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IMBRICATION AND UNROOFING OF THE HIMALAYAN THRUST STACK OF THE NORTH INDIAN PLATE, NORTH PAKISTAN.

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ABSTRACT.

The northern part of the Indian Plate in North Pakistan is dominated by a crustal scale south-verging thrust stack composed of a number of thrust nappes, each of which is stratigraphically distinct. Major nappes recognised in the Swat to Kaghan area of north Pakistan are the Besham, Swat, Hazara, Banna, Lower Kaghan and Upper Kaghan nappes. Metamorphism was synchronous with early ductile stages of Himalayan deformation, the metamorphic pile being subsequently disrupted during the development of the thrust stack which marks the last phase of southeasterly directed Himalayan thrusting. Within each nappe the metamorphic grade increases upwards, an overall inversion that represents post-metamorphic imbrication within individual nappes, synchronous with the main phase of nappe stacking, rather than an originally inverted metamorphic gradient. As a result of this "within-nappe" imbrication each thrust slice within any particular nappe contains rocks of a higher metamorphic grade than those in the slice below, with sharp metamorphic breaks across the imbricating thrusts as well as across the major shears that bound the individual thrust nappes. Exhumation and unroofing of the rocks within the thrust stack was rapid. The assembly of the stack triggered rapid erosion, recorded in the Oligocene and Miocene molasse basins, and regional extension that included significant northward extension within the Main Mantle Thrust zone. Cooling ages imply that peak metamorphism was completed by 40 Ma ago, or within 15 to 20 Ma of collision; that the post-metamorphic thrust stack had been assembled by 25 Ma ago, and that much of the subsequent exhumation was completed by 18 Ma ago.

INTRODUCTION

In N. Pakistan the Indian and Asian Plates are separated by the Kohistan Island Arc. The suture between the Kohistan Island Arc and the Indian Plate to the S is marked by the Main Mantle Thrust (MMT) which is the western continuation of the Indus Tsangpo Suture Zone. Initial collision along the suture was at about 50 (Patriat and Achache, 1984) to 55 Ma ago (Coward et al., 1986). The tectonic and deformational effects of this collision have been documented in detail elsewhere (Coward et al., 1982, 1986, 1987; Searle et al., 1987; Treloar et al., 1989 a, b). In essence the leading edge of India was subducted underneath the Kohistan Island

Arc with the result that a wide range of imbricated thrust scrapings were developed in the sedimentary cover sequences of the Indian Plate, restorations across which imply a shortening in excess of 470 km (Coward and Butler, 1985). That this shortening is largely restricted to the cover sequence implies that the sedimentary cover sequences were decoupled from the lower- to middle-crustal basement, which must itself underplate Kohistan north of the MMT.

Rather than extending north as a rigid slab, the decoupled Indian Plate basement was deformed beneath Kohistan by internal imbrication driven by ductile shearing and recumbent folding. This deformation accounts for much of the crustal thickening underneath Kohistan. Characteristic of this deformation are considerable thicknesses of intensely sheared ductile blasto-mylonites, best exposed in the immediate footwall of the MMT. This ductile basement deformation occurred at depth under Kohistan synchronously with the deformation, under more brittle conditions at higher crustal levels, of the decoupled sedimentary sequences. Later structures, which further thickened the northern margin of India, increasing the taper of the Kohistan thrust pile, include thrusts which re-imbricate the cover and basement rocks, back folds and cross folds, and backthrusts.

REGIONAL FRAMEWORK

A number of large scale crustal nappes, each internally imbricated and separated from each other by late thrusts have been recognised S of the MMT (Treloar et al., 1989 a, b). Each nappe is stratigraphically distinct from those adjacent to it. Six major nappes have been recognised in the internal zone of the belt to the north of the Panjal Thrust (Fig.1), although the metamorphic and structural geometries suggest that a number of smaller slices were stacked with them.

The *Besham nappe* (see Williams, this volume) is dominated by the gneisses of the Precambrian Besham Group (Fletcher et al., 1986; Treloar et al., 1989b). They include both granitic and biotite-rich orthogneisses, together with a sequence of metasedimentary gneisses and schists, marbles and amphibolites. As most of the contacts are sheared the original relationships between the ortho- and para-gneisses are uncertain, although it is likely that the former formed a basement to the latter. In areas of low Himalayan strain there is evidence of a pre-Himalayan deformation and metamorphism in some of the gneisses. Preliminary Rb/Sr and K/Ar data demonstrate the occurrence of a thermal event, probably associated with major orogenesis, in the basement rocks at about 1850 Ma (Treloar et al., 1989c). The Besham Group gneisses are imbricated with metasediments of the (probably) Palaeozoic Karora Group (Fletcher et al., 1986; Treloar et al., 1989b). A conglomerate at the base of the Karora Group includes clasts of deformed granite, granite gneiss and slate (Williams et al., 1988). This passes upwards through grapitic schists, into psammites which become increasingly calcareous upwards and are capped by marble.

The Besham nappe is structurally overlain to the W by the *Swat nappe*. This nappe, the base of which is marked by a ductile shear zone termed the Alpurai Thrust, is constituted by the Precambrian Manglaur crystalline schists, which are intruded by the prophyrytic Swat Granite (Kazmi et al., 1984) and which are unconformably overlain by the calcareous schists, marbles and amphibolites of the Alpurai Group (Lawrence et al., 1989). These cover sediments are of Palaeozoic age (Humayun, 1986).

The *Hazara nappe*, which is separated from the Besham nappe by the mylonitic Thakot

