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^{18}O Fractionation in Feldspars from the Nanga Parbat-Haramosh Massif, Northern Pakistan

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ABSTRACT: *The Nanga Parbat-Haramosh Massif in northern Pakistan represents the northernmost exposure of the Indian plate that has been juxtaposed against the Kohistan-Ladakh island arc along Raikot-Sassi and Astak faults. The massif is a complex mixture of paragneisses, orthogneisses, minor metabasics, calc-silicate rocks, and post-metamorphic pegmatite dikes. These gneisses are metamorphosed under high pressure upper amphibolite facies conditions (5.5-10 kb, 650-750°C; Khattak, 1990).*

The $^{18}O_{SMOW}$ isotopic compositions of the rocks and their constituent minerals in the massif and adjacent areas of the Kohistan-Ladakh arc along the Indus and Astore Rivers varies as following: whole rock $\delta^{18}O_{SMOW}$ = 7-15.3‰; quartz = 7.4-16.4‰; feldspar = 7-16.1‰; garnet = 5.3-13.7‰; biotite = 3.9-12.6‰; muscovite = 6.7-12.7‰; and hornblendic amphibole = 4.4-7.2‰ (Khattak, 1994). Feldspars isotopic compositions show maximum scatter indicating refractory nature of the minerals. ^{18}O thermometry results based on coexisting quartz-feldspar fractionation curves show disequilibrium in some of the samples. Calculation of the ^{18}O composition of fluids that were in equilibrium with different minerals in the temperature range of 500-700°C reveals that there is one pre-metamorphic and one post-rnetamorphic fluid activity affecting the isotopic composition of the rocks of the massif. The pre-metamorphic fluids probably originated from an igneous parent, depleting the rocks in -2‰, especially along the major faults. The post-metamorphic fluids probably originated from prograde metamorphic reactions and were heavy enough to enrich the feldspars up to ~1 8‰. Retrograde paths indicate that the massif was probably quick in its upward flight from depths of around 35 kms as shown by pressure estimates of Khattak and Stakes (1993).

INTRODUCTION

The Himalayan mountain range (Fig. 1) is the surface expression of collision between the Indian and Asian plates which closed the Neotethyan ocean at about 55 Ma (Powell, 1979). This collision caused the leading edge of the Indian plate to be intensely deformed and greatly thickened, faulted, regionally metamorphosed, and intruded by post-collisional, anatectic granites. In northern Pakistan, an intra-oceanic island arc, the Kohistan-Ladakh Island Arc (KLIA), is sandwiched between the Asian and indian plates. The Nanga Parbat-Haramosh Massif (NPHM), a NNE-trending unique geologic feature of the Himalayas of northern Pakistan, is thrust up from underneath the KLIA rocks (Fig. 1). Recent geothermobarometric studies show that NPHM followed an increasing P-T and KLIA a decreasing P-T path (Khattak & Stakes, 1993).

