-clockwise) and the Ladakh arc a decompressional (clockwise) P-T path, consistent with the tectonic history of the Himalaya of northern Pakistan.*

Geothermobarometry on garnet-biotite and garnet-plagiocalse pairs from pelites in the massif indicates that the rocks started their metamorphic history at ~5.5 kb and ~625°C. During collision, the pressure and tempeature rose ~9 kb and about 725°C. The Ladakh garnets started to grow at ~10 kb and ~725°C with a subsequent decrease in metamorphic pressure and temperature to ~8.5 kb and ~625°C. After the collision, the massif and the adjacent areas equilibrated at ~8 kb and ~700°C.

INTRODUCTION

The Himalayan mountain range was formed as a result of about 55 Ma old collision between the Indian and Asian plates. In the northwestern Himalayas a third microplate, the Kohistan-Ladakh island arc (KLIA), is sandwiched between the Asian and Indian plates and is enclosed by a northern suture or Main Karakorum Thrust (MKT) and a southern suture or Main Mantle Thrust (MMT; Tahirkheli et al., 1979). Whereas in the rest of the chain, the collision is directly between the Asian and Indian plates, the Himalayan collision in northern Pakistan is effectively between the KLIA and the Indian plate, with the arc thrust southwards on top of the Indian plate. This study concerns the Nanga Parbat-Haramosh Massif (NPHM; Fig. 1) which forms a NNE-tredning window of the Indian plate rocks that have been bent up from underneath the overlying blanket of the island arc rocks of Kohistan and Ladakh.

Recent geothermobarometric and geochronological studies on the evolution of the

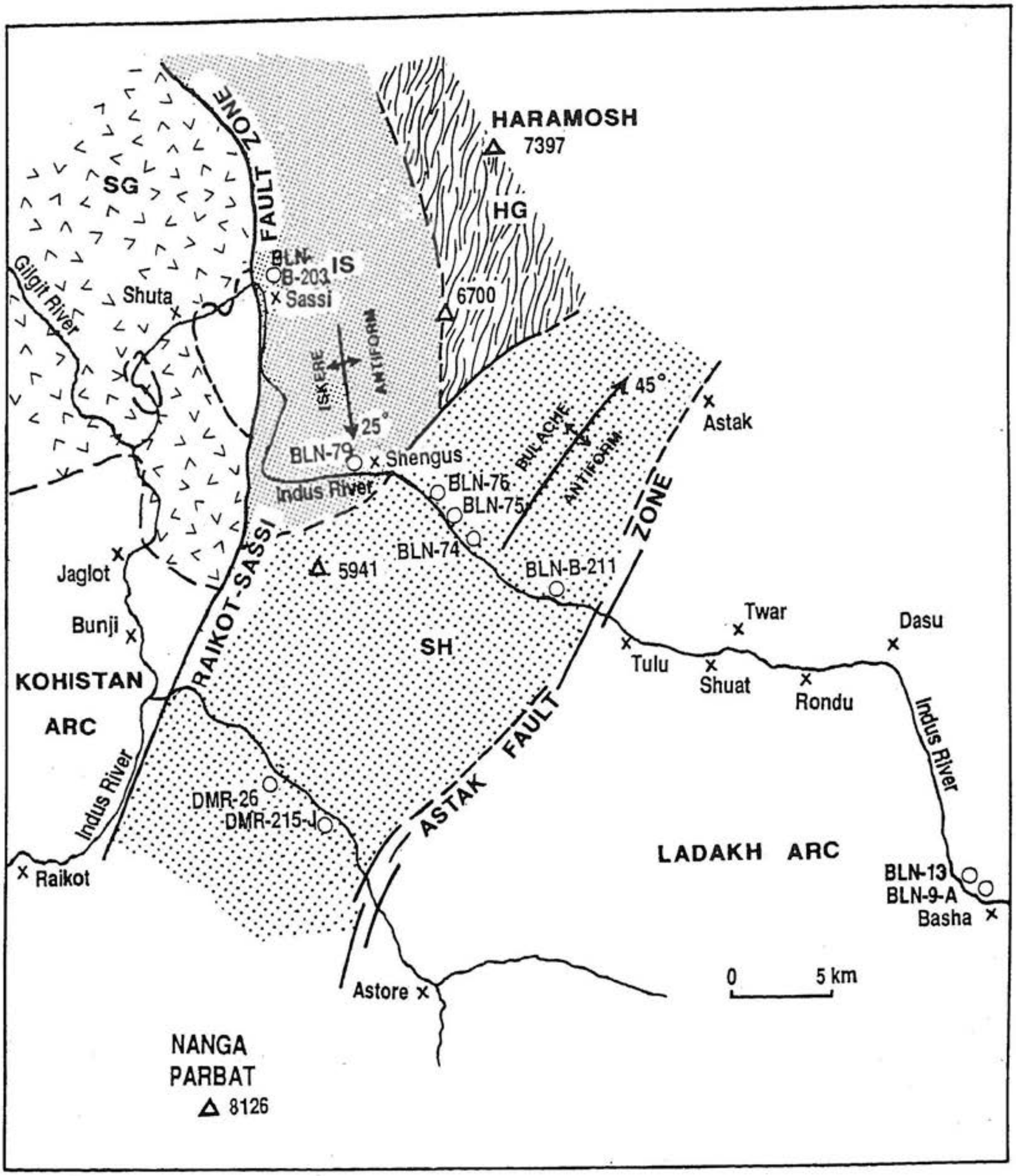


Fig. 1. Geological and sample location map of the Nanga Parbat-Haramosh massif and the adjoining areas of the Kohistan-Ladakh arc, respectively, west and east of the NPHM, in northern Pakistan. The distinction of HG: Hramosh Gneiss, IS: Iskere Gneiss and SH: Shengus Gneiss is after Madin (1986) and Verplanck (1986), and SG: Shuta Gabbro after Chamberlain et al., 1989. The present study did not see any distinction in the three gneiss units of the NPHM as described by Madin (1986) and Verplanck (1986). The elevations are in meters above sea level.

NPHM and the adjacent Kohistan arc rocks (Chamberlain et al., 1986, 1989) suggested that the two terrains followed different P-T paths, the NPHM followed and increasing P-T and the Kohistan a decreasing P-T path, and that the peak conditions of final equilibration were 7.5 kb and 580°C. Although the contrasting P-T paths in the two terrains seem to record the thrusting of the KLIA on top of the NPHM, however, the peak temperature of metamorphism appear to be too low to equilibrate *Ky/Sill + Or* assemblage found in the rocks. This paper presents additional P-T data on the pelitic horizons from the NPHM and new data on the Ladakh arc pelites to the east of the NPHM, based on: (a) more extensive sampling along the two traverses through the massif (Indus and Astore rivers), (b) a better constrained data set in that it includes petrologically important inclusions as well as matrix assemblages, and (c) it results in P-T conditions that are more conistent with the *Ky/Sill + Or* assemblage in the rocks. Our geothemobarometric results show that the NPHM and the Ladakh arc rocks underwent peak P-T conditions of at least 8.7±0.5 kb and 725±25°C and provide further evidence that the two terrains followed different pressure-temperature paths, as originally suggested by Chamberlian et al.(1989).