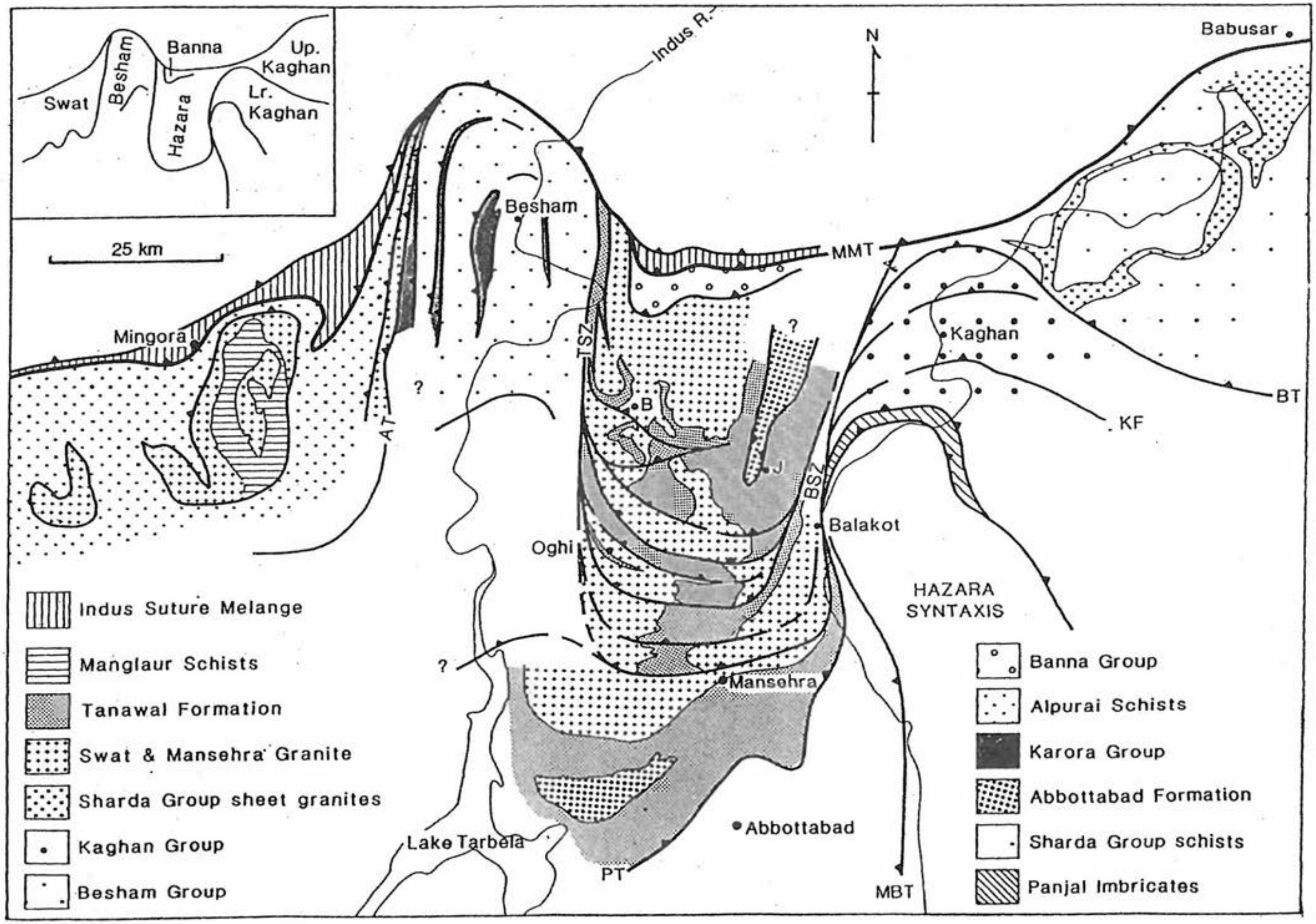

Fig. 1. Geological map of the Swat to Kaghan section of the Indian Plate within North Pakistan to show (inset) the locations of the major crustal nappes described in the text. B: Batagram; J: Jabori; BT: Batal Thrust; KF: Khannian Fault; AT: Alpurai Thrust; MBT: Main Boundary Thrust; PT: Panjal Thrust; BSZ and TSZ: Balakot and Thakot Shear Zones.

Shear Zone, is largely constituted by the metapelites and metapsammites of the Precambrian Tanawal Formation (Calkins et al., 1975). These are intruded by the late Cambrian porphyrytic Mansehra Granite (Le Fort et al., 1980), which may be correlable with the Swat Granite. In the S of the Hazara nappe, in areas of low Himalayan strain and metamorphism, chiastolite and cordierite,within the aureole of the Mansehra Granite, overprint a slaty fabric indicative of a period of Precambrian deformation (Williams et al., 1988). In places calcareous sediments of the Palaeozoic Abbottabad Formation (Latif, 1975) unconformably overlie the Tanawal rocks.

Two nappes, separated from the Hazara nappe by the mylonitic Balakot Shear Zone, are recognised in the Kaghan Valley area. Rocks within these nappes contain a series of essentially pelitic sediments originally loosely ascribed to the Precambrian Salkhala Formation (Calkins et al., 1975; Ghazanfar and Chaudhry, 1985). This stratigraphy has recently been redefined and divided into two groups (Ghazanfar and Chaudhry, 1986), the Kaghan Group to the S of the north-dipping Batal Thrust, and the Sharda Group to the N. The latter group includes the Naran and Burawai calcareous garnet-kyanite bearing schists and associated marbles and amphibolites which are superficially similar, at least, to the Alpurai schists and which, like them, may be Palaeozoic in age. The Sharda Group rocks form the *Upper Kaghan nappe* and the Kaghan Group the *Lower Kaghan nappe.*

A final nappe, the *Banna nappe*, contains a series of chlorite bearing slates, interbedded with limestones with characteristically brittle deformation features, and which belong to the Banna Formation. These low grade rocks are separated from the underlying sillimanite gneisses of the Hazara nappe by a major extensional thrust, the Banna thrust, shear-related folds parasitic on which, imply a N or NW sense of displacement. The low grade Saidu schists, which structurally overlie the higher grade Alpurai schists of the Swat nappe, may occupy a similar position above a large scale, late extensional fault (M.P. Williams, pers. comm.)

Although no direct stratigraphic correlations can be made between different nappes, possible correlations are indicated in Table. 1

TABLE 1. POSSIBLE LITHOSTRATIGRAPHIC CORRELATIONS BETWEEN THE DIFFERENT CRUSTAL-SCALE NAPPES WITHIN THE CRYSTALLINE INTERNAL ZONES OF THE NORTHERN PART OF THE INDIAN PLATE.

SWAT	BESHAM	HAZARA	BANNA	L.KAGHAN	U.KAGHAN
Alpurai Schist		: Abbottabad Formation	Banna Group		Sarda Group
	Karora Group	:			
Swat Granite		Mansehra Granite			
Manglaur Crystalline Schist		Tanawal Formation			
	Besham Group Paragneiss			Kaghan Group (=Salkhala)	
	Besham Group Orthogneiss				

STRUCTURE.

A simplified sturctural history with a number of phases of deformation related to south to southeast directed overthusting, followed by a late period of cross-folding and associated NW-verging backfolds and backthrusts, can be recognised in the Indian Plate (Table 2). Three phases of south to southeast overthrusting deformation are recognised.

TABLE 2. DEFORMATION CHRONOLOGY FOR THE INTERNAL ZONES OF THE NORTHERN MARGIN OF THE INDIAN PLATE.

LATE STRUCTURES RELATED TO INTERFERING MOVEMENT DIRECTIONS AT THE NW TIPS OF THE MAIN HIMALAYAN THRUSTS.	
Post- or syn- D4	Steep north striking faults which accommodate part of the uplift of the domal Besham Antiform (or syntaxis).
D4	Large scale NNE-plunging WNW-verging upright folds with associated NW-verging backthrusts. (Related to Nanga Parbat syntaxial development)
STRUCTURES RELATED TO EXTENSIONAL THINNING OF THE SUB-MMT THRUST WEDGE.	
D3	N-verging extensional normal faulting within the MMT zone. NE- to NW-verging extensional thrust within the Indian Plate
Pre- D3?	Top-side E- or NE-directed extension that re-activated D2a surfaces.
STRUCTURES GENERATED IN THE FOOTWALL OF THE MMT DURING SOUTHWARD OBDUCTION OF KOHISTAN.	
	Small NW-verging backthrusts and minor folds, related to the last stages of thickening of the sub-MMT thrust wedge.
D2a.	Thrusts with southerly transport which stack and internally imbricate crustal scale nappes.
D2.	Crenulations and folds, throughout S-facing, although strongly sheath-like in the N. Probably a diachronous continuation of D1.
D1.	Main fabric forming event related to southward overthrusting of Kohistan over India. Ductile blastomylonites, thickened by small-scale thrust-related folds in the N. Becoming more brittle to the S, where the fabric is increasingly typical of a shortening rather than shearing deformation, with shear strains increasingly accomodated in narrow mylonite zones.

