Tectonics of the SW margin of the Nanga Parbat–Haramosh massif

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Abstract: We present an analysis of the tectonic evolution of the southwestern portions of the Nanga Parbat massif, Pakistan Himalaya, based upon detailed mapping and structural analyses from the Bunar, Biji, Diamir, Airl, Niat and SW Rupal valleys. Mainly metasedimentary cover rocks of the Indian plate are divided into upper and lower cover. There is a marked structural thinning of the cover in the main Bunar valley from south to north, and this is attributed to a major frontal ramp in the original Main Mantle Thrust (MMT). A hitherto unmapped shear zone, the Diamir Shear Zone, is identified, that is associated with a syn-kinematically intruded belt of granitic rocks, the Jalhari Granite. The shear zone is a several kilometre thick, generally W-vergent, ductile to brittle shear zone that is associated with local overturning of the entire MMT section, typified by the Gashit Fold. $^{40}Ar/^{39}Ar$ cooling ages from across the area indicate a steep cooling age gradient across the Diamir Shear Zone from >40 to <5 Ma. The Diamir Shear Zone is mechanically linked to part of the Raikhot Fault System and, together, they are seen to be a crustal-scale reverse fault that has allowed relative uplift and overthrusting of the core of Nanga Parbat.

The Nanga Parbat–Haramosh massif (NPHM) is of considerable interest in the investigation of the India–Asia collision, and collisional tectonics at large. There are a number of salient features of the NPHM worth noting.

(1) It coincides with the NW terminus of the >2500 km Himalayan arc—the western 'syntaxis' of Wadia (1931, 1932).
(2) It forms an anomalous spur (Fig. 1) of Himalayan rock that has resulted from high-grade Indian plate basement gneisses being exhumed from beneath the structurally overlying cover rocks of the upper Indian plate, that are in turn juxtaposed beneath the fossil island arc Kohistan–Ladakh series (KLS), by the Main Mantle Thrust (MMT—Tahirkheli & Jan 1979; Bard *et al.* 1980; Tahirkheli 1982; Bard 1983).
(3) This exhumation is due to crustal-scale antiformal folding (Gansser 1964; Coward 1985) that occurs in the form of both NNE-trending axes of folding recognized within the generally W–E trending Indus Gorge (Madin 1986; Madin *et al.* 1989; Treloar *et al.* 1991; Butler *et al.* 1992; Wheeler *et al.* 1995), and as a pair of antiformal folds in the Astor River Gorge—the Burdish Ridge and Dichil antiforms, in the west and east, respectively (Edwards 1998; Schneider *et al.* 1999*a*).
(4) It is composed of Indian plate crystalline rock that seems to be reworked Proterozoic crust (Chamberlain *et al.* 1989; Smith *et al.* 1992; Schneider *et al.* 1997, 1999*b*; Zeitler *et al.* 1989), a feature presently unreported from studies of the Himalayan crystalline slab outside of the NW Himalaya.
(5) It represents an area of exceedingly young (*c.* 0.9 to >9.0 Ma) plutonism, metamorphism and cooling (Zeitler *et al.* 1982, 1989,

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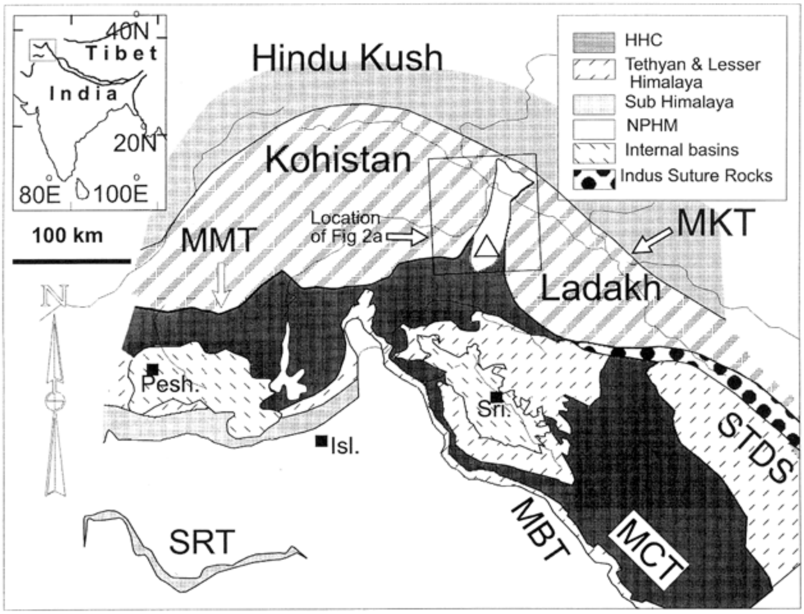


Fig. 1. Regional map of the northwest Himalaya. MKT, Main Karakoram Thrust; MMT, Main Mantle Thrust; SRT, Salt Range Thrust; STDS, Southern Tibet Detachment System (section shown is Zanskar Shear Zone); MCT, Main Central Thrust; MBT, Main Boundary Thrust; NPHM, Nanga Parbat–Haramosh massif (western Himalayan syntaxis); Pesh, Peshawar; Isl, Islamabad; Sri, Srinigar. Regional location of area is identified by box in northwestern part of 'India–Tibet' map shown in inset. Compiled from our own published and unpublished observations and Gansser 1964; Coward *et al.* 1988; Greco & Spencer 1993.

1993; Zeitler 1985; Chamberlain *et al.* 1989; Treloar *et al.* 1991; Zeitler & Chamberlain 1991; Smith *et al.* 1992; George *et al.* 1993, 1995; Winslow *et al.* 1994, 1995, 1996; George & Bartlett 1996; Whittington 1996; Schneider *et al.* 1997, 1999*a*, *b*).

(6) These young events seem to require exhumation of up to 5–10 mm a^{-1} (Craw *et al.* 1994), and hence require tens of kilometres of rock to have been removed from the NPHM in the last few million years.

Identification of the geological structures that are associated with this extremely young exhumation/unroofing and uplift of the NPHM was undertaken by us as part of the multidisciplinary Nanga Parbat Continental Dynamics project. In addition to lithological and structural mapping and general structural analyses, one of our key objectives was to examine which major structures have accommodated large displacements of rock related to (1) differential exhumation between the inner and outer portions of the massif, and (2) tectonic exhumation of the massif by low-angle normal fault/detachment-type mechanisms. This contribution presents results for the southwestern portion of the NPHM.

Geological background of the SW region of the NPHM

The principal hitherto-recognized feature that is relevant to tectonic investigation in the SW region of the NPHM is the Raikhot Fault. The Raikhot Fault (Madin 1986; Butler & Prior 1988; Madin *et al.* 1989; Butler *et al.* 1989) is a zone of shear structures that forms much of the western margin (KLS–NPHM contact) of the northern and central portions of the NPHM. A portion of the Raikhot Fault Zone cuts away the Main Mantle Thrust at the large bend in the Indus River near Raikhot Bridge (Fig. 2). In this area, the significant displacement sense associated with the fault zone (a strong SE-plunging lineation) is consistent with the NPHM moving upwards with respect to Kohistan, and much of the original linear fabric related to the MMT appears to have been reworked or obliterated. Because the hanging wall is dominated by high-grade rocks that are common to the core of the NPHM and cooling gradients across the Raikhot are extremely steep (Zeitler 1985; George *et al.* 1995), it is generally agreed that the Raikhot Fault is locally the focus for a large portion of the displacement of the NPHM summit region that has continued

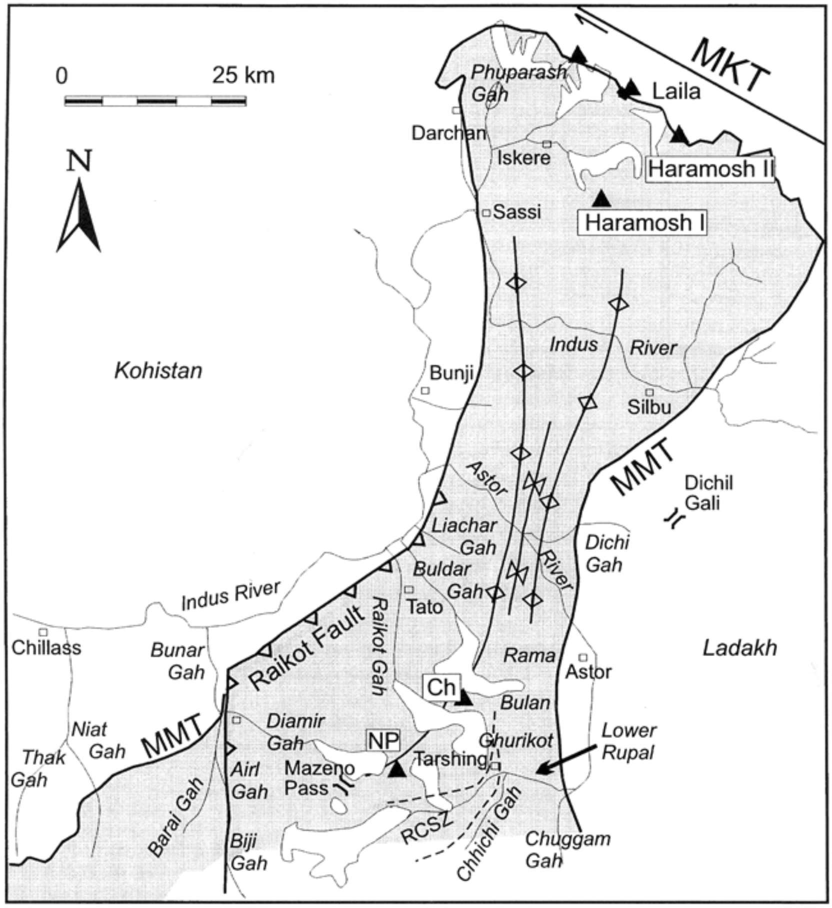
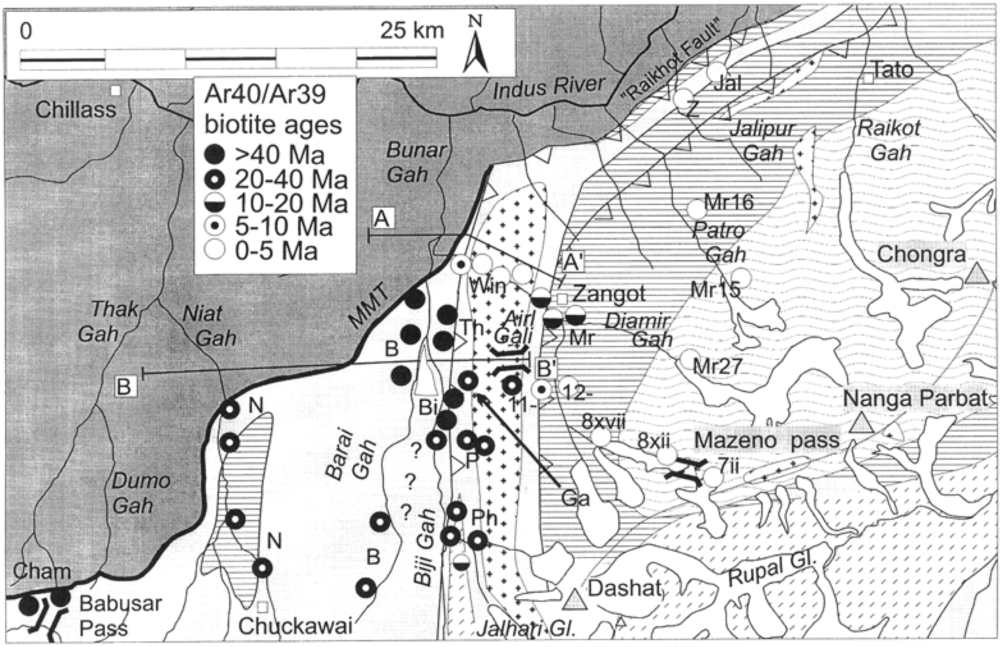


