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P-T-t paths of garnets from the Nanga Parbat-Haramosh Massif, the Kohistan and the Ladakh island arc terranes, northern Pakistan

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ABSTRACT: *Metamorphic rocks of the Nanga Parbat-Haramosh Massif (NPHM) are represented by an intercalated sequence of para- and orthogneisses, with minor metabasites, calc-silicate rocks, and post-metamorphic pegmatite dikes. Garnets from two gar-bio-sill paragneisses in the NPHM are characterized by three distinct textural zones: (1) an inclusion-free core, (2) an inclusion-filled intermediate zone, and (3) inclusion-free rims. These garnets are characterized by distinct chemical zoning profiles from core to rim. Equilibration temperatures for these garnets, calculated with the garnet-biotite geothermometer, are ~650°C in the inclusion-free core, ~725°C in the inclusion-filled intermediate zone, and ~500°C in the inclusion-free rim. Garnets in a paragneiss adjacent to the Astak Fault Zone and the Ladakh arc terrane are inclusion-free throughout, and have nearly flat, unzoned chemical profiles. Equilibration temperatures for these annealed garnets are ~700-684°C, with thin rims ~610°C. The dominance of relatively high equilibration temperatures in all of these garnets is confirmed by oxygen isotope partitioning studies, which show that most garnet-quartz, feldspar-quartz, biotite-quartz mineral pairs equilibrated at ~700°C in the NPHM (Khattak, 1995).*

The Ladakh arc terrane, east of the Astak Fault Zone, consists largely of meta-volcanic rocks, but also contains minor paragneiss horizons. Garnets found in gar-bio-sill paragneisses from the Ladakh arc terrane contain minor inclusions in the core but have inclusion-free rims. These show a sharp step-like change in chemistry at the boundary between core and rim, with relatively high temperatures in the inclusion-filled cores (~720-650°C) and lower temperature rims (~580°C).

The chemical zoning, P-T estimates, and the textural features of these garnets are interpreted as indicative of the tectonic history of the area. The flat chemical zoning indicates annealing (re-equilibration) of the garnets during or after the peak of upper amphibolite facies metamorphism. The occurrence of inclusions coincides with the preservation of the original growth zoning under dynamic, rapid growth conditions. The following tectonic history is proposed: (1) the inclusion-free core of the NPHM garnets may represent collision of the Indian plate with the Ladakh arc; (2) the higher temperature inclusion-filled intermediate zone in the NPHM garnets and the inclusion-filled core of the Ladakh garnets indicates growth during collision of the India-Ladakh package with the Asian plate; and (3) the outermost inclusion-free

zones in garnets from both the terranes probably formed during unroofing/cooling. Annealed garnets of the NPHM adjacent to the Astak Fault Zone probably reflect heating by the hot base of the over-riding Ladakh arc.

INTRODUCTION

The Himalaya is the surface expression of collision between the Indian and Asian plates and the closure of the Neotethys at about 50 Ma. As a result of this collision, the frontal edge of the Indian plate has been intensely deformed, faulted, regionally metamorphosed and intruded by post-collisional, anatetic granites. The Himalaya of northern Pakistan is characterized by remnants of a third microplate, the Kohistan (-Ladakh) Island Arc (KLIA), an intra-oceanic arc sandwiched between the Indian and Asian plates. The KLIA is thrust southwards on top of the leading edge of the Indian plate. Another unique geological feature of the northwestern Himalayas is the Nanga Parbat-Haramosh Massif (NPHM) which forms a NNE-trending window of the Indian plate rocks that have been updomed (Fig. 1). The massif is up to ~40 km wide and covers an area of about 1500 km^2. The boundaries of the massif are N-trending, high angle fault zones dominated by vertical slip directions (Fig. 1; Lawrence & Ghauri, 1983; Madin, 1986; Verplanck, 1986).

This study documents the thermal history of the massif using phase equilibrium and oxygen isotope thermometry, and major element zoning patterns in garnets from both the NPHM and the KLIA. We show that major element zoning in garnets coincides with discrete stages of garnet growth, based on abundance and distribution of mineral inclusions. Garnet-biotite temperature estimates for these discrete growth stages imply counter-clockwise metamorphic P-T-t paths for the NPHM and clockwise P-T-t paths for the adjacent Ladakh arc terrane (Khattak & Stakes, 1993). Such P-T-t paths, have been used in the past (Spear & Selverstone, 1983; Spear et al., 1982, 1984) to decipher tectonic history of a terrane. These growth stages in northern Pakistan probably represent dynamics and timing of the collision between India and Eurasia.

