

Two-phase exhumation of ultra high-pressure and medium-pressure Indian Plate rocks from the Pakistan Himalaya

PETER J. TRELOAR¹, KATHRYN J. VINCE^{1,2} & RICHARD D. LAW³

¹*Centre for Earth and Environmental Sciences Research, Kingston University, Penrhyn Road, Kingston-upon-Thames KT1 2EE, UK (e-mail: P.Treloar@kingston.ac.uk)*

²*Present address: Landmark EAME Ltd, Hill Park South, Springfield Drive, Leatherhead KT22 7NL, UK*

³*Department of Geosciences, Virginia Tech, Blacksburg, VA 24061, USA*

Abstract: The Indian Plate rocks of NW Pakistan contain evidence for both Eocene and Miocene phases of post peak metamorphic exhumation. The Eocene phase shortly followed peak synchronous ultra high-pressure (UHP) and Barrovian metamorphism and was driven by the rapid return towards the surface of deeply buried, positively buoyant coesite-bearing UHP rocks, flanked by thrusts below and extensional shears above. Uplift of the UHP rocks contributed to crustal thickening and resulted in internal imbrication of the Barrovian metamorphic rocks onto which they were thrust. The Eocene and Miocene events were separated by a phase of large-amplitude and -wavelength folding. Upright folds related to this event have shallow WNW or ESE plunges. Quartz *c*-axis data suggest that the maximum stretching direction paralleled the fold axes. During the Miocene the Main Mantle Thrust was reactivated as a major top-side-north extensional fault zone. Cascading folds on its hanging wall and cascading folds and a variety of ductile to brittle top-side-north meso- and micro-structures on its footwall document significant top-side-north movement. The driving force for Miocene extension is unlikely to be channel flow as suggested for the central Himalaya. Instead, rapid shortening of the overriding plate following Late Oligocene slab break-off could have destabilized the wedge and driven extension in its upper parts.

Many orogenic belts contain evidence for extension synchronous with continuing lithospheric shortening. Coeval normal faulting at high structural levels and thrust faulting at deeper levels is recognized in many orogens including the Caledonides (Fossen 2000), the Alps (Reddy *et al.* 1999, 2003) and the Himalaya (Burg *et al.* 1984; Burchfiel & Royden 1985; Burchfiel *et al.* 1992; Searle 1999, 2003; Searle *et al.* 2003). A consequence of synconvergent extension is the exhumation of medium- to high-pressure rocks metamorphosed earlier in the orogenic event. Exhumation is accommodated through movement along hinterland-directed normal faults that operate synchronously with foreland-directed thrusts. Such exhumation implies bulk horizontal stretching of the upper crust, but not necessarily of the whole lithosphere.

Care must be taken to confirm that major, hinterland-directed faults are extensional structures (Wheeler & Butler 1994). In a south-vergent orogenic pile, fault zones that dip south with a top-side-north displacement sense could be back thrusts whereas fault zones that dip northward with a top-side-north displacement could be back thrusts rotated through the horizontal. More evidence than just a north-vergent sense of displacement is needed to confirm that such

structures accommodate extension. In addition, fault zones with a top-side-north displacement (regardless of dip direction) could be associated with some form of wedge extrusion or channel flow, with the fault zone marking the top of the wedge or channel.

What drives synconvergent extension remains a matter of debate (e.g. Ring *et al.* 1999). It might be lithospheric or crustal in scale. Extension in both Tibet and the Betic Cordillera is interpreted as a result of gravitational potential following crustal uplift driven by lithospheric delamination (England & Houseman 1988; Platt & Vissers 1989; Vissers *et al.* 1995). In contrast, in the Alps and the Himalaya extension is on a crustal scale and is accommodated by extensional structures on the hanging wall of a major, foreland-propagating thrust system.

There are a number of possible mechanisms to account for synconvergent extension within a Himalayan-type system. It may be a simple function of over-steepening of the critical taper of the thrust wedge (Platt 1993). If material continues to be added to the base, or rear, of the wedge at a rate greater than that at which rock is removed by erosion from the top, or front, of the wedge, then the critical taper can only be maintained by horizontal stretching of the upper part of the

wedge. In this case, extension along the top of the wedge will commence once sufficient thickening has occurred and should continue for as long as shortening persists. Collapse of the wedge may be encouraged by changes in the constitutive relation between stress and strain rate of material within the belt (including an increase in pore pressure, presence of melt and the brittle–ductile transition), and changes in the distribution of shear traction on the base of the wedge (England & Molnar 1993). Extension may also result from a reduction in the horizontal normal stresses applied to the belt (England & Molnar 1993). These could be driven by changes in far-field stresses, possibly the result of slab break-off (Davies & Von Blanckenburg 1995) and/or a change from a retreating to a converging character of the plate boundary (see Royden 1993*a,b*). In the event of collapse, material movement within the wedge may follow paths similar to those predicted by corner flow models (i.e. Platt 1993, 2000). However, kinematic indicators and flow vortices in the crystalline slab of the High Himalaya in Nepal and NW India (Vannay & Grasemann 2001) are not readily reconcilable with such a model. Instead, they may be consistent with a channel flow model (Grujic *et al.* 1996; Beaumont *et al.* 2001, 2004; Jamieson *et al.* 2004) in which ductile material is forced through a narrow channel with a thrust sense below and an apparent extensional sense above.