Fig. 2. Overview map of the NPHM. selected valleys and towns shown. Grey, undifferentiated Indian rocks; white, undifferentiated KLS rocks or (north of MKT) undifferentiated Karakoram Terrane. Names in white boxes beside black triangles are major peaks: NP, Nanga Parbat; Ch, Chongra Northern Peak; MKT, Main Karakoram Thrust. MMT, Main Mantle Thrust. RCSZ, Rupal–Chichi Shear Zone (dashed lines are approximate margin locations). Names of valleys/rivers are in italics. Heavy lines with barbs are reverse faults; paired barbs represent (W–E) Burdish Ridge Antiform, Dashkin Synform and Dichil Antiform, respectively. Open squares and villages. Map sources: Kidd, Edwards, Asif Khan, unpublished data; Madin 1986; Madin *et al.* 1989; Treloar *et al.* 1991; Lemmenicier *et al.* 1996; Pêcher & Le Fort 1998.

for the last few Ma until the present day. The nature, if any, of the Raikhot Fault to the south and southwest is not clear as very little of the area west of Raikhot Bridge has been described. Within and west of Bunar Gah, the MMT is present, in its common form, as the KLS/Indian plate contact (Ahmed & Chaudhry 1976; Ghazanfar *et al.* 1991; Khan *et al.* 1998; this study) and it is not removed, nor is the fabric extensively transposed, by the Raikhot Fault, or any other fault. Between Bunar Gah and Raikhot Bridge, therefore, the Raikhot Fault, or some mechanical equivalent that is associated with large cooling age gradients between the inner and outer portion of the massif, must cut structurally downward into the Indian plate, and the surface trace must accordingly fork off from the Kohistan margin towards the SSW. The MMT west of the NPHM is described in general by Ahmed & Chaudhry (1976), Ghazanfar *et al.* (1991), Khan *et al.* (1998), and DiPietro *et al.* (2000), as part of the general descriptions of the Kohistan terrane in the area. However, the only information hitherto available for the rocks of the Indian plate immediately southwest of the summit regions of the NPHM are from Hubbard *et al.* (1995), some of whose descriptions and interpretations have been questioned by Burg *et al.* (1996). We incorporate local portions of, and where necessary re-interpret, the data presented in Hubbard *et al.* (1995) in light of our new mapping.

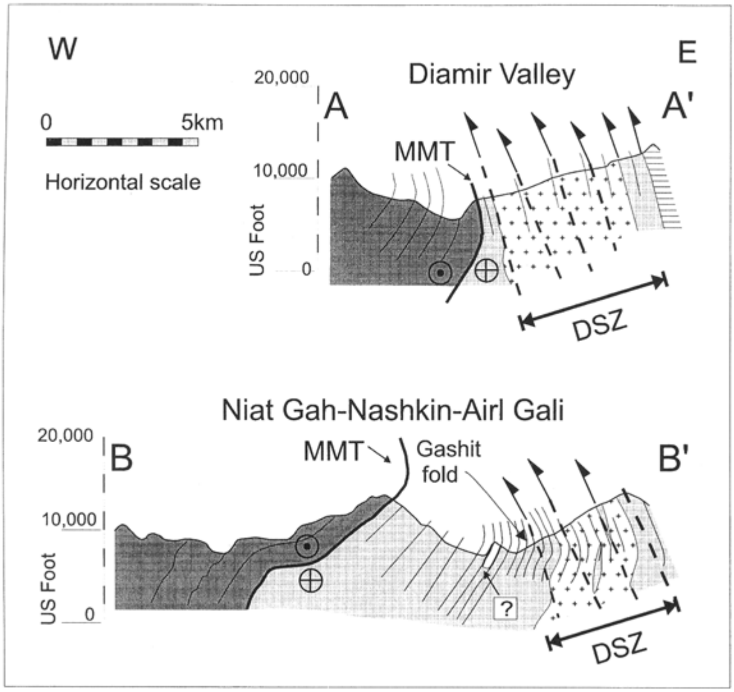
General geological observations

Our investigations southwest of Nanga Parbat were conducted (Figs 3 & 4) in two areas: (1) the N–S trending Bunar Gah, and Biji Gah (the direct southern continuation of Bunar Gah), and the eastern tributaries of Jalhari Gah (forking off at the village of Phailobat), Diamir Gah (WNW–ESE trending), and Airl Gah (*c.* W–E trending), as well as the lower (eastern) portion of Nashkin Gah (a W–E trending tributary to Barai Gah); and (2) the Niat valley. The Diamir Gah and the Nashkin and Airl Gah valleys all provide excellent sections that cut through at a high angle to foliation.



(a)

Fig. 3. (**a**) Geological and thermochronological map of SW NPHM. Dark grey, undifferentiated Karakoram Terrane; light grey, undifferentiated Indian cover rocks; horizontal line ornament, undifferentiated Indian basement rocks; undulating parallel line ornament in NP summit region, approximate location of basement in which cordierite is present (NE boundary from Chamberlain, unpublished data); white with oblique dash, undifferentiated augen gneiss; plus pattern, granite or deformed granite. A–A′, B–B′, locations of the Diamir and Niat–Nashkin–Airl, respectively, composite cross-sections presented in (b). Barbed black lines are general margins of large brittle and ductile shear zones with reverse sense displacement (Diamir Shear Zone is marked by Jalhari Granite). Thick black line is the Main Mantle Thrust. Grey triangles are high peaks (labelled); white squares are villages/towns. Names of valleys, glaciers (Gl.) and rivers are in italics; sites are in normal script. Variably shaded dots are sample localities for Ar/Ar analyses, divided into five age brackets (see legend). Adjacent normal script single letter or pairs identify individual or groups of dots fully corresponding to those detailed in Table 1 (except: '11' is 11-vii in Table 1; group '12-' is 12-i and 12-iv in Table 1; group 'Win' is group of four bt Ar/Ar [from W to E 5.7, 2.9, 2.0, 1.4 Ma] reported in Winslow *et al.* 1996; group 'Cham' is 22–25 Ma Ar/Ar from Indian rocks near Babusar Pass reported in Chamberlain *et al.* 1991). Area of white at Biji/Barai confluence is Manogoush gneiss, question marks to the south hint at uncertainty of extent of Manogoush gneiss (see Fig. 4 and text for discussion). (**b**) Cross-sections along the Diamir section [A–A′] and the Niat–Nashkin–Airl composite section [B–B′]. Horizontal scale in kilometres, vertical scale in feet. No vertical exaggeration. Shading/ornament as employed in (a). Plus/dot symbols in circles respectively represent 'tail' and 'head' of arrow, indicating that, on the MMT, the hanging wall ('Kohistan') has moved outward (with respect to the plane of view) while the footwall ('India') has moved inward. Note overturning of metasedimentary cover rocks in MMT footwall in response to NPHM uplift-related west-vergent overthrusting. The Diamir Shear Zone (DSZ) is primarily located in the Jalhari Granite, emplaced syn-kinematically. Area of white in valley ridge (Manogoush Ridge) is outcrop of Manogoush gneiss, question mark below hints at uncertainty of extent of gneiss (see Fig. 4 and text for discussion).



(b)

In addition to reports from the two main drainage areas of Bunar and Niat, we present a summary of observations from the westernmost Rupal valley, in an examination of regional continuity of the observed structural and lithological trends. As will be seen, the geology and structures of the uppermost Rupal valley become fundamental for accurate characterization of the geology of the SW region of the NPHM.

Main Mantle Thrust hanging wall rocks

In Bunar Gah and in Niat Gah (Fig. 4), we have clearly identified and mapped the MMT. Throughout both areas, the contact between the dark mafic rocks of the KLS and the paler Indian plate rocks is clear and highly recognizable (Fig. 4). The MMT in Bunar Gah outcrops near the confluence of Diamir Gah where the contact is clearly visible on each side of the valley, and can be followed all the way to the >4000 m ridge above the western wall of Bunar/Barai Gah (Fig. 5). In Niat Gah we again visited the MMT in outcrop. A strong contrast in spectral character on Thematic Mapper (TM) satellite imagery allows us to interpolate confidently the surface trace of the MMT over ridge tops between the areas where we have mapped it in the valleys.

Rocks of the Kohistan arc are well exposed in the northern portions of the Bunar and Niat/Thak valleys, and include both the Chilas Complex and the Niat Amphibolite. The two units are easily distinguishable; the Chilas Complex comprises medium to coarse-grained gabbronorites, anorthosites, dunites and peridotites (in order of decreasing abundance), while the Niat Amphibolites (which outcrop to the south of the Chilas Complex) are fine-grained, foliated and banded metabasalts. Rocks of the ultramafic–mafic–anorthosite association of the Chilas Complex (Khan *et al.* 1998), characterized by common graded layering and cross-layering, crop out at the mouth of Bunar Gah valley. Immediately south, these are replaced by homogeneous gabbronorites similar to those forming the bulk of the Chilas Complex elsewhere. Foliation of these rocks in both Bunar Gah and Niat Gah is orientated *c.* E–W, and dips moderately north. Further south, the gabbronorites are deformed, forming foliated but lithologically homogeneous amphibolites which are often garnetiferous. These strongly foliated amphibolites are occasionally mylonitic in appearance, with fabrics that dip moderately north in Thak–Niat but steeply to the SE in Bunar Gah. The foliated amphibolites have a sharp tectonic contact with the underlying Niat Amphibolites.

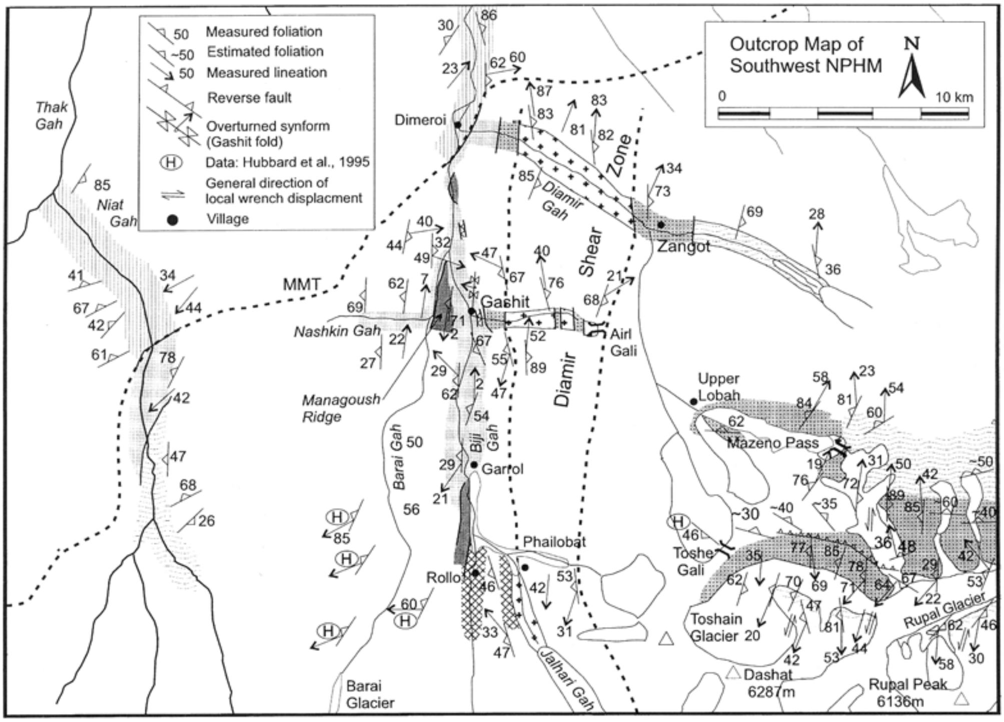


Fig. 4. Outcrop map of SW NPHM showing outcrops that were visited and examined. Dark grey, lath unit; basket-hatch ornament, porphyroclastic orthogneiss; light grey, upper cover; horizontal line ornament, undifferentiated Indian basement rocks; plus pattern, granite or deformed granite; dots with grey background, lower cover; white, glacial moraine (or glaciers where at river heads). Heavy dashed black lines are remote field and TM interpolation of field-constrained boundaries. Belt of Jalhari Granite runs from Diamir Gah to Jalhari Gah; DSZ coincides approximately with margins of Jalhari belt. Note trends in foliation and lineation are highly consistent from western Rupal valley across Toshe Gali (anomalous measurement marked with H is from Hubbard *et al.* 1995; location and orientation of all the Hubbard *et al.* (1995) measurements has only been estimable through visual inspection. Higher in the massif region on the northern side of Rupal valley, however, there is a notable variation (see full discussion in text).