FIELD SETTING

In the northwestern Himalayas, a northern suture or Main Karakoram Thrust (MKT) and a southern suture or Main Mantle Thrust (MMT) enclose a deformed Cretaceous island arc, the KLIA, which is intruded by the calc-alkaline rocks, named as the Kohistan-Ladakh batholith. The Kohistan arc overrode the Indian plate during the Eocene, forming the MMT as well as other thrusts to the south (Fig. 1). South of the MMT are rocks of the Indian plate. The dominant rock-types are psammitic, calcareous and pelitic metasediments of Precambrian to Early Eocene age that are extensively intruded by granites (Tahirkheli et al., 1979). The metamorphic grade and the deformational intensity decreases from kyanite/sillimanite grade adjacent to the MMT to chlorite grade slates and weakly deformed mudstones in the south (Tahirkheli et al., 1979).

The western boundary of the NPHM is the NNE-trending Raikot-Sassi "dextral reverse" fault zone (Fig. 2; Lawrence & Ghauri, 1983), which truncates the MMT south of Raikot. The trace of this steep thrust fault zone is characterized by a 2-2.5 km discontinuous band of mylonite (in some places hydrothermally metasomatized), hot springs, and numerous minor reverse faults, some of which are active (Lawrence & Ghauri, 1983; Madin, 1986; Butler & Prior, 1988; Butler et al., 1989). The southern extent of the fault zone is not known. This fault more or less follows the trace of MMT between Raikot and Sassi. To the

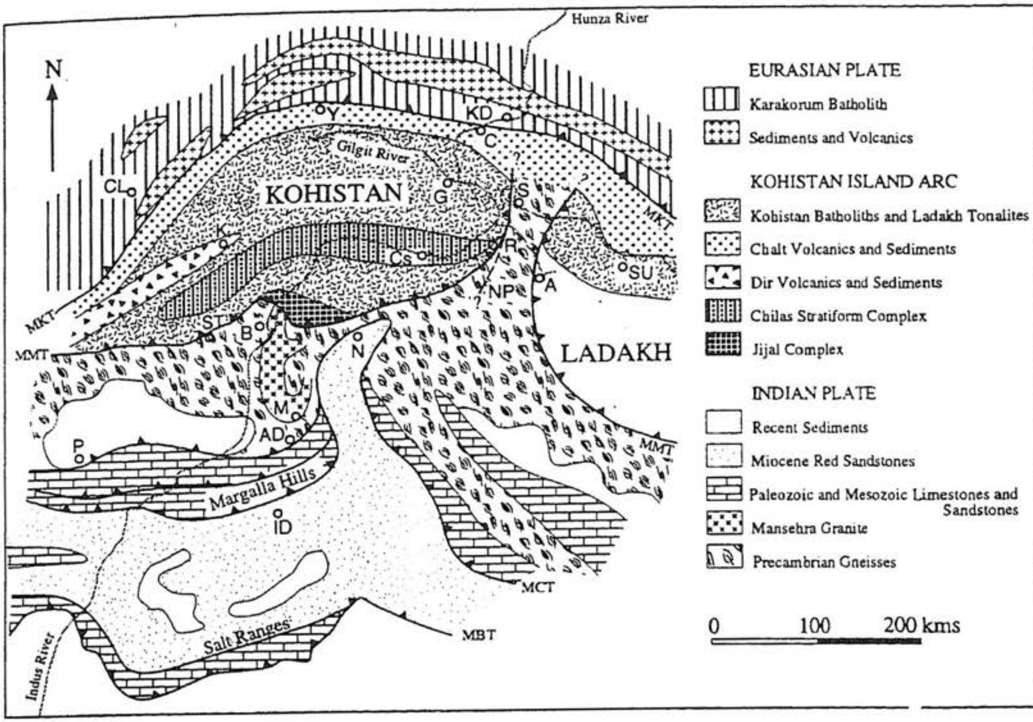

Fig. 1. Generalized geological map of northern Pakistan (modified after Treloar et al., 1989). A=Astore, AD=Abbottabad, B=Bisham, C=Chalt, CL=Chitral, Cs=Chilas, G=Gilgit, ID=Islamabad, K=Kalam, KD=Karimabad, M=Mansehra, MBT=Main Boundary Thrust, MCT=Main Central Thrust, MKT=Main Karakorum Thrust, MMT=Main Mantle Thrust, N=Naran, NP=Nanga Parbat., P=Peshawar, R=Raikot, S=Sassi, ST=Swat, SU=Skardu, Y=Yasin.

