Vol. 2

Himalaya

(Geological Aspects)

Edited by :
Prof. P.S. Saklani

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About the Book

The volume is mainly focussed on structural and metamorphic characteristics of the Himalayan rocks exposed in various sectors of the Himalaya. The peridotites in the Spongtang nappe of Ladakh are mylonitised and occur in superposed imbrications. The regionally metamorphosed pelitic rocks of a part of Kashmir show low pressure, intermediate and medium pressure of metamorphism. The Buniyar granite is an intrusive plunton in the Dogra Slates (Precambrian) in the Western part of Kashmir. The NE-SW compressional stress was responsible for development of multiple folds in metamorphics of Chamba area. The radiometric date of granites in Chor mountain is Pre-Tertiary (1000 m.y and 525 m.y.). The metamorphic and folding processes of the Chor pelites were terminated by the Jutogh thrusting phenomena. The crystallines of Palampur (Himachal) are characterised by the Chail thrust and contain about 12 types of garnet texturally. The Manali-Rohtang Pass area forms a part of an overturned limb of the Crystalline nappe. The thrusts in the Kumaun region developed from the hinterland to foreland. The total displacement of the Munsiari, Krol and Berinag Sheets was about 330 km. The Purola area in Garhwal is located between the Main Central Thrust and the Tons Thrust. Metamorphics in the Bhagirathi valley were formed at the temperatures ranging from 479° to 666° C. The uranium mineralisation in the granite-gneisses and the footwall quartzite took place after the formation of the Main Central Thrust III in Tehri Garhwal. The rock-fabric (b-c girdles of quartz) in rocks of Lansdowne Crystalling nappe developed along the thrust-transport direction with rotation which is exhibited by triclinic symmetry. The fracture and lineament patterns were formed in the frontal parts of the Himalaya. The Lesser Himalaya region in Himachal Pradesh has overlapping crystalline thrust. The Chail nappes are traceable throughout the length of the Lesser Himalaya. The nappe thrusting in two phases occurred in Eastern Nepal during middle Tertiary and Quaternary times. Simple shear type of deformation affected the rocks in Eastern Nepal. The high heat flow in rocks of Darjiling region was responsible for the first phase of metamorphism which was followed by overturning and thrusting during the second phase of deformation. The metapelites in Eastern Sikkim are characterised by Kyanite-sillimanite isograd with associated quartzofeldspathic melt during pre-and syn-kinematic deformation. The reflected Aravalli trends are present in Arun transanticline and Tista Dome in Bhutan. The Central Tibetan region was possibly the homeland for the nappes in the Eastern Himalaya.

These volumes would be useful to earth scientists, academicians, research scholars and for those interested in complex problems of the geology of the Himalaya.

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Dr. P.S. Saklani (b. 28.8.1941) is a Professor of Geology at the University of Delhi for the last three decades. Formerly he was the Vice Chancellor of HNB Garhwal University, Uttaranchal from 1999 to 2001 and the Chairman of the Commission for Scientific and Technical Terminology, Govt. of India from 1994-1998. He was elected as President of Earth System Sciences of the 85th Session of the Indian Science Congress in 1997-98. Prof. Saklani has been a recipient of several and awards (e.y. Consulting Editor of American Biographical Institute, Releigh, U.S.A; 21st Century Award 2000; U.P. Ratna Award etc.). He has authored four original books and published 56 research papers on Himalayan Geology. He has guided 11 strudents for Ph.D. and 11 Students for M.Phil. degrees.

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THE CENTRAL HIMALAYAN GNEISSES IN NORTHERN PAKISTAN*

R. D. Broughton and B. F. Windley

ABSTRACT

The Central Himalayan Gneisses on the northern margin of the Indian plate in the Hazara and Lower Swat areas of N. Pakistan comprise; orthogneisses with minor schists, amphibolites and calc-silicates, overlain unconformably by a cover sequence of graphitic and calcareous schists, marbles and minor amphibolites. These rocks are bounded to the south by a major thrust (equivalent to the Himalayan Main Central Thrust), and to the north by the Main Mantle Thrust (Indus Suture). To the south of the MCT there is a thrust slice of basement paragneisses with no relics of cover. The dominant gneissose foliation parallels the main thrusts, and is modified by numerous, - large-scale N-S trending open folds.

The ortho- and para-gneisses and cover sequence are isofacial, and underwent two phases of metamorphism, prior to 35 Ma. Mineral equilibria indicate conditions for the cover sequence in the range 550~620°C and 8.0-8.9 kb, and for the paragneiss basement at~ 650°C and 6.7-6.8 kb. The two pressure ranges come from different thrust slabs. These data indicate an average cooling rate of ~ 17° C my^{-1}, and an average uplift rate of ~ 0.8 mm yr^{-1} over the last 35 My, for the relic cover sequence.

INTRODUCTION

The southern part of the area was mapped by Calkins et al. (1975), who indicated orthogneisses and granites in the section north of Batagram. The Lower Swat section from Besham to Mingora formed the basis of a reconnaissance study by Martin et al. (1962), and more detailed work by King (1964). The Mansehra granite formed the subject of a study by Le Fort et al. (1980), which determined a Rb-Sr whole rock isochron of 516±16 m.y. Coward et al. (1982b) include a preliminary map and description of the geology, and Maluski and Matte (1984) report ^{40}Ar-^{39}Ar dates in the area. Considerable recent attention has been paid to the Kohistan Sequence immediately to the north, *interalia* Bard et al. (1980, Coward et al. (1982a, b) and Bard (1984); and to the blueschists along the Main Mantle Thrust (Indus Suture), Desio (1979) and Shams et al. (1980), see Fig. 1. There are, however, very little published data on the crystalline rocks of the Indian Plate to the south, and their correlation with the rest of the Himalaya. We describe here the local geology of a N-S section from Batagram to Besham, and lateral sections from Besham westward to Mingora, and eastward to Banna. We report mineral chemical data, P-T conditions of metamorphism, and new mineral dates recording the time of metamorphism.