Khan *et al.* (1998) described a 50–60 m wide shear zone marking this contact in Niat–Thak, and in Thor Gah, a valley further to the west. The Niat Amphibolites are fine to medium grained and metabasaltic, and frequently foliated to massive and have a banded appearance due to (1) small-scale feldspathic bands, that probably mimic original volcaniclastic–lava banding and/or are a product of metamorphic segregation, and (2) common veins and dykes of granitic and trondhjemitic composition. The Niat Amphibolites record epidote–amphibolite facies with rare garnet. Garnet is common in the leucogranite–trondhjemite veins and dykes, is primary, and together with common muscovite, identifies their peraluminous nature. Khan *et al.* (1998) suggest that at least some of these trondhjemites are the product of partial melting of the Kohistan terrane basal crust.

For the Niat Amphibolites there is also a significant difference in orientation of foliation between Niat Gah and Bunar Gah. The principal (stretching) lineation in Niat Gah generally plunges subhorizontally to moderately towards the SSW. The main layering is steeply NW dipping (Niat–Nashkin–Airl composite section [B–B′] in Fig. 3b), and is observed to be only locally overturned (on a scale of tens of metres) to become steeply SE dipping. (NB we use the term overturned with respect to the tectonostratigraphic section that forms the MMT foot- and hanging walls, where the original regional orientation of the MMT and the main fabric is NNW dipping.) About midway between the confluence of Thak Gah and Niat Gah, and the MMT, over a few km structural thickness, there is a decrease in the foliation dip. In Bunar Gah, however, the main layering dips steeply ESE, and

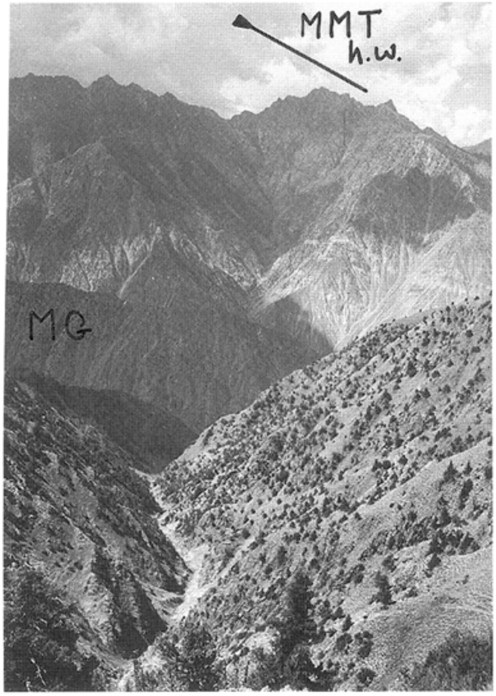


Fig. 5. Looking west from Airl Gali pass. Included in field of view is: (1) Airl Gah valley (foreground) where >5 km of structural thickness of Jalhari Granite is represented (Gashit Fold [Fig. 7] at foot of gully outcrops immediately beyond where gully turns out of field of view), (2) Manogoush Ridge (labelled: 'MG') where a belt of porphyroclastic gneiss is present, (3) Nashkin valley, where *c*. 2600 m of vertical relief, and >8 km of cover sequence is exposed, and (4) dark rocks of Kamila amphibolite that mark the MMT hanging wall at very top of furthest ridge.

the lineation is steeply S to SE plunging. There is thus a change in orientation of the main foliation of the KLS rocks throughout Bunar Gah; dips steepen to become vertical and then are overturned on a large (kilometres) scale, illustrated on the Diamir section [A–A′] of Fig. 3b (also Figs 4, 5 & 6). The overturning in Bunar Gah includes the MMT and much of the footwall Indian plate rocks discussed below. Nowhere are the Niat Amphibolites structurally overturned on a large scale and, hence, neither is the MMT in this area.

Indian plate cover rocks

Indian plate lithologies are exposed south of the MMT (Fig. 4). In Niat Gah, Indian plate rocks are exposed along much of the valley, although glacial till and remaining soil from the recently discontinued forest covers some of the hillsides. In the Diamir–Bunar/Barai/Biji area, exposure is excellent throughout, where the Indian plate cover rock sequences are up to >6 km thick. The continuous exposure between, for example, Nashkin and Airl Gali (Fig. 3, cross-section [B–B′]) allows the lithologies to be mapped in detail, and we are able to divide the cover rocks into an upper and a lower cover. Further afield, constraints are from correlation with (1) 'remote observation' (e.g. clear variety of colours distinguishing foliation on west wall of Bunar Gah in Figs 5 and 7), and (2) TM imagery at 1 : 50 000.

Lithological description of the upper cover rocks

The upper cover has over 50% of meta-carbonate; in decreasing order of abundance, marbles, calc-pelitic schists, calc-silicates, pelitic schists and amphibolites. Marbles are both pure and mixed with calc-silicates and calc-pelites. They are commonly medium to coarse grained and contain grossular garnet, diopside, phlogopite, apatite and graphite in a calcite-rich matrix. In calc-pelites, bands rich in calcite alternate with those rich in feldspar, quartz, muscovite and chlorite. The latter contain prismatic grains of zoisites which are poikiloblastic and contain trails of graphite. Like zoisites, large (at places >1 cm in size) garnets are poikiloblastic and overprinted on the fabric (in one instance the graphite trails containing zoisite are microscopically folded and included in garnet). The calc-silicates comprise a creamy white matrix comprising quartz, plagioclase, calcite, sphene and apatite with garnet porphyroblasts. The latter are rich in quartz inclusions. The pelitic rocks in the upper cover sequence are represented by bluish-grey paragneisses with large garnets that also show internal rotation patterns. These rocks comprise quartz, garnet, kyanite, biotite, muscovite, k-feldspar, rutile and graphite. Garnet and kyanite porphyroblasts incorporate a pre-existing fabric in the form of quartz and graphite trails. The matrix is ductilely deformed with anastamosing bands of mica and quartzofeldspathic layers. Some overgrowth of the micaceous foliation by garnets with inclusion spirals in the innermost grain may indicate more than one generation of deformation-induced garnet growth.

The thick upper cover rocks are identical, in terms of constituent lithologies and kyanite-grade of metamorphism, to rocks of this nature found in the SE portion of the NPHM, where they form a thin part of the section in the Dichil (north and south fork), E. Astor, Rama, Bulan, Ghurikot (north, middle & south fork) and Lower Rupal valleys (Edwards & Kidd 1997; Edwards 1998). Several km of thickness are also present in Chichi Nullah (Edwards and Kidd 1997; Edwards 1998), Chuggam Gah and Rattu area (Edwards & Kidd 1997; Edwards 1998; Argles this volume). The upper cover is also similar to rocks described in Kaghan (Greco *et al.* 1989; Greco & Spencer 1993) and Swat (Treloar *et al.* 1989; DiPietro *et al.* 1993). These rocks are probably a metamorphosed product of the Permian 'Panjal Traps'—basic igneous rocks repeatedly intruded as sills or extruded as flows during carbonate platform development on the NW passive margin of India, that resulted in a widespread sequence that is typified by inter-layered marbles and amphibolites that define part of the recognized cover rocks in the NW Himalaya (Wadia 1931; Honegger *et al.* 1982; Papritz & Rey 1989; Greco *et al.* 1989).

Lithological description of the lower cover rocks

The lower cover lithology is primarily composed of a garnet–two mica schist which contains minor chlorite, tourmaline and zoisite. In most cases the garnet fabric is parallel to the principal fabric in the schists but frequently also incorporates spiral patterns, implying rotation and suggesting that growth is both pre- and syn-kinematic. Meta-psammites are also present in the lower cover. These are massive but foliated and contain muscovite, biotite, tourmaline, garnet, epidote, graphite and rutile. Muscovite and biotite define the fabric while garnet is pre- to syn-kinematic. Local calc-silicates in the inner cover contain quartz, garnet, zoisite, biotite, muscovite in a calcite–siderite matrix. Kyanite, which is common in the upper cover sequence, is not observed in the lower cover sequence.

Two different types of granitic rocks were observed to be present in between the upper and lower cover in continuous outcrop sections (e.g. Diamir section [A–A′] and Nashkin–Airl section [B–B′]), and nowhere did we see the upper and lower cover in contact with one another. The two granitic suites were also observed elsewhere within the lower cover section, together with a third granitic suite—the Jalhari Granite plutonic belt (discussed below).

Structural description of the Indian plate cover

In the Diamir–Bunar/Barai/Biji drainage area, Indian plate cover rocks are exposed *c.* 2 km south of the Diamir Gah confluence with the Bunar valley near Dimeroi, where they comprise a few hundred metres of garnetiferous metapelite (lower cover), and *c.* 100 m of marbles and amphibolite (upper cover), sandwiched between the MMT and the western margin of the Jalhari Granite plutonic sequence. Local foliation is moderately to steeply ESE-dipping, with a general stretching lineation plunging moderately to steeply northwards, although occasionally south plunging (Fig. 6). The main foliation is parallel with the structurally overlying MMT hanging wall, and it is clear that here the regionally NW-dipping cover sequences and MMT hanging wall are locally overturned to become ESE-dipping. The overturned section extends north of Dimeroi in Bunar Gah for at least 3 km (where mostly KLS rocks are exposed), and south for 8 km to the Gashit Fold (a recumbent open fold at the confluence of Airl Gah with Bunar/Biji, by the village of Gashit—Fig. 4), where the eastward dipping cover rocks form the upper, overturned, E-dipping limb (Fig. 7). This fold hinge therefore marks a point of regional overturning of several kilometres of MMT foot- and hanging wall sequences. South and west of the village of Gashit, layering is again the 'right way up', and is predominantly W-dipping. The hinge line of the Gashit Fold plunges *c.* 20°N. The general stretching lineation in the region plunges moderately to steeply toward the north, although locally there are a few occurrences of moderately SE plunging stretching lineation.