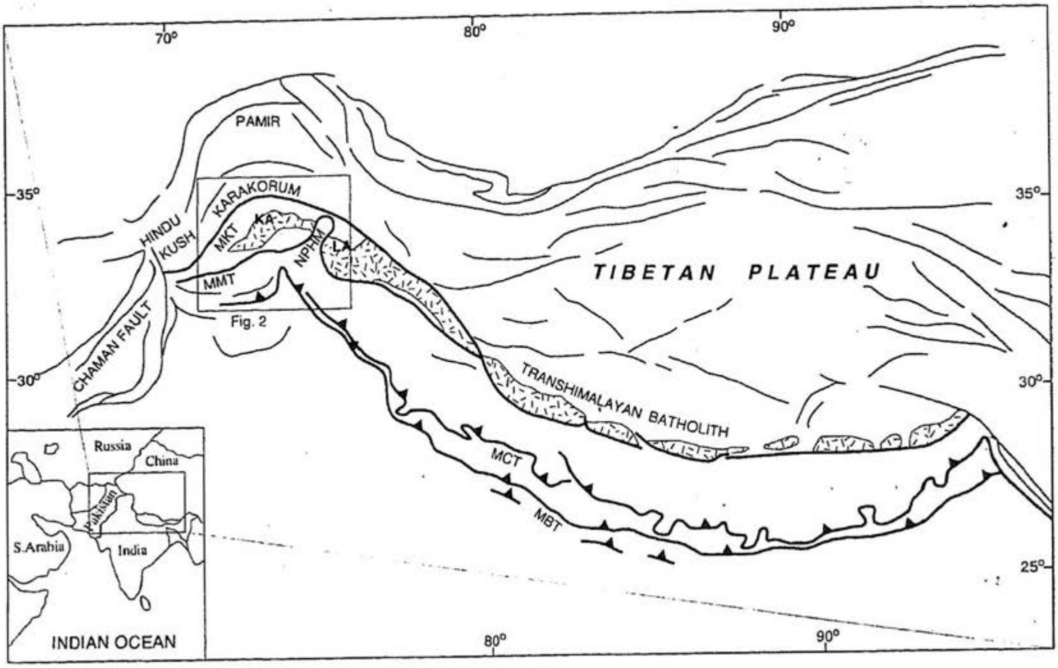

Fig. 1. Generalized tectonic map of the Himalayas. KA=Kohistan arc; LA=Ladakh arc; NPHM=Nanga Parbat-Haramosh Massif; MBT=Main Boundary Thrust; MCT=Main Central Thrust; MMT=Main, Mantle Thrust; MKT=Main Karakoram Thrust (redrawn after Khattak, 1994).

This study concerns the ^{18}O isotope geothermometry of rocks from the massif and adjacent areas of the Kohistan and Ladakh arc. We have used ^{18}O fractionations among contemporaneous mineral pairs to estimate the temperatures of formation of these assemblages during the last metamorphism in NPHM. The use of mineral pairs in thermometry is useful because it is independent of the isotopic composition of the metamorphic fluid and the absolute value of the minerals themselves. It is only dependent on the difference in isotopic value between the two contemporaneous minerals. Stable isotope geothermometry is superior in comparison to mineralogical geothermometers in that the fractionation is independent of the pressures involved. This research is aimed at independently estimating the peak temperatures at the time of metamorphism and to make a petrogenetic interpretation of the *Ky/Sill* grade metamorphic rocks of the massif.