BATAGRAM-THAKOT-BESHAM SECTION

The main rock types are para- and ortho-augen gneisses with subordinate schists, calc-silicates, marbles and amphibolites. The gneisses are distinguishable genetically by small, rounded sedimentary xenoliths in ortho-gneisses and continuous sedimentary layers in

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paragneisses. Both types are foliated, with tabular K-feldspar megacrysts up to 80 mm long, oriented in the plane of the foliation. There are mineralogical differences; the paragneisses have common garnet, kyanite and/or sillimanite, whilst the orthogneisses have more feldspar and quartz. Sheets of amphibolite lie in the plane of the foliation, and are commonly boudinaged. Marble bands are up to 4m thick, and contain radiating fibrous aggregates of tremolite. The foliation has a constant E-W strike and northerly dip with common isoclinal folds and minor thrusts at outcrop scale. Pegmatites and quartz veins are deformed by these F_2 folds. Just north of Thakot, the basement changes in nature from sillimanite- K-feldspar para-augen gneisses to more granitic rocks further north. Northwards calc-silicate, granite and pegmatite become increasingly common. A major thrust is postulated here, striking east-west, separating sillimanite-bearing para-gneisses of the basement to the south, from granitic orthogneiss basement and relics of a kyanite-bearing cover sequence to the north (Fig. 1). This thrust is also probably responsible for the course of the Indus in this area. Folding is intense immediately to the south of the MMT, with development of a considerable thickness of blastomylonite (Lawrence and Ghauri, 1983). To the north of the MMT is the Jijal complex of garnet granulites and harzburgitic peridotites, which comprise the lowest part of the Kohistan Sequence.

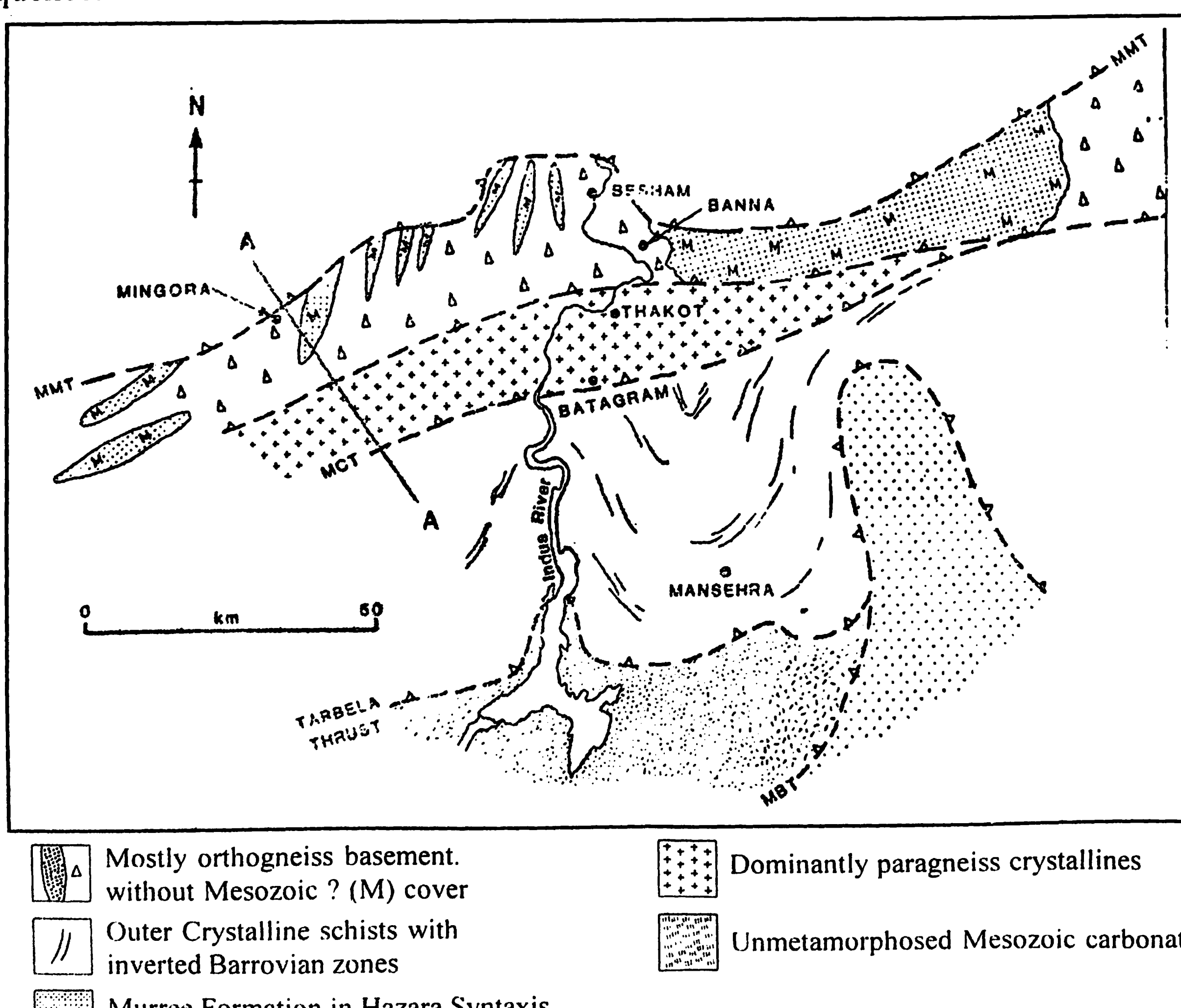

Fig. 1. Map of the study area. A-A is the line of the section shown in Figure 2.