The Nashkin–Airl section (Fig. 3b, B–B′), crosses the Gashit Fold, while the Diamir section (Fig. 3b, A–A′) crosses the Diamir Gah/Bunar valley confluence. It is clear from the sections and map that between the two areas there is a massive northward thinning of the cover rocks; a few hundred metres at Dimeroi compared with >6 km to the south of Nashkin Gah. This is reflected by the map trace of the MMT orientated *c.* NE, while the local strike of foliation between the Nashkin–Airl and the Diamir section remains *c.* N–S. This northward thinning of the cover rocks is probably too large to be an original depositional variation and is discussed below.

Throughout the southern portions of the Bunar/Biji area, foliation consistently dips moderately to the west. There is local (centimetre to metre scale) tight asymmetric 'parasitic' folding, but this is not significant on a large scale. Stretching lineations plunge moderately to steeply towards the NW or SW. Layering observed in the field can be clearly recognized on suitably processed TM scenes for this area

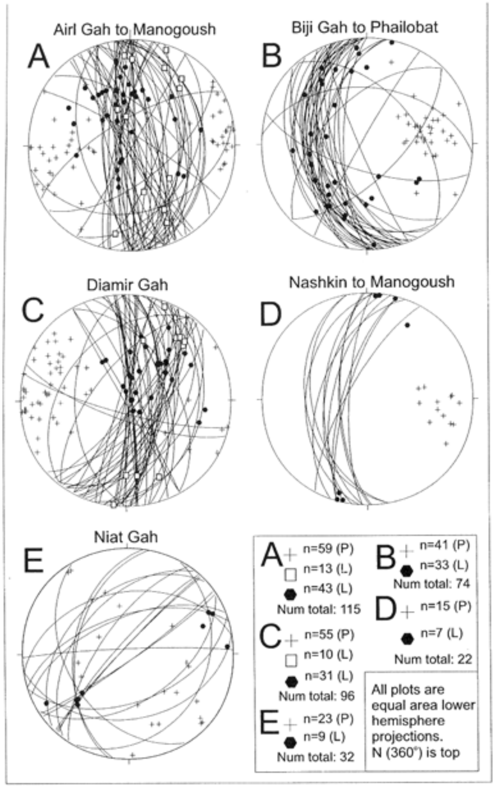


Fig. 6. Lower hemisphere equal-area projections of foliation and lineation measurements in SW NPHM. Lineations in B, D & E represent lineations in the upper and lower cover. Lineations in A and C are divided into Jalhari Granite (black dots) and Indian plate cover rocks (white boxes). Note that Jalhari Granite lineations are generally steep and NE to E-plunging; they are associated with the E over W deformation in the Diamir Shear Zone (see text).

and, in the case of Barai Gah, the thick section of upper cover rock that was mapped in Nashkin can be confidently traced up the valley. Lithological descriptions from Barai Gah by Hubbard *et al.* (1995) are consistent with this interpretation, indicating a general widespread presence of the 'cover'. On Fig. 4, therefore, we reproduce their four foliation and lineation data points from southern Barai Gah (fig. 1c of Hubbard *et al.* 1995). These structural data are consistent with ours, indicating an overall NW dipping foliation and SW plunging lineation. We note that the attention they drew to an absence in the SW region of the NPHM of a NW-plunging MMT footwall convergence-related lineation, that is reported elsewhere by other workers (e.g. Treloar *et al.* 1989), does not appear to hold true for any significant areal coverage (Figs 4 & 6).

The Indian plate sequences in Niat Gah include a short section of upper cover rocks that consist of marbles, amphibolites and a significantly greater presence of metapelite than in the Bunar Gah section to the east. The thickness of the cover is small, occurring structurally above a local section of basement that outcrops to the south. We did not observe the lower cover in this area. The main foliation in Niat Gah dips moderately WNW (locally steeper, and also locally flattening to dip gently ESE in places in the upper portions of the valley). Lineation development is not widespread but, where measured, lineations plunge moderately to the SW, and are accompanied by a top-to-SW displacement sense.

Granitic rocks

The porphyroclastic orthogneiss and the lath unit

The first of three plutonic rocks that we recognize is a grey orthogneiss with 1–3 cm porphyroclast-rich and (locally) porphyroclast-poor horizons. This is found cropping out in four areas: *c.* 2 km south of Dimeroi, near Gashit, near Garol, and in southern Biji Gah south of Rollo (Fig. 4). This is a granitic gneiss with coarse (<2 cm) feldspar augen. It has a platy, predominantly biotite-rich matrix. Large thicknesses of this orthogneiss south of Rollo are indicated by extensive outcrop on both walls of the valley.

The second of the three plutonic units is a gneiss containing 1–>4 cm laths of feldspar set in a garnetiferous, pink biotite quartzofeldspathic matrix (Fig. 8). The feldspar laths are characteristic of this rock, and are frequently deformed into augen or other shapes resulting from high strain. This rock is present (Fig. 4) *c.* 1 km south of Diameroi, within the Manogoush Ridge (Fig. 5), and on the western wall between Garol and Rollo. An identical rock to this is present in the SE region of the NPHM, where it has been termed the 'lath unit' (Edwards 1998) and we use the term here.

The Manogoush Ridge site was selected for petrologic sampling of the lath unit where the extensive exposure allowed a sampling of a representative portion (Fig. 8). The lath unit is deformed into varying porphyroclastic laminated high strain fabrics, possibly more extensively developed at the margins of the unit. At Manogoush, the rock mostly retains the characteristic feldspar laths, preferentially orientated parallel to the high strain fabric that defines the matrix. Garnet is common in the matrix as well

Fig. 7. Looking NNW to an outcrop of the Gashit Fold, on the right bank of the foreground (near mouth of Airl Gah valley). In this outcrop, the fold is within metasedimentary cover, *c.* 1.5 km west of the edge of the Jalhari Granite. The fold accommodates regional overturning (eastward dip) of MMT footwall, and is inferred to be due to the W-verging, E-dipping Airl-Gah/Diamir Shear Zone. North and east of this point, layering is predominantly E-dipping. South and west of this point, layering is predominantly W-dipping (note W-dipping cover rocks in background on far (west) side of Bunar Gah). Hinge line plunges *c.* 20°N. Trees are a few metres in height.

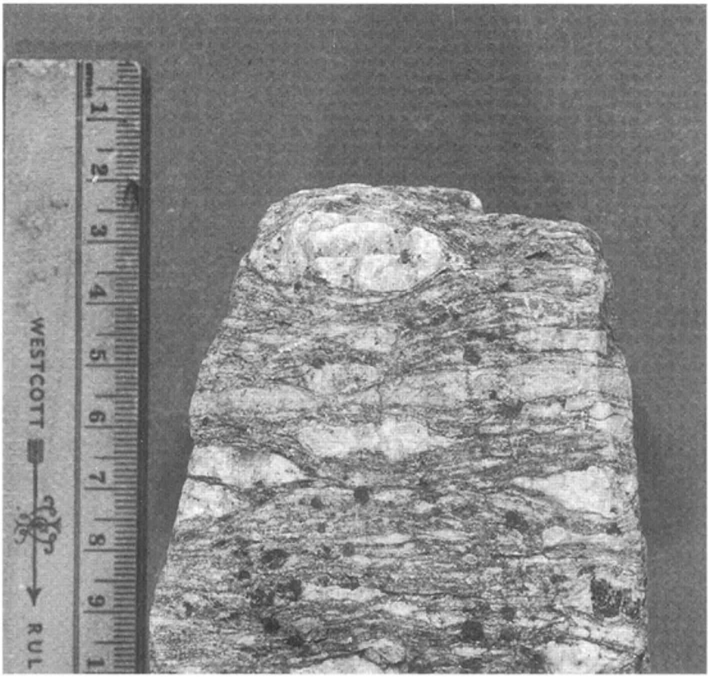


Fig. 8. Sample of lath unit sampled between Garol and Rollo. Note presence of rusty garnets, deformed and lesser deformed feldspar 'laths' (in cases extending across length of sample), local development of asymmetrical ('sense of shear') fabric. U–Th–Pb age for equivalent outcrop of this unit in Manogoush Ridge is *c.* 480 Ma (see text for discussion).

as forming porphyroclasts surrounded by an aggregate of quartz grains. The matrix is rich in muscovite with subordinate biotite, both orientated preferentially together with ribbon quartz to define the high strain fabric. Muscovite flakes are commonly rimmed by biotite at grain boundaries and cleavages. Fine to medium-grained prismatic crystals of kyanite are abundantly disseminated in the matrix within the preferred orientation of fabric. Bent crystal structure in some grains and preferential growth of others in the fabric plane suggests that kyanite is pre- to syn-kinematic. In comparison, garnet is mostly lenticular in shape, apparently grown in the preferred orientation of the fabric, and inferred to be syn-kinematic. Some, however, are skeletal and are overprinted on the fabric, suggesting a syn- to post-kinematic origin. Some larger garnet grains are zoned in terms of inclusions; they contain fibrous sillimanite in the cores and kyanite in their rims. The pink, garnet–muscovite–kyanite-rich matrix allows the lath unit gneiss to be distinguished from those C/S augen gneisses derived from, or those in the vicinity of, the Jalhari Granite. Preliminary ion microprobe data (Schneider *et al.* 2000), for the lath unit sampled at Manogoush Ridge yield concordant zircon U–Pb ages of *c.* 480 Ma.

The outcrop extent of the lath unit at Manogoush Ridge is not constrained. It is present as a tapering thin sheet at the northern tip of the ridge, but how far it persists to the south is unclear (hence the use of question marks on Figs 3a & b). Hubbard *et al.* (1995) discriminated an augen gneiss from their Indian cover rock/basement rock classification scheme. They show the augen gneiss on their Fig. 1c as extending from southern Barai to the central portions of the Manogoush Ridge. Unfortunately they do not describe the augen gneiss; there is only a photomicrograph of a quartzo-feldspathic portion of a thin section, and a report of old sillimanite being found as an inclusion in K-feldspar. Sillimanite is present both in the portion of the lath unit that we identify at the northern end of Manogoush Ridge, and in the porphyroclastic orthogneiss at Rollo, and there is no way to identify which of the two units is the augen gneiss of Hubbard *et al.* (1995). It is possible that the entire length of the Manogoush Ridge is composed of the lath unit. Alternatively, there may simply be only discontinuous scattered outcrops.

The Jalhari Granite

The third of the three plutonic suites that we recognize is the Jalhari Granite. It is named from its occurrence in Jalhari Gah, south of the village of Phailobat. It was also mapped in the Airl Gah and Diamir valleys and we recognize the Jalhari Granite as a N–S trending continuous belt several kilometres wide and tens of kilometres long (Figs 3a & 4). It is a biotite granite/granodiorite that is intrusive into the pelitic–siliceous lower cover. The western margin of the belt is in contact with metapelite *c.* 2 km from Dimeroi, while the eastern contact is a pervasively retrogressed, highly chloritized, metapelite, about 1 km west of the confluence of Zangot. The granite is more commonly deformed than not and, throughout the belt, the deformed portions of the granite have a varying intensity of foliation that is everywhere N–S striking, dipping moderately to steeply to either the west or east. In Jalhari Gah, the deformed granite frequently takes on an augen gneiss appearance marked by a local, very coarse crenulation of biotite layers about the quartz and feldspar grains. The intersection of this coarse crenulation causes spectacular parallel ridges on the main (W-dipping) foliation surfaces of the granite that can be seen from some distance (Fig. 9). In Jalhari Gah, this lineation is SSW plunging on moderately W-dipping surfaces.