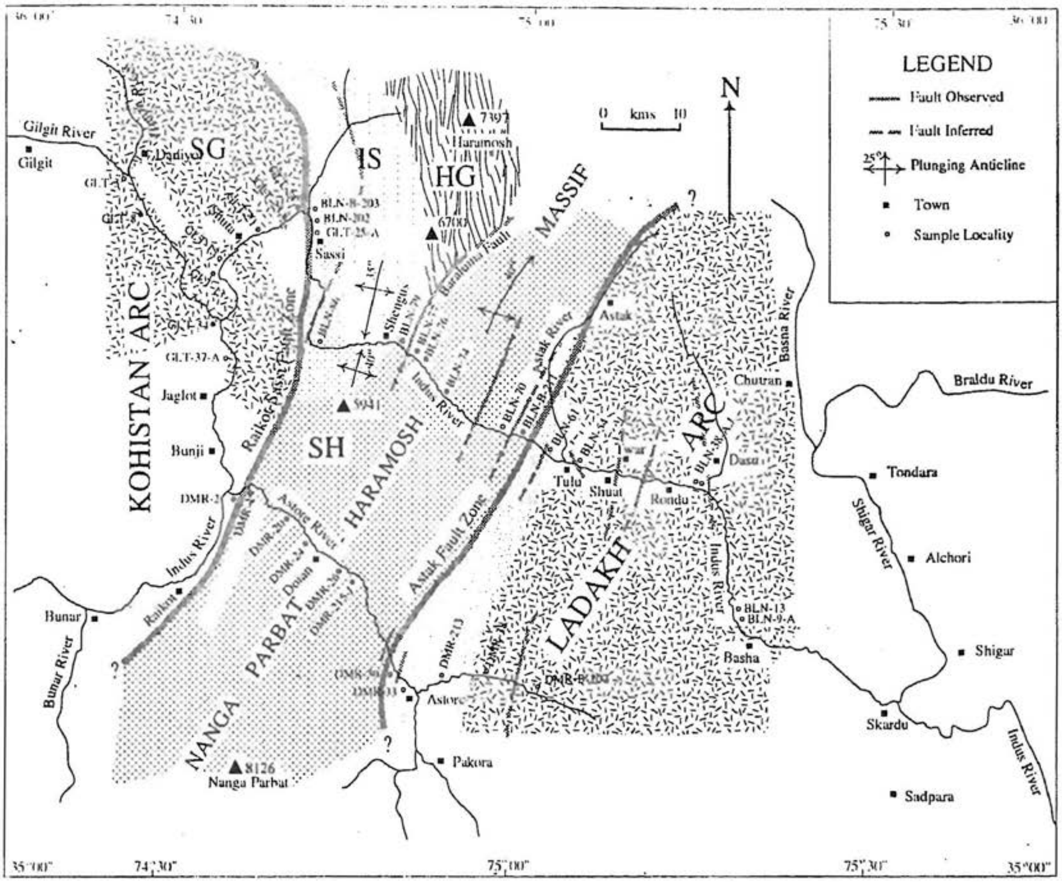

Fig. 2. Geological and sample location map of the Nanga Parbat-Haramosh Massif and the adjoining areas of the Kohistan-Ladakh arc, respectively on west and east of the massif in northern Pakistan (redrawn after Khattak & Stakes, 1993) The elevations are in meters above sea level.

REGIONAL SETTING OF THE NPHM

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 where the dominant rock-types are pelitic, calcareous and psammitic metasediments of Precambrian to Early Eocene age that are extensively intruded by granites. 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.

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 (such as Liachar thrust), some of which are active (Lawrence & Ghauri, 1983; Butler et al., 1989). The southern extent of the Raikot-Sassi fault zone is not known. This fault more or less follows the trace of MMT between Raikot and Sassi. To the west of the fault zone are exposed rocks of the Kohistan arc, with local lenses of the Kohistani arc material brought up alongwith MMT. The eastern boundary of the NPHM is the Astak fault zone (Fig. 2), which lies to the east of MMT 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 Laclakh 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 meta-sedimentary 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, occurring between the MMT and the Astak fault (Khattak, unpubl. data). The mafic-ultramafic assemblages are either an extension of the Chilas stratiform complex of the Kohistan terrane probably looping around the NPHM, or these assemblages belong to Tethyan oceanic material caught up between the arc and Indian plate, 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 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 consipicuous.

BACKGROUND OF THIS STUDY

The Indus and Astore river valleys provide northeast-southwest cross-sections across the NPHM (Fig. 2). The rocks of the NPHM can be divided into psammitic gneiss, granitic gneiss, calc-silicate rock, pelitic gneiss, amphibolite, and siliceous-pegmatitic and mafic dikes. These units are interlayered tabular bodies separated by fairly sharp contacts conformable with foliation and lithologic layering. All units, except the siliceous pegmatite dikes, have experienced kyanite/sillimanite grade metamorphism accompanied by intense deformation which has transposed original structures and modified original thicknesses. Whether the present relative position of these units or layers reflects their relative ages is not known.

TABLE 1. TEXTURE AND MINERALOGY OF THE REPRESENTATIVE ROCKS FROM THE NPHM AND THE KOHISTAN-LADAKH ARC TERRANES, SELECTED FOR ^{18}O ANALYSIS.