BESHAM-ALPURAI-MINGORA SECTION

To the west of Besham is a basement of dominant orthogneiss, with minor pegmatite, schist and calc-silicate. The strike of the dominant foliation is broadly N-S. Within this basement sequence are infolded synclinal keels of a sedimentary and subordinate volcanic cover sequence, with a marked unconformity and basal conglomerate, now metamorphosed to kyanite-staurolite grade (Fig. 2). The thickest part of the sequence comprises:

marble	20 m
calc-pelite	40 m
pelite-psammite	20m
graphitic pelite	60 m
graphitic conglomerate	5 m
basement orthogneisses	

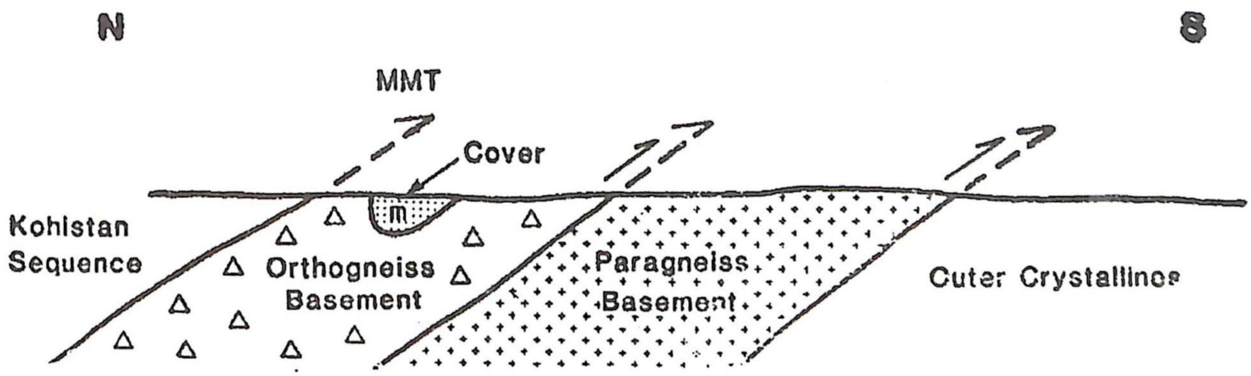

Fig. 2. Sketch cross-section. For location, see Figure 1.

Material in the basal conglomerate can be correlated with lithologies which locally form the basement. The graphitic pelitic rocks commonly contain garnet, staurolite and kyanite porphyroblasts, and are highly micaceous. The non-graphitic pelites and psammites are less aluminous and contain garnet but no staurolite or kyanite. Calc-pelites commonly contain large, euhedral garnet, smaller epidote and locally, kyanite. The groundmass commonly comprises calcite, dolomite and quartz. The marbles are fairly pure, the major impurities being muscovite, epidote and quartz. Interbedded with the cover sedimentary sequence are a number of amphibolite bands, locally garnetiferous. They display isoclinal folds with limbs parallel to bedding and minor plagioclase segregation toward the margins.; S_1 (bedding foliation) is commonly parallel to S_0 (bedding), and interacts with S_2 to produce a prominent intersection lineation. The S_2 is variably developed, and parallels axial surfaces of minor F_2 structures, which are parasitic on the limbs of the major F_2 synclines. The cover sequence is cut locally by thin calcite veins, and also by large quartz veins, which locally contain garnet, muscovite and kyanite. The basement + cover sequence is overthrust by blueschists at Shangla, and harzburgite and serpentinite at Mingero (Jan et al., 1981), where the ultramafics form lenses in a matrix of chloritoid-bearing slates.

BESHAM-BANNA SECTION

East of Besham, exposed basement is made up of gneisses, calc-silicates and occasional meta-volcaniclastics (R. C. Leake, pers. comm.). Further east, the cover sequence comprises mainly graphitic pelites and marbles, and shows two main phases of deformation. The pelitic rocks are fine-grained, and only locally are porphyroblastic. Rarer calc-pelites contain garnet and epidote, porphyroblasts and locally kyanite. Concordant garnetiferous amphibolite is common, and the whole sequence is cut by common quartz veins and pegmatite. The contact between cover and basement is not seen in this section, as the cover forms a mote extensive and continuous outcrop. The basement to the east and south of Banna is identical to that in the Batagram-Thakot section.

PETROGRAPHY AND MINERAL CHEMISTRY

The basement paragneisses show a well-developed planar fabric produced mainly by biotite and muscovite. Augen of muscovite commonly enclose kyanite, whilst kyanite and sillimanite commonly occur at muscovite-quartz grain boundaries. Biotite is pleochroic in shades of mid- to red-brown due to high TiO2 content (up to 4.9 wt%). Garnet tends to be flattened into the plane of the foliation, and contains inclusions of ilmenite and quartz. Garnet is generally unzoned, and has the general composition: almandine 75%, pyrope 13% with minor spessartine and grossular contents. Plagioclase rarely forms porphyroblasts, and is commonly zoned, with Na-rich rims and Ca-rich cores. Coexistent K-feldspar commonly contains up to 15% mole albite.