The Diamir and Airl Gah valleys both offer almost continuous outcrop sections through the Jalhari belt. In these valleys, the granite is a course- to medium-grained, biotite granite that grades into granitic and porphyroclastic gneiss. Figure 10a illustrates the degree of variability of the Jalhari Granite across the belt as a whole. Note the variation in the amount of felsic component and the porphyroclast preservation. Sections through the granite in Diamir Gah and Airl Gah show that narrow horizons or screens of pelitic and calc-silicate schists and paragneisses, belonging to the lower cover, persist between hundreds of metres wide bodies of Jalhari Granite. Metasedimentary screens, frequently retrograde and highly chloritized, are typically a few tens of metres wide. A few are wider, up to several hundred metres, particularly at the eastern margin of the granite in Diamir Gah. Rare pelitic and granite xenoliths (Fig. 10b) are widely scattered in the granite sections. Throughout the area are internally undeformed portions of the granite that preserve magmatic textures and mineral assemblages. These were selected as characteristic sites for both geochronologic and petrologic sampling.

The Jalhari Granite is characterized by black biotite that occurs either in clusters between the large feldspar grains or forms large equant poikilitic crystals, often in excess of a centimetre in size, enclosing feldspar and quartz grains, and in some samples, hypersthene. These textures are

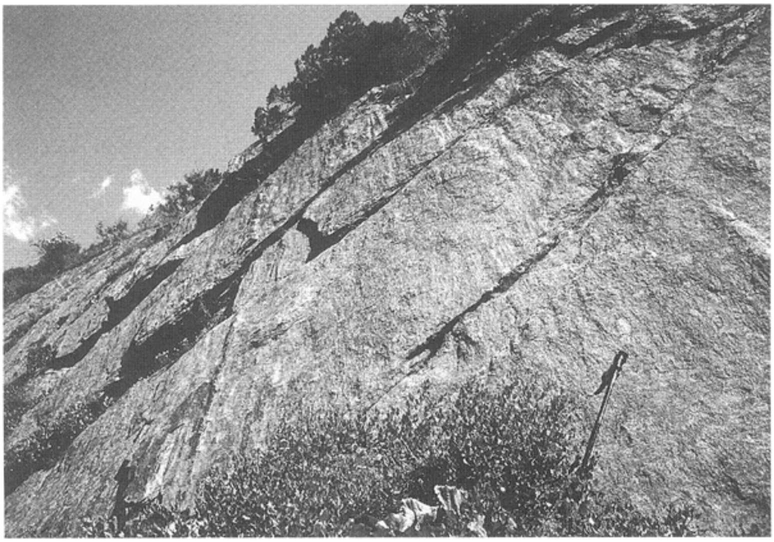


Fig. 9. Deformed augen gneiss-rich portion of Jalhari Granite outcropping on east wall of Jalhari Gah. In this instance, Jalhari Granite has a strong foliation striking N–S and dipping moderately to the W. Lineation is SSW plunging. Intersection on the main foliation surfaces of coarse crenulation of biotite layers about <0.5 cm quartz and feldspar grains causes spectacular parallel ridges of the granite that are seen in photo. Ski stick for scale.

apparently due to late-magmatic, post-cumulus, crystallization from liquids trapped in interstices between cumulus feldspar crystals. The predominant mineral is feldspar, including both orthoclase and albite–oligoclase, with the former dominant. Quartz, biotite, hypersthene and opaque minerals, in decreasing order of abundance, make up the assemblages in most of the fresh rocks sampled from the least deformed portions of the granite in Diamir Gah, although many fresh samples do not show hypersthene. Poikilitic biotite encloses all other minerals, quartz grains include feldspar and hypersthene, while feldspars include only hypersthene. These textural relations suggest earliest crystallization of hypersthene, successively followed by feldspar, quartz and biotite. A reaction relationship is noted between hypersthene and feldspar; the two are rarely in direct contact, and are commonly separated by fresh quartz and biotite. Minor interstitial muscovite is typically present in all samples, except for those from undeformed portions in Diamir Gah. Hypersthene relicts have been noted in two samples collected from near Jalhari village.

For microstructural analyses of the Jalhari Granite we examined 22 petrographic sections from the Diamir valley, Airl Gah and Jalhari Gah. The microstructure of the granite varies with the degree of deformation, although the principal foliation is everywhere defined by preferred grain orientation of biotite and quartz aggregates. In lesser deformed samples, feldspar grains frequently retain their original shapes, but fining of quartz grains, through grain recrystallization and through cataclasis, and alteration to fine-grained disseminated muscovites, is common. Figures 11a & b show optical photomicrographs of thin sections cut from portions of the Jalhari Granite sampled in Airl Gah that are representative of the variability of microstructure. Figure 11a is a finer-grained augen gneiss that displays a strong macroscopic non-coaxial fabric (porphyroclast augen asymmetry and C/S fabric) and has an N-plunging stretching lineation. Based upon the partial development of polymineralic ribbons, the extensive quartz and mica domains recrystallized in preferred orientation, and lack of intracrystalline plasticity in the large feldspar grains, we suggest that deformation temperatures in this rock may have reached *c.* 500°C (Tullis & Yund 1985, 1991; Dell Angelo & Tullis 1989). This assumes that hyper-solidus deformation did not create a strong anisotropy or a pre-existing fabric through, for instance, generating a strong biotite alignment that caused the subsequent growth of quartzo-feldspathic grains to mimic ribbons that form through deformation. A dextral sense of shear in the figure is indicated by S and C surfaces defined by the biotite and recrystallized quartz grains, and coarser recrystallized quartz grains that mark a strain shadow in the lower left edge of the large feldspar grain. The microstructure is

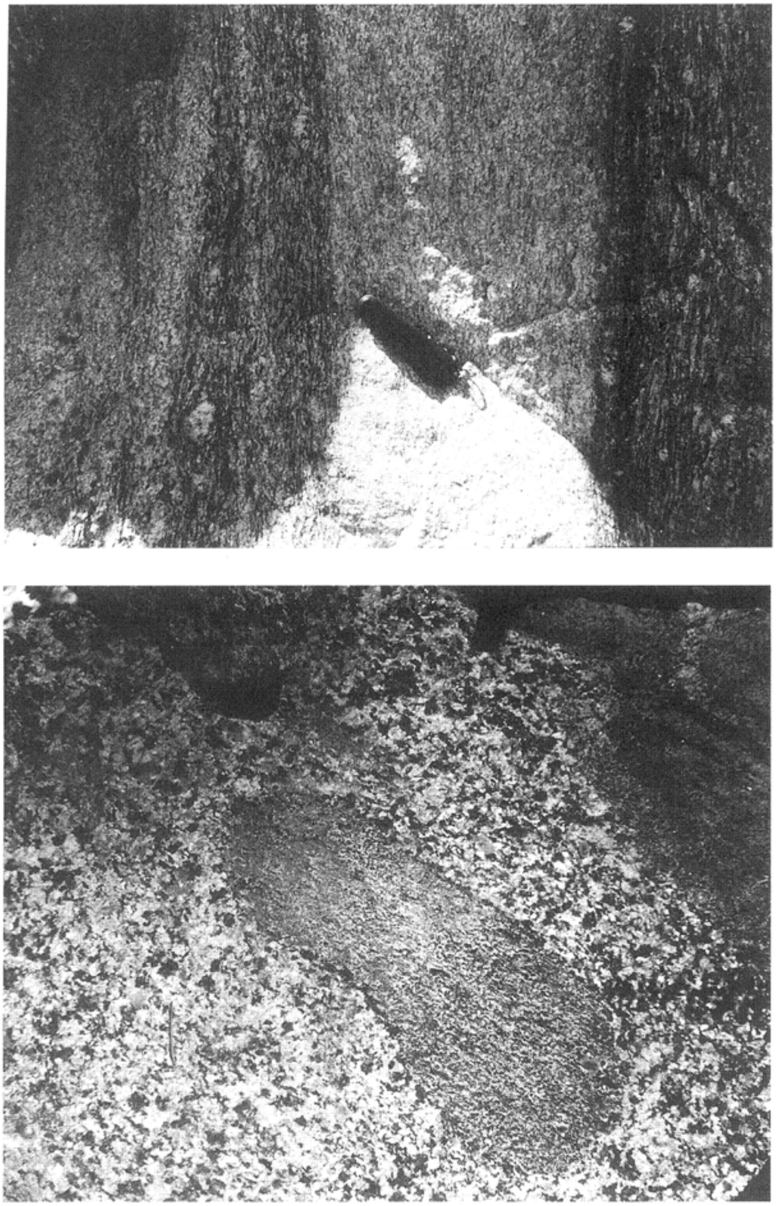
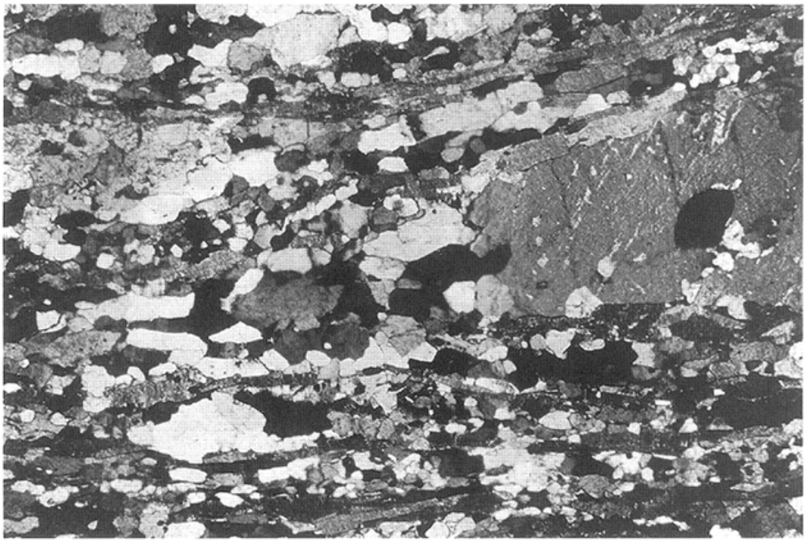
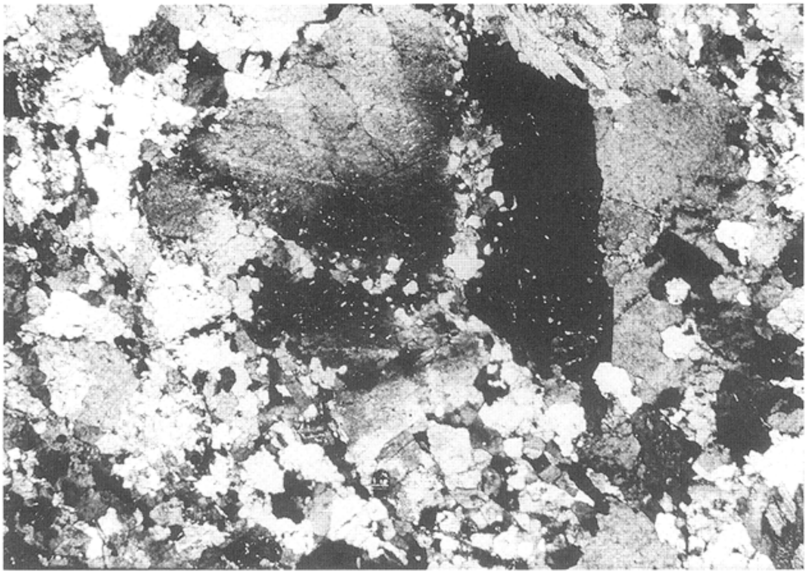