west of the fault zone are exposed rocks of the Kohistan arc, with local lenses of the Kohistan arc material brought up alongwith MMT. The eastern boundary of the NPHM is the Astak Fault Zone (Fig. 2; Verplanck, 1986), which lies to the east of the suture between the Indian and Kohistan plates in western Ladakh. The sense of movement on this fault is sinistral-normal (i.e. west-side-up along KKH). To the east of the Astak Fault Zone lies the Ladakh terrane, which extends eastward through Ladakh into southern Tibet (Fig. 1). The eastern boundary of the massif is marked by significant changes in lithology, from interlayered dominantly metasedimentary lithologies on the west to strongly deformed complex zone of metaigneous and metasedimentary rocks of the Ladakh arc on the east. This boundary is a zone about 5 km wide characterized by a complex of slices of rock-bodies belonging to both of the adjacent terranes; at places, mafic and ultramafic lenses are exposed along the Indus River along this boundary of the massif. The mafic-ultramafic assemblages are possibly an extension of the Chilas stratiform complex of the Kohistan terrane probably looping around the NPHM. North of Sassi and Astak the western and eastern faults of the massif trends westward and eastward respectively. The northern extensions of the Raikot-Sassi and the Astak Faults lie beneath the Chogo Lungma glacier and it is not

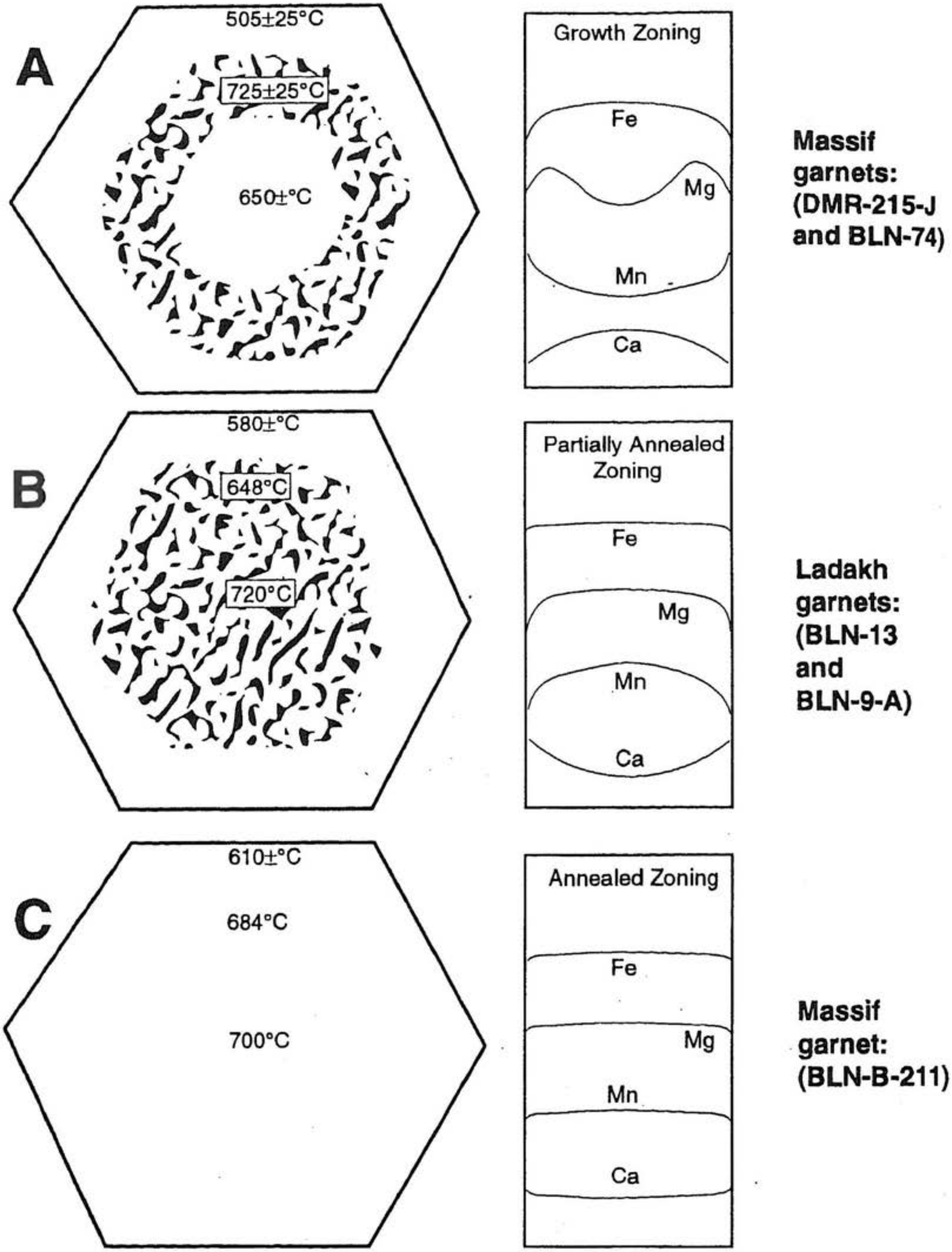

Fig. 2. Diagrammatic representation of the textural (left) and chemical (right) zoning patterns found in the garnets from the Nanga Parbat-Haramosh Massif and the Ladakh island arc terranes. Also given are temperature estimates deduced from the phase equilibria. Note that the garnets from the NPHM are either annealed or display strong chemical and textural zoning whereas those from the Ladakh island arc terrane display partially annealed zoning pattern.

known yet whether the two faults join in the north to form a continuous loop around the massif or they truncate against the MKT. The anastomosing feature of the felsic dikes (aplite and pegmatite) on the island arc side of the Raikot-Sassi and Astak Faults is conspicuous.