In aluminous pelites of the cover sequence, kyanite occurs as micro- and macro-porphyroblasts, inclusions in garnet, and in pseudomorphs after staurolite. Within one sample blades of kyanite are deformed around F_2 folds, and overgrow F_2 folds in the groundmass; we interpret this to represent kyanite growth over a long time period. The porphyroblasts contain inclusions of quartz, rutile, ilmenite, tourmaline, muscovite and graphite. The only detected impurity in kyanite is Fe_2O_3 up to 0.4 wt%.

Staurolite occurs as ragged porphyroblasts and occasionally as small groundmass grains,- and inclusions in garnet rims. Its relation to deformation is generally equivocal, but in one sample staurolite clearly overgrows F2 folds in the groundmass. It has X_{Mg} (Mg/Mg + Fe) from 0.05-0.19. ZnO from 0.9 to 4.5 wt% and TiO_2 up to 0.6 wt%.

Garnet porphyroblasts are common in most pelitic, calc-pelitic and basic rocks, but vary considerably in their size, shape, and distribution of inclusions. In kyanite-bearing rocks ilmenite forms common inclusions in garnet cores, and rutile becomes progressively common toward rims. Other species of inclusion are kyanite, staurolite, chloritoid, quartz and graphite in pelites, clinozoisite, calcite, dolomite and quartz in calc-pelites, and ilmenite, quartz and hornblende in amphibolites. Rotational fabrics occur in numerous samples, but it is uncertain to which deformational episode these relate. Garnet growth appeared to commence pre-F_1 and continued through to post-F_2. Garnet analyses from three aluminous pelites (MG 13, MG 29 and MG 34) are given in Table I, from calc-pelites in Table II, and from amphibolites in Table III. Zoning is absent from garnets in pelitic and calc-pelitic rocks, but minor ' normal' zoning occurs in some amphibolite garnets.

Table I. Representative analyses from cover sequence pelites.

	MG 13			MG 29			MG 34			
	GT	PL	ST	GT	ST	CTD	GT	CTD	PAR	MU
SiO_2	37.9	59.4	28.7	37.0	28.6	24.4	37.2	23.3	43.3	45.8
TiO_2	—	—	.4	—	.5	—	—	—	—	.4
Al_2O_3	21.5	26.0	54.8	21.2	54.1	40.8	21.2	38.3	40.8	35.0
FeO	30.7	—	9.7	33.2	12.1	22.5	33.2	28.5	.5	1.0
MnO	—	—	—	.3	_	—	.3	.3	—	—
MgO	3.0	—	1.1	3.8	1.3	4.0	1.8	.7	—	.9
CaO	7.0	7.1	—	4.6	—	—	7.1	—	2.3	—
Na_2O	—	7.2	—	—	—	—	—	—	5.4	1.4
K_2O	—	—	—	—	—	—	—	—	.8	8.8
ZnQ	—	—	4.1	—	0.8	—	—	—	—	—
Total	**100.1**	**99.7**	**98.8**	**100.1**	**97.4**	**91.7**	**100.8**	**91.1**	**93.1**	**93.3**
O	12.000	32.000	23.000	12.000	23.000	12.000	12.000	12.000	22.000	22.000
Si	3.003	10.598	3.937	2.958	3.943	2.009	2.972	2.005	5.692	6.173
Ti	—	—	.041	—	.052	—	—	—	—	.041
Al	2.008	5.468	8.862	1.998	8.804	3.960	1.996	3.885	6.322	5.560
Fe	2.034	—	1.113	2.220	1.451	1.550	2.218	2.051	.055	.113
Mn	—	—	—	.020	—	—	.020	.022	—	—
Mg	.354	—	.225	.453	.352	.491	.214	.090	—	.181
Ca	.594	1.357	—	.394	—	—	.608	—	.324	—
Na	—	2.491	—	—	—	—	—	—	1.376	.366
K	—	—	—	—	—	—	—	—	.134	1.513
Zn	—	_	.412	—	.079	—	—	—	—	—
Sum	**7.993**	**19.914**	**14.591**	**8.043**	**14.681**	**8.010**	**8.030**	**8.053**	**13.903**	**13.946**

Chloritoid forms microporphyroblasts in kyanite-free samples, and inclusions in kyanite-bearing rocks. It is compositionally constant within a thin section, but between rocks X_{Mg} varies from 0.18 to 0.29, and ZnO was below detection. For all sections analysed, X_{Mg} varies in the order chloritoid > staurolite > garnet.

White-mica is the dominant K-bearing phase with biotite present in only a few sections. Muscovite has 0.1 to 0.34 Fe, and 0.09 to 0.49 Mg per 22 O, whilst paragonite has 0,05 to 0.09 and 0.0 to 0.28 per22 O respectively, X_{Na}(Na/Na+ K) varies from 0.06 to 0.34 in muscovite, and 0.66 to 0.85 in paragonite. Muscovite forms the dominant fabric in most samples.