Synconvergent extension is capable of bringing rocks metamorphosed at medium pressures back toward the surface during later stages of continuing convergence. However, the exhumation of UHP metamorphic rocks, metamorphosed early in an orogenic cycle, poses a different problem. UHP rocks probably return to surface through more than one phase of exhumation, with initial stages of exhumation of many high-pressure (HP) to UHP terranes occurring before thermal relaxation of the thickened crust (e.g. Chemenda *et al.* 1996, 2000). Data from both the western Alps and the western Himalaya show that exhumation of UHP rocks was coeval with early stages of crustal shortening. In these regions, exhumation from depths of *c.* 100 km to within 15–20 km of the surface occurred within a few million years (Desmons *et al.* 1999; Gebauer 1999; Rubatto & Hermann 2001; Treloar *et al.* 2003). The rapid loss of > 80 km of vertical section requires some form of extensional tectonics, which was clearly synorogenic as it was followed by further crustal stacking. In contrast to late orogenic extension, modelling by Chemenda *et al.* (1996) suggested that early orogenic extension implies bulk horizontal shortening of the lithosphere and the incorporation of the UHP

rocks into a developing thrust stack. ‘Extension’ is probably the wrong term to use here as rapid unroofing of a UHP sequence cannot be due solely to orogenic collapse but, instead, requires buoyant, upward transport of a segment of crust. UHP rocks unroofed in this way should be bounded by stacks of fault and shear zones, each marked by metamorphic breaks, with a normal sense above and a reverse, or thrust, sense below. The distinction of shears associated with deep-level differential uplift of UHP rocks from shallow-level faults associated with orogenic collapse is a major problem in collisional orogens.

Geochronological and structural data from the Indian Plate in North Pakistan (Fig. 1), to the west of the Nanga Parbat Syntaxis, as well as from the structurally overlying Kohistan Arc, permit construction of a model for Indian Plate exhumation that demands two discrete, short-lived phases of rapid exhumation separated by a long period of erosive exhumation with low unroofing rates. Evidence for this is summarized below and mechanical implications are assessed.

Deformation and metamorphism in the internal zones of the Indian Plate to the west of the Nanga Parbat Syntaxis

Collision in the NW Himalaya was between the leading edge of continental India and the Kohistan Arc (Fig. 1). During collision the arc was thrust onto continental India along the Main Mantle Thrust (MMT). The best constraints on the timing of collision are from palaeomagnetic (Patriat & Achache 1984) and sedimentological (Garzanti *et al.* 1996; Pivnik & Wells 1996; Rowley 1996; Najman *et al.* 2001; Zhu *et al.* 2005) data. These data indicate collision at *c.* 50 Ma or shortly thereafter. The structurally highest Indian Plate rocks contain strongly transposed, planar shear fabrics that show evidence, marked by L–S to L-tectonites (Fig. 2a), for high constrictional strains. Thrusting rather than recumbent folding was the dominant mechanism of crustal thickening. Planar foliations parallel the major thrust surfaces. Linear fabrics (Fig. 3) indicate a southward transport direction, varying from SW-directed, in the Kaghan Valley, to SSE-directed in the Hazara region (Treloar *et al.* 1991).

Much of the metamorphism in the internal zones of the Indian Plate in northern Pakistan was along a chlorite- to sillimanite-grade Barrovian-type metamorphic gradient at 9 ± 2 kbar (Treloar *et al.* 1989*a,b*; DiPietro 1991; DiPietro & Lawrence 1991; Treloar 1997; Foster