The mineralogy and lithologic variation point to a sedimentary protolith for much of the gneiss in the NPHM. These sediments were formed as the continental shelf sequence at the northern Andean-type margin of the Indian plate. Thick, augen-bearing, orthogneiss layers/units were probably derived from plutons that intruded the sedimentary rocks. The conformable amphibolite layers probably represent basaltic material interfingering with the continental shelf sediments, a feature noticed in the shelf sequences in general (Stakes, pers. comm.). Subsequently, the entire sequence was metamorphosed and deformed. The siliceous pegmatite dikes most likely represent the latest intrusive activity.

CHEMICAL ZONING AND MORPHOLOGY OF GARNET

The petrologically important lithology studied from the massif and the KLIA is a fine-grained foliated, prophyroblastic, mylonitized pelitic gneiss consisting of quartz, plagioclase, orthoclase, garnet, biotite, kyanite/sillimanite, and accessories. The stable association of kyanite (or sillimanite) and orthoclase indicates that the gneisses have crystallized above the "second-sillimanite" isograd (Thompson, 1976). The pelites typically display a completed Ky/Sill + Or reaction (to the exclusion of muscovite), but there also are examples of incomplete reaction (assemblages with stable muscovite, orthoclase, quartz, and an aluminosilicate) in the adjacent areas within the massif. Garnet porphyroblasts in the pelites typically contain inclusions of rutile, orthoclase, biotite, ilmenite, and sillimanite. In the core of the massif, the garnet porphyroblasts are rotated and have developed pressure shadows, indicating syntectonic growth (Khattak & Stakes, 1993).

Two phases of equilibration are interpreted in the massif from the petrological data; a widespread upper amphibolite facies prograde and a very local lower amphibolite facies retrograde phase. The upper amphibolite facies prograde phase is evidenced by completed 'second-sillimanite' reaction. The lower amphibolite facies retrograde phase is inferred from (a) the occurrence of post-kinematic muscovite, (b) Mus + Qtz, (c) low temperature estimates of the garnet outermost rims (Khattak & Stakes, 1993), and (d) ~ 500°C or lower temperature estimates from ^{18}O data of amphibole, biotite, and muscovite (Table 1; Khattak, 1995).

The garnets in the metapelites of the massif and Ladakh show two morphological and chemical zoning patterns (Fig. 2). The massif garnets are chemically and texturally zoned, in general, however, there is one sample where the garnets are chemically annealed and contain no or minor inclusions of other minerals. The zoned massif garnets and their textures (Fig. 2-A) are interpreted to be the result of three growth stages. The inclusion-free core, with a temperature estimate of ~650°C, represents relict garnet of the first growth stage; the inclusion-filled zone surrounding the core (with temperature estimates of 725±25°C) shows crystallization during the second growth stage; and the outermost inclusion-free rims, having temperature estimates of 505±25°C, represent garnet growth during cooling (Table 1). The inclusion-filled cores of the Ladakh garnets correspond to the inclusion-filled middle zones of NPHM garnets, based on the morphology and the temperature estimates. The chemically annealed garnets of the massif (Fig. 2-C) do not display any textural features indicating or negating any growth stages. The major element distribution in the analyzed gar-

TABLE 1. TEXTURE, MINERALOGY, TEMPERATURE ESTIMATES (BASED ON *GAR-BIO* PHASE EQUILIBRIUM, AND BASED ON $\delta^{18}O$ FRACTIONATION BETWEEN *GAR* AND *QTZ*) OF THE STUDIED ROCKS FROM THE NPHM AND THE LADAKH ARC TERRANES