Sample ID	Rock	Texture	Mineralogy (in the order of decreasing abundance)	Q	F
BLN-38-A	tonalite	M,G	pg,qz,or,bi,sph,gt,ep,opq,ap	9.8	8.4
BLN-54	amphibolite	C,E	pg,hbl,bi,ep,opq,qz,ap	9.7	11.1
BLN-61	tonalite	F,P,S	pg,or,qz,mus,bi,gt,ap,zir,chl	10.4	9.5
BLN-70	amphibolite	M,P,G	pg,hbl,gt,qz,ep,bi,opq,sph,ap	9.3	8.1
BLN-74	metapelite	F,P,G	qz,pg,or,bi,ky,sill,mus,ep,opq,ap	14.1	13.3
BLN-76	metapelite	F,P,G	qz,pg,or,bi,gt,ky,mus,opq	11.7	9.3
BLN-77	granitic schist	F-M,G	pg,or,qz,bi,mus,spq,chl	12.6	10.1
BLN-79	metapelite	F,P,G	pg,qz,or,bi,mus,gt,sill,opq	8.4	9.4
BLN-86	granitic schist	C	pg,or,qz,bi,mus,opq	12.0	12.7
BLN-202	granitic schist	F-M,P,G	qz,pg,gt,bi,mus,ap,opq	14.7	16.1
BLN-B-211	metapelite	F,P,G	pg,or,qz,bi,gt,ky,sill,rt,opq,ap	14.7	10.4
DMR-2	amphibolite	M,S	pg,bi,hbl,qz,ep,chl,opq,ap	8.8	7.5
DMR-4	amphibolite	C,I,G	pg,qz,chl,ep,mus,cc,sph,allan,opq	10.6	7.6
DMR-20-A	granitic schist	M,S	pg,qz,bi,mus,opq,ap,ep,chl,seri,zir	11.6	13.0
DMR-24-B	granitic schist	M,G	pg,qz,bi,mus,ap,opq,ep,sph	12.0	10.1
DMR-26-B	metapelite	F,P,G/B	qz,pg,or,bi,gt,mus,ky,opq,rt,ap		14.8
DMR-38	tonalite	C	pg,or,qz,mus,ep,bi,opq	9.4	12.0
DMR-B-207	tonalite	C,P	pg,or,qz,bi,mus,sph,ep/allan,opq,ap	7.4	10.0
DMR-215-J	metapelite	F-M,P,G/B	qz,or,pg,bi,mus,gt,ky,sill,rt,il,sph,ap,opq	12.7	11.4
GLT-3	metagranite	M,E	pg,or,qz,mus,gt,cc,opq	15.3	13.5
GLT-8	metagranite	C,I	pg,or,qz,mus,bi,gt,ap	11.0	9.4
GLT-13	metagranite	M,E	qz,pg,or,gt,mus,bi,allan	9.7	7.8
GLT-15	granitic schist	F-M,P,G	qz,pg,or,bi,hbl,gt,ep,opq,ap	11.5	9.9
GLT-21	metagranite	M,S	pg,or,qz,bi,ep,ap,zir,rt,opq,hbl	8.8	7.0
GLT-23	metagranite	C,P,G	pg,or,qz,bi,mus,chl,ep,hbl,ap,zir,opq	10.8	12.2
GLT-24	granitic schist	F,P,G/B	qz,or,pg,hbl,bi,gt,sph,opq,cc,mus,ap,zir	11.3	13.5
GLT-25-A	granitic schist	F,G	pg,qz,bi,mus,ap,opq,zir,sph	11.6	12.9
GLT-34	metagranite	M-C,S	pg,or,qz,bi,ep,opq,allan,ap	10.3	8.6
GLT-37-A	metagranite	M-C,S	pg,or,qz,hbl,bi,allan,sph,ap,mus,cc	11.4	9.9

Textures: B=banded; C=coarse grained; E=equigranular; F=fine grained; G=gneissose; I=inequigranuiar; M=medium grained; My=mylonitized; P=porphyroblastic; and S=schistose. Mineralogy: *allan*: allanite; *ap*: apatite; *bi*: biotite; *cc*: calcite; *chl*: chiorite; *cor*: cordierite; *ep*: epidote; *fel*: feldspars; *gt*: garnet; *hbl*: hornblende; *ky*: kyanite; *mus*: muscovite; *opq*: opaque minerals; *or*: orthociase; *pg*: plagiociase;

qz. quartz; *rt*: rutile; *seri*. sericite; *sill*. sillimanite; *sph*: sphene; and *zir* zircon. Q=quartz; and F=feldspar $\delta^{18}O_{SMOW}$ composition expressed in parts per mil (‰).