Fig. 10. Degrees of variation in granite rock observed in the Diamir Shear Zone. (**a**) Strained portion of Jalhari Granite within the Diamir Shear Zone, Diamir Gah: Note large variety of granitic gneiss locally housed. Although the large changes across the small area preserved here are atypical of the Jalhari Granite in the Diamir Shear Zone, the sample is nevertheless highly representative of the degree of variation that can be found along a transect through the Jalhari Granite as a whole. Swiss knife for scale. (**b**) Xenolith of finer-grained granite rock that is feldspar poor relative to host—a typical occurrence of Jalhari Granite in Airl Gah. Xenolith is *c*. 30 cm in length.

typical of the entire thin section, and because the thin section is cut parallel to the N-plunging stretching lineation, it represents a west-vergent reverse and dextral displacement. This direction of displacement is typical for a determined sense of shear in all the Jahari Granite thin sections where microstructure shows non-coaxial strain. In addition to the sense of shear indicators seen



(a)



(b)

Fig. 11. Optical photomicrographs of thin sections of Jalhari Granite from Airl Gah. (**a**) Augen gneiss portion with strong C/S fabric and stretching lineation (here plunging 50° towards 350°). Note the partial development of polymineralic ribbons (see text for discussion). The photo shows the characteristic microstructure of deformed granite in the Diamir Shear Zone. Grain size is relatively fine (biotites <300 μm, quartzofeldspathic grains <400 μm). The biotite picks out nicely the S and C surfaces. Sense of shear in this case is clearly dextral and W-vergent. Cut parallel to lineation and perpendicular to foliation (170°/89°E). South is to the left, west is to the top of the image. Base of image is 5.5 mm and parallel to main fabric. (**b**) Flattened portion of granite without C/S fabric development. Note deformed feldspar grains with some sutured internal grain boundaries, and extensive suturing and new grain growth at margins of larger grains, indicating that grain boundary migration and wholesale grain size reduction have operated extensively (both in field of view and elsewhere in thin section) as indicated by very fine (50–100 μm) grain size of surrounding quartzofeldspathic component. Base of image is 5.5 mm. Crossed polars.

in Fig. 11a, other frequently observed microstructures that were used to determine sense of shear include throughgoing fabrics and oblique objects (Means 1981; Lister & Snoke 1984; Passchier & Trouw 1996); C′-surfaces (Berthé *et al.* 1979); *Mica 'fish'* (Eisbacher 1970); porphyroclasts and stiff objects produce strain shadows, 'tails' (trails) and 'wings' that form delta, sigma and quarter structures (Hanmer 1984; Passchier & Simpson 1986; Hooper & Hatcher 1988). These features were consistently observed in a variety of widely distributed samples of deformed portions of the Jalhari Granite from the Diamir and Airl valleys.

Figure 11b is a typical example of the microstructure preserved in the Jalhari Granite in Diamir, where there is no significant C/S fabric or other obvious non-coaxial fabric preserved in hand specimens. Sutured internal grain boundaries of feldspar grains, and extensive suturing and new grain growth at margins of larger grains, indicate significant grain boundary migration and wholesale grain size reduction and suggest conditions of deformation of $>500°C$ (Dell Angelo & Tullis 1989; Tullis & Yund 1991).

In addition to microstructure, deformed portions of the Jalhari Granite show a range of outcrop-scale structures that we used to identify sense of shear. Throughout the Diamir Shear Zone, in both the Airl Gah and Diamir Gah valleys, lenses of the Jalhari Granite, tens to hundreds of metres thick, that show little to no sub-solidus deformation, are separated by, or frequently grade into, tens to hundreds of metres thick layers of augen gneiss with significant sub-solidus strain. Ductile fabric that is associated with microstructures includes spectacular C/S relationships, C′ shears a few millimetres to few centimetres in length, and asymmetry of porphyroclasts up to a few centimetres in size. These non-coaxial strain features are associated with a well-developed mineral stretching lineation in the Jalhari Granite belt that plunges moderately to steeply N or NE (Fig. 6a & c), and consistently indicates a W-vergent reverse displacement with a portion of, typically dextral, wrench motion. In addition to ductile fabrics, brittle and transitional structures include:

(1) narrow zones, tens of centimetres wide where hydrothermal flux has developed thick biotite accumulations (probably late ductile strain features), where well-developed asymmetric folding (centimetre-wavelength) of the biotite layers frequently indicates east side up and over west;
(2) well-developed suites of a few metres long, a few centimetres wide, west-vergent shear bands;
(3) sets of tens of metres long, 5–20 cm wide, local fault gouge horizons that often develop preferentially in areas where brittle deformation involved a broader zone of cataclasis as opposed to a single fracture plane; and
(4) planar, steep, faults that cut all fabrics whose W-vergent reverse displacement is recognized by drag folding of fabric or marker offsets (a few tens of metres).

On the large scale, the E over W sense of displacement is readily identifiable from both the brittle and ductile fabric that define regions of low and high strain; Fig. 12 illustrates higher strain layers of the Jahari Granite anastamosing around the lesser/undeformed granite lenses, marking reverse faults that are seen to 'climb' to the west.

In both Diamir Gah and Airl Gah, the entire thickness of the Jalhari belt has experienced west-vergent reverse faulting with local wrench motion that is constrained by the micro- and outcrop structures. The dextral wrench component is stronger in Airl Gah (compare lineations of Fig. 6a with 6c), although the principal state of strain in the two valleys is similar. The overall deformation is indicative of a major N–S striking steep shear zone. In view of the absence outside the Jalhari belt of any significant development of structures indicative of west-vergent reverse faulting, we regard the width of the shear zone to approximate to that of the main body of the Jalhari belt (4–6 km). We term this the Diamir Shear Zone. We did not conduct a traverse across the southern part of the Jalhari belt, although the outcrop at the margin (Fig. 4) and glacial boulders from Philobat North fork glacier indicate a consistent style of deformation of this part of the granite, and we infer that the Diamir Shear Zone continues south at least to here.

Basement rocks

The basement in Diamir Gah extends from *c.* 500 m west of Zangot to the interior of the NPHM. Several hundred metre structural thickness of quartzofeldspathic gneisses with centimetre to tens of centimetre scale compositional layering due to, for example, differing Fe-weathering and biotite content. These are characteristic of the southern region of the NPHM basement gneisses (Edwards 1998). Foliation is moderately to steeply E-dipping and lineation plunges moderately north. These rocks are replaced by a monotonous granitic orthogneisses sequence that

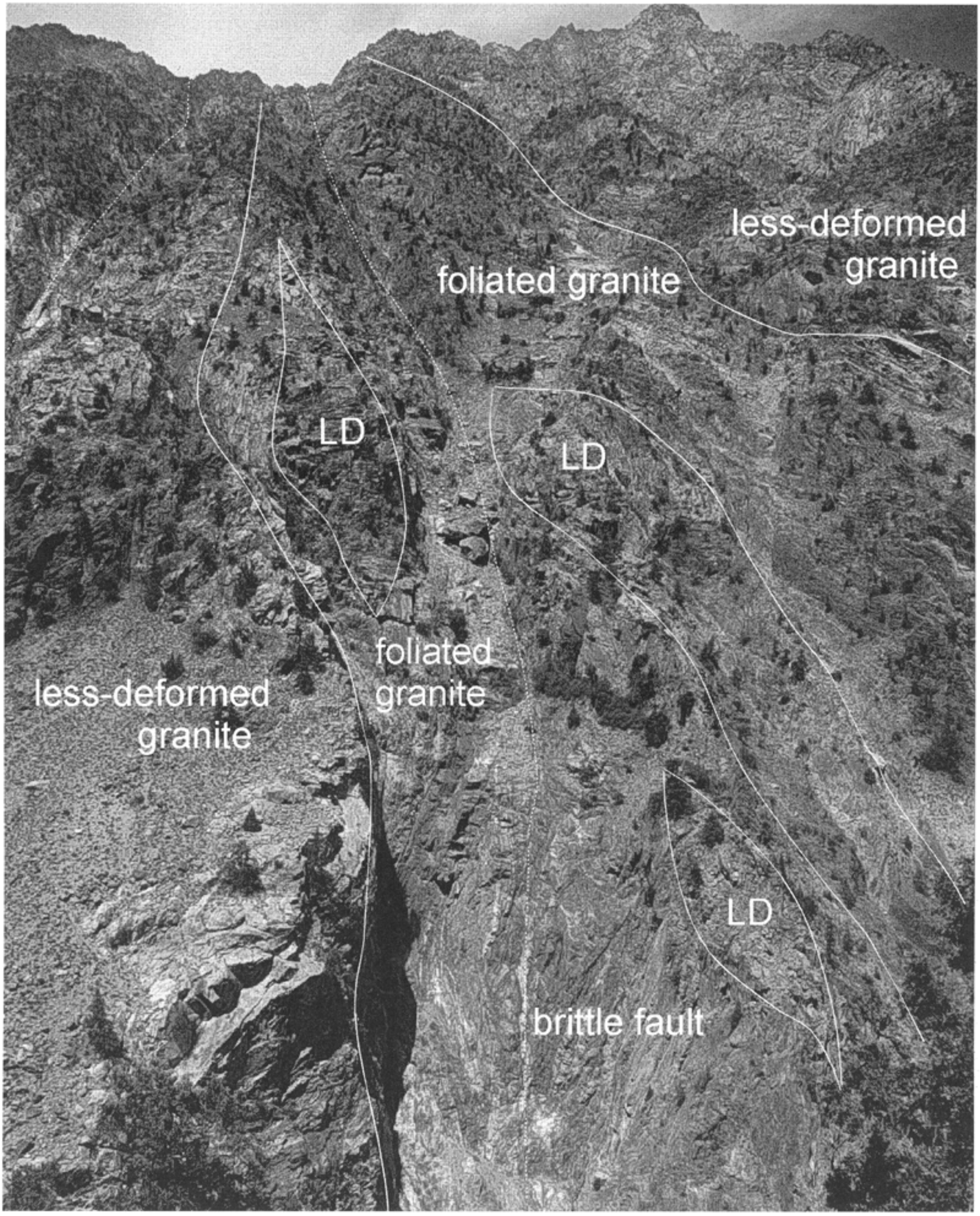


Fig. 12. Right bank view of Diamir Gah looking to the north of right bank of Diamir Valley, showing > 2 km high valley wall made up of Jalhari Granite, which is deformed by the W-vergent, reverse sense Airl–Gah/Diamir shear Zone. LD is less-deformed granite. Observations are based upon remote observation with field glasses and correlation with identical styles on left bank (where viewer stands). Note much ductile strain is localized into gneissic layers (tens to hundreds of metres) that anastamose around lenses of lesser- and undeformed granite.

continues for at least several kilometres towards the central portions of the NPHM. Foliation is N–S trending and moderately E-dipping, with north plunging lineations. A few sense of shear structures were observed but were found to be inconsistent across the area.

The basement in Niat Gah is marked by a prominent grey (occasionally porphyroclastic) quartzofeldspathic gneiss, and a much larger amount of amphibolite than in the basement section east of Zangot. The main foliation in Niat Gah dips moderately NW or SE. We note that the map of Hubbard *et al.* (1995, Fig. 1c) seems to group a portion of the basement in the cover, possibly under the assumption that significant volumes of amphibolite are characteristic only of the Indian plate cover rocks. We disagree with this in view of the fact that there is no evidence elsewhere that amphibolite is rare within basement rocks in this region, and, moreover, the rocks in question are mostly quartzofeldspathic and are devoid of pelites, and are therefore consistent with basement rocks mapped in Diamir, and in the SE region of the NPHM (Edwards 1998). The section of basement in Niat Gah is structurally very 'high' and is bounded by cover rocks to the north and to the south. We interpret this as the product of kilometre-scale imbrication associated with a possible duplexing, and discuss this below. We disagree with the tens of kilometres-scale nappe that is proposed by Hubbard *et al.* (1995) in the SW region of the NPHM to account for this section of basement. This model requires extrapolation of the footwall anticline in Niat Gah from the <3 km observed half-wavelength (Fig. 3b) to >27 km (cf. fig. 1d of Hubbard *et al.* 1995). Our new observations in the SW region of the NPHM provide no evidence to support this.