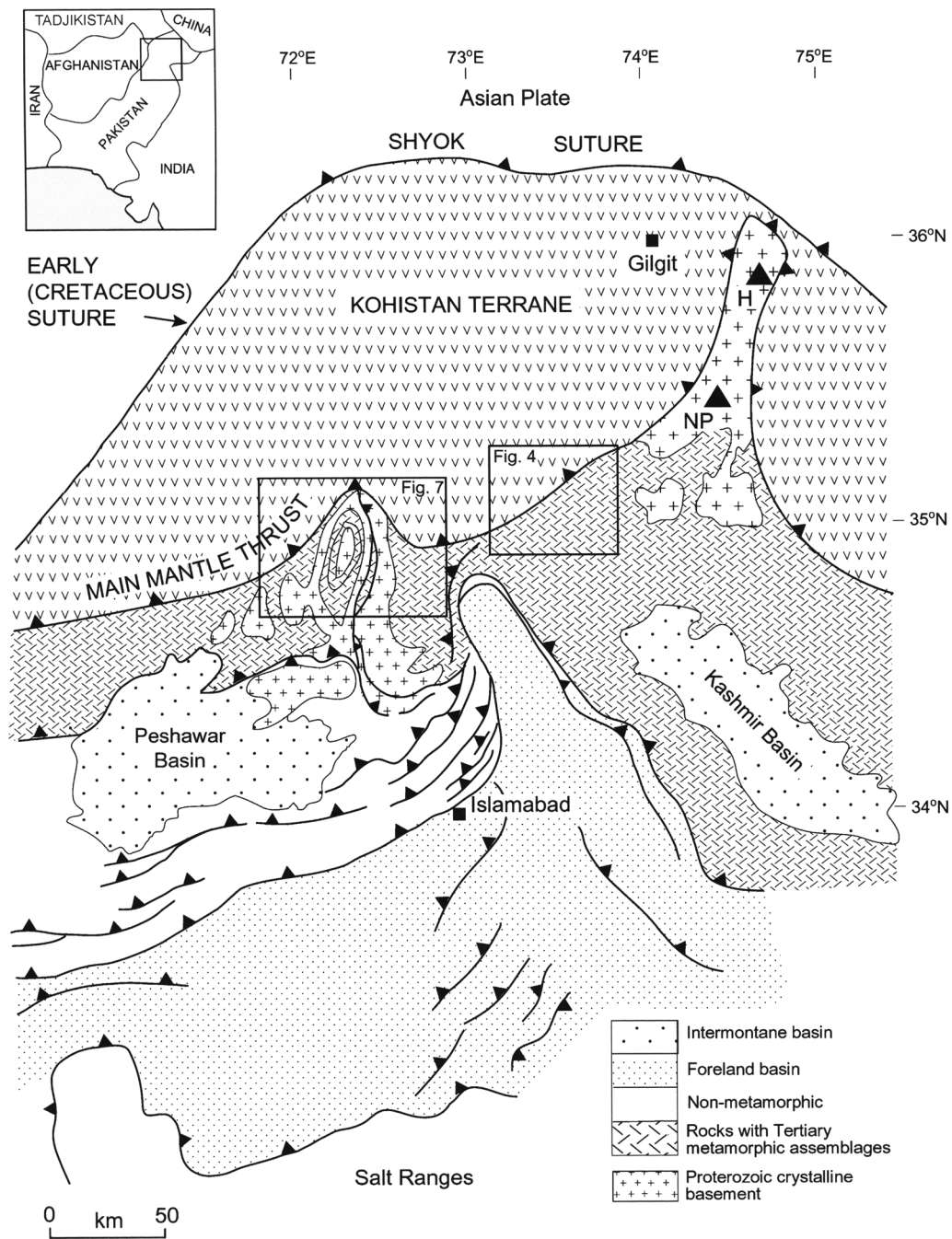
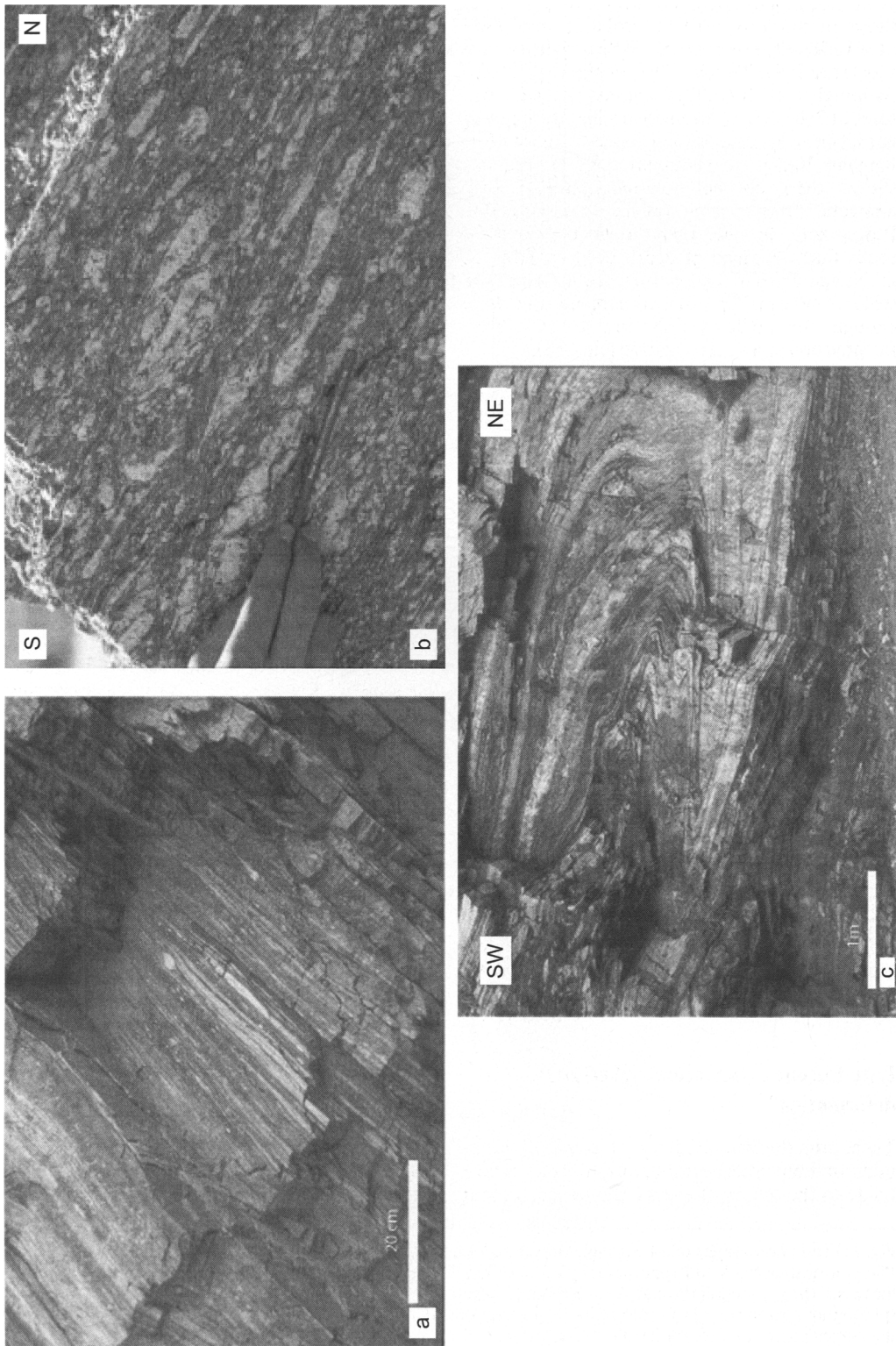


Fig. 1. Geological map of North Pakistan showing the separation of the Indian and Asian plates by the Kohistan Island Arc, the position of the Main Mantle Thrust and the locations of Figures 4 and 7.



et al. 2002). Peak temperatures barely reached those of anatexis, with a probable maximum of 650 °C (Treloar *et al.* 1989a; DiPietro & Lawrence 1991; Treloar 1997; Foster *et al.* 2002). Although Treloar (1997) suggested that temperatures of 750 °C were attained in sillimanite-grade, garnet-bearing migmatitic gneisses of the Upper Kaghan Valley, re-examination of these rocks shows them to be poly-metamorphic with anatectic fabrics being pre-Tertiary, probably Proterozoic, in age. Only those Indian Plate rocks that remained at depth until recently, as at Nanga Parbat, had a sufficiently long time scale over which to attain temperatures high enough for anatexis (Winslow *et al.* 1995). Porphyroblast–matrix relationships and *P–T–t* modelling suggest that metamorphism followed a path of increasing pressure and temperature and was synchronous with tectonic burial of the leading edge of continental India beneath the Kohistan arc (Treloar *et al.* 1989c; Treloar 1997; Foster *et al.* 2002). Peak Barrovian metamorphism is dated at *c.* 47 ± 3 Ma (Smith *et al.* 1994; Foster *et al.* 2002). Hornblende Ar–Ar data date post peak metamorphic cooling at *c.* 41 Ma (42.6 ± 1.6 Ma, Chamberlain *et al.* 1991; 41 ± 2 Ma, Smith *et al.* 1994; 39.8 ± 1.6 Ma, Hubbard *et al.* 1995; 40 ± 1 Ma, Treloar & Rex 1990a,b).