Sample ID	Rock	Texture	Mineralogy (in the order of decreasing abundance)	W	Q	F	G	B	Temperature based on 0-18 data	Posi-tion	N&H	P bars
BLB-9-A	metapelite	M,P,G	qz,pg,or,bi,mus,gt,sill,opq	15.3	16.2		13.3	12.6	736(Q-G); 661(G-B)	C	746	9940
										mid	738	8492
										M	618	9828
BLN-13	metapelite	M-C,P,G	qz,bi,pg,or,mus,gt,sill,opq,chl	14.1	16.4		13.7	11.7	764(Q-G), 584(Q-B), 313(G-B0	C	691	9828
										mid	648	8113
										M/IM	609	8201
BLN-74	metapelite	F,P,G	qz,pg,or,bi,ky,sill,mus,ep,opq,ap	13.2	14.	13.3	11.1	8.2	789(Q-G),637(Q-B),384(F-G),382(F-B),378(G-B)	C	652	5448
										M	734	8448
DMR-215-J	metapelite	F-M,P,G/B	qz,or,pg,bi,mus,gt,ky,sill,rt,il,sph,ap,opq,	11.4	12.7	11.4	9.4	10.1	772(Q-G),759(Q-B),344(F-G),449(F-B),925(G-B)	C	592	5046
										mid	630	8282
											741	13548
BLN-B-211	metapelite	F,P,G	pg,or,qz,bi,gt,ky,sill,rt,opq,ap	13.3	14.7	10.4	12.0		764(Q-G), 571(F-G)	C	574	9814
										mid	684	10631
										M	656	11415

Texture Abbreviations: B=banded; C=coarse grained; F=fine grained; G=gneissose; M=medium grained; and P=porphyroblastic texture. Mineralogy: *ap*: apatite; *bi*: biotite; *chl*: chlorite; *ep*: epidote; *gt*: garnet; *ky*: kyanite; *mus*: muscovite; *opq*: opaque minerals; *or*: orthoclase; *pg*: plagioclase; *qz*: quartz; *rt*: rutile; *sill*: sillimanite; and *sph*: sphene. Temperatures are in degrees Celsius. All $\delta^{18}O_{SMOW}$ values are expressed in parts per mil (‰).W=whole rock $\delta^{18}O_{SMOW}$ composition. Temperatures of equilibration derived from $\delta^{18}O_{SMOW}$ data using Bottinga and Javoy's (1975) formulation of mineral-water fractionations. The mineral-water equations were converted into mineral-mineral equations by simple mathematics. B=biotite; F=feldspar; G=garnet; Q=quartz.

nets, in general, matches the textural discontinuities within the garnet porphyroblasts (Fig. 2). The Ladakh garnets typically show partially annealed chemical zoning and well preserved growth morphology. The chemical and textural zoning in the Ladakh garnets (Fig. 2-B) is interpreted as indicative of two growth stages. The inclusion-filled core (with temperature estimates of 720-648°C) represents the first growth stage and the inclusion-free rims (of temperature estimates of 580 ± °C) is a result of the garnet growth during cooling (Table 1).

THERMOBAROMETRY

Metamorphic temperatures were determined from garnet and biotite compositions as well as stable isotopic data of contemporaneous minerals, and pressures were derived from coexisting garnet-plagioclase pairs. The temperature estimates derived from the phase equilibrium studies closely match those derived from the stable isotopic data (Khattak, 1995). The P-T conditions of metamorphism,. based on the two independent techniques, are 700+ °C, 8.5kb, which match the upper amphibolite mineral assemblages common in the rocks in question. Pelitic isograds cannot yet be drawn for the massif.

In general, the garnets from the NPHM and the Ladakh are almandine-rich whilst those from Ladakh slightly more Mn-rich (NPHM: alm_{74-81} py_{9-21} $spess_{2-9}$ $gross_{2-6}$; Ladakh: alm_{67-72} py_{12-17} $spess_{8-14}$ $gross_{6-7}$). The biotites contain appreciable Ti and Al^{VI} (ann_{31-51} phl_{27-53} $^{Ti}bio_{3-8}$ $^{Al}bio_{9-19}$ $^{Mn}bio_{0-0.4}$), typical of high grade biotites (Guidotti, 1984). The plagioclase of the NPHM varies from An_{10} to An_{30} and those of the Ladakh terrane range between An_{46} and An_{96} among the analyzed samples. Pressure-temperature histories were determined using data from studies of disequilibrium mineral textures, minerals included in garnet and zoning in the garnet. Results from petrographic studies indicate that the rocks in the NPHM have undergone a significant pressure (and possibly temperature) increase during the last high-grade metamorphism. The P-T estimates on core to margin mineral compositions also suggest that the massif rocks followed a compressional path with increase in temperature from early to late stage of crystallization (Khattak & Stakes, 1993). The rocks in the Ladakh arc followed a different P-T history. The disequilibrium mineral textures and the mineral inclusions in the garnets from Ladakh suggest that the temperature possibly decreased to cause sillimanite transformation to kyanite (sample BLN-9-A; Khattak & Stakes, 1993). The P-T history based on chemical zoning in the garnets also shows that the Ladakh rocks followed a decompression path while cooling (Khattak & Stakes, 1993).