Western Rupal valley

Figure 4 presents data from the westernmost Rupal valley, and enables examination of the regional continuity of the structural and lithological trends. There is a contrast between the inner/upper regions of the left bank, the 'summit region' of Nanga Parbat, and SW Rupal, which includes the lowermost portion of the Toshain Glacier left bank and the right bank of the Toshain and Rupal glaciers up to Shaggin' Glacier to the east of the map area.

In the SW region of the Rupal valley, lineations everywhere plunge SSW, and the main foliation is N or NE striking, dipping steeply to the west. Lineation and foliation are therefore similar to the southern portions of the Bunar and Niat/Thak valley systems. On highly strained foliation planes (dipping moderately to WNW) a consistent sense of shear is recognized across all of the Toshain Glacier right bank. Sense of shear is also demonstrated by microstructures which, in most cases, indicate that recorded, stable, deformation largely proceeded at temperature of <400 °C. Displacement sense is sinistral with top down to the south-southwest, and an accompanying sinistral wrench component (Fig. 4). This displacement sense is consistent with reports from Hubbard *et al.* (1995) and Burg *et al.* (1996) from Bunar, Niat/Thak, and other areas further to the west.

There is a minor lithological contrast in the SW region of the Rupal valley between the left and right bank of the Toshain Glacier. On the right bank, a sequence of L-tectonite orthogneiss forms mega-lenses and boudins, tens of metres in diameter that are discordantly intruded into a more weakly lineated finer-grained grey gneiss. The original intrusive relationship is preserved in spite of subsequent deformation that has affected both. Stretching lineations in the L-orthogneiss and the grey gneiss are parallel and steeply S to SW plunging.

The principal foliation in the summit region of Nanga Parbat is very steep and N to NE to E striking (Fig. 4). Lineations plunge moderately to steeply to the north. The switch in trends of lineation and foliation between the inner/upper regions of the left bank of SW Rupal is marked by a series of brittle and ductile faults (shown schematically on Fig. 4), whose net offset is not known but is thought to be in the order of several kilometres (Edwards 1998). The N-plunging lineation is an expression of the south-southeast vergence of the summit region over the footwall rocks in the central Rupal valley. This is a part of the general displacement on the Rupal Chichi Shear Zone—a major NE-striking shear zone that represents several kilometres of deep crustal displacement (Edwards 1998; Schneider *et al.* 1999*a*) that is marked by a clear summit-ward younging of biotite cooling and leucogranite ages (Schneider *et al.* 1999*b*, *c*). The eastward change in strike of foliation from NE to E is regarded as part of a gradual swing in foliation that is a product of the Rupal Chichi Shear Zone.

The brittle and ductile faults of the left bank of the Toshain Glacier also mark a lithological contrast. The dominant lithologies in the uppermost Nanga Parbat summit region are basement gneisses including compositionally layered gneisses and monotonous granitic orthogneiss; it is not clear what is the maximum metamorphic grade attained. Immediately SE of Mazeno Pass, green pinnitized cordierite in coarse (pegmatitic) granitoid float was seen in scree debris but not in outcrop. At the pass, a leucogranite pluton (Fig. 4) intrudes the compositionally layered gneisses. Schneider *et al.* (1999*a*) obtained a U–(Th)–Pb monazite and zircon emplacement age of 1.4 ± 0.4 Ma for the Mazeno Pass Pluton. In the eastern part of the left bank, there is a lithological change whereby pelitic metasedimentary (apparently cover) rocks are frequently interlayered with the granitic orthogneiss. This is regarded as part of the general imbrication that is associated with major reverse faulting on the Rupal Chichi Shear Zone.

Thermochronology of the SW region of the NPHM

In order to constrain some of the cooling history of these rocks, we performed multigrain laser total fusion $^{40}Ar/^{39}Ar$ analyses on biotites from samples from throughout the SW region of the NPHM area. Fusing of samples and flux monitors was performed at Lehigh University via CO_2 laser under visual observation. Results are compiled in Table 1 and displayed in Fig. 3. Cooling ages east of the Diamir Shear Zone, in the hanging wall where Nanga Parbat has been displaced upwards, are generally young (<5 Ma), typical for Nanga Parbat (Winslow *et al.* 1956; Schneider *et al.* 1997). However, a marked age increase occurs west across the shear zone into the Indian cover metasediments; biotite cooling ages there are >20 Ma. Our Early Miocene and older cooling ages are consistent with cooling ages in the Babusar area (Chamberlain *et al.* 1991) and cooling ages

Table 1. *Multigrain laser total fusion $^{40}Ar/^{39}Ar$ biotite ages*

Sample	40/39	37/39	36/39	%Ar^{40*}	Age (Ma)	s.e.	LU#
B-3	58.95	−0.0187	0.0291	85.36	28.66	0.19	802
B-9	120.8	0.0490	0.1321	67.68	49.19	0.56	674
B-5	47.73	0.0246	0.0119	92.57	26.74	0.28	675
B-10	194.1	−0.0011	0.0285	95.65	103.41	0.55	804
B-15	130.7	−0.0716	0.1236	72.03	53.07	0.41	807
BI-2	96.26	−0.1020	0.0138	95.73	52.82	0.35	794
BI-3	100.9	−0.2524	0.0133	96.04	55.37	0.40	795
BI-4	67.92	−0.0384	0.0496	78.36	30.58	0.35	796
GA-4	50.08	0.0382	0.0140	91.68	26.37	0.22	797
JAL	6.177	0.0096	0.0114	44.97	1.60	0.02	798
MR-15	6.437	0.0038	0.0157	27.38	1.05	0.02	788
MR-16	7.332	0.0016	0.0142	42.43	1.84	0.02	789
MR-23	26.72	0.0058	0.0296	67.21	10.61	0.05	790
MR-24	25.88	0.0150	0.0181	79.20	11.77	0.07	799
MR-27a	10.26	−0.0150	0.0199	42.41	2.57	0.03	791
MR-32	24.12	0.0101	0.0215	73.59	10.35	0.06	793
N-1	52.76	0.0471	0.0310	82.60	26.38	0.29	676
N-2	50.19	0.0442	0.0542	68.07	20.71	0.23	677
N-3	52.67	0.0336	0.0300	83.13	29.69	0.33	678
N-7	120.6	0.0630	0.2919	28.43	20.78	0.57	679
P-1	58.93	0.0065	0.0335	83.18	27.64	0.29	731
P-2	45.90	0.0032	0.0117	92.42	23.95	0.24	732
PH-1	64.78	−0.0049	0.0147	93.24	34.23	0.27	808
PH-2	53.46	0.0217	0.0181	89.96	27.31	0.21	809
PH-3	23.64	0.0043	0.0129	83.77	11.29	0.06	810
PH-4	37.29	−0.0126	0.0093	92.59	19.65	0.20	811
TH-1	193.3	0.0733	0.0186	97.15	104.87	0.56	800
TH-4	88.40	0.0595	0.0142	95.22	47.72	0.26	801
Z-1	12.07	0.0258	0.0313	23.22	1.84	0.06	668
7-II	5.718	0.0057	0.0098	48.82	1.70	0.03	687
8-XII	6.172	0.0087	0.0041	79.96	2.98	0.03	686
8-XVII	7.554	0.0071	0.0181	28.99	1.39	0.14	685
11-VII	59.51	0.0021	0.0109	94.53	33.78	0.36	684
12-I	17.15	0.0269	0.0118	79.56	8.26	0.12	682
12-IV	10.74	0.0187	0.0157	56.72	3.70	0.05	683

Table represents isotopic results of $^{40}Ar/^{39}Ar$ analyses on multigrain biotite separates from the southwestern valleys of NPHM indicated by scheme of dot symbols detailed in Fig. 3a. Total fusing of samples and flux monitors was performed via CO_2 laser under visual observation. For complete discussion, see Schneider *et al.* (2000).

Sample nomenclature: B = Barai; BI = Biji; GA = Gasht; JAL = Jalipur; MR = Main Massif Region (upper Diamir and Patro valleys); N = Niat; P = Picora; PH = Phailobat; TH = Thamrus; Z = Zangol; Roman numerals = transect from Mazeno to Airl Gali (these samples appeared as e.g. 95/7-ii, cf. Edwards 1998, p. 272).

farther to the southwest in Indian plate rocks of the Hazara syntaxis (Smith *et al.* 1994). Thus, the older ages obtained in this study are probably initial Himalayan cooling dates and not the result of a widespread excess radiogenic argon that is restricted to the Indian cover rocks. The cooling age profile across the Diamir Shear Zone is similar to the cooling age profiles across the Raikhot–Liachar fault system (Zeitler 1985; George *et al.* 1995) in the northern sections of the NPHM and probably similarly represents large displacement of the shear zone. Cooling ages within the shear zone reflect varying degrees of 'resetting' most likely the result of deformation and fluids.

Discussion

Diamir Shear Zone/Jalhari Granite

We define the Diamir Shear Zone (DSZ) as the 4–6 km thick N–S trending shear zone with extensively developed non-coaxial ductile and brittle strain that is associated with steep NE-plunging stretching lineation within the Jalhari Granite belt. The DSZ coincides with almost the entire thickness of the belt. The $^{40}Ar/^{39}Ar$ cooling age gradient that accompanies the shear zone indicates several kilometres of E over W relative displacement across the zone, and, in view of the width of the belt, we infer that the shear zone continues for several kilometres below the surface. Between the exposed Gashit Fold and a few kilometres north of Dimeroi is the surface exposure of the overturned MMT and its immediate foot- and hanging wall. We regard this overturning as a mechanical response of the E over W vergence that has developed adjacent to the DSZ; it is clear that the Diamir Shear Zone and the overturning play key roles in accommodating relative uplift of the central parts of Nanga Parbat with respect to the outer portions of the massif. A similar overturning is recognized in the SE region of the NPHM (Edwards 1998).

Strain in the Jalhari Granite is apparently partitioned into zones of high strain that anastamose around lesser deformed regions (e.g. Fig. 12). Although this may be a true strain partitioning (i.e. regions that experience differing parts of the instantaneously straining area), it is also possible that the lesser deformed regions have been intruded during the ongoing strain, and have therefore experienced only a (later) part of the finite deformation; during continued displacement on the shear zone, some of the lesser- or undeformed portions of the Jalhari Granite many have been intruded as discrete plutons. Preliminary geochronologic investigations on the crystallization age of deformed and undeformed portions of the Jalhari Granite indicate Th–Pb monazite ages that range from *c.* 12 Ma to 3–2 Ma (Schneider *et al.* 2000). Although work is in progress, it appears the granite is young or has recently undergone sufficient reworking during this time to incur Pb loss. Based upon this, we suggest that there has been syn-kinematic magmatism; protracted plutonism has partly overlapped with ongoing deformation between 12 ad 2 Ma.

The portions of Raikhot Fault Zone in the area of Raikhot Bridge (Fig. 2) represent a W to NW-vergent, reverse sense major shear zone that is associated with steep cooling age gradients (Zeitler 1985; Madin 1986; Butler & Prior 1988; Madin *et al.* 1989; Butler *et al.* 1992; George *et al.* 1995). On the large scale, the DSZ is therefore comparable to this section of the Raikhot Fault Zone. We propose that, on a first order basis, the DSZ forms the mechanical continuation of the main Raikhot Fault; noting, however, that the latter is much narrower (<2 km) and represents more focused strain.