UHP coesite-bearing eclogites, metamorphosed at >20 kbar, crop out in the most internal zones of the Indian Plate metamorphic stack in the Kaghan Valley (Fig. 4; O'Brien *et al.* 2001; Kaneko *et al.* 2003; Treloar *et al.* 2003). A number of thermochronometers date peak UHP metamorphism at about 47 Ma (Tonarini *et al.* 1993; Kaneko *et al.* 2003; Parrish *et al.* 2003) and show that post-peak metamorphic cooling was well advanced by 44 Ma (Treloar *et al.* 2003). As initial India–Asia collision was at *c.* 50 Ma, burial of upper crustal Indian Plate rocks to *c.* 100 km must have been rapid, residence time there short, and exhumation to mid-crustal regions at rates as high as *c.* 20 km per million years.

Late Eocene exhumation and related deformation

There are three main lines of evidence for a mid- to Late Eocene exhumation event. These relate to the timing of events, the structures that

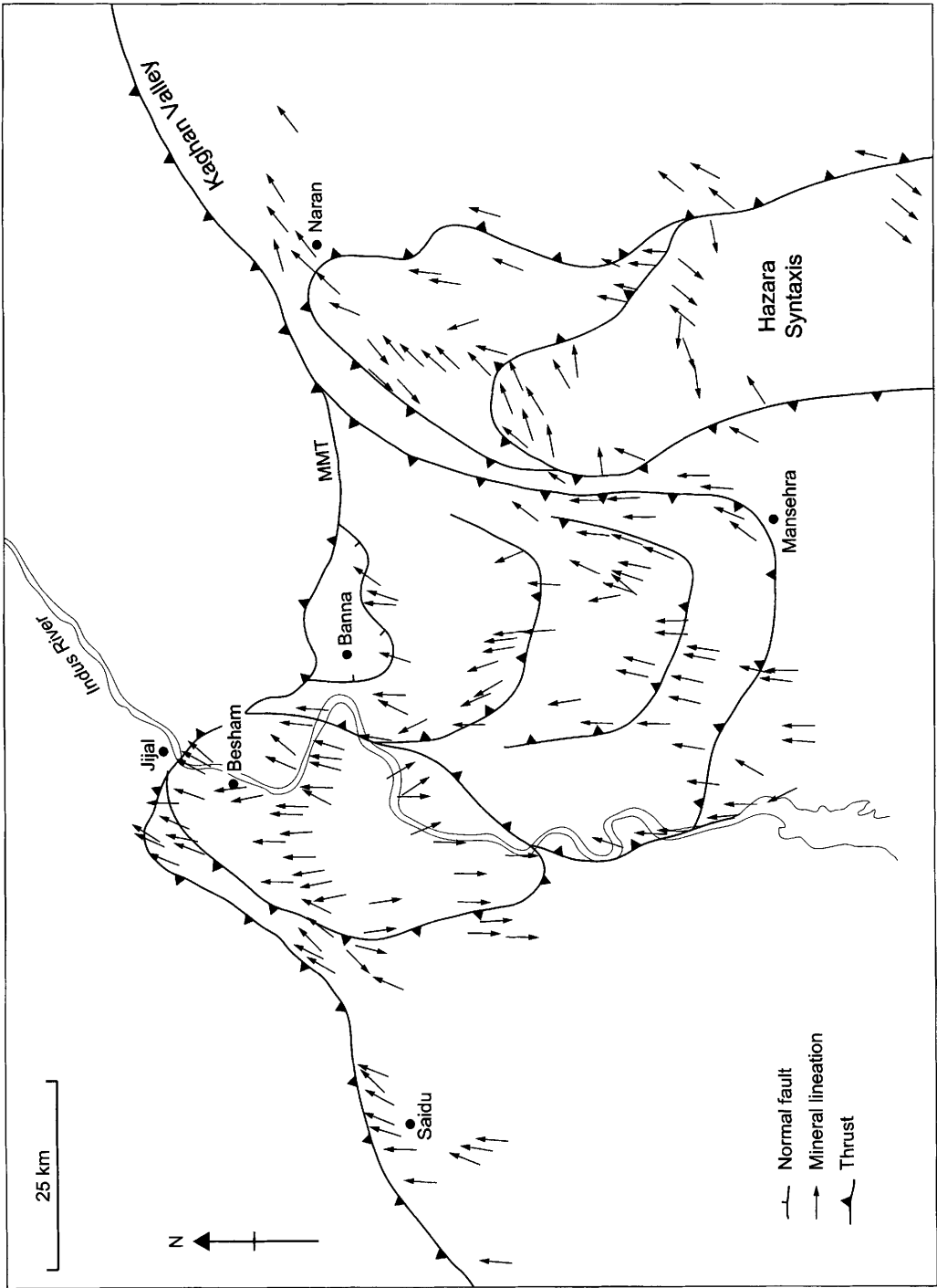
accommodated rapid exhumation of the UHP coesite-bearing eclogites and the structures that accommodated metamorphic inversion in the Barrovian rocks within the MMT footwall.

Age data from the Pakistan Himalaya suggest that both Barrovian facies and UHP metamorphism were rapid. A combination of initial India–Asia collision at *c.* 50 Ma, peak metamorphism at *c.* 47 Ma and cooling back through 500 °C by 40 Ma suggest rapid post-peak metamorphic cooling. These data constrain the amphibolite- to greenschist-facies transition to about 40 Ma, and suggest that residence times at peak metamorphic conditions were short and that post-peak cooling was rapid and accommodated by Eocene unroofing and exhumation.