D1 is characterised by the development of intense ductile simple shear fabrics. These are mylonitic in places, especially immediately underneath the MMT (Lawrence and Ghauri, 1983). Southwards, both deformation intensity and ductility decrease, with shear strains increasingly accommodated in narrow zones of mylonitisation. The southern limit of D1 ductile deformation is marked by the Oghi Shear (a later D2a thrust) with brittle fabrics dominant further S, although some of the late phase fabrics to the N of the shear are also brittle. D2 is probably a diachronous continuation of D1. D2 crenulations and small scale folds are sheath like, with curvilinear hinges, in the N but become less so towards the S.

Fabric-porphyroblast relationships imply that the main phase Himalayan metamorphism was largely synchronous with the two earliest deformation phases. Spiral garnets and garnets with curving inclusion trails, which occur in all of the nappes, imply that the garnets rotated while growing during D1 simple shear in the footwall of the MMT. That some garnets predate D1 is shown by straight inclusion trails that record the pre-D1 fabric rather than the external D1 simple shear fabric. Within the Alpurai schists, ragged staurolite and chloritoid porphyroblasts external to garnet and inclusions of both phases within garnets indicate that they grew before, or early during garnet growth. Kyanite crystals postdate garnet, but being folded by D2 crenulations predate D2. By contrast, in the Hazara nappe, where staurolite porphyroblasts overgrew D2 crenulations and were themselves replaced by kyanite, peak metamorphism continued until after D2.

D2a deformation features include the last of the south or southeast verging structures. These are late shears and thrusts which, in places, are seen to cut earlier structures and which stack and imbricate rocks metamorphosed earlier in the deformation history. As with the D1 fabrics the more northerly of these shears are characterised by ductile fabrics and the more southerly by brittle deformation features. D2a thrusts and shears include the Thakot and Balakot Shear Zones, as well as large number of similar age structures developed on both their hanging and footwalls. These include both the Oghi Shear, and the Alpurai and Batal Thrusts. These are the structures responsible for the stacking and internal imbrication of the crustal scale nappes. Late stage D2a structures include small, brittle NW-verging backthrusts and associated NW-verging minor folds and thrusts. These backfolds and backthrusts, with a movement sense oblique to the main southerly movement direction, probably developed within the Kohistan thrust sequence as part of the thickening thrust wedge (Coward et al., 1988). D1, D2 and D2a structures are all developed in rocks in the footwall of the MMT which largely acts as a passive hanging wall detachment zone above them, although is locally breached by some NW-verging D2a backthrusts.

D3 structures are generally brittle features, developed at relatively high crustal levels late in the cooling history. They include: i) shear bands related to N or NE-verging movement along re-activated D2a surfaces. These are clearly seen in the Besham area where W-side up indicators on the W of the Besham Antiform and E-side down indicators on the E are consistent with subsequent folding of the re-activated surfaces; ii) N-side down extensional structures developed both within the MMT zone itself and within the Kohsitan complex above it; and iii) large N- or NW-verging extensional faults such as the Banna backthrust, which account for substantial late stage thinning of the Indian Plate. All of these structural types have extensional displacements related to collapse of the tectonically thickened pile.

D4 structures, which are the most obvious of the late structures, are large scale folds such as the domal Besham Antiform, and parallel synforms in the Swat Valley and Mansehra-Batagram areas. The Besham Antiform, and small scale folds parasitic on it, verge towards the WNW (Treloar et al., 1989b) and small brittle backthrusts associated with the development of the Besham Antiform also have a WNW-directed sense of shear. Although the Besham structure is essentially an antiformal fold, at least part of its growth is accomodated by brittle, north-striking normal faults on each limb, which locally cut the MMT (Lawrence et al., 1989). In places, the easterly of these faults deforms the mylonites of the Thakot shear zone. The large scale D4 structures are interpreted as being synchronous with, and related to, the development of the Nanga Parbat and Hazara syntaxes. The Besham Antiform sits above the Indus Kohistan Seismic Zone (Seeber and Armbruster, 1979), a NW-verging thrust fault that may be analogous to the NW-verging Liachar Thrust in the Raikot-Sassi Fault Zone that marks the western margin of the Nanga Parbat syntaxis (Butler and Prior, 1988a,b). All of these late structures can be interpreted as having developed through interference between the SW-verging thrusts of the main Himalayan arc and the S or SE-verging structures of N. Pakistan. Young (c 5 Ma) apatite fission track ages from within the, partly fault bounded, Besham Antiform (Zeitler, 1985) suggest that the structure developed synchronously with the Nanga Parbat syntaxis, of which it may be a small scale analogue.

METAMORPHISM

A metamorphic map of the northern part of the Indian Plate in N. Pakistan, between the Swat and Kaghan Valleys, is shown in Fig 2. The metamorphic zones and related 'isograds' are based on assemblages in metapelitic rocks. In the region between Mansehra and Thakot, in particular, where the sediments were intruded by large volumes of granite during the Cambrian (Le Fort et al., 1980), the exact location of the isograds is often poorly defined, although they give a consistent sense of northward increase in metamorphic grade. Within all of the nappes metamorphism is typically Barrovian in type.

We have seen above that metamorphism was essentially synchronous with the D1 and D2 phases of deformation. Peak metamorphic conditions have been calculated for rocks from the Swat, Hazara and Kaghan nappes (Fig 3). These conditions have been calculated from rim compositions from co-existing phases using garnet-kyanite-plagioclase-quartz barometry (Newton and Haselton, 1983); garnet-biotite-muscovite-plagioclase barometry (Hodges and Crowley, 1985); and garnet-biotite thermometry (Ferry and Spear, 1978) with a Ca in garnet correction after Hodges and Spear (1982). For the Alpurai schists of the Swat nappe conditions are 600 ± 50°C at 10 ± 2 kb. For the Karora Group cover sediments imbricated with Besham Group gneisses in the Besham nappe temperaturs increase from 400°C in the slices in the core of the antiform to >600 C in those slices on the limbs (see Treloar et al., 1989b). In the Hazara nappe, staurolite grade rocks were metamorphosed at 550 ± 50°C at 6 - 11 kb and kyanite and sillimanite grade rocks at 650–700°C at 7 ± 2 kb (Treloar et al., 1989a). In the Upper Kaghan nappe, the highest grade rocks (sillimanite grade with extensive partial melting) were metamorphosed at 675 ± 50°C at 11 ± 2 kb; while in the Lower Kaghan nappe garnet grade rocks were metamorphosed at pressues of 6 to 9 kb (Treloar and Chaudhry, unpublished data).

Within the Alpurai schists of the Swat nappe, in rocks saturated in kyanite and plagioclase, ilmenite inclusions occur in garnet cores and rutile inclusions in garnet rims as well as in the groundmass. Phase relations within the Fe-Ca-Al-Ti-Si-O system (Bohlen et al., 1983; Bohlen and Liotta, 1986) show this distribution of inclusions to be indicative of a marked pressure increase through the course of the syn-D1 metamorphism in the nappe. Such a path is indicated in Fig 4. This metamorphism is thus interpreted as having taken place during the thickening and active subduction of the Indian Plate underneath Kohistan during an early phase of the orogeny. The cessation of metamorphism in the Swat nappe relatively early in the deformation sequence (pre-D2) may be the result of rapid crustal rebound of initially subducted continental material back up the subduction zone. That metamorphism in the Hazara nappe, for instance, continued unitl after D2 implies that the tectonic environment during metamorphism was not the same for each nappe.