ANALYTICAL METHODS

Eight samples of *Ky/Sill + Or* assemblage were selected from within the pelitic horizons found in the NPHM along the Indus and Astore rivers (Fig. 1). Chemical analyses of minerals (Table 1) were conducted with an automated Jeol 733 electron microprobe analyzer at the University of Washington, and with a Cameca SX-50 microprobe at the University of South Carolina. Natural and synthetic silicate minerals were used as standards. Chemical compositions were determined from the X-ray intensities using the correction scheme of Bence and Albee, (1968). Analytical conditions in microprobing were 15 kv accelerating voltage and a beam current of 25 nA on brass. Pressures and temperatures were calculated using standard geothermobarometric procedures applying various calibrations. Pressure-temperature history was constructed using information from the mineral inclusions, mineral reaction textures and geothermobarometry.

Uncertainties in geothermobarometic calculations of metamorphic rocks are critical to evaluate in order to meaningfully constrain the metamorphic evolution of the terrain in question. Such uncertainities arise from: (a) whether the mineral compositions used in the calclations represent chemcial equilibrium, (b) whether there has been re-equilibraion (by net-transfer and/or by cation-exchange reaction mechanisms) during cooling from the peak metamorphic conditions of metamorphism, (c) whether diffusional homogenization has changed the composition of the minerals in question from the one at the peak condistion and (d) precision and accuracy of the techniques used.

The chemical zoning profiles of garnets and biotites from the NPHM and the Ladakh terrain show that these minerals, in general, have flat zoning profiles (Fig. 2). The extreme rims (up to 50 microns in most cases) have either depleted (in FeO, MgO, and MnO) or enriched (in CaO) profiles, probably representing re-equlibration during colling. Diffusional homogenization in garnets is known to be significant at temperatures above 580°C, however at this stage we can not constrain the uncertanities due to diffusion at high temperatures or during cooling. Nevertheless, since we did not use the extreme 50 micron edge compositions that were depleted or enriched in different elements, we argue that our estimates, specially the margin conditions, are probably insignificantly off from the actual conditions that ex-

TABLE 1. GARNET, BIOTITE AND PLAGIOCLASE COMPOSITIONS FROM THE SELECTED SAMPLES USED IN THE GEOTHERMOBAROMETRIC CALCULATIONS. SAMPLES BLN-9-A AND BLN-13 ARE FROM THE LADAKH ARC.

Sample	Pos	Pyrope	Alman	Spessa	Grossu	Annite	Phlog	Ti-Bio	Al-Bio	Mn-Bio	K-fels	Na-fels	Ca-fels	T (C)	P (bars)
BLNA-9-A	C/IC	—	—	—	—	—	—	—	—	—	0.004	0.213	0.783	—	8883
	mid	—	—	—	—	—	—	—	—	—	0.002	0.126	0.872	—	7494
	M/IM	—	—	—	—	—	—	—	—	—	0.000	0.044	0.956	—	7544
	C	0.169	0.678	0.093	0.060	0.393	0.401	0.057	0.147	0.002	0.009	0.527	0.464	746	9940
	mid	0.166	0.685	0.094	0.055	0.402	0.406	0.061	0.128	0.002	0.007	0.468	0.525	738	8492
	M	0.120	0.671	0.142	0.067	0.412	0.411	0.066	0.109	0.002	0.005	0.409	0.586	618	8311
BLN-13	C/IC	—	—	—	—	—	—	—	—	—	0.000	0.186	0.814	—	9398
	mid	—	—	—	—	—	—	—	—	—	0.001	0.115	0.883	—	7727
	M/IM	—	—	—	—	—	—	—	—	—	0.005	0.067	0.929	—	7730
	C	0.150	0.703	0.079	0.068	0.424	0.427	0.053	0.095	0.001	0.002	0.413	0.584	691	9828
	mid	0.145	0.713	0.080	0.062	0.409	0.430	0.053	0.107	0.002	0.000	0.306	0.694	648	8113
	M/IM	0.126	0.718	0.087	0.068	0.408	0.414	0.057	0.120	0.001	0.002	0.257	0.741	609	8201
BLN-74	C	0.132	0.801	0.034	0.033	0.439	0.346	0.078	0.136	0.001	0.025	0.800	0.175	652	5448
	M	0.179	0.756	0.024	0.041	0.403	0.390	0.071	0.135	0.001	0.019	0.691	0.290	734	8448
BLN-75	C	0.108	0.748	0.105	0.039	0.476	0.339	0.066	0.115	0.004	0.005	0.810	0.186	644	5688
	M	0.134	0.750	0.081	0.036	0.453	0.355	0.049	0.138	0.004	0.003	0.883	0.115	704	9192
BLN-76	C	0.090	0.810	0.062	0.039	0.501	0.284	0.063	0.148	0.003	0.009	0.826	0.162	628	5030
	M	0.103	0.754	0.088	0.056	0.506	0.292	0.055	0.144	0.004	0.006	0.762	0.233	727	9145
BLN-79	C	0.099	0.788	0.075	0.037	0.459	0.309	0.039	0.191	0.001	0.018	0.834	0.148	612	5280
	M	0.101	0.781	0.065	0.053	0.504	0.266	0.072	0.154	0.004	0.015	0.761	0.224	742	8737
BLN-B-203	C	0.174	0.776	0.027	0.023	0.391	0.419	0.034	0.155	0.001	0.006	0.810	0.184	647	5177
	mid	0.191	0.750	0.026	0.033	0.390	0.427	0.039	0.143	0.000	0.005	0.805	0.190	712	9105
	M	0.195	0.750	0.025	0.030	0.388	0.399	0.048	0.164	0.000	0.004	0.801	0.195	748	8907
BLN-B-211	C	0.201	0.753	0.018	0.027	0.316	0.526	0.069	0.089	0.000	0.014	0.889	0.097	574	9814
	mid	0.205	0.749	0.020	0.026	0.367	0.465	0.070	0.098	0.000	0.012	0.886	0.102	684	10631
	M	0.209	0.744	0.017	0.030	0.343	0.485	0.077	0.095	0.000	0.009	0.883	0.108	656	11415
DMR-26	C	0.140	0.776	0.053	0.031	0.416	0.401	0.069	0.113	0.001	0.016	0.824	0.159	610	5427
	M	0.178	0.753	0.028	0.041	0.404	0.425	0.078	0.092	0.001	0.012	0.800	0.188	702	9783
DMR-215-J	C	0.147	0.790	0.033	0.029	0.403	0.421	0.074	0.102	0.000	0.011	0.825	0.164	592	5046
	mid	0.159	0.774	0.028	0.039	0.388	0.421	0.078	0.112	0.000	0.013	0.816	0.170	630	8282
	M	0.176	0.748	0.021	0.055	0.413	0.416	0.064	0.105	0.002	0.016	0.808	0.177	741	13548