Clinozoisite is common as porphyroblasts and inclusions in garnet in most calc-pelitic samples. Texturally, it appears to be late, and commonly exhibits deep-blue interference colours. The main substitution mechanism is Fe^{3+} for Al, with up to 6.3 wt% Fe_2O_3. In one sample, two compositionally distinct groups of epidote occur, one with -5.4 wt% Fe_2O_3, and the other, which appear to be pseudomorphs after kyanite, with 1.2 wt%.

Table II. Representative analyses from calc-pelites.

	BN 16				BS 32			
	GT	PE	CZS	MU	GT	PL	CZS	CZS
SiO_2	37.6	57.2	37.7	46.7	37.3	60.8	38.2	38.5
TiO_2	—	—	.3	1.0	—	—	.2	—
Al_2O_3	21.2	26.5	28.5	32.9	21.1	23.6	28.6	31.8
FeO	29.5	—	5.1	1.3	29.9	—	5.4	1.4
MnO	.3	—	—	—	.7	—	—	—
MgO	3.0	—	—	1.5	2.7	—	—	—
CaO	8.5	8.5	21.8	—	7.9	5.3	23.4	24.4
Na_2O	—	6.8	—	.8	—	8.1	—	—
K_2O	—	—	—	9.3	—	—	—	—
Total	**100.1**	**99.0**	**93.4**	**93.4**	**99.6**	**97.8**	**95.8**	**96.1**
O	12.000	32.000	12.500	22.000	12.000	32.000	12.500	12.500
Si	2.984	10.344	3.063	6.304	2.984	11.001	3.044	2.998
Ti	—	—	.018	.098	—	—	.012	—
Al	1.983	5.649	2.729	5.233	1.990	5-.033	2.686	2.918
Fe	1.958	—	.347	.146	2.001	—	.360	.091
Mn	.020	—	—	—	.047	—	—	—
Mg	.355	—	—	.292	.322	—	—	—
Ca	.713	1.647	1.898	—	.677	1.028	1.998	2.036
Na	—	2.384	—	.215	—	2.842	—	—
K	—	—	—	1.604	—	—	—	—
Sum	**8.024**	**20.024**	**8.054**	**13.891**	**8.021**	**19.903**	**8.101**	**8.043**

Calcite and dolomite occur as groundmass phases in most calc-pelites and marbles. They form interlocking mosaics, commonly with quartz and tremolite in marbles and with quartz, garnet and epidote in calc-pelites. Calcite and dolomite in most samples have considerable Fe contents, see Table IV, but Mn is below detection in most analyses.

Metabasic rocks are largely composed of hornblende and plagioclase, with variable amounts of garnet, epidote, quartz, sphene, ilmenite, rutile and chlorite. Some samples show a tendency towards segregation of plagioclase-rich and hornblende-rich layers. Hornblende is generally elongate, with long-axes lying in the plane of the foliation. Plagioclase and quartz are generally sub- to euhedral, and occupy the interstices between hornblende grains. Hornblende shows considerable chemical variation, partly due to original rock chemistry, but largely due to substitution reactions during metamorphism. These reactions are dominantly Si=Na, Al (edenitic) and Si, Mg/Fe=Al, Al (tschermakitic), with Al content increasing with grade. Figure 3 shows the Hazara-Lower Swat hornblendes to be most comparable with the hornblendes in the medium pressure Dalradian rocks of Scotland.

Table III. Representative analyses from metabasic rocks.

	BS23			BS35			MG4		MG17	
	AMPA	GT	PL	GT	AMPH	PL	GT	AMPH	GT	AMPH
SiO_2	40.6	36.8	63.7	37.3	.40.6	60.7	37.3	41.8	36.4	39.8
$Ti0_2$	.5	.3	—	—	.9	—	—	.8	—	.7
$A1_20_2$	13.6	20.8	21.2	21.3	14.8	23.2	21.0	14.9	20.6	14.4
FeO	18.0	23.5	—	29.5	17.2	—	27.9	17.2	26.0	18.4
MnO	.5	4.4	—	13	—	—	2.0	—	4.5	—
MgO	7.5	1.5	—	3.3	8.7	—	2.6	8.4	2.2	7.5
CaO	10.8	11.5	2.4	8.2	11 3	5.2	9.1	11.2	9.7	10.4
Na_2O	1.9	—	9.4	—	1.9	7.8	—	1.4	—	2.7
K_2O	.7	—	—	—	.6	—	—	.6	—	.9
Total	**94.1**	**98.8**	**96.7**	**100.7**	**96.0**	**96.9**	**100.0**	**96**	**.99.4**	**94.8**
O	23.000	12.000	32.000	12.000	23.000	32.000	12.000	23.000	12.000	23.000
Si	6.373	2.967	11.545	2.952	6.216	11.064	2.974	6.329	2.944	6.224
Ti	.061	.017	—	—	.098	—	—	.095	—	.087
Al	2.514	1.977	4.532	1.987	2.666	4.987	1.974	2.666	1.960	2.653
Fe	2.366	1.587	_	1.955	2.199	—	1.863	2.172	1.760	2.411
Mn	.068	.304	—	.085	—	—	.136	—	.309	—
Mg	1.749	.184	—	.385	1.990	—	.313	1.900	.260	1.743
Ca	1.824	.991	.468	.692	1.849	1.016	.778	1.814	.843	1.751
Na	.573	—	3.286	—	.552	2.750	—	.417-	—	.819
K	.132	—	—	—	.119	—	—	.118	—	.172
Sum	**15.660**	**8.027**	**19.832**	**8.055**	**15.689**	**19.817**	**8.039**	**15.511**	**8.076**	**15.858**

PRESSURE AND TEMPERATURE ESTIMATES

These have been obtained by a number of solid-solid and cation exchange equilibria, utilizing mineral analyses obtained on a Cambridge Instruments Microscan V microprobe at Leicester University. Accelerating voltage was 15 kV, and specimen currents were -3 nA for energy, and 20 nA on Cu for wavelength dispersive (WD) analyses. Analyses for P-T calculations were obtained by WD, using a range of pure and synthetic mineral, and pure metal standards. Precision by WD analysis is significantly better than by ED, but most oxides can only be quoted with confidence to one decimal place.