The mineralogy and lithologic variation (Table 1) 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 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 intertwined with the continental shelf sediments. Subsequently, the entire sequence was metamorphosed and deformed. The siliceous pegmatite dikes most likely represent the latest intrusive activity. The rock types included in this study are metagranite, granitic schist, amphibolite, metapelite, and tonalite (Table 1).

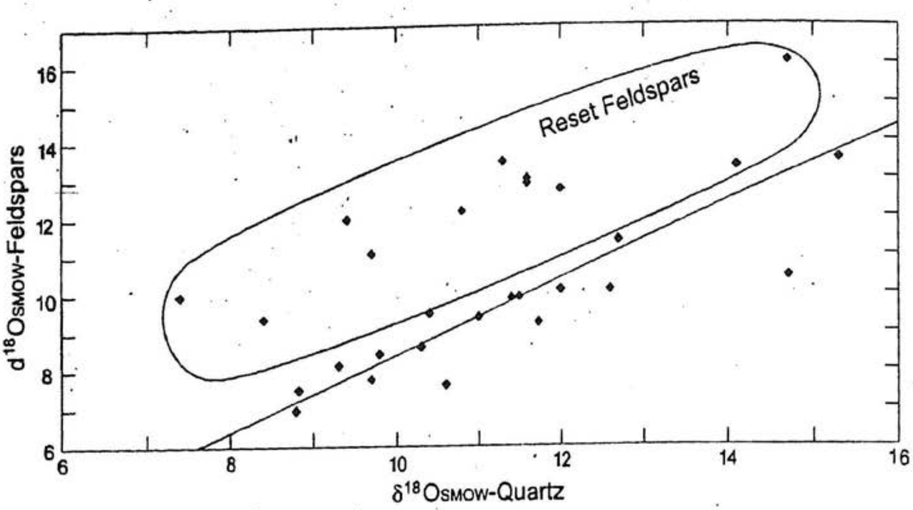

Fig. 3. $\delta^{18}O_{SMOW}$ Qtz-Fel plot showing reequilibrated feldspars, mostly enriched in their ^{18}O composition by probably a post-metamorphic fluid activity. This fluid probably originated as formation waters resulting.

DISCUSSION

Fig. 3 is a plot showing the variation of $\delta^{18}O$ values of Qtz-Fel pairs. Superimposed on these δ-δ values is a line of theoretical Δ_{xy} ($\cong 10^3 \ln\alpha_{xy}$) = 1.57, corresponding to temperatures of 700°C using Bottinga and Javoy's (1975) calibration of the fractionation factors. Some of the feldspars (and OH-bearing minerals in the rocks; Khattak, unpublished data) have reset their isotopic compositions after the peak of last metamorphism. This is indicated by the encircled feldspars in figure 3 displaying extremely enriched $\delta^{18}O$ values. The high $\delta^{18}O$ values of these feldspars when employed with corresponding quartz $\delta^{18}O$ values result in erroneous temperature estimates, indicating that these mineral pairs are not isotopically contemporaneous and that isotopic composition has been modified by a later event. Since feldspars are isotopically less refractory, they have re-equilibrated after the peak of metamorphism with fluids very rich in $\delta^{18}O$ values. These fluids prevalent subsequent to the main metamorphism probably originated from metasediments as a result of prograde metamorphic reactions (Khattak et al., 1997a). This re-equilibration probably occurred under lower amphibolite conditions (~500°C, 5-6kb) supported by petrographic evidence in occasional assemblages. This interpretation may indicate that the re-equilibrated phases (like feldspars, biotite, muscovite and amphibole) are mutually contemporaneous and reveal the cooling (retrograde) history of the rocks (Khattak, unpubl. data).

Two phases of equilibration are interpreted in the massif from the petrological data, a widespread upper amphibolite facies (approaching granulite facies conditions) and a very local lower amphibolite facies (Khattak & Stakes, 1993). The former is evidenced by completed 'second-sillimanite' reaction; whereas the latter is inferred from the occurrence of post-kinematic muscovite, occurrence of cordierite and the absence of *KylSill+Or* pair due to back reaction of this pair to *Mus+Ctz*. Both of these metamorphic events are confirmed by the stable isotopic analysis of the rocks (Khattak et al., 1997a,b).