Sample locations are in Fig. 1. C = Core; IC = Plagioclase inclusion core composition; M = margin; IM = Plagioclase inclusion margin composing; mid = midway between core and margin. T (°C) is after Ferry and Spear (1978) with Hodges and Spear's (1985) and Newton and Haselton's (1981) modifications and P (bars) is after Ghent (1976) with Newton and Haselton's ibid and Ganguly and Saxena's (1984) solution models.

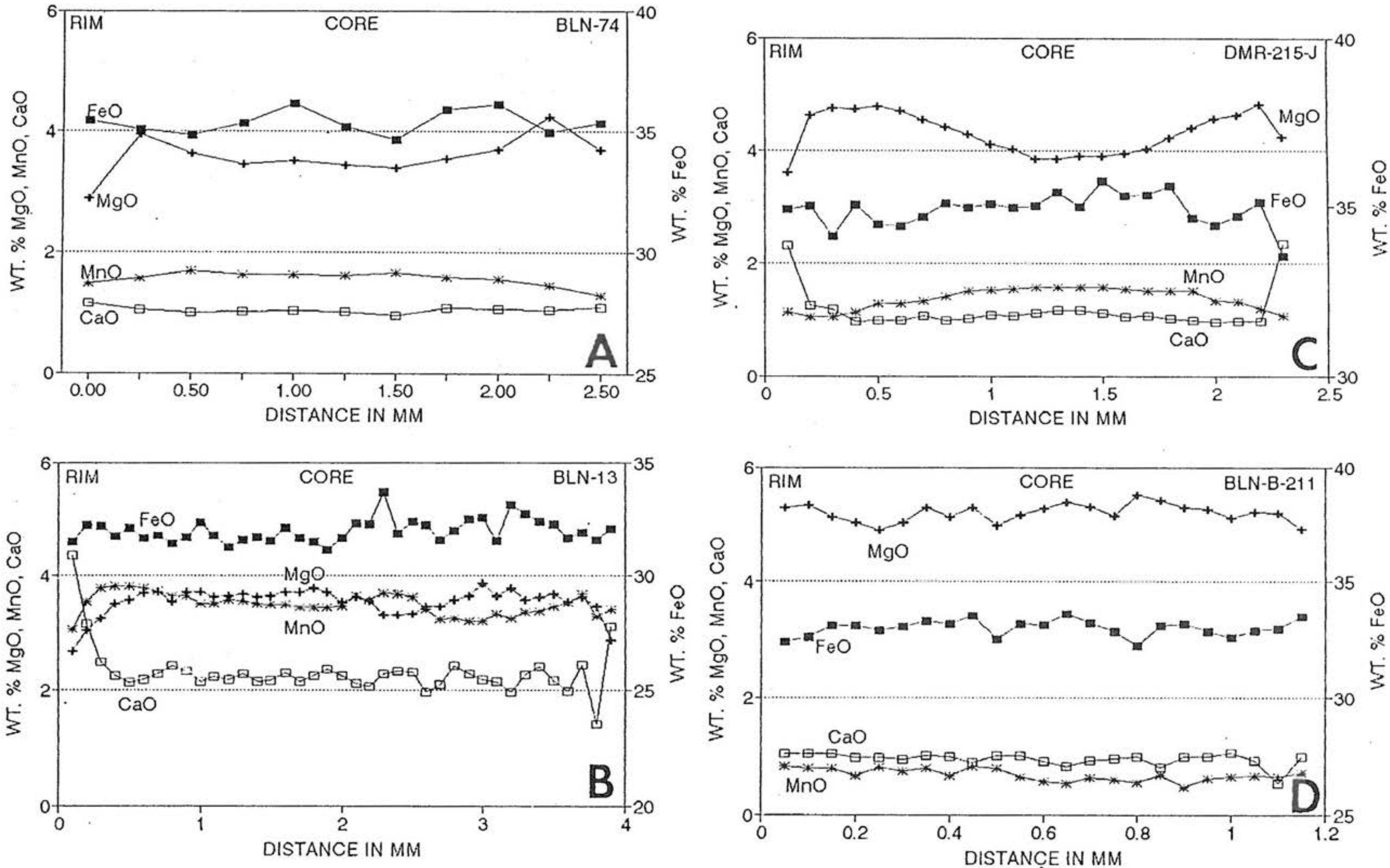


Fig. 2. Garnet zoning profiles for representative samples from the NPHM and the Ladakh arc. Filled boxes: FeO; plusses: MgO; Asterisk: MnO; empty boxes: CaO; A: BLN-74; B: BLN-13; C: DMR-215-J; D: BLN-B-211. Locations are given in Fig. 3.

isted at the time of metamorphism of these rocks. Although it is impossible to prove that the mineral compositions were in equilibrium, the grain sizes, the (second-sillimanite grade) assemblages with the general lack of low temperature minerals in the selected samples, essentially no chemical zoning in the garnets and biotites and a rather narrow range of P's and T's resulting from the calculations suggest that most of the compostions used were probably in mutual equlibrium. The accuracy of our P-T data depends on the accuracy of the calibrations used and on how accurately do the solution models used in the calculations represnt the activity-composition relationships. In order to choose the best calibraion for our rocks, 7 different models for Fe-Mg Gt-Bi thermometer were used. The calibration that resulted with minimum scatter in the overall termperatures and consistency from sample to sample was chosen. For barometry, garnet-plagioclase-aluminosilicate-quartz barometer (Ghent, 1976) was used with the modification set forth by Newton and Haselton (1981).

Extreme care was taken in choosing the mineral compositions in garnet, biotitie, and plagioclase used in this study for thermobarometric calculations in order to minimize the overall effect of the above uncertainties. Biotite inclusion composition in garnet was used with the adjacent garnet core composition to estimate the temperature of the early stage of the cystallization history. In other cases, where biotite inclusions were not found in garnet, in-contact garnet and biotite grains were chosen for thermometry. If the biotite inclusion composition was different than the matrix biotite composition, both compostions were used with the adjacent garnet to get the peak temperature estimate. In cases where the biotite core and margin compositions were different and biotite could not be found as inclusion in the garnet, garnet core and margin compostions were used respectively with core and margin biotite compositions to estimate the peak temperature.