The temperature increase in the metamorphic history of the NPHM rocks, evidenced by P-T results on biotite inclusions in garnet (Khattak & Stakes, 1993), is supported by the observation that inclusions of alkali feldspar, sillimanite, and rutile are found in the outer half of the garnets in the NPHM. The inner half of these garnets either lacks inclusions altogether or has petrologically unimportant inclusions of quartz, apatite, and biotite. These features suggest that the temperature rose during the garnet growth from below the second-sillimanite conditions to above second-sillimanite isograd where *Ky/Sill+Or* assemblage could stabilize (Khattak & Stakes, 1993).

There is petrographic evidence that pressure also increased during metamorphism of the NPHM. This pressure increase is indicated by sillimanite inclusions in the garnet porphyroblasts in kyanite-bearing rocks (Khattak & Stakes, 1993). One sample (BLN-B-203) contains relict (early?) kyanites within an early folded foliation. The garnet porphyroblasts contain sillimanite inclusions. The matrix contains post-kinematic muscovite and late cordierite and lacks orthoclase (Khattak & Stakes, 1993). This reaction texture suggests a rise in pressure to cause reaction of sillimanite to kyanite during the main stage metamorphism. Absence of kyanite (other than the microfold) and of orthoclase and the occurrence of muscovite and cordierite suggest later equilibration (or a metamorphic event) under substantially lower pressures than the stability field of *Ky+Or* (Khattak & Stakes, 1993). Geobarometry studies of the *Gar-Pg* pairs in six out of eight massif samples indicate a pressure increase from core to rim ranging from 3 to 4.1kb (Khattak & Stakes, 1993). The other two samples from the massif give erroneous margin pressure estimates relative to the petrogenetic grid approximations, however, these margin pressures are again higher than the core pressures (Khattak & Stakes, 1993).

Conversely, the reaction textures, thermometry on biotite inclusions in garnets, and barometric studies on zoned plagioclases in stable association with garnets within the Ladakh terrane show a different P-T history for these rocks. The assemblage *Sill+Or* in Ladakh samples supports the high temperature estimates (>725°C; Khattak & Stakes, 1993). In Ladakh the temperature appears to have decreased during the garnet growth, probably representing a normal cooling path (Khattak & Stakes, 1993).

The outermost rims of garnets from both the massif and Ladakh give temperature estimates of 575±20°C (Khattak & Stakes, 1993), indicating lower amphibolite facies conditions. Such conditions were probably prevalent during the uplift/unroofing of the Ladakh arc and the massif, possibly after they had been juxtaposed against each other in the upper amphibolite facies regime. An interesting point is that the Ladakh garnet cores have annealed but the massif garnets could not. This probably had something to do with the time spans these two terranes spent while being hot. Similar estimates for the outermost garnet rims of both the massif and the Ladakh garnets probably record the closure temperatures for the garnet-biotite thermometer (~580°C).

The P-T path results are interpreted here to be the result of thrusting of the Kohistan-Ladakh Island Arc (KLIA) over the Indian continent along the Main Mantle Thrust (Fig. 1). The rocks presently exposed in the NPHM were probably buried approximately 15 km (5-5.5 kb $P_{gt\ core}$ of NPHM; Khattak & Stakes, 1993) before the collision with the KLIA. Upon collision, the deeper KLIA rocks, about 26 km deep (based on 9.4-9.5 kb $P_{gt\ core}$ of Ladakh, Khattak & Stakes, 1993), were thrust over the Indian plate along the MMT. Thrusting of a hot arc over Indian plate resulted in increasing pressure and temperature paths in the NPHM (lower plate) and decreasing pressure and temperature paths in the arc rocks (upper plate). The rocks on either side of the MMT were juxtaposed after thrusting at depths of 23-25 km and thermally equilibrated at upper amphibolite facies metamorphic conditions (700-750°C; Khattak & Stakes, 1993). The temperature differences observed in these two terranes (Table 1) have probably resulted from heat transfer from the hot overriding plate (Ladakh) to the cooler lower plate (NPHM) during thrusting. Rocks within the NPHM underwent about a 100°C temperature increase due to thrusting, whereas rocks in Ladakh cooled about the same amount during decompression, based on the garnet core to rim thermometry.

The stable isotopic geochemistry of the NPHM confirms that the quartz and garnet mineral pairs are contemporaneous and represent isotopic equilibrium. The ^{18}O fractionation among quartz and garnet confirms the peak temperature of the last high-grade metamorphic episode to be 700°C. The whole rock and mineral $\delta^{18}O_{SMOW}$ values, in general, are strongly depleted along (and adjacent to) the Astak and the Raikot-Sassi

Fault Zones (Fig. 1), probably indicating hydrothermal alteration by lighter waters (possibly igneous waters) in these deep (and several kilometers wide) fault zones (see Khattak, 1995). Fifteen of the sixteen Qtz-Gar pairs' fractionation factors vary from 2.8‰ to 3.8‰ giving a range of temperatures from 764°C to 599°C respectively. The 1.0‰ variation in fractionation is greater than the expected error and thus indicates a real variation in the maximum temperatures (Khattak, 1995). However, at temperatures of 600°C and above, the isotopic composition of a garnet is strongly dependent on its chemical composition (Valley, 1986).