CRUSTAL STACKING IN THE INTERNAL ZONES OF THE INDIAN PLATE

The structure of the region S of the MMT, between the Swat and Kaghan valleys, can be modelled as a crustal scale S-verging thrust stack, composed of a series of internally imbricated thrust nappes. The development of this thrust stack occurred during D2a. The thrust

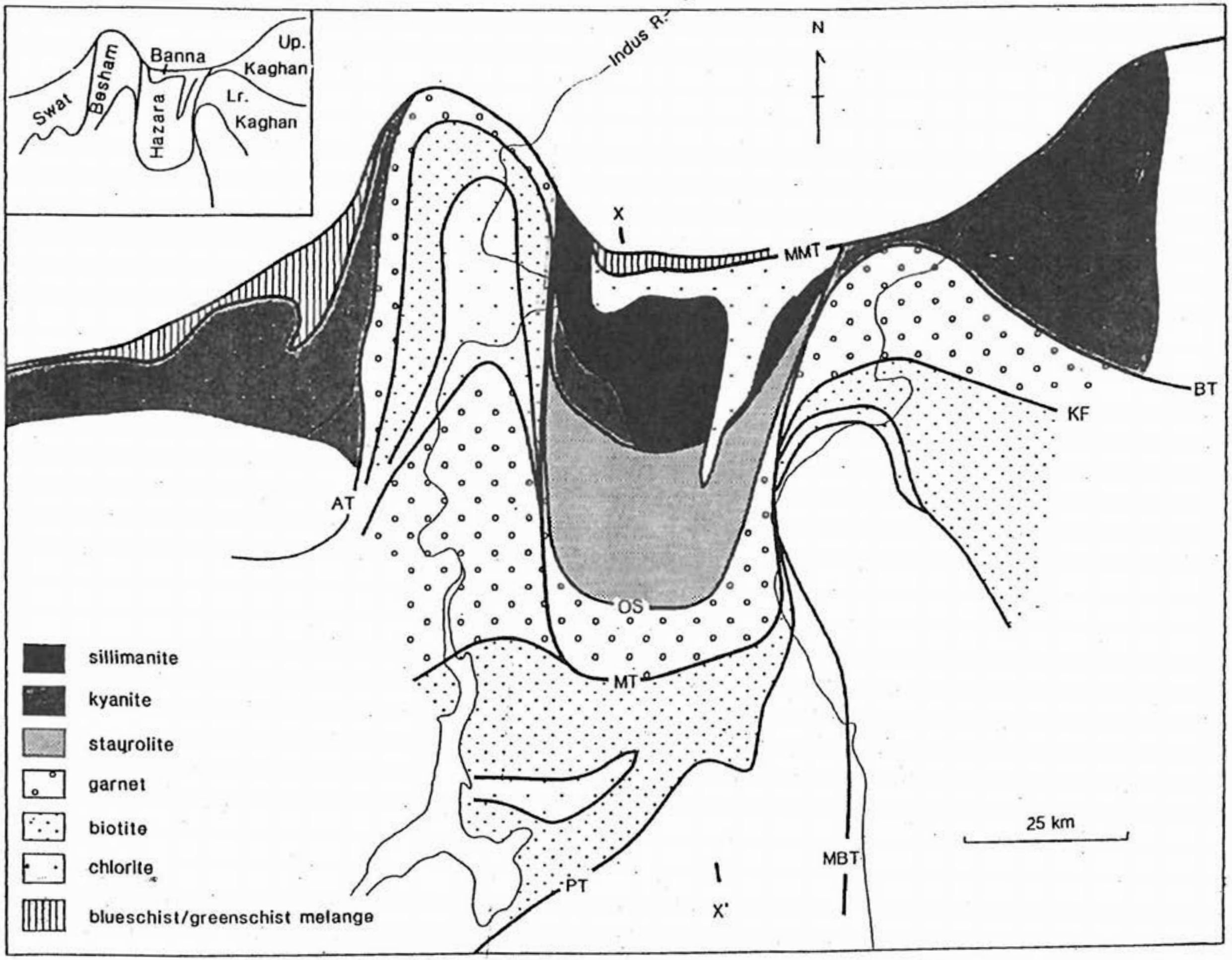

Fig. 2. Metamorphic map of the Swat to Kaghan section of the Indian Plate within North Pakistan. BT: Batal Thrust; KF: Khannian Fault; AT: Alpurai Thrust; MBT: Main Boundary Thrust; OS: Oghi Shear; MT: Mansehra Thrust; PT: Panjal Thrust; X-X': line of section in Figure 5.

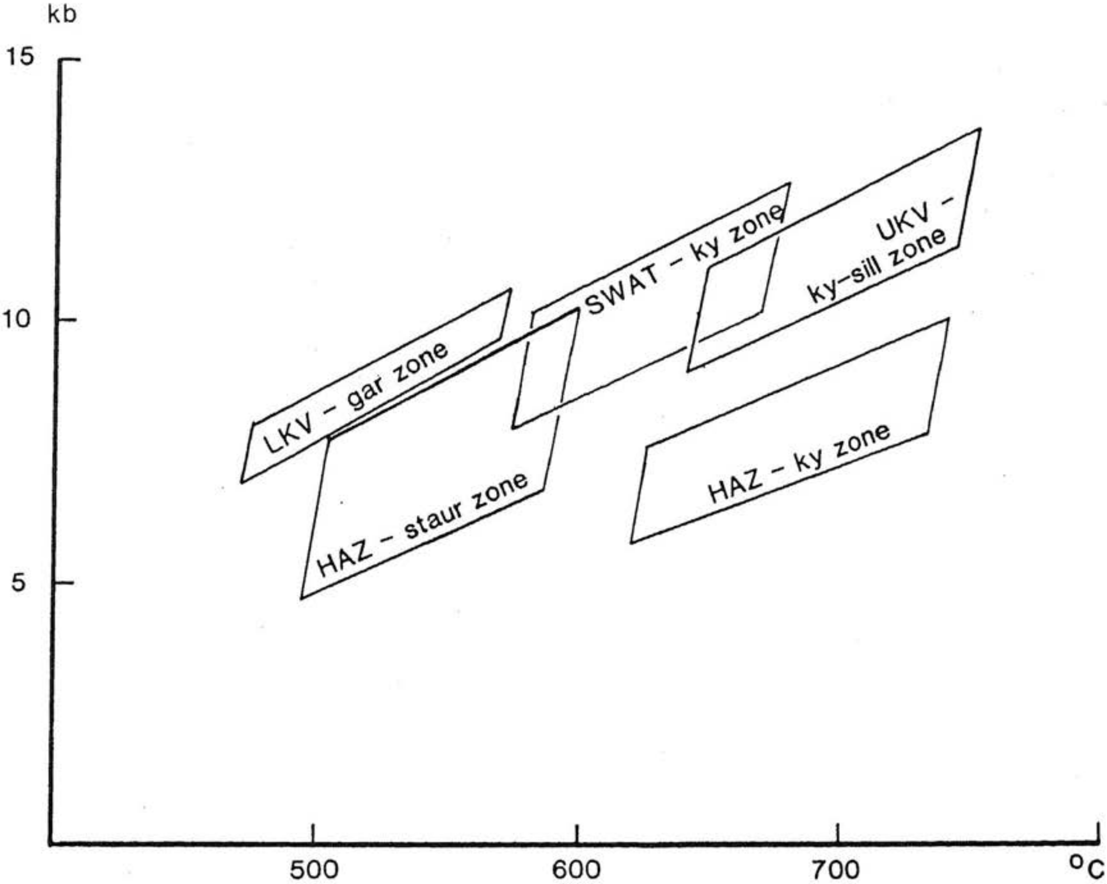

Fig. 3. Conditions of metamorphism for the Hazara, Swat, Upper Kaghan and Lower Kaghan nappes defined by equilibria from a number of samples. All data generated for rim compositions using thermometers and barometers described in the text. Data for the Hazara nappe is from Treloar et al. (1989a), for the Swat nappe is from Treloar et al. (1989b); and from the Kaghan Valley nappes is unpublished data from Treloar and Chaudhry. LKV-gar zone: garnet zone, Lower Kaghan Valley nappe; UKV-ky-sill zone: high temperature rocks from the Upper Kaghan Valley nappe; Swat-ky zone: kyanite grade rocks from the Alpurai schists; HAZ-staur zone and ky zone: staurolite and kyanite grades rocks respectively from the Hazara nappe.