During the Eocene the UHP coesite-bearing eclogites were brought back to mid-crustal levels and thrust on top of the Barrovian sequences of the Kaghan Valley. Field relationships summarized by Treloar *et al.* (2003) show the UHP eclogite-bearing sequence to be flanked by south-vergent thrusts below and extensional, top-side-north shears above, and that thrusting, extension and the transition from amphibolite- to greenschist-facies metamorphism were synchronous. Part of the exhumation was accommodated by uplift along a south-vergent thrust, mapped near Besal (Fig. 4), which places UHP rocks on top of Permo-Triassic cover rocks metamorphosed to eclogite facies. Rather than being south-vergent, the dominant microstructures on the hanging wall of the thrust are penetratively developed S–C' shear bands with top-side-north displacement sense, which document a phase of pervasive top-side-north extensional shearing (Treloar *et al.* 2003). Hornblende amphiboles parallel a down-dip stretching lineation, which plunges at 32° toward 180°.

Initial exhumation of the Barrovian rocks was synchronous with that of the UHP rocks. Metamorphic grade within the Barrovian sequence decreases structurally downward (Treloar *et al.* 1989a; Treloar 1997). Rather than resulting from an originally inverted metamorphic gradient, inversion is due to imbrication by post-metamorphic ductile shear zones, each of which have higher grade rocks on the hanging wall than on the footwall. The ductile shear zones are S–L tectonites (Fig. 2b) with shear fabrics that anastomose around garnet, kyanite and K-feldspar porphyroclasts. Kinematic criteria indicate transport toward the SSE. Hornblendes from the

Fig. 2. Field photographs of: (a) strongly transposed shear fabrics developed in the uppermost part of the Indian Plate footwall of the MMT (photography taken on the Thakot to Besham road near Thakot (see Fig. 7 for location); (b) x–y section through S–L tectonites in shear zones that stack the Barrovian metamorphic sequence (photograph taken from just south of Batagram); (c) sheath fold developed in Indian Plate basement gneisses on the immediate footwall of the MMT, south of Jijal in the Indus Valley.



shear zones have Ar–Ar ages of *c.* 40 Ma, similar to those outside the shear zones, suggesting that stacking predated cooling through 500 °C (Treloar & Rex 1990*a,b*). Imbrication occurred on the footwall of the major south-vergent thrusts that brought the UHP rocks rapidly from depth to mid-crustal levels and placed them on top of the Barrovian rocks. The UHP rocks in the Kaghan Valley carry pervasive top-side-north shear bands suggesting that they are flanked above by major extensional zones (Treloar *et al.* 2003). They are thus flanked by top-side-north extensional shears above and south-vergent thrusts below, both of which operated together. Cooling through the amphibolite–greenschist facies transition in both the UHP and Barrovian sequences was synchronous with thrusting. This suggests that the Barrovian rocks were themselves being uplifted on the hanging wall structurally lower south-vergent thrusts at the same time as they were being overthrust by the UHP rocks.

Although the Eocene shear zones that lie structurally above the UHP rocks have a top-side-north extensional geometry, they did not develop within an extensional regime. Lithospheric and crustal shortening was continuing and the apparently extensional structures are a result of buoyancy driven uplift of the UHP rocks, which contributed to continuing thickening of the developing orogenic pile.

Early Miocene upper crustal stretching

The second top-side-north stretching event that affected the metamorphic rocks of the internal zones of the Pakistan Himalaya was Miocene in age and is defined by structural data, major metamorphic breaks and cooling histories. Vince & Treloar (1996) showed that amphibolite-facies Indian Plate rocks on the immediate footwall of both the MMT and the Banna Fault carry ductile S–C' fabrics with a top-side-north displacement sense. The ductile fabrics are locally cut by brittle fractures with a top-side-north displacement sense. Both fabrics are related to the same event (Vince & Treloar 1996). That the structures spanned the ductile to brittle transition implies that the sequence cooled during exhumation. This argument is supported by age data as well as metamorphic discontinuities within the upper

part of the Indian Plate and across the MMT. A period of slow cooling from 500 °C to >400 °C in the upper Indian Plate (Fig. 5) followed the Eocene until *c.* 22 Ma when a period of rapid cooling started. MMT hanging wall rocks have a very different cooling history from the footwall rocks. The two sequences share a common cooling history only after both cooled through the apatite fission-track annealing temperature. These data are consistent with the MMT acting as a top-side-north normal fault zone during the Early Miocene. Major metamorphic breaks are recognized within the upper Indian Plate and along the MMT (Fig. 6). The MMT zone itself is marked by blueschist- and greenschist-facies rocks, which lie structurally above mid- to upper amphibolite-facies, sillimanite- to kyanite-grade Indian Plate rocks. These data suggest reactivation of the MMT as an extensional fault zone during both the Eocene and the Miocene.