Thinning of cover rocks

An abrupt northward thinning of cover sequences in the southwest region of the NPHM is evident from the change in the upper cover structural thickness from a few hundred metres near Dimeroi to *c.* 12 km at Nashkin Gah. Even very steep palaeotopography of the original depositional surface is unlikely to result in such a large variation in original thickness and there must therefore be some type of tectonic excision, with >5 km thickness of material removed. The same thinning of the Indian cover is also clearly displayed along the southeast and eastern margin of the NPHM (Fig. 2), where there is no younger, NPHM-age, modification or truncation of the Himalayan and MMT fabrics. There are three possibilities; an MMT frontal ramp, post-thrusting MMT normal displacement, or lateral ramps in the Indian basement/cover or MMT (Fig. 13).

Our favoured interpretation (Fig. 13A) involves a large frontal ramp in the MMT which results in a duplex structure with extensive imbricated slices of Indian cover and basement. This hypothesis provides a plausible explanation for the occurrences of basement 'high' in the thick Indian cover in Niat and also for larger examples of basement highs found to the S and SE of the NPHM. In addition it is consistent with structural interpretations further west along and to the south of the MMT (Coward *et al.* 1988; Treloar *et al.* 1989). Our frontal ramp

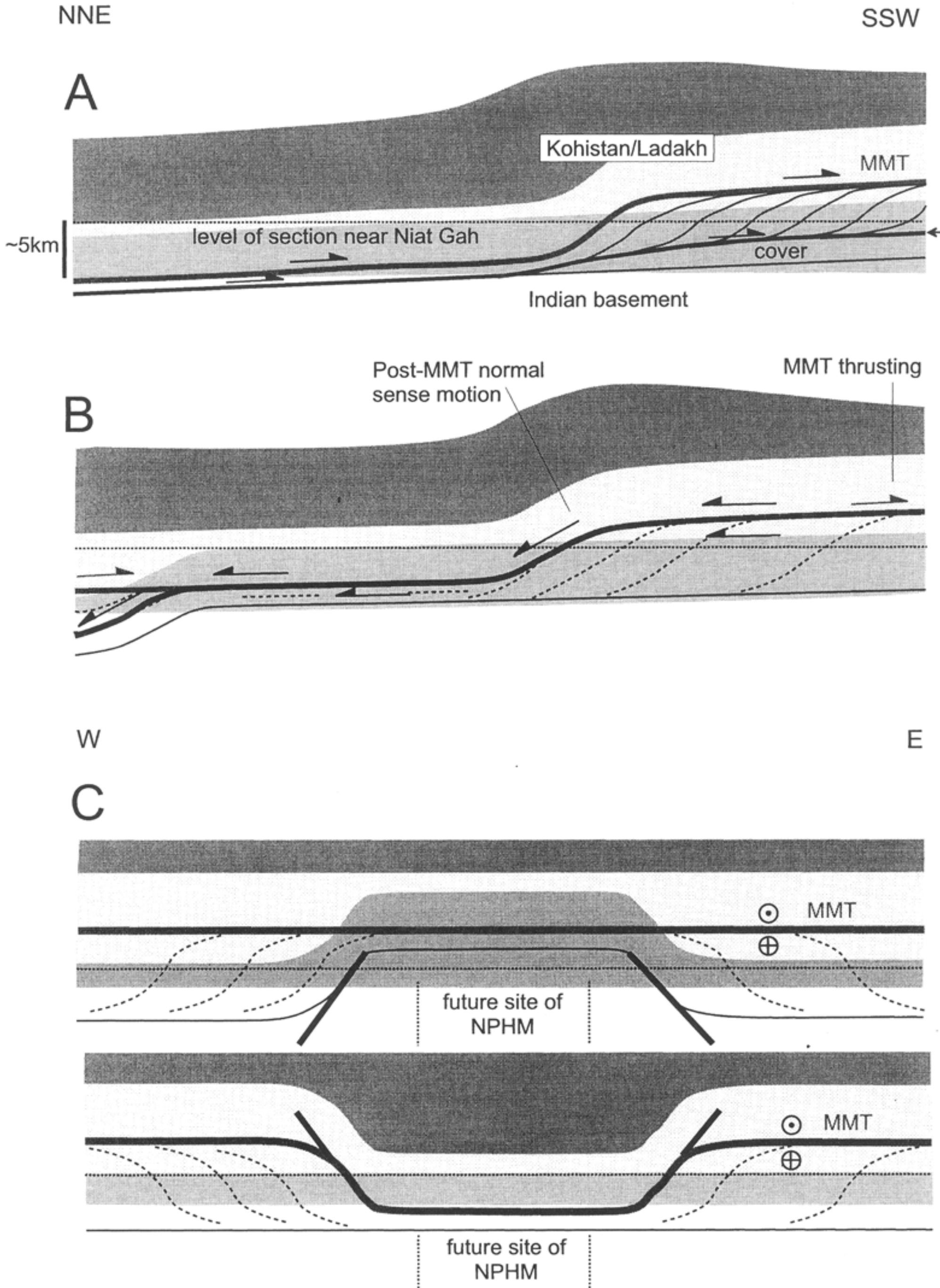


Fig. 13. Cartoon structural sections depicting three possible scenarios prior to Nanga Parbat exhumation and uplift. Weight of shading labelled in A is used throughout. See discussion in text.

model is additionally consistent with the dominant thrust motion seen on the MMT around the north end and along the eastern side of the NPHM (Edwards 1998), and can also explain the presence of the lath unit. In addition to the various outcrops of the lath unit in the SW region of the NPHM, it has been recognized extensively throughout the SE region of the NPHM (Edwards 1998) and is correlated with a typically high strain pink matrix gneiss that is present along the eastern margin of the NPHM in the Indus Gorge (Madin 1989; Wheeler *et al.* 1995). In many cases the lath unit, or an equivalent high strain pink gneiss, is structurally sandwiched between two contrasting suites of rocks (e.g. the upper and lower cover) whose juxtaposition is probably the result of displacement accommodated in part by deformation within the lath unit. We therefore suggest that the lath unit is a site for localization of the floor thrust that accompanies our inferred duplex in the Indian cover that developed from a ramp in the MMT. The very deformed portions of the lath unit, including the high strain pink gneiss found in the northern regions of the NPHM, represent large amounts of floor thrust displacement while the relatively lower strain parts of the lath unit (e.g. Fig. 8) are inferred to have been imbricated into the duplex and preserved after experiencing a smaller amount of floor thrust displacement.

Edwards (1998) has documented spectacular strain variation in the lath unit and its intrusive origin is clear. In addition to the *c.* 480 Ma U–Pb zircon microprobe age for the lath unit from Manogoush (Schneider *et al.* 2000), Foster *et al.* (1999) have obtained *c.* 500 Ma monazite SHRIMP ages from the cores of garnets within the lath unit from the SE region of the NPHM, and Zeitler *et al.* (1989) obtained a 500 Ma inheritance age from a NE NPHM Shengus gneiss sample. It is clear that the lath unit represents the deformed product of, or a suite of, widespread Cambro-Ordovician granitoids bodies intruded into the basement-cover contact, or upper cover–lower cover contact.

We do not think that the abrupt northward thinning of cover sequences in the SW region of the NPHM is due to post-thrusting MMT normal displacement, or lateral ramps within the Indian plate. Although post-thrusting MMT normal displacement (Fig. 13B) explains the thinning of Indian plate cover between Raikhot and Bunar, it does not explain the occurrences of basement at Niat and other areas in the southern portions of the NPHM, nor is it consistent with the absence of evidence for significant normal motion on the MMT. Large pre-thrusting lateral fault ramp(s) in the Indian cover/basement contact (Fig. 13C, upper) or on the MMT (Fig. 13C, lower) could explain some of the thickness variation in the Indian cover, but cannot provide an explanation for the direction of shear sense along the MMT subparallel with the length of the NPHM, the distribution of basement within the cover, or the presence of high strain rocks, including the lath unit, located near the base of the cover sequence on both sides of the NPHM.

Stretching lineations

SW of the NPHM, Burg *et al.* (1996) and Hubbard *et al.* (1995) report regionally distributed SW-directed shear fabric that is accompanied by a *c.* SW plunging lineation on W to NW dipping foliation. We have observed lineation trends with a corresponding plunge in the southern portions of the Bunar and Niat/Thak valley systems, and in the SW region of Rupal valley. South of the portion where lineation is related to the northward dip of the main Rupal Chichi Shear Zone in SW Rupal, the *c.* SW plunging lineation is accompanied by clear SW-vergence (top to the SW); an apparently extensional motion that is consistent with that observed by Hubbard *et al.* (1995). Hubbard *et al.* (1995) proposed a tens of kilometres wide extensional shear zone based upon this apparently extensional motion and a simple assessment of metamorphic grade and deformation from which they concluded that lower grade rocks pass structurally downwards into medium and higher grade rocks. Burg *et al.* (1996) argued that the extensional fabric described by Hubbard *et al.* (1995) was actually a misinterpreted SW-directed shear fabric that was generated early in the history of India underthrusting the Kohistan island arc. We concur with Burg *et al.* (1996), applying their interpretation to much of our mapping outside the DSZ. In, for example, the SW Rupal valley, the extensive occurrence of a SW-plunging lineation coinciding with steep *c.* W-dipping foliation can be easily restored to a NE plunge if the foliation is rotated to become N-dipping, as part of a retrodeformation to a time that predates NPHM relative uplift. In this, we assume that the relative uplift of the centre of the massif has caused all the foliation on the western flank of the syntaxis to be rotated to steep W-dipping or locally overturned. This assumption is consistent with the observed E over W thrusting and overturning that is part of, or associated with, the Diamir Shear Zone.

In the southern portions of the Bunar and Niat/Thak valley systems, and in the lower cover of the Diamir and Airl Gah sections, we additionally observe N- or NE-plunging lineations (Fig. 6). We suggest that these are part of the regional, non-overturned, MMT-related NW-plunging stretching lineation (Greco *et al.* 1989; Treloar *et al.* 1989); this lineation plunge would rotate to SW where original foliation has been overturned.

In the southwestern region of the NPHM, therefore, and indeed across the remainder of the massif (Edwards 1998; Schneider *et al.* 1999*a*), we have found no evidence for any major extensional structure (such as an STDS-type low angle detachment) that has allowed the very young unroofing and exhumation of the massif.

Conclusions

The Diamir Shear Zone is an E over W displacement structure with a minor wrench component that represents a crustal-scale reverse fault, together with the Raikhot Bridge portion of the Raikhot Fault System. It has resulted in overturning of the local MMT section in association with the Gashit Fold, as a response to the relative uplift/overthrusting, or 'bulging out', of the NPHM. NPHM-related rotation of pre-existing fabric is recognized throughout the Biji/Bunar and SW Rupal valleys. The $^{40}Ar/^{39}Ar$ cooling data show a steep age gradient that coincides with the Diamir Shear Zone, and indicates that it has accommodated very young relative uplift of the central portions of the Nanga Parbat massif.

The Indian plate cover rocks are thinned by >5 km due to variation in imbrication in the MMT footwall. The thick sequences that continue south from Nashkin–Airl are most likely the product of a frontal ramp in the MMT footwall, and they neither show evidence for any extensional thinning/exhumation, nor a tens of kilometre-scale nappe structure.

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