nappes, each of which is stratigraphically distinct, are separated by major shear zones such as the D2a Thakot and Balakot Shear Zones into which the shears which internally imbricate each nappe curve. The Thakot and Balakot Shear Zones are complementary mylonitic shear zones one on the E of the Hazara region and the other on the W. They have the characteristics of a pair of lateral ramps, probably steepened during D4, that link at depth in a thrust system which transported the Hazara nappe metamorphics southward over the Besham and Kaghan Valley nappes. The Oghi Shear and similar structures which internally imbricate the Hazara nappe are hanging wall splays off the linked lateral ramp thrust system. Shear zones, such as the Thakot and Balakot shear zones, which separate the major crustal nappes, show sharp metamorphic discontinuities across them. For instance, along the Thakot Shear Zone at Thakot sillimanite rocks of the Hazara nappe are adjacent to biotite rocks of the Besham nappe although with pods

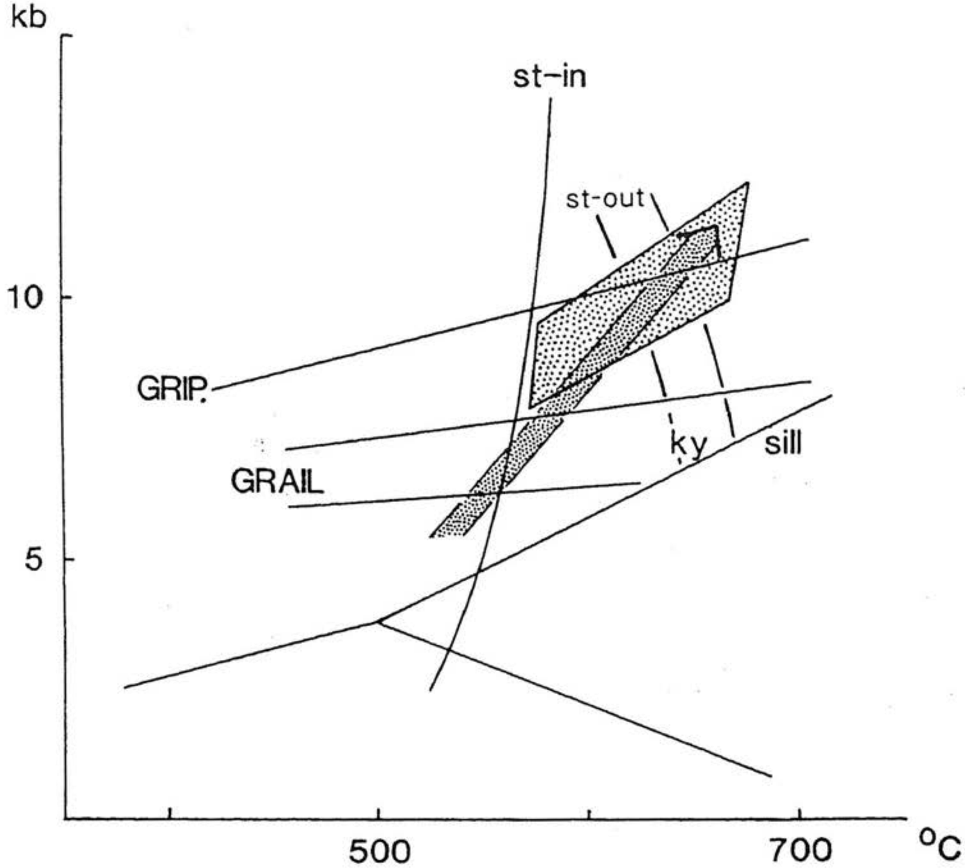

Fig. 4. A possible P-T-t path for metamorphism in the Alpurai schist sequence showing that metamorphism is consistent with rapid burial during D1. GRAIL and GRIP lines are averaged P-T curves for the Barometers of Bohlen et al. (1983) and Bohlen and Liotta (1987) respectively. The lightly stippled box is that for the Swat nappe in Fig 3.

of staurolite rock tectonically enclosed in the former, and of garnet rock in the latter. Similarly kyanite grade migmatitic rocks of the Upper Kaghan nappe are thrust S on to garnet grade rocks of the Lower Kaghan nappe along the ductile mylonites of the Batal Thrust (Ghazanfar and Chaudhry, 1986).

We have seen above that metamorphism was synchronous with the D1 and D2 phases of ductile simple shear deformation related to the overthrusting of Kohistan over India along the MMT. This metamorphic pile was disrupted during D2 by the evolution of the main Indian Plate thrust stack. That the D2a shears and thrusts post-date the main metamorphism is clearly indicated by microscopic textural relationships. In thin section the late stage shear fabrics, which are often mylonitic, clearly deform the peak metamorphic assemblages. Metamorphic garnets, with curving inclusion trails date as being syn-D1 in age, are wrapped by a new fine-grained mylonitic muscovite bearing fabric. Elsewhere, coarse garnets are wrapped by fine-grained mylonitic aggregates of quartz, feldspar and mica; similar aggregates, often with quartz ribbon fabrics developing, anastomose around relic porphyroblasts of quartz and feldspar with often signs of extensive internal deformation; primary metamorphic zones in which they underwent brittle deformation and grain size reduction or, in the case of garnet, often recrystallised to spongy aggregates elongated parallel to the fabric. That muscovite and biotite, rather than chlorite, are stable within these shear zones, often within new shear band fabrics, implies that deformation was at tempertures no lower than mid-greenschist facies.

Within the Besham nappe, Precambrian basement gneisses of the Besham Group have been imbricated with three slices of cover rocks of the Karora Group. The cover-basement sequence was imbricated during the D2a thrusting event, and subsequently refolded within the, partly fault bounded, domal D4 Besham Antiform. Within this folded imbricate sequence the cover slices with the lowest metamorphic grade, which contain chlorite, occur in the core of the antiform, and the higher grade slices, which contain garnet, towards the limbs, a geometry with an overall sense of metamorphic inversion (Williams, this volume).

Within the Hazara nappe, metamorphic grade within the Tanawal Formation decreases towards the S (Fig.3). The isograds are coincident with major N-dipping thrusts, each of which has higher grade rocks in the hanging wall than in the footwall. In this way the Mansehra Thrust places garnet grade on top of biotite grade rocks; the Oghi Shear places ductile staurolite grade rocks on top of brittle garnet grade ones; and a thick ductile shear zones S of Batagram places kyanite and sillimanite grade rocks on top of lower grade staurolite and garnet grade ones. The isograds and thrusts strike E-W in the centre of the area but to the W they curve northwards into the Thakot Shear Zone. To the E they show a similar curvature into the complementary sinistral Balakot Shear Zone, which forms a mylonite zone to the NW of the Hazara syntaxis (Bossart et al., 1988).