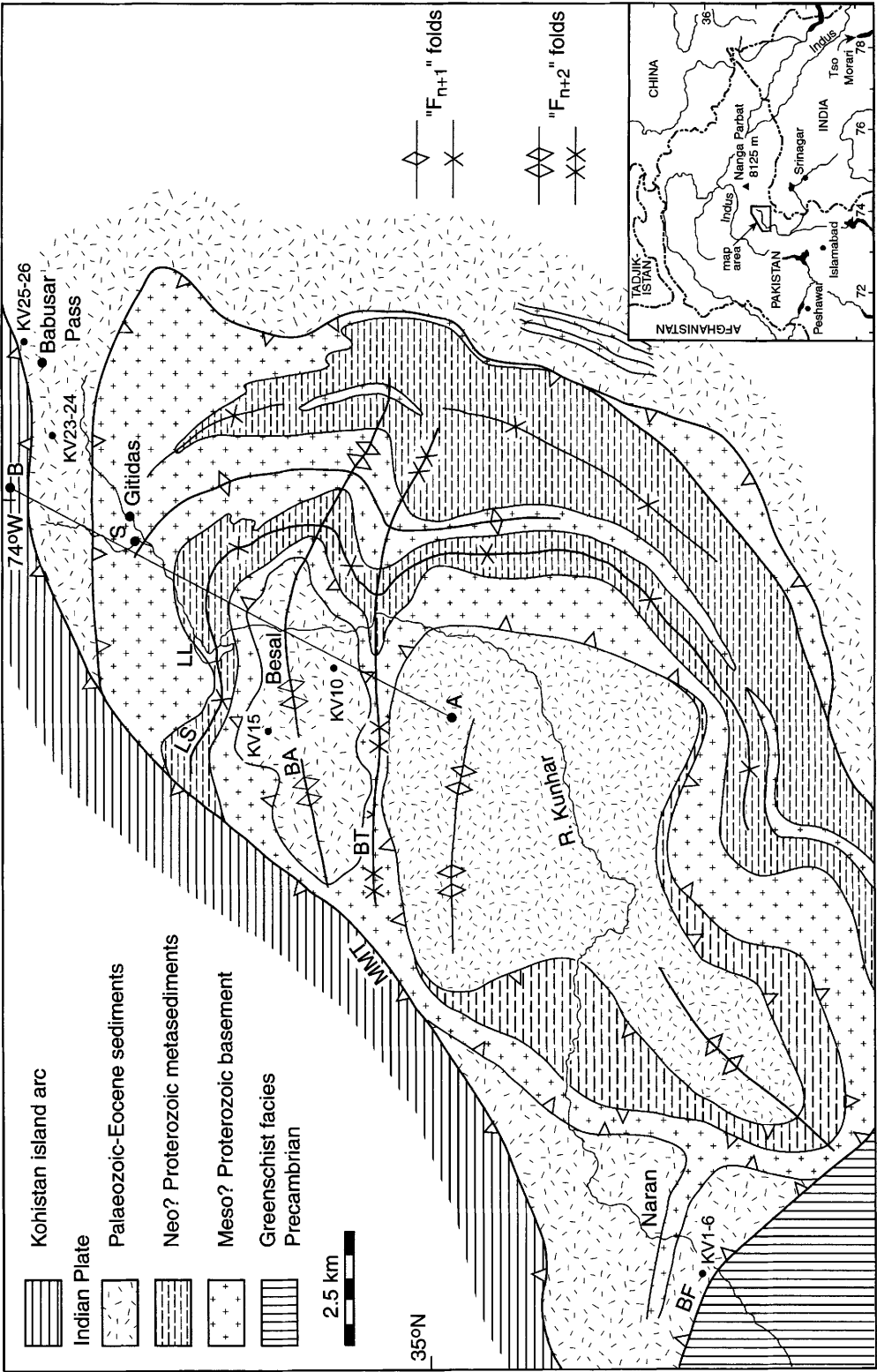
This paper documents new data for the Miocene event from three sections through the MMT footwall (Fig. 7) and from the Kaghan Valley (Fig. 4). Two of the sections through the MMT footwall traverse muscovite-free, biotite-bearing gneisses of the Besham Group. The third traverses hanging-wall and footwall rocks of the Banna Fault.

Traverses through the Besham Group gneisses on the MMT footwall

Indian Plate Besham Group gneisses are biotite-bearing quartzo-feldspathic gneisses with a Palaeo- to Meso-Proterozoic deformational and metamorphic history but little evidence for a Tertiary thermal overprint (Baig *et al.* 1989; Treloar *et al.* 1989*d*; Treloar & Rex 1990*a*; DiPietro & Isachsen 2001). The sequence includes amphibolite-facies metabasic layers with hornblende Ar–Ar ages of *c.* 1850 Ma (Baig *et al.* 1989; Treloar *et al.* 1989*d*). Fabrics are cut by undeformed granitoids with Proterozoic ages. The Shang Granite is dated at 1864 ± 4 Ma (DiPietro & Isachsen 2001) and the Dubhair Granite at 1858 ± 7.2 Ma (Zeilinger 2002).

The dominant meso- and micro-structures present in the intensely deformed Besham Group gneisses on the immediate footwall of the MMT date from emplacement of the Kohistan Arc onto the Indian Plate during early stages of orogeny. On the Karakoram Highway, south of Jijal, the mylonitic fabrics are folded by recumbent, isoclinal folds with apparent SE vergence (Fig. 2*c*). These folds, described as sheath folds by Williams (1989), plunge at $040^\circ/26^\circ$, subparallel to the locally developed stretching lineation (Fig. 8).

Fig. 3. Map of mineral and stretching lineations developed in the approximately south-vergent shear zones of the internal, crystalline zones of the Indian Plate. Linear fabrics vary from SW-directed in the Kaghan Valley to SSE-directed in the Indus Valley.



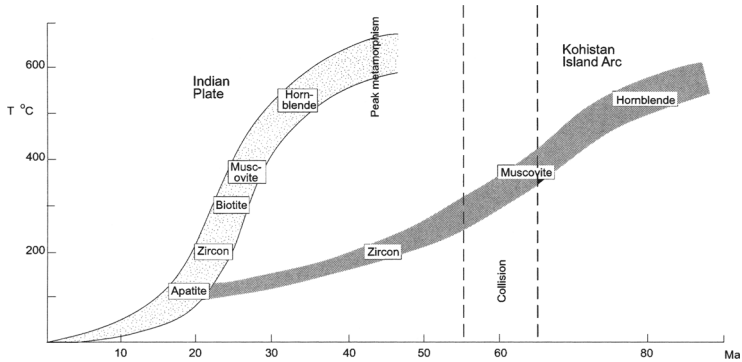


Fig. 5. Temperature–time path for post-metamorphic cooling in both the internal zones of the Indian Plate and the Kohistan Arc. Modified from Treloar & Rex (1990*a,b*) and Vince & Treloar (1996).