DISCUSSION AND CONCLUSIONS

Being the northern-most exposure, the NPHM records the collisional and metamorphic history of the Indian plate. The ~55 Ma collision of the Indian plate with the Asian plate is well documented (Searle et al., 1987). Treloar et al. (1989) compiled geochronologic studies carried out in the Kohistan and Karakoram regions of Himalayas of Pakistan and have interpreted the collision of the Kohistan and Asian plate by a presuturing Matum Das (north of Gilgit; Fig. 1) granite pluton Rb/Sr age of 102 Ma (Peterson & Windley, 1985) and by hornblende cooling ages of ~75 Ma derived from post-suturing dikes. Final plutonism in Kohistan and Ladakh are dated by Rb/Sr whole rock method as 40 ± 6 Ma (Peterson & Windley, 1985) and 38.8±1.3 (Honneger et al., 1982), respectively. Further south the Kamila amphibolites give $^{39}Ar/^{40}Ar$ ages of 75 Ma on hornblende and the Shangla blueschists are 80±5 m.y. old (Shams, 1980; Maluski & Matte, 1984).

There are three different interpretations of the above age and stratigraphic constraints in terms of the tectonics of the Himalayas (Fig. 3). One group of geoscientists (e.g. Searle et al., 1987; Treloar et al., 1989; Tahirkheli et al., 1979) thinks that the collision between the Asian plate and the Kohistan occurred first (Late Cretaceous-Paleocene), followed by continued subduction of the Tethyan oceanic crust under the Kohistan, and finally (at ~55 Ma) by collision of the Indian plate with the Kohistan (Pliocene-Early Oligocene; Fig. 3-A). Bard (1983a,b) thinks that the collision between the Indian plate and the Kohistan arc occurred first while some oceanic crust still existed between the Asian plate and the Kohistan arc. Collision of India with the Kohistan caused the northern boundary of the Kohistan to have characters like an Andean-type continental margin at one stage. Later, the united India-Kohistan block collided with the Asian plate to form the present topology of the different blocks in the northwestern Himalayas (Fig. 3-B).

Another team of geoscientists (e.g. Srikantia, 1987; Thakur, 1987; Virdi, 1987) suggests that the Indian plate collision with the Kohistan arc in Late Cretaceous-Paleocene caused the opening of a shallow sea between the Asian plate and the Karakoram microplate (and one between the Karakoram and the Kohistan arc; Srikantia, 1987). The microplate later sutured with the Asian plate in Jurassic and at the time the southern boundary of the united Asia-Karakoram was an Andean-type margin. Later, in Pliocene-Miocene, the united India-Kohistan block collided with the Karakoram and Asia (Fig. 3-C).

Still another tectonic model suggests that the Kohistan arc was lying diagonally in a northwest-southeast extension in the Tethyan ocean between the Asian plate in the north and the Indian plate in the south (Sharma, 1987). This type of scenario would result in a complex (oblique) collision between India, Kohistan and Asia. With continued northward movement of the Indian plate, the Kohistan arc would collide with India toward the eastern edge of the arc but with Asia toward the western edge of the arc. Later with continued northward push of India,