The net effect of this post-metamorphic stacking and imbrication is that each nappe shows an upward increase in metamorphic grade. In other words, within each nappe the metamorphic profile is inverted. Rather than reflecting an originally inverted thermall gradient, this inversion results from the post-metamorphic tectonic imbrication by D2a thrusts. Throughout these nappes, isograds papallel the thrusts, with a constant relationship between higher grade rocks in hanging walls and lower grade ones in footwalls. The "isograds" here are not primary metamorphic features, but are tectonic artefacts, that reflect post-metamorphic thrusting. Whether individual thrust slices are metamorphically the right way up is not possible to say, both because errors on the geothermobarometry are too large and the thrust slices too narrow. It should be stressed that the "isogradic" thrusts are not the only D2a shears present. There are numerous shears and thrusts of D2a age which internally deform the individual nappes, although they are most clearly recognised through the repeated imbrication of Mansehra Granite and Tanawal Formation metasediments within the Hazara nappe. Although the general sense of thrusting is always to place higher grade rocks above lower grade ones, only a few, such as the Oghi Shear, actually mark changes in metamorphic paragenesis.

Schematic north-south and east-west sections through the area show the stacking of the imbricated thrust nappes south of the MMT (Figs. 5 and 6). Figure 5 shows the internal imbrication within the Hazara nappe, the northward and upward increase of metamorphic grade within that nappe, and the way that it structurally overlies the Besham nappe along the D2a Thakot Shear Zone. The depth to the Thakot Shear Zone, and hence the basement rocks of the Besham nappe immediately below it,- is constrained by a busk style construction, drawn east-west through Batagram. This depth to basement here is similar to that south of the Main

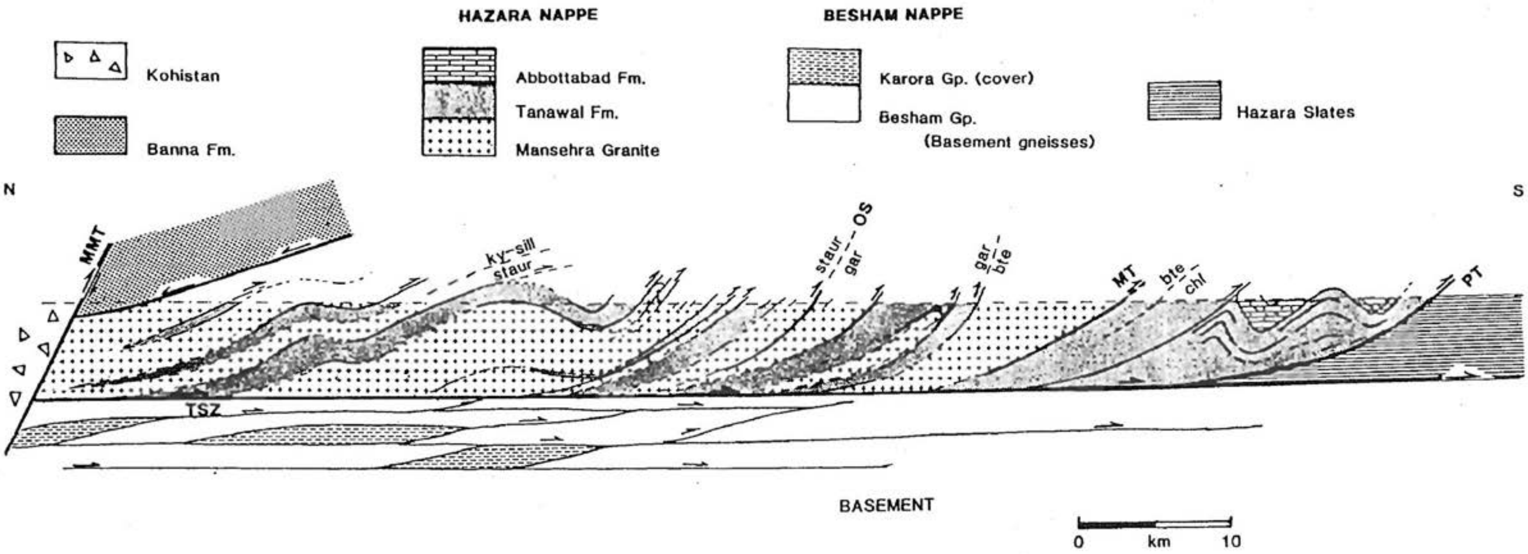

Fig. 5. A north-south cross section (X-X' Fig. 2) from the MMT to south of Mansehra to show the internal imbrication of the Hazara nappe, and the northward and structurally upward increase in metamorphic grade in that nappe; the stacking of the Hazara nappe above the Besham nappe along the Thakot Shear Zone (note the shallow depth of basement, e.g. the Besham nappe below the Thakot Shear Zone); the position of the late extensional thrust which places chlorite grade rocks of the Banna nappe on high grade rocks of the Hazara nappe; and the folding of biotite and chlorite rocks south of, and in the footwall of, the Mansehra Thrust. MMT: Main Mantle Thrust; MT: Mansehra Thrust; OS: Oghi Shear; TSZ: Thakot Shear Zone. The biotite, garnet, staurolite and kyanite-sillimanite in "isograds" are marked.