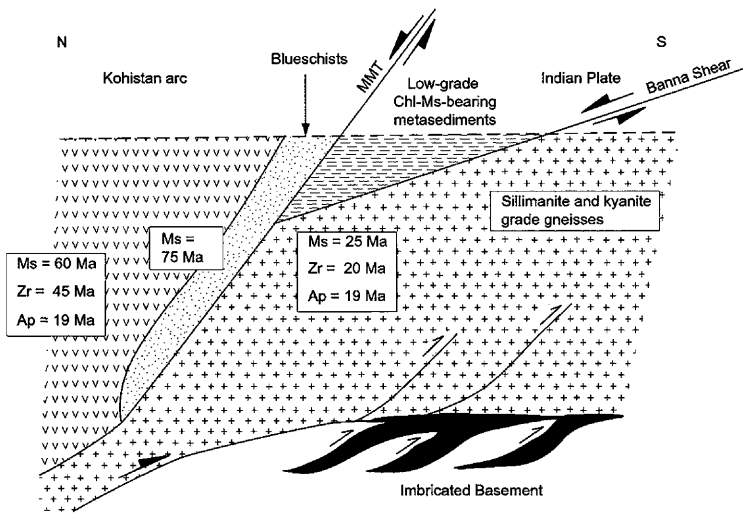


Fig. 6. Schematic illustration (modified from Vince & Treloar 1996) showing the main metamorphic breaks across the margin between the northern part of the Indian Plate and the Kohistan Arc, together with relevant age data (Zeitler 1985; Treloar & Rex 1990*a,b*).

The mylonites are strongly foliated and moderately lineated, with a foliation defined by planar, quartz-rich domains and elongate trails on feldspar grains. Matrix quartz grains are intensely flattened and quartz ribbons display preferred alignment of elongate recrystallized grains (S_b) oblique to foliation (S_a). A top-side-SW or WSW shear sense is indicated by deformation features in samples KV.29 and KV.30 (Fig. 9). These features include strongly asymmetric quartz

c-axis fabrics, obliquity between macroscopic foliation and elongate dynamically recrystallized quartz grains, shear bands and delta-shaped tails on feldspar porphyroblasts. Quartz grains were deformed and recrystallized under regime II, possibly regime III, conditions of Hirth & Tullis (1992). Quartz *c*-axis opening angles for samples KV.29 and 30 are 54° and 57°, respectively. By correlation with the data of Kruhl (1998, fig. 2), combined with additional data reported by Law

Fig. 4. Geological map of the Kaghan Valley (from Treloar *et al.* 2003) showing the location of the Besal and Batal thrusts and of the UHP rocks, sample locations mentioned in the text, and the line of section (A–B) shown in Figure 22. BF, Batal Thrust; BT, Besal Thrust; BA, Besal Antiform; LS, Lalusar Synform; LL, Lalusar Lake; S, Saleh-de-Baihkh coesite eclogite locality; MMT, Main Mantle Thrust.

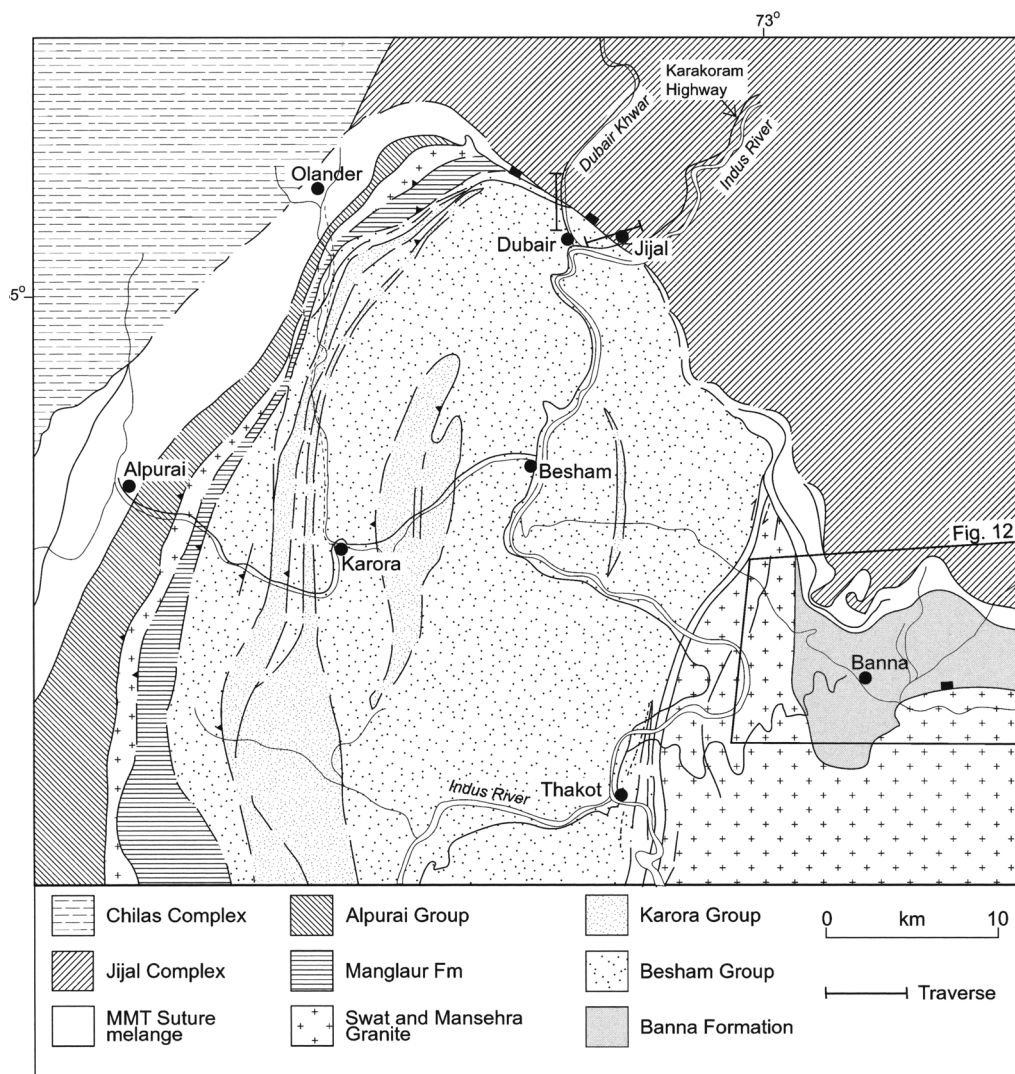


Fig. 7. Geological map of the northernmost part of the Indian Plate in the Indus valley section (from Vince 1997). The locations of Fig. 12 and of the Dubair Khwar and Karakoram Highway traverses through the MMT footwall are shown.

et al. (2004, fig. 7) and Morgan & Law (2004), these fabric opening angles suggest deformation temperatures of $415\text{--}460 \pm 50^\circ\text{C}$. These temperature estimates are in good agreement with deformation temperatures inferred from the well-developed quartz subgrain rotation microstructures (regime II recrystallization) and weakly developed grain boundary migration microstructures (see Stipp *et al.* 2002, figs 2 and 4).