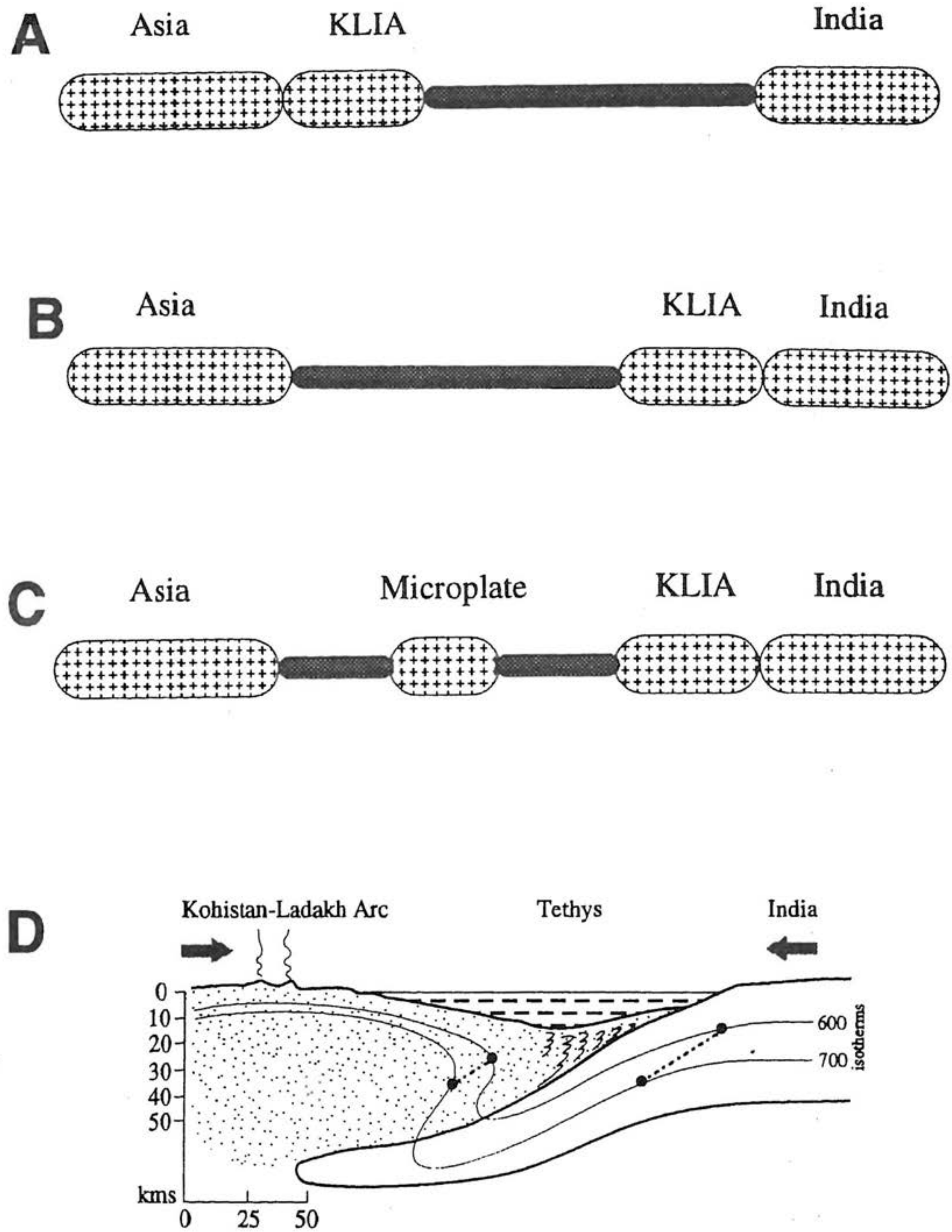

Fig. 3. Different possible tectonic models representing the collision history between the Indian and the Asian plates (A-C). Model D is a tentative cross-sectional model for the suturing of India against Kohistan (true in A, B, and C), showing the PT path the two terrains probably followed (redrawn from Khattak, 1995).

the arc probably rotated counterclockwise to attain the present topology of the three major terranes.

The petrologic (Khattak & Stakes, 1993) and the stable isotopic (Khattak, 1995) results provide important information on the tectonic, thermal and fluid history of the Nanga Parbat-Haramosh Massif, as well as the Pakistan Himalayas. One important implication from this research is that the NPHM preserves a prograde metamorphic history which is brought about as a consequence of the collision between the Indian plate and the Kohistan (-Ladakh) arc. The petrological data presented here provides further information on the relative chronology of the tectonic events occurring in the northwestern Himalayas.

The three types of garnets in the massif and the Ladakh terrane shed light on the sequence of events taking place in the India-Ladakh-Asia collision (Fig. 3). Zoned garnets from the massif show three zones from core to rim:

i. the innermost zone lacking any inclusions, including growth in static conditions;

ii. the middle zone displaying lots of inclusions of quartz, feldspar and biotite, suggesting growth under extremely dynamic conditions; and

iii. the outer inclusion-free zone, showing growth in stable, non-dynamic conditions.

The innermost zone is interpreted as a result of collision of the Indian plate with the Kohistan-Ladakh arc which steepened the geothermal gradient for the shelf sediments of the Indian plate. The middle inclusion-rich zone of the garnet is interpreted as a consequence of collision of the India-Ladakh package with the Asian plate, which oversteepened the geothermal gradient and caused very rapid garnet growth. The outermost zone is a product of unroofing/cooling/obduction of the rocks. This interpretation is supported by the fact that the zoned garnets of the Ladakh arc display only two outer zones described above and is consistent with the P-T calculations and the P-T path constructed for the two terranes. The inner (inclusion-rich) zone in the Ladakh garnets probably grew during the collision of the Kohistan-India package with the Asian plate and the outer (inclusion-free) zone grew while cooling from high temperatures. Further research, especially geochronological studies, will probably prove this petrology-based conclusion of the relative timing of collision between different blocks in the northwestern Himalayas. Extreme rims of the studied garnets, with lowest Mg content and texturally showing wavy edges in contact with biotite, are probably the result of resorption of garnet to form biotite during cooling.

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