GEOLOGY

Nanga Parbat-Haramosh Massif

The walls of the Indus and Astore river valleys provide northeast-southwest cross-sections of the NPHM (Fig. 1). The Indus river sectoin is dominated by two large antiforms, the NE-trending N-plunging (45°N) Bulache antiform, and the NNW-trending S-plunging (25°S) Iskere antiform. The two antiforms are separated by a local fault, the Baraluma fault. Lithologically, the rocks of the NPHM can be divided into granitic gneiss, pelitic gneiss, amphibolite calc-silicate rock, and mafic dikes. These units are a NNE-trending sequence of interlayered tabular bodies separated by fairly sharp contacts conformable with foliation and lithologic layering. All of these units, except the siliceous pegmatite dikes which are post-metamorphic, have experienced upper amphibolite facies metaqmorphism accompanied by intense deformation. Lithologic layers commonly vary in thickness up to a meter and are laterally continuous. Orthogneiss layers may be as thick as 500 meters occasionally. The rocks, in general, have a fine-grained (locally somewhat mylonitized) texture, presumably representing formation under dynamic conditions. The rocks commonly contain garnet porphyroblasts, occasionally up to 10 cm in diameter in the rare coarse-grained varieties.

Pelitic gneiss is fine-porphyroblastic, mylonitized, foliated, and typically contains garnet, biotite, kyanite/sillimanite,. orthoclase, plagioclase, quartz, and accessories. The stable association of kyanite (or sillimanite) and orthoclase indicates that the gneisses have crystallized above the second "sillimanite" isograd. The pelites typically display a completed *Ky/Sill + Or* reaction (to the exclusion of muscovite) but there are examples of incomplete reaction (assemblages with stable muscovite, ortholcase, quartz, and an aluminosilicate) in the adjacent areas within the massif (Fig. 3). Garnet porphyroblasts in the pelites typically contain inclusions of rutile, orthoclase, biotitie, ilmenite, and sillimanite. In the core of the massif, the garnet porphyroblasts are rotated and have developed pressure shadows, indicating syn-tectonic growth. Pelitic isigrads cannot yet be drawn for the massif.

Siliceous pegmatitic and amphibolitic dikes intrude the gneisses. The amphibolitic dikes cut the regional layering, have vaguely defined margins with the host, and display very fine-grained, subequigranular, locally porphyroblstic texture. These (amphibolite) dikes are pre-kinematic, having foliation parallel to that of the host gneiss, and have gone through amphibolite facies metamorphism. Siliceous pegmatite dikes are post-kinematic, generally 1-2 m wide, and mineralogically consist of massive quartz, plagioclase, and othoclase, and minor amount of muscovite, biotite, beryl (aquamarine), garnet, schorl (tourmaline), epidote, lepidolite, cleavelandite, topaz, and spodumene (Madin, 1986; Verplanck, 1986). Some of these minor constituents are of gem quality and have been mined by the Gemstone Corporation of Pakistan.

Ladakh arc rocks

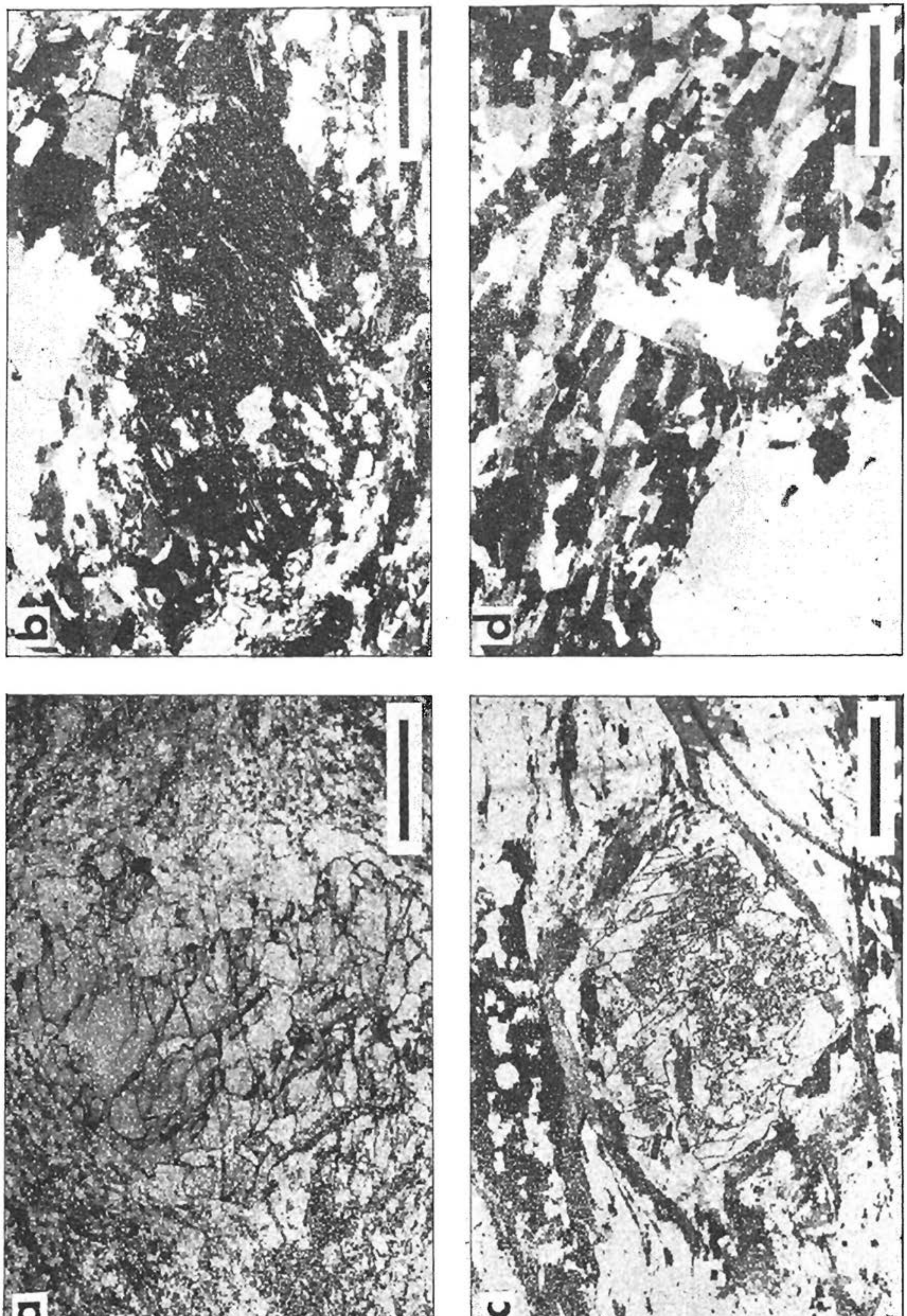
The Ladakh arc rocks east of the NPHM correspond to those of the Kohistan arc to the west of the NPHM (Fig. 1). Adjacent to the massif, tonalites are the dominant arc rocks, which intrude well-foliated garnet-amphibolites that are intercalated with subordinate pelitic schists and calc-silicates. The rocks are stratigraphically classified into metasediments (oldest), tonalite, gabbro, and felsic dikes (youngest). The metsediments mainly comprise garnet amphibolites with minor interbeds of granitic gneiss, peilitic gneiss (Fig. 3), and calc-silicate rocks. This unit corresponds to the southern amphibolites of Kohistan (Tahirkheli et al., 1979). The gabbroic rocks of Ladakh are similar to the Shuta gabbro of Madin (1986), and the tonalites of Ladakh are presumably the counterparts of the Kohistan granites of Tahirkheli et al. (1979). To the east of the confluence of the Astor and Indus rivers, felsic dike swarm, similar to the one at the confluence of the Gilgit and Indus rivers (Fig. 1), cross-cuts all of the above lithologies of Ladakh.