Table IV. Representative carbonate analyses.

	BN 16		BS 32		MG2		MG18		MG33	
	DOL	CC	DOL	CC	DOL	CC	DOL	CC	DOL	CC
FeO	10.8	3.3	10.1	3.3	10.3	3.9	10.7	3.2	10.5	3.3
MnO	.1	.0	.2	.4	—	—	.1	.1	.1	.1
MgO	13.8	2.3	14.2	2.2	14.4	2.4	14.1	1.8	13.2	2.4
CaO	28.5	48.6	28.7	51.5	29.9	53.8	27.8	48.7	28.1	47.8
Total	**53.1**	**54.2**	**53.2**	**57.4**	**54.6**	**60.1**	**52.7**	**53.8**	**51.9**	**53.6**
O	2.000	1.000	2.000	1.000	2.000	1.000	2.000	1.000	2.000	1.000
Fe	.299	.047	.279	.044	.277	.051	.299	.046	.300	0.48
Mn	.002	.001	.006	.005	—	—	.002	.001	.003	.001
Mg	.682	.059	.698	.054	.691	.055	.702	.047	.670	.063
Ca	1.017	.894	1.017	.897	1.032	.894	.997	.906	1.028	.888
Sum	**2.000**	**1.000**	**2.000**	**1.000**	**2.000**	**1.000**	**2.000**	**1.000**	**2.000**	**1.000**

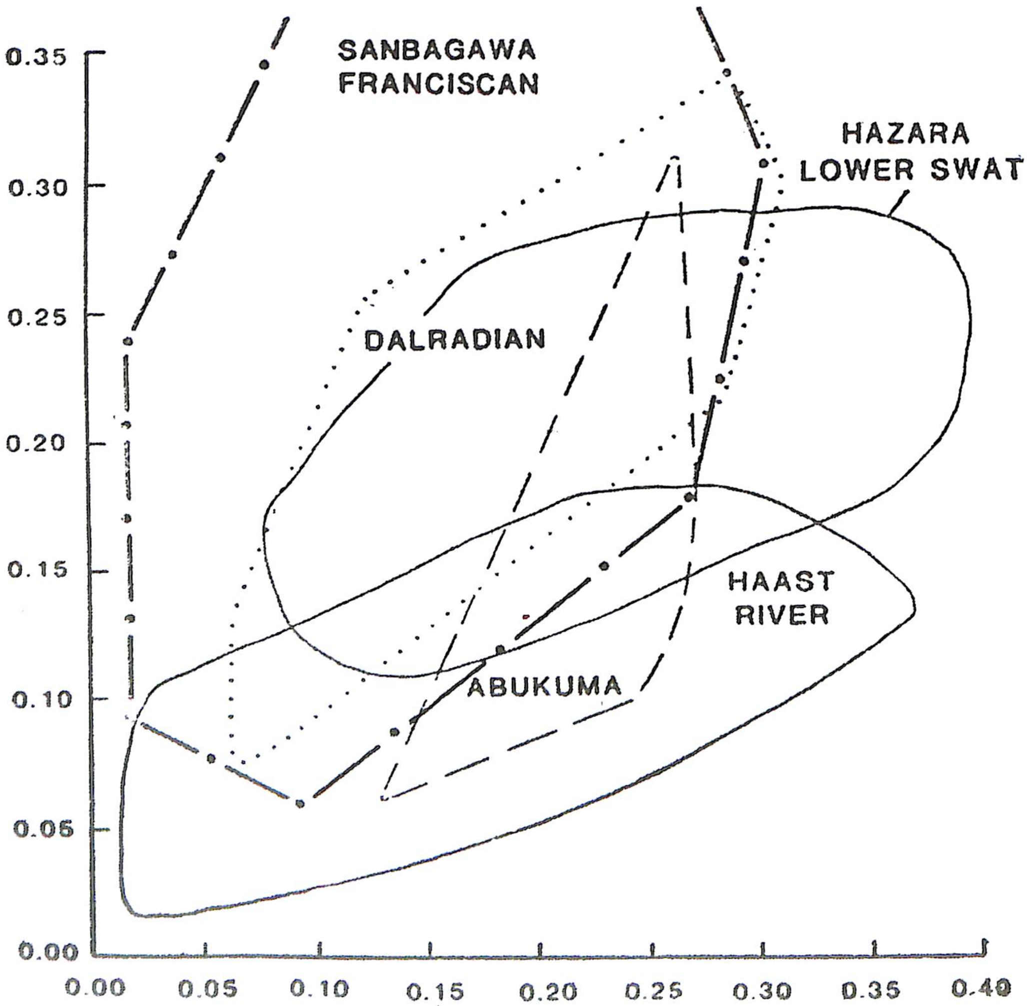

Fig. 2. Hornblende composition variation diagram.