In addition, the $\delta^{18}O$ data also suggest that there probably was an earlier pre-burial episode during which recognizable $\delta^{18}O$ depletion of rocks took place (Khattak, 1994).

CONCLUSIONS

The stable isotopic results presented here show a prograde metamorphic history for the NPHM which is brought about as a result of collision between India and Kohistan arc and a retrograde metamorphic imprint on the massif resulting from cooling and unroofing. The peak conditions of the last burial metamorphism were 700+°C, 8.5kb, based on two independent thermometric derivations, the ^{18}O fractionation and Fe-Mg exchange between coexisting mineral pairs (Khattak et al., 1993). The retrograde metamorphic conditions were probably lower amphibolite or greenschist facies conditions (~500°C, 5-6kb). Lack of significant migmatization in the metasediments and general absence of granulite assemblages from the massif suggest that the temperatures were not significantly higher than 700°C and that the rocks were not water rich. Low amount of water in metasediments of the massif seems unusual, however, it is possible that much of the water from the rocks was squeezed out during previous metamorphic events. Although there is no petrographic evidence of former metamorphic episodes but it is possible that the last upper amphibolite metamorphism obliterated all imprints of the previous events.

Some of the feldspars (and OH-bearing minerals) have reset their isotopic compositions after the climax of last metamorphism. The fluids prevalent subsequent to the main metamorphism probably originated from metasediments as a result of prograde metamorphic reactions (Khattak et al., 1997a,b). This re-equilibration probably occurred under lower amphibolite or greenschist facies conditions (~500°C, 5-6kb).

REFERENCES

Bottinga, Y. & Javoy, M., 1975. Oxygen isotope partitioning among the minerals in igneous and metamorphic rocks. Reviews of Geophysics and Space Physics, 13, 401-418.

Butler, R.W. H., Prior, D. J. & Knipe, R. J., 1989. Neotectonics of the Nanga Parbat syntaxis, Pakistan, and crustal stacking in the NW Himalayas. Earth Planet. Sci. Letts., 94,329-343.

Khattak, M. U. K., 1990. Geothermometry and Geobarometry of the Nanga Parbat-Haramosh Massif and adjoining Ladakh arc terrane, northern Pakistan. Unpubl. M. S. thesis, University of Washington.

Khattak, M. U. K., 1994. Petrology and stable isotope geochemistry of the Nanga Parbat-Haramosh Massif, northern Pakistan. Unpubl. Ph.D. Dissertation, University of South Carolina.

Khattak, M. U. K. & Stakes, D. S., 1993. New data on the geothermobarometry of the Nanga Parbat-Haramosh Massif and adjoining Ladakh arc terrane, northern Pakistan. Geol. Bull. Univ. Peshawar, 23, 1-1 6.

Khattak, M. U. K., Shervais, J. W. & Stakes, D. S., 1997a. Metamorphism of the Nanga Parbat-Haramosh Massif -1: Stable Isotopic Thermometry. Poster presented at the XII HKT Workshop, 16-18 April, Rome, Italy.

Khattak, M. U. K., Shervais, J. W. & Stakes, D. S., 1997b. Stable Isotope Thermometry of the Nanga Parbat-Haramosh Massif and the Kohistan-Ladakh Island Arc, Northern Pakistan. Geol. Bull. Univ. Peshawar, 28, 95-105 (this issue).

Lawrence, R. D. & Ghauri, A. A. K., 1983. Evidence of active faulting in the Chilas district, northern Pakistan. Geol. Bull. Univ. Peshawar 16, 185-6.

Powell, C. McA., 1979. A speculative tectonic history of Pakistan and surroundings: Some constraints from the Indian Ocean. In: Geodynamics of Pakistan. (Abul, Farah & Kees, A. DeJong, eds.), Geol. Survey of Pakistan, Quetta, 5-24.