GEOTHERMOBAROMETRY

Geothermometry

Mineral pairs were chosen from eight samples from the NPHM (BLN-74 to -79, -B-203, -B-211, and DMR-26 and -215-J) and two samples from the Ladakh arc (BLN-9-A and BLN-13; Table 1). For the Kohistan arc, Chamberlain et al.'s (1986, 1989) data are referenced here and their data for the massif are presented for comparison. The new data on the pressure-temperature estimates and history of the massif rocks, in general complements the data presented by these authors.

Metamorphic temperatures were determined using Fe-Mg exchange between coexisting garnet and biotite (Ferry & spear, 1978). Since our biotites contain appreciable amounts of Ti and ^{VI}Al, and the garnets have substantial Ca and Mn, appropriate corrections were made for these elements as used by Hodges and Spear (1982) and Newton and Haselton (1981). The observed range of temperatures in the NPHM is 574°C to 748°C, and in the Ladakh arc is 609°C to 746°C. Based on the petrongenetic grid and supported by these temperature calculations, we suggest the peak temperatures during the main phase metamorphism of the rocks


a
b
c
d

in the study area were around 725°C, and that these calculated temperatures represent the early and final stages of the peak metamorphism in the area studied. Significantly lower or higher esimates compared to the petrogenetic grid interpretation probably represnt an overall effect of the errors introduced due to disequilibrium compositions used, microprobing, poor calibration of thermometers, and, to a lesser extent, poorly constrained phase equilibria.

Geobarometry

Pressures were calculated based on the garnet-aluminosilicate-quartz-plagiocalse (GASP) barometer (Ghent, 1976) using Newton and Haselton's (1981) solution model for anorthite activity and Ganguly and Saxena's (1984) model for grossular activity. Temperatures and pressures of final equilibration (Table 1) were determined by simultaneous solution of the garnet-biotite thermometer and GASP geobarometer. The observed pressure estimates vary from 5 to 13.5 kb in the NPHM and from 7.5 to 9.9 kb in the Ladakh arc. Two samples (BLN-B-211 & DMR-215-J) give unusually high pressure estimates (9.8-13.5 kb), indicating that probably a disequilibrium pair was chosen (Table 1).

Pressures for the pelites from the Ladakh arc were determined using compositions from both matrix and inclusion plagioclase grains (Table 1). It is interesting to note that the pressures estimated using the plagiocalse inclusion compositions are, in general, similar to those estimated using matrix plagioclae compositions. Also, the pressure history (discussed below) as suggested by these plagiocalse inclusion barometry is similar to that indicated by the matrix plagiocalse estimates. This observation, supported by the fact that no additional phases (*Ky/Sil* and *Qtz*) were found coexisting with plagiocalse inclusions in the garnets, suggests that the chemistry of these reversely zoned plagiocalse inclusions has not changed since their entrapment in the garnets.

PRESSURE-TEMPERATURE HISTORY

P-T history based on mineral assemblages and textural relationships

The mineral assemblages in the NPHM and Ladakh rocks, namely *Ky/Sill* + *Or* pair in the pelites along the Indus and Astore Rivers (this study), *Ky/Sill* + *Or* in the pelites and Wo + An pair in the calc-silicates at the Nanga Parbat high (Misch, 1964), and *Zo* + *Ky* pair at

Fig. 3. Photomicrographs of::

A: a large S-shaped garnet porphyroblast in sample BLN-B-211, having inclusions of quartz, plagioclase, orthoclase, rutile, and sillimanite. The same feature is also found in samples BLN-B-203 and DMR-215-A. Matrix contains kyanite + orthoclase association. The bar represents 1mm. 2.5 x Plane Polarized Light (PPL).

B: small garnet porphytoblasts in DMR-215-A. The garnets are somewhat elongated parallel to the foliation. Internal foliation in the garnet defined by the sillimanite prisms is at an oblique angle. Note the intensity of the sillimanite inclusions. Larger garnet porphytoblasts have much less inclusions. Matrix contains kyanite + orthoclase association. Scale bar = 250 microns; 10 x PPL.

C: a garnet prophyroblast with inclusions of quartz, biotite, and idioblasts of reversely zoned plagioclase in sample BLN-9-A. Matrix assemblage in this rock is sillimanite + fibrolite + orthoclase. Note the secondary muscovite after sillimanite + orthoclase on the left of the garnet porphyroblast. Scale bar = 1 mm; 2.5 x PPL.

D: post-kinematic muscovite, oblique to the foliation defined by biotite, in sample BLN-13. The muscovite grain has inclusions of biotite and magnetite. This sample has stable sillimanite + orthoclase assemblage in the matrix. Scale bar represents 500 microns; 5 x PPL.

Astak high (Zannetin, 1964), incicate that the rocks crystallized in the upper amphibolite facies conditions. Extreme pressures and temperatures within this facies are suggested by the common absence of staurolite and cordierite in the pelites. Petrographically, the upper limits of the metamorphic conditions are also indicated by the absence of pericalse in the magnesian carbonates, absence of two pyroxenes, and common occurrence of biotite. This is consistent with the calculated temperatures and pressures.