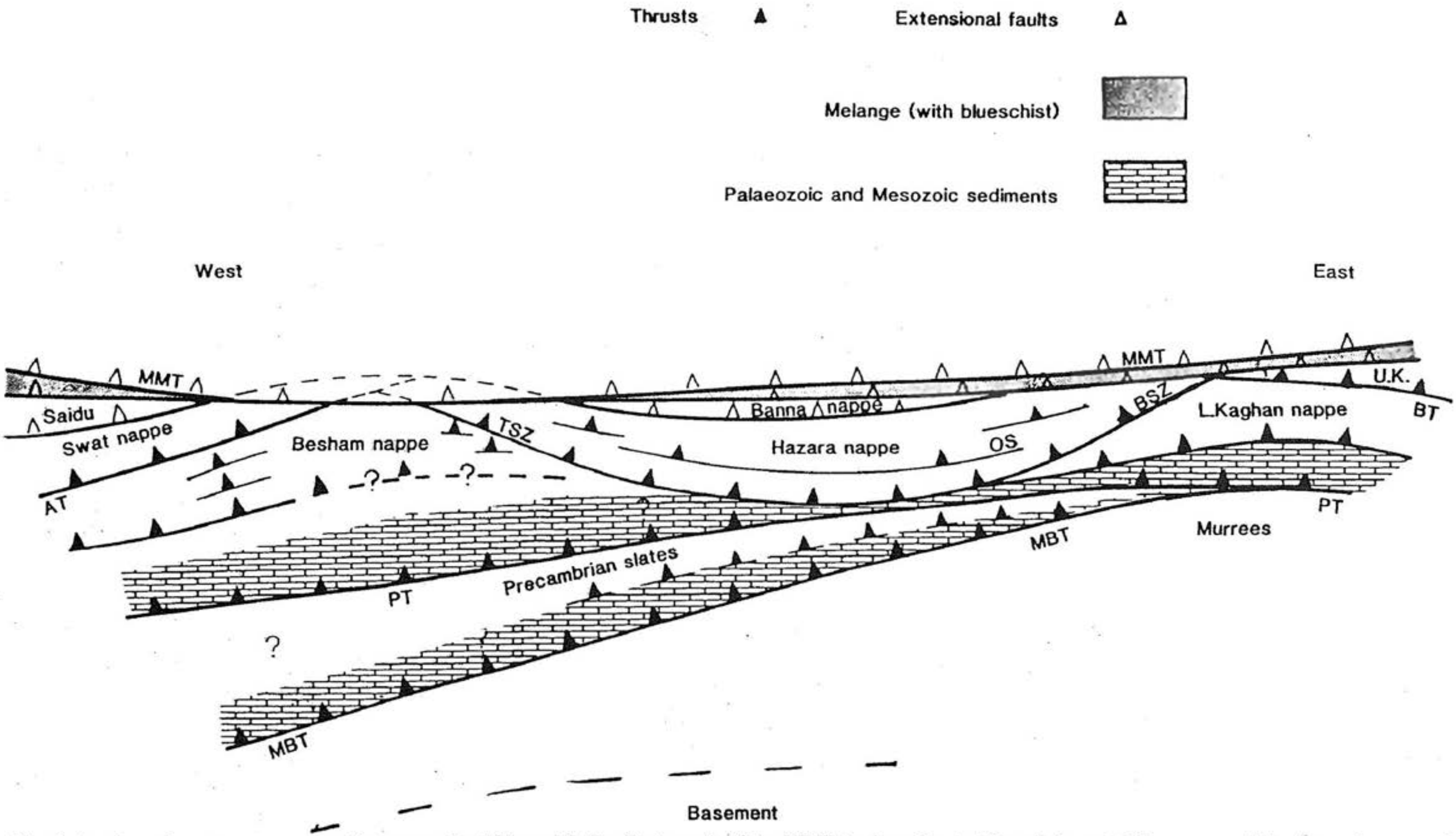

Fig. 6. A schematic east-west cross-section across the thickened Indian Plate south of the MMT to show the stacking of the crystalline nappes of the internal zones and their position, after subsequent southward transport, structurally above the unmetamorphosed rocks of the external zones; and the zone of late extensional structures at the top of the thickened pile. The westward extension of the Panjal Thrust probably correlates with the Khairabad and Hissartang Faults of the Kalachitta and Cherat-Attock ranges, and the disposition of Precambrian and Phanerozoic rocks there are interpreted here from Yeats and Hussain (1987). The "Saidu" sheet represents the low grade Saidu schists which structurally overlie the kyanite bearing Alpurai Schists, the boundary possibly representing an extensional fault such as that underlying the Banna Fm. MMT: Main Mantle Thrust; MBT: Main Boundary Thrust; BSZ and TSZ: Balakot and Thakot Shear Zones; AT: Alpurai Thrust; BT: Batal Thrust; PT: Panjal Thrust; OS: Oghi Shear; UK: Upper Kaghan Valley nappe.

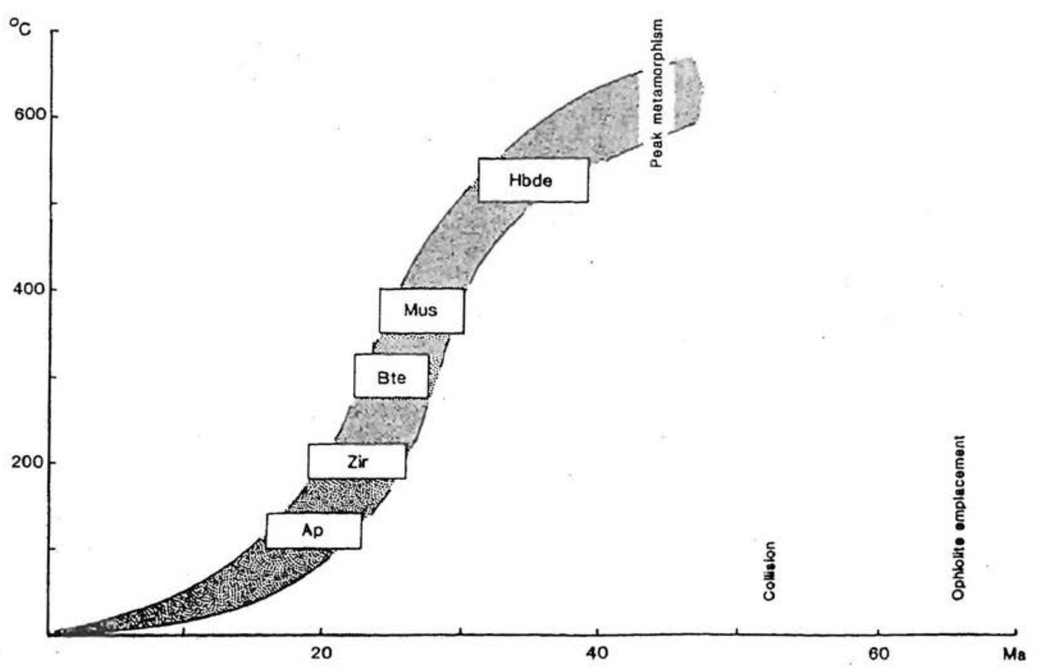

Fig. 7. Time vs temperature plot to show the timing of collison, and of metamorphism and subsequent uplift of the internal zones of the Indian Plate. Boxes Hbde (hornblende), Musc (muscovite), Btc (biotite), Zir (zircon) and Ap (apatite) are derived from Ar-Ar, K-Ar and fission track goechronological data (Treloar and Rex, in prep; Zeitler, 1985).

Boundary Thrust (C.N. Izatt, pers. comm.) implying that the major structures which control basement-cover relationships south of the MMT are essentially sub-horizontal. Figure 6 shows the stacking of the crystalline nappes of the internal zones and how, after subsequent southward transport along thrusts such as the Panjal and Main Boundardy Thrusts, the crystalline stack now structurally overlies the unmetamorphosed rocks of the external zones. Especially clear here is the concentration of late extensional structures at the top of the thickened pile.

In the same way that the more northerly of the imbricating shears are ductile and the more southerly brittle, so the Thakot and Balakot Shear Zones become more brittle along strike to the S. This decrease in the ductility of the late shear zones reflects their southward propagation into higher level cooler rocks and implies that as they developed they cut up through the crustal pile. This pattern is as expected as the shears were associated with a major phase of crustal uplift after the initial collision related thickening.

GEOCHRONOLOGY

It is possible to place some age constraints on the metamorphism and deformation of the internal zones of the Indian Plate. K/Ar and Ar/Ar cooling ages, from the Swat, Besham and Hazara nappes, define a post-metamorphic cooling history for the Indian Plate thrust stack.

Hornblende, muscovite and biotite cooling ages of 35 ± 4, 24-30 and 22-26 Ma (Fig. 7) respectively date cooling through the relevant blocking temperatures of 500-550, 350-400 and 300 ± 25°C (Lawrence et al., 1989 in press; Treloar et al., 1989c; Zeitler, 1985; Maluski and Matte, 1984; Treloar and Rex, in prep.). Zircon and apatite fission track data from the Swat and Hazara nappes date further regional cooling through 200 and c 120°C at 20-24 and 16-20 Ma respectively (Zeitler, 1985). If cooling took plact at 55 ± 5 Ma, heating of the Indian Plate lithosphere to temperatures in excess of 650°C in the highest grade regions must have been rapid. The muscovite to apatite part of the cooling curve (Fig. 7) has a steeper slope than is indicated for the earlier and later time intervals. Fabrics within the D2a shear zones are largely ductile with growth of new muscovite and biotite in micaceous shear bands, although becoming more brittle with time. As ages within the shear zones are similar to those within the nappes which they stack, it would appear that cooling through the mica blocking temperatures must have been synchronous with, or post-dated, development of the D2a shear zones.