PRESSURE ESTIMATES

Garnet - rutile - ilmenite - kyanite - quartz (Bohlen *et al.*, 1983). This method requires precise and accurate measurement of garnet, since the other phases are generally pure. We have assumed ideal mixing on three sites (12 O basis), ideal mixing between Fe-Mg and Fe-Ca garnets, and excess free-energy of mixing of 1990 cal mol^{-1} (Newton and Haselton, 1981) for Mg-Ca garnet components.

Garnet-plagioclase-kyanite / sillimanite-quartz was used to calculate pressure, given compositions of garnet and plagioclase, and mixing parameters as above according to the formulation of Newton and Haselton (1981). The main sources of uncertainty with this barometer are the large extrapolation required for the experimental calibration to geologically reasonable conditions, and the large uncertainty involved in the measurement of a small (typically -5% mole) grossular component in the garnet. Pressure estimates are given in Table V.

Table V. Pressure Estimates.

Sample	XCa, Gt	XFc, Gt	XAn pl,	T(Est)	P(l)	P(2)
Cover sequence						
BN16	.241	.647	.430	585	8.6	8.3
K159	.164	.661		570		8.7
K230	.180	.722		610		8.5
MG13	.206	.691	.350	580	8.6	8.0
MG31	.122	.707		580		8.9
MG34	.207	.741		580		8.9
Paragneiss basement						
RB138	.051	.780	.190	635	6.7	
RB141	.057	.792	.220	660	6.8	
RB163	.038	.853	.170	620	6.7	

P(l) gt-pl-ky/sill-qz : Newton and Haselton (1981)
P(2) gt-ilm-rut-ky-qz : Bohlen et al. (1983)
T (Est) Preferred T estimate from independent equilibria
XCa, Gt Ca/(Fe+Mn+Mg+Ca)
XFe. Gt Fe/(Fe+Mn+Mg+Ca)
XAn, Pl Ca/(Ca+Na+K)

TEMPERATURE ESTIMATES

Garnet-Hornblende pairs in metabasic rocks were analysed, and temperatures obtained from the equations of Wells (1979) and Graham and Powell (1984). The Graham and Powell (1984) model takes account of the Ca-content of garnet, and consistently gives higher temperatures than that of Wells (1979). Garnet in metabasic rocks is negligibly zoned, and near-rim compositions were used with ground-mass hornblende. Temperatures obtained from hornblende inclusions in garnet cores gave marginally higher estimates than groundmass hornblende.

Hornblende-Plagioclase assemblages were used to estimate temperatures according to the equation of Spear (1980). Both plagioclase and hornblende are zoned. They are subject to considerable Na-Ca exchange on cooling, and the estimated temperatures are lower than those indicated by other methods. Temperatures obtained by the garnet-hornblende and hornblende-plagioclase thermometers are given in Table VI.

Table VI. Metabasic Temperature Estimates.

Sample	lnK_1	lnK_2	XCa, Gt	T°C(1)	T°C(2)	T°C(3)
BS23	-3.60	1.65	0.32	520	610	690
BS35	-2.90	1.52	0.23	550	625	650
MG4	-3.60	1.67	0.28	520	595	655
MG14	-2.70			555		
MG17	-3.20	1.65	0.26	540	600	645
N724		1.49	0.27		635	690

lnK1 = $X_{An, Pl,} X_{Na, M4} / X_{Ab, Pl,} X_{Ca, M4}$
lnK2 = $({}^{a}Alm, Gt/{}^{a}pyr. Gt)^{1/3}$, $({}^{a}par, Hb/{}^{a}Fe\text{-}par, Hb)$ 1/4
T°C(1) = Spear (1980) Hornblende-Plagioclase
T°C(2) = Wells (1979) Garnet-Hornblende
T°C(3) = Graham and Powell (1984) Garnet-Hornblende

Calcite-Dolomite pairs were used to estimate temperatures in marbles and calc-pelites. The carbonate phases contain appreciable Fe and therefore, the methods of Bickle and Powell (1978), and Powell et al. (1984) are more applicable than that of Rice (1977). Analyses were obtained by wavelength dispersion using a defocussed beam. Temperature estimates are given in Table VII.

Table VII. Calcite-Dolomite Temperature Estimates.

Sample	XMg,Cc	XFe,Cc	XFe, Dol	T_1	T_2	T_3	T_4	T_5
BN16	.060	.047	.151	565	650	610	570	575
BS31	.047	.048	.203	525	600	575	530	555
BS32	.054	.045	.139	545	615	575	550	560
BS34	.065	.033	.117	580	610	610	575	585
MG2	.054	.051	.140	545	645	575	555	560
MG18	.047	.046	.150	520	585	545	520	540
MG33	.063	.048	.154	575	680	625	580	580

T_1 Rice (1977) Uncorrected for Fe
T_2 Bickle + Powell (1978) Corrected for Fe in calcite.
T_3 Bickle + Powell (1978) Corrected for Fe in dolomite
T_4 Powell et al. (1984) Corrected for Fe in calcite
T_5 Powell et al. (1984) Corrected for Fe in dolomite

Estimated pressures for the cover sequence are in the range 8.0 to 8.9 kb, and for the paragneiss basement sequence between Datagram and Thakot 6.7 to 6.8 kb. The two pressure ranges come from rocks which belong to different thrust slabs, which have suffered different tectonic histories. There is good agreement between the two barometers used. There is poorer agreement between the various methods of thermometry, with temperatures ranging from -520 to 690°C, with the majority of estimates in the 550-650°C range. The estimated conditions are consistent with the stability fields of the phases found.