The common disequilibrium mineral textures found in the rocks of the NPHM are: (a) growth of muscovite around kyanite/sillimanite and vice versa and (b) inclusions of sillimanite and orthocalse in garnet porphyroblasts in a matrix containing kyanite and orthocalse. These disequilibrium textures and the minerals included in the garnets indicate that the massif rocks have undergone changes in pressure and temperature during metamorphism. The garnets contain inclusions of sillimanite, orthocalse, and rutile, whereas the matix contains (*Ky* + *Or*. Both the assemblages have equilibrated at or above the second sillimanite curve in the P-T space, meaning that the temperatures were high enough for the breakdown of muscovite-quartz pair to equilibrate *Ky*/*Sill* + *Or* assemblage. The *Ky* + *Or* pair in the matrix indicates an increase in pressure (or a decrease in temperature) with a minimum pressure of ~5 kb (Fig. 4). Mineral assemblages in samples from the Indus river section suggest a difference in the pressur-temperature conditions within the massif. The core of the massif (around Shengus in Fig. 1) has stable *Sill* + *Or* assemblages whereas the edges have *Ky* + *Or*, indicating relatively higher pressure (or lower temperatures) towards the margins of the massif. This probably suggests a faster uplift of the edges than the core of the massif, assuming horizontal isograds at the time of peak metamorphism.

Sample BLN-B-203 contains relict (early?) kyanites within an early folded foliation. The garnet-porphyroblasts contain sillimanite inclusions and the matrix contains post-kinematic muscovite and late cordierite and lacks orthoclase. This reaction texture suggests a rise in pressure to cause reaction of sillumanite to kyanite during the main stage metamorphism. Absence of kyanite (other than the folded foliation) and of orthoclase and the occurrence of muscovite and cordierite suggests later low temperature equilibration (or a metamorphic event) under substantially lower pressures than the stability field of *Ky* + *Or*.

Mineral assemblages and their textures in Ladakh rocks also display equilibration above the secand sillimanite isograd (8~9 kb, ~700°C). The sample BLN-9-A of the Ladakh arc has sillimanite + orthoclase assemblage in the matrix as well as inclusions in the garnet porphyroblast. Sample BLN-13, located about 500 meters from BLN-9-A (Fig. 1), also shows the stable association of sillimanite and orthoclase. However, in BLN-13 there is found post-kinematic muscovite growing across the foliation defined by biotite (Fig. 3). Calculated pressures are ≥7.5 kb, but the temperatures vary from 609-746°C (Table 1). The reaction textures of BLN-9-A and BLN-13 are thus interpreted as indicative of simultaneous decrease in temperature as well as pressure during thrusting over the NPHM.

P-T history based on pressure-temperature estimates

Geothermobarometric studies on garnet-biotite and garnet-plagioclae pairs from the NPHM and the Ladakh confirm important infomration about the pressure-temperature histories of the two terrains (Fig. 4). Garent-biotite thermometric results show that NPHM underwent substantial temperature increase (up to ~125°C; Table 1) during the Tertiary metamorphism.

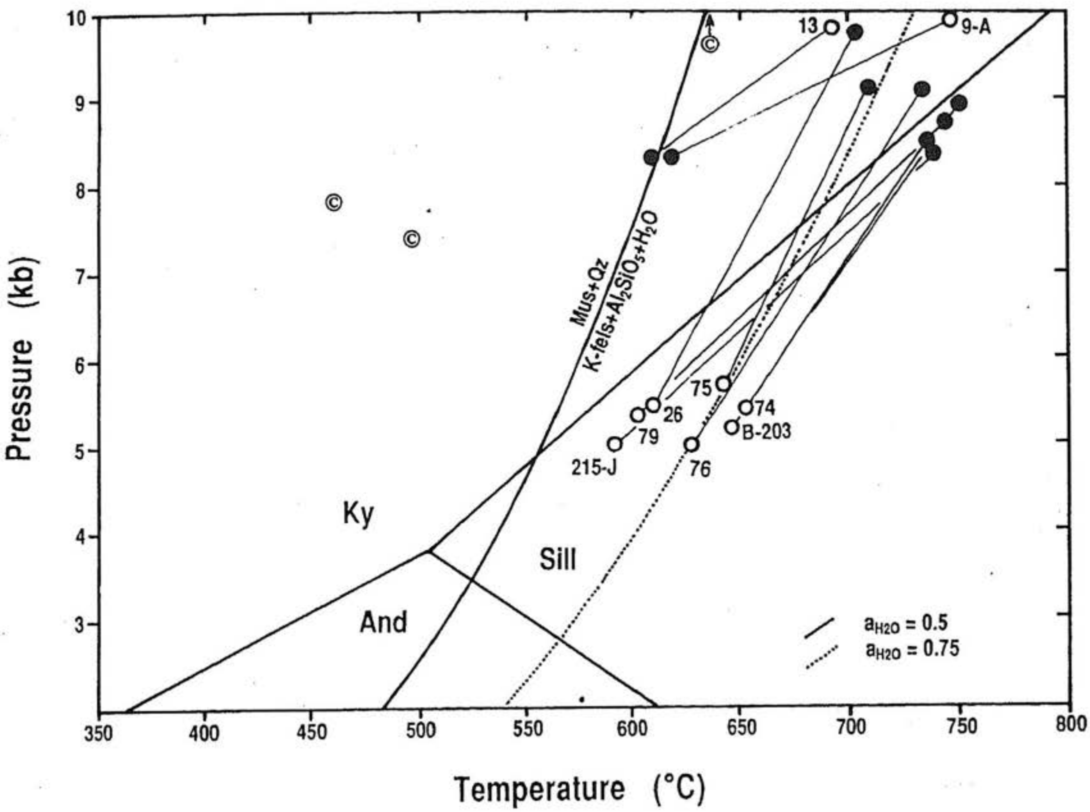


Fig. 4. Pressure-temperature conditions for the NPHM and the Ladakh arc. The reaction curves represent only a part of the phase diagram for the KCASH system using Berman's (1988) GEOCALC programme and internally consistent thermodynamic data set, keeping water activity at 0.5 and 0.75. Majority of the calculated pressures and temperatures plot in the *Ky/Sill+Or* field, consistent with the petrographic observations and strongly suggesting that the water activity must have been substantially low (0.5 to 0.75) in order to prevent partial melting in the rocks. Open circles = core pressures and temperatures; filled circles = margin conditions. Chamberlain et al.'s (1989) three samples from the NPHM using GASP geobarometer are also plotted for comparison, represented by ©. GASP estimates for the Kohistan sample are not reported by the aforesaid authors.

The garnet growth probably started around 620°C (mean core temperature). During subduction underneath the Ladakh rocks, the temperatures in the massif increased to around 720°C (mean margin temperature). The mineral assemblages found in the massif rocks support the temperatures calculated for these samples. Geobarometry, using garnet-plagioclase pairs in five out of eight samples from the NPHM, indicates a significant pressure increase (up to about 4 kb from garnet core to rim; Table 1). Two samples from the massif give erroneously high pressure estimates, but the garnet rim pressures are still higher than the core pressures (Table 1).