We believe that the increased rate of cooling between the mica and apatite blocking temperatures is related to rapid unroofing and exhumation of the thrust stack. This unroofing is a combination of extension and erosion. Extension within the MMT zone is documented by widespread extensional north-side down shear bands. This extension is part of a significant period of crustal thinning and extension, which includes thinning of Kohistan in the hanging wall of the MMT, normal type extensional displacements within the MMT zone itself, and extension in the upper parts of the Indian Plate (see next section). Erosion is documented by the widespread Miocene age molasse sediments of the Siwalik group deposited in the foreland basins (Johnson et al., 1979). This combination of erosion and extension probably shortly post-dates the development of the D2a crustal-scale thrust stack, and is a direct consequence of the evolution of that stack.

IMPLICATIONS FOR THE HISTORY OF THE MAIN MANTLE THRUST (MMT)

Although the obvious sense of movement along the MMT is to thrust Kohistan southwards onto the Indian Plate, the structure is somewhat enigmatic as many of its secondary features are apparently inconsistent with such a simple interpretation.

1) The hanging wall rocks change substantially along strike, both in lithological type and in depth of origin and metamorphism. At Jijal, they are high pressure garnet-granulites of the Jijal complex; to east and west they are of the mid-crustal Kamila Shear Zone amphibolites; whereas near Nanga Parbat they are high level island arc volcanics and sediments.

2) In many localities metamorphic grade and ductility of the deformation fabrics show a sharp break across the MMT. N of Besham at Jijal the Indian Plate gneisses in the footwall have a high grade amphibolite facies ductile blastomylonitic fabric, whereas the hanging wall Kohistan lithologies are of a low grade greenschist facies type with relatively brittle deformation features. This difference in deformation fabric type across the MMT is inconsistent with them having been fromed in close proximity at the same time.

3) Near Alpurai low grade glaucophane bearing blueschists within the Indus Suture Zone melange abut directly against the amphibolite facies metasediments of the Alpurai schists, and west of Besham sillimanite bearing rocks of the Hazara nappe are in direct tectonic

contact with lowgrade ophiolitic melange material.

4) There is a sharp thermal discordance recorded across the MMT zone by both fission track (Zeitler, 1985) and K/Ar and Ar/Ar (Treloar et al., 1989) chronologies. This is clearly demonstrated by the zircon fission track data. In the Besham and Swat region, zircon cooling ages (>30 Ma within Kohistan but about 20 Ma in the Indian Plate) imply that the MMT separates rocks in the hanging wall that cooled through 200°C more than 10 Ma earlier than those in the footwall.

5) Major D2a shears and thrusts, such as the Alpurai Thrust and the Thakot Shear Zone, strike at high angles to the MMT. They do not appear to curve into and detach against the MMT but appear to cut it, suggesting that the present MMT postdates the D2a structures.

Zeitler (1985) suggested that the thermal discordance indicated by fission track ages was the result of thermal re-equilibration within the Indian Plate after its overthrusting by Kohistan. However, all the above points, when considered together, argue for substantial late movements along the MMT. Regardless of the thermal transfer operative across the MMT, the juxtaposition of blueschists against amphibolite grade schists, and of rocks with ductile deformation fabrics against those with brittle fabrics suggest that this late movement had a considerable displacement. That the MMT cuts the imbricating D2a structures implies that at least part of this movement postdated that imbrication.

The variation in hanging wall lithologies led Butler and Prior (1988b) to suggest the present MMT to be a late high level feature developed as a breakback thrust within the Kohistan arc, removing, in places, the early ductile MMT and the rocks on both its hanging- and footwalls. Although this may be valid in explaining some of the variations in hanging wall lithologies, most of the features listed above are explained if the MMT zone is recognised as one of extension with substantial downthrow to the north. This extensional movement, initiated in response to the D2a crustal stacking, is recorded by a plethora of post-D2a extensional shear bands within both the upper parts of the Indian plate and the MMT itself. On a larger scale, structures such as the extensional Banna Thrust probably represent extension within the Indian Plate itself, although the geometry of the metamorphic stratigraphy implies that this early extenstion was probably succeeded by large displacement extensional movements along the MMT zone with high level cold parts of Kohistan dropped down against lower levels of the Indian Plate along N-side down normal fautls that may have re-used the MMT surface. Such extension was not limited to the MMT zone itself. Widespread normal faulting within Kohistan testifies to large scale thinning of the Kohistan sequence in the MMT hanging wall. Extension along the MMT and associated thinning of Kohistan is one method by which the rapid exhumation of the thrust stack implied by the geochoronology could have occurred.

This north verging late extension is similar in type to the NE directed extensional events recorded in Kashmir (Herren, 1987) and Nepal and Tibet (Burg et al., 1984; Royden and Burchfiel, 1987; Hodges et al., 1988) generated there by the collapse of the more ductile thickened crust.

CONCLUSIONS

The leading edge of the Indian Plate was extensively deformed and metamorphosed during the Himalayan collision in the footwall of the Main Mantle Thrust, along which the basic rocks of the Kohistan Island Arc were thrust southwards over India. Early in the deformation, cover sequences were detached from the basement, with both cover and basement deformed by internal imbrication at differnet crustal levels. Metamorphism was synchronous with the early phases of ductile simple shear deformation and crustal thickening although some areas show evidence for a more extended period of metamorphism which continued until after the main shearing phase.

Subsequent to the main metamorphism, rocks of the crystalline internal zones of the Indian Plate were stacked and imbricated along thrusts and shears, D2a in age, which mark the early stages of crustal uplift. During this period the cover sequences, originally detached from basement earlier in the event, were re-imbricated with basement slices. Major shears define large scale crustal nappes, transported southwards as lithologically and metamorphically discrete packages. These nappes were internally imbricated by shears developed on the hanging walls of the transporting thrust systems. As a result of the internal imbricaton, the metamorphic sequence was disrupted and tectonically stacked such that in each case higher grade rocks now tectonically overlie lower grade ones. This overall inversion of metamorphism within individual nappes represents a tectonic stacking rather than an inverted themal gradient as in the 'hot iron' model frequently quoted in the MCT zone of India and Nepal.

The N. Pakistan sector of the Indian Plate is significantly different from the analogous metamorphic zones of India and Nepal. As in the eastern Himalayas, there is evidence of an early c 40 Ma (Searle and Rex, 1989; Hodges et al., 1988) deformation-related Barrovian-type metamorphism, but unlike India and Nepal there is no evidence for either a late metamorphic overprint or for a widespread partial melting event followed by leucogranite emplacement, both of which are associated with deformation along the MCT zones (Le Fort, 1986).

In NW Pakistan the development of the D2a crustal scale south verging thrusts stack triggered rapid unroofing and exhumation driven by both rapid erosion and thinning of the tectonic pile, the latter accomplised by north-directed extension along the MMT zone, in its hanging wall and in the upper parts of the Indian Plate. Cooling histories indicate that stacking and subsequent unroofing had proceeded to such an extent that the metamorphic pile had cooled to below 300°C by 25 Ma.

Although most of the deformation within the Indian Plate was related to the overthrusting of Kohistan over India along the MMT, the structure represented by the present day MMT is essentially a late, brittle reworking of the original ductile thrust zone characterised by substantial extensional displacements.

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