Hornblende from one sample in the cover has been dated by ^{40}Ar-^{39} Ar and conventional K-Ar methods at Leeds University by D. C. Rex (pers. comm). The 4°Ar-39Ar method gives a plateau at 33.7 + 0.7my, and K-Ar gives 36±2my. Other ^{40}Ar-^{39}Ar dates by Maluski and Matte (1984) in this region are of the order of 3 5 my. Taking a blocking temperature for Ar diffusion from hornblende of ~525°C, this suggests a cooling rate of around 17° Cmy^{-1}. Using the same blocking temperature, and the pressure estimates given above, we estimate an average uplift rate of -0.8 mm yr^{-1} over the last 35 m.y. for these cover rocks on the northern margin of the Indian plate.

REFERENCES

Bard, J. P., 1984. Metamorphism of an obducted island arc: example of the Kohistan sequence (Pakistan) in the Himalayan collided range. *Earth Planet. Sci. Lett.*, **65**, 133-144.

Bard, J. P., Maluski, H., Matte, P. and Proust, F., 1980. The Kohistan sequence, crust and mantle of an obducted island arc. *Geol. Bull. Univ. Peshawar. Spec. Issue*, **13**, 87-94.

Bickle, M. J. and Powell, R., 1977. Calcite-dolomite geothermometry for iron-bearing carbonates. *Contrib. Mineral. Petrol,* **59**, 281-292.

Bohlen, S. R., Wall, V. J. and Boettcher, A. L., 1983. Experimental investigations and geological applications of equilibria in the system FeO-TiO_2-Al_2O_3-SiO_2-H_2O. *Amer. Min.* **68**, 1049-58.

Calkins, J. A., Offield, T. W., Abdullah, S. K. M. and Tayyab Ali, S., (1975) Geology of the southern Himalaya in Hazara, Pakistan and adjoining areas. *Prof. Pap. U. S. Geol. Surv.*, **716C**, 29.

Coward, M. P., Jan, M. Q., Rex, D., Tarney, J., Thirlwall, M. and Windley, B. F., 1982a. Structural evolution of a crustal section in the Western Himalaya. *Nature*, London, **295**, 22-4.

Coward, M.P., 1982b. Geo-tectonic framework of the Himalaya of N. Pakistan. *Jour. Geol. Soc. London,* **139**, 299-308.

Desio, A., 1979. The occurrence of blueschists between the middle Indus and the Swat Valleys as an evidence of subduction (North Pakistan). *Rend. Accad. Naz. Lincei.*, **62**, 1-9.

Ferry, J. M. and spear, F. S., 1978. Experimental calibration of the partitioning of Fe and Mg between biotite and garnet. *Contrib. Mineral. Petrol.*, **66**, 113-7.

Graham, C. M. and Powell, R., 1984. A garnet-hornblende geothermometer: calibration, testing, and application to the Pelona Schist, Southern California. *Jour. Metam. Geol.*, **2**, 13-31.

Jan, M. Q., Kamal, M. and Khan, M. I., 1981. Tectonic control over emerald mineralization in Swat. *Geol. Bull. Univ. Peshawar,* **14**, 104-9.

Laird, J. and Albee, A. L., 1981. Pressure, temperature, and time indicators in mafic schist; Their application to reconstructing the polymetamorphic history of Vermont. *Amer. Jour. Sci.,* **281**, 127-75.

Lawrence, R. D and Ghauri, A. A. K., 1983. Obssrvations on the structure of the Main Mantle Thrust at Jijal, Kohistan, Pakistan. *Geol. Bull. Univ. Peshawar,* **16**, 1-10.

Le Fort, P., Debon, P. and Sonet, J., 1980. The 'Lesser Himalayan' cordierite granite belt, typology and age of the pluton of Mansehra, Pakistan. *Geol. Bull. Univ. Peshawar,* **13**, 51-61.

Maluski, H. and Matte, P., 1984. Ages of Alpine tectonometamorphic events in the northeastern Himalaya (northern Pakistan) by ^{39}Ar- ^{40}Ar methods. *Tectonophysics*, **3**, 1-18.

Martin, N. R., Siddiqui, S. F. A. and King, B. H., 1962. A geological reconnaissance of the-region between the Lower Swat and Indus rivers of Pakistan. *Geol. Bull. Panjab Univ.*, **2**, 1-14.

Newton, R. C. and Haselton, 1981. Thermodynamics of the garnet-plagioclase-Al_2SiO_5-quartz geobarometer. In: R.C.Newton, A. Navrotsky and B. J. Wood (Eds.). *Thermodynamics of Minerals and Melts.* Springer-Verlag, New York, 129-45.

Powell, R., Condliffe, D. M, and Condliffe, E., 1984. Calcite-dolomite geothermometry in the system $CaCO_3$-$MgCO_3$-$FeCO_3$: an experimental study. *Jour. Metam. Geol.*, **2**, 33-41.

Rice, J. M., 1977. Progressive metamorphism of impure dolomitic limestone in the Boulder aureole. Montana. *Contrib. Mineral. Petrol.,* **59**, 237-259.

Shams, F. A., Jones, G. C. and Kempe, D. R. C., 1980. Blueschists from Topsin, Swat District, NW Pakistan. *Min. Mag. London,* **43**, 941-2.

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

Wells, P. R. A., 1979. P-T conditions in the Moines of the Central Highlands, Scotland. *Jour. Geol. Soc. London,* **136**, 663-71.