In contrast, calculated thermobarometric results from Ladakh show a different pressure-temperature history for these rocks. Comparison of garnet core temperatures of the massif and the Ladakh rocks reveals that the initial garnet growth started at substantially higher temperatures in the latter than in the former

Temperature estimates on garnet core to rim in the Ladakh rocks suggests that garnets in this terrain grew under decreasing temperature conditions (from 746 to 609°C; Table 1). The stable assemblage of *Ky/Sill* + *Or* in the two Ladakh samples (Table 1) supports the calculated high pressures and temperatures for these samples (7.5-9.9 kb, 700+°C; Table 1). The pressure estimates show that the garnet core grew under higher pressures than the rims, probably indicating equilibration before thrusting of the Asian plate onto the Indian plate. Towards the garnet rims the pressure decrease (up to 1.6 kb; Table 1) represents equilibration during thrusting.

The reversely zoned plagioclase inclusions in garnets also give consistent and similar high pressure result as do the zoned matrix plagioclases. This probaly indicates that the garnet and plagioclase compositions used in geobarometric calculations were in equilibrium. Similar pressures from two quite different plagioclase compositions (matrix: labradorite-bytownite; inclusions: anorthite; Table 1) is interesting and strengthens the assumption that the plagioclase inclusions within garnet represent relict compositions. Another possibility is that the change in the matrix plagioclase core to rim composition might be a manifestation of temperature that could not affect armored plagioclase inclusions.

DISCUSSION

The thermobarometric estimates and the pressure-temperature paths displayed by the rocks of the NPHM and the Ladakh arc most probably resulted from the collision of the Indian plate with the KLIA microplate. Before this collision the rocks of the massif were buried at about 15 km depth (5.3 kb mean core pressure of samples BLN-74, -75, -76, -79, -B-230, & DMR-215-J; Table 1). Upon collision, about 30 km deep KLIA rocks (based on 9.9 kb mean core pressure of Ladakh samples, Table 1; and 9-9.5 kb core pressures reported by Chamberlain et al., 1989, for the Kohistan rocks; Fig. 4) were thrust over the Indian plate. During thrusting pressure and temperature increased in the manssif and decreased in the KLIA. After thrusting, the two plates equilibrated at upper amphibolite facies metamorphic conditions (725±25°C; Table 1) at depths of about 25 km (based on 8.3 kb mean garnet margin pressure in samples BLN-9-A and BLN-76 in Table 1 and about 8 kb garnet margin pressures reported by Chamberlain et al., 1989, for Kohistan).

Table 1 shows that the margin pressures and temperatures are in general higher than the core pressures and temperatures in the massif and vice versa in the Ladakh arc. This probably indicates that the obduction of KLIA onto the NPHM along a major thrust, probably the MMT, caused the change in the thermal regime of the rocks. The temperatures decreased about 100°C (BLN-9-A & BLN-13; Table 1) during thrusting and the pressures decreased up to 1.6 kb in the KLIA rocks. The massif rocks underwent up to 125°C increase in temperature and up to 4 kb increase in pressure (BLN-76, BLN-B-203, DMR-26; Table 1) during thrusting.

(Contd. from page 13)

temperature (<500°C) path followed by heating during decompression (4.5 kb, 600°C) whereas the NPHM started its history from >12 kb, 550°C and ended at 4.8 kb, 710°C (curves K1 and N1 for Kohistan and NPHM respectively, Chamberlain et al., 1986). Later, these authors restudied their samples and suggested P-T histories represented by curves K2 and N2 (Chamberlain et al., 1989). The open and filled square symbols, in this case, are early and final stages of probably the prograde metamorphic history of the Tertiary metamorphism of the Kohistan arc and the massif

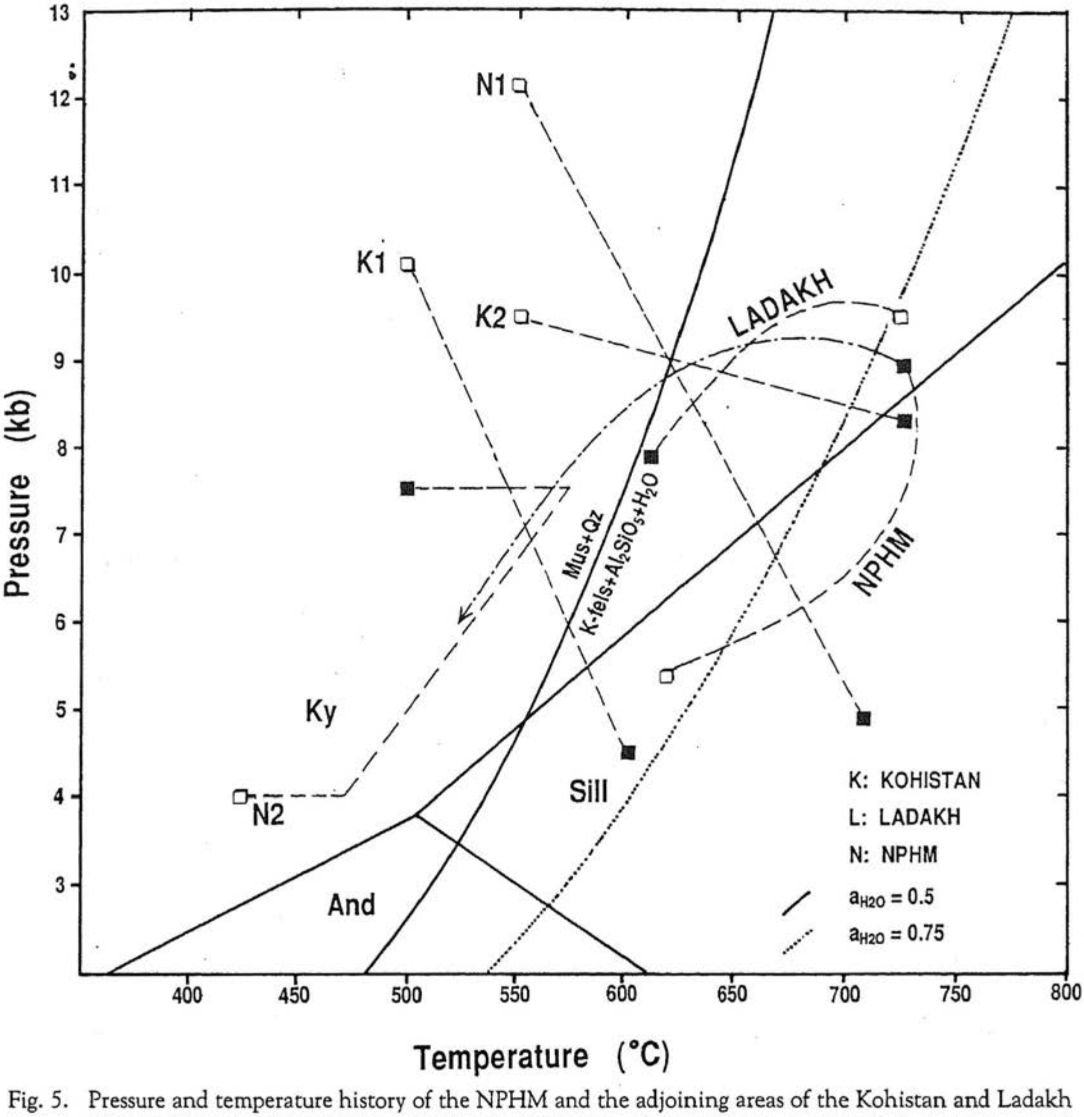


Fig. 5. Pressure and temperature history of the NPHM and the adjoining areas of the Kohistan and Ladakh arc terrains in northern Pakistan. The dashed curves are drawn assuming a smooth loop representing the metamorphic evolution of the rocks in these terrains. The vortex of these curves is imaginary. The NPHM and the LADAKH curves are based on the mean core (open squares) and margin (filled squares) pressure and temperature estimates of Table 1, supported by the disequilibrium textures and mineral inclusions in the garnet. The dash-dot-dash part of the NPHM curve is based on the occurrence of late stage cordierite found in the sample BLN-B-203. This curve extends up to the approximate stability field of cordierite in pelitic rocks (where the arrow is), and is inferred here as the obduction path of the massif from depth onto the surface subsequent to the peak metamorphism. For comparison of the P-T histories of the massif and the surrounding blocks, Chamberlain et al.'s (1986, 1989) data on Kohistan and NPHM are also plotted. Based on Gibb's method calculations, these authors reported that the Kohistan arc underwent an early high pressure (>10 kb) and low

(Contd. on page 12)

By comparing the temperature history of the rocks from the Kohistan arc west of the massif to that of rocks collected from the Ladakh arc east of the massif, an important difference is encountered (Fig. 5). Rocks in the Kohistan arc west of the massif show a significant temperature increase during decompression (Chamberlain et al., 1989) whereas rocks from the Ladakh arc east of the massif show cooling paths (this study). Since the sample from the Kohistan side displaying heating during overthrusting is collected within a few kilometers from the Shuta gabbro, we agree with Chamberlain et al.'s interpretation that the temperature increase observed in the Kohistan rocks, west of the massif, is probably a result of heating (at least partly) by syn-tectonic gabbros (Coward et al., 1982). The samples from the Ladakh arc on the east side of the massif also come from the vicinity of tonalitic plutons, but display cooling behavior during decompression; thus the Kohistan-Ladakh arc lithologies from the two sides of the massif display somewhat different pressure-temperature history. If these temperature results are affected by the collision of the massif (Indian plate) with the KLIA, it can be implied that the equilibration of the metamorphic assemblages in the rocks are synchronous with the thrusting phenomenon. However, recent U-Pb studies on monazites from the massif rocks (Smith et al., 1992) show that the metamorphism in the massif is Late Tertiary (4-11 Ma). This would indicate that the metamorphism in the KLIA was probably syn-tectonic with and that in the NPHM is several tens of million years post-tectonic to the ~55 Ma collision of the Indian plate and the KLIA.

Another important result of this study is the restricted range of water activity (around~0.5) in these rocks during the Late Tertiary metamorphism. The position of a reaction curve in the pressure-temperature space depends upon the purity of the phases involved in the reaction. Petrographic evidences of *Ky/Sill* + *Or* assemblage in the massif and Ladakh and, in general, lack of migmatites along the Indus and Astore rivers sections (Fig. 1), supported by the calculated temperature and pressure estimates, suggest that the water activity during the last metamorphic episode was most probably around 0.5 (Fig. 4, 5). Conversely, the massif rocks in the Nanga Parbat summit area south of Raikot (Fig. 1), display extensive migmatization (Chamberlain, pers. comm.; Misch, 1964). The evidence that low X_{CO2} values (probably because of dilution due to water) existed in the summit area to cause the formation of concentric mineral zones in the calc-silicates (Gordon & Greenwood, 1971), suggests a rather high water activity in that area. Lack of appreciable migmatization along the Indus and Astore rivers (Fig. 1) strongly suggests that the water activity varies from place to place in the massif. No migmatization occurred where the water activities remained low (~0.5), whereas the areas where the water activities ≥0.75, extensive migmatites were formed in the pelites.

CONCLUSIONS

In the Nanga Parbat region of the western Himalayas, the collision and subsequent overthrusting of the 'hot' KLIA caused a prograde upper amphibolite facies metamorphism. This is evidenced by the widespread *Ky/Sill* + *Or* assemblage in the rocks, indicating high temperatures to cause breakdown of muscovite-quartz pair, and by the pressure-temperature estimates of the rocks. Comparing the Nanga Parbat-Haramosh window of the Indian plate with other areas south of the MMT in north Pakistan (Treloar et al., 1989) and south of the Indus-Tsangop suture in central Himalayas (Honnegar et al., 1982) indicates that the Late Tertiary metamorphism (Smith et al., 1992) in the massif has obliterated all imprints of the previous metamorphic episodes and that the rocks in and around the massif had probably lost some of their water during these earlier metamorphic events. Lack of sufficient water inhibited migmatization and partial melting during the last upper amphibolite facies metamorphism in the northern half of the massif. In the southern half, Chamberlain (pers. comm.) and Misch (1964) reported migmatites at apparently same grade of metamorphsim. Moreover, lower amphibolite facies and greenschist facies assemblages are uncommon. This probably indicates a long burial time during which extensive upper amphibolite equilibration could take place, and a very short rapid uplift so that lower grade equilibrations were not possible. Such interpretation is also supported by the relatively flat compositional zoning profiles of garnet porphyroblasts from the massif rocks with very thin edges where resetting during colling (uplift) could produce enrichment or depletion of Fe, Mg, Mn and Ca. Rapid uplift rates for the massif and the adjacent Kohistan arc are confirmed by Zeitler et al. (1982a, b).

Two phases of metamorphism are interpreted from the P-T estimates and the petrological data: (a) upper amphibolite facies metamorphism, starting from *Mus* + *Qtz* reaction, through *Sill* + *Or* (muscovite-out) assemblage, to *Ky* + *Or* assemblage and (b) local equilibration under lower amphibolite facies conditions, evidenced by the post-kinematic muscovite and cordierite, and by the absence *Ky-Or* pair in the matrix. The first phase occurred before and during the thrusting of the KLIA onto the Indian plate, whereas the second phase is a result of downloading and rapid uplift during cooling. Metamorphic isograds are yet to be drawn in the massif.

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