Subsequent top-side-north deformation of the Besham Group gneisses along the Dubhair

Khwar traverse (Fig. 7) was accommodated by a variety of ductile to brittle structures. Although some top-side-north structures are common throughout the traverse, others are developed locally at discrete levels within the MMT footwall. Immediately beneath the MMT, the gneisses contain abundant, NNE-dipping ductile shear surfaces that extensionally displace the Tertiary mylonites down to the north. The shear surfaces dip *c.* 20° more steeply toward the NNE than the mylonite fabrics that they displace.

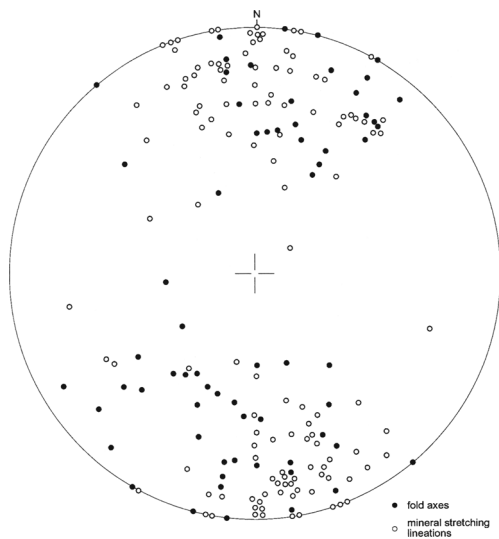


Fig. 8. Stereographic projection of linear fabrics developed in the Indian Plate basement gneisses on the immediate footwall of the MMT south of Jijal in the Indus valley.

Most shears are < 5 cm long and curve onto, and crenulate, the mylonitic surfaces that date from the earlier SW-vergent shearing. Other than the ductile shears, the majority of the top-side-north structures along the Dubair Khwar traverse are brittle. Small-scale, north- to NE-dipping brittle shear fractures, between 4 and 20 cm long, crop out along the entire length of the traverse. Steeply north-dipping, brittle normal faults are common and are associated with secondary shears that dip steeply to either north or south. Synthetic Reidel shears form repetitive, north-dipping secondary fractures developed at angles of $21\text{--}35^\circ$ to the main extensional fault planes. Infrequent, south-dipping extensional faults and associated synthetic Reidel shears may be conjugate to the dominant north-dipping shear zones. Small-scale synthetic and antithetic Reidel shears, < 10 cm long with displacement of < 1 cm, which developed in response to north-directed normal displacements along brittle shear surfaces, are oriented parallel or subparallel to the mylonitic fabric and occur dominantly within phyllosilicate-rich layers. About 100 m south of the MMT, south-vergent mylonitic fabrics within the basement gneiss are cut by tension gashes $c. 5$ cm long, which dip to the north or NE at an angle of $35\text{--}40^\circ$ to the plane of the mylonitic fabric. The tension gashes are occasionally filled by quartz fibres that grew parallel to the minimum principal stress direction and indicate

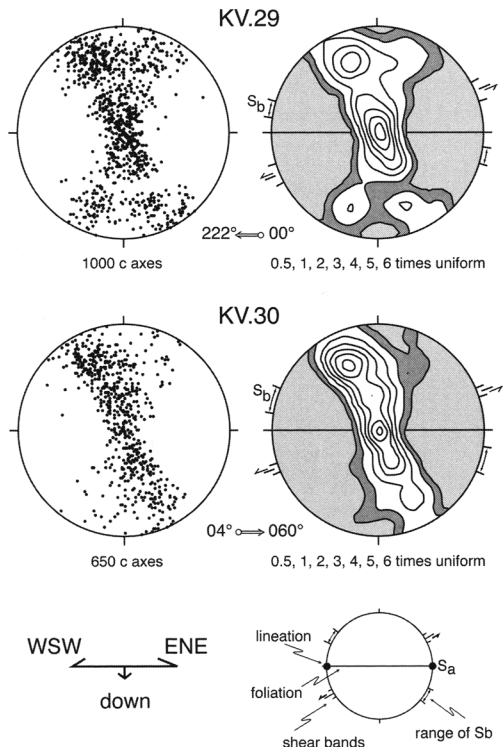


Fig. 9. Quartz c -axis fabrics from intensely deformed Indian Plate granitic basement rocks on the immediate footwall to the Main Mantle Thrust, south of Jijal (see Fig. 7 for location). Equal area projections on xz surfaces viewed towards the NW and NNW. S_a , macroscopic foliation; S_b , alignment of elongate recrystallized grains in quartz-rich domains. Plunge and trend of lineation are indicated. Data were derived using optical universal stage analysis.

formation during a late, brittle stage of top-side-north to-NE shearing. Between 400 and 700 m south of the MMT, the mylonitized Indian Plate rocks contain a few north-dipping brittle shear surfaces up to 1 m in length, which offset the mylonitic fabrics by up to 8 cm. Both these shears and the ductile shears, seen at structurally higher levels, resemble C' shear planes (Berthe *et al.* 1979).

Immediately below the MMT at Jijal (Fig. 7), and generally within the upper 30–35 m of the MMT footwall, Besham Group gneisses along the Karakoram Highway contain abundant north-dipping ductile normal shear planes. The shear planes are predominantly defined by biotite, are generally < 5 cm long and curve onto, and crenulate, the mylonitic surfaces, which they extensionally displace down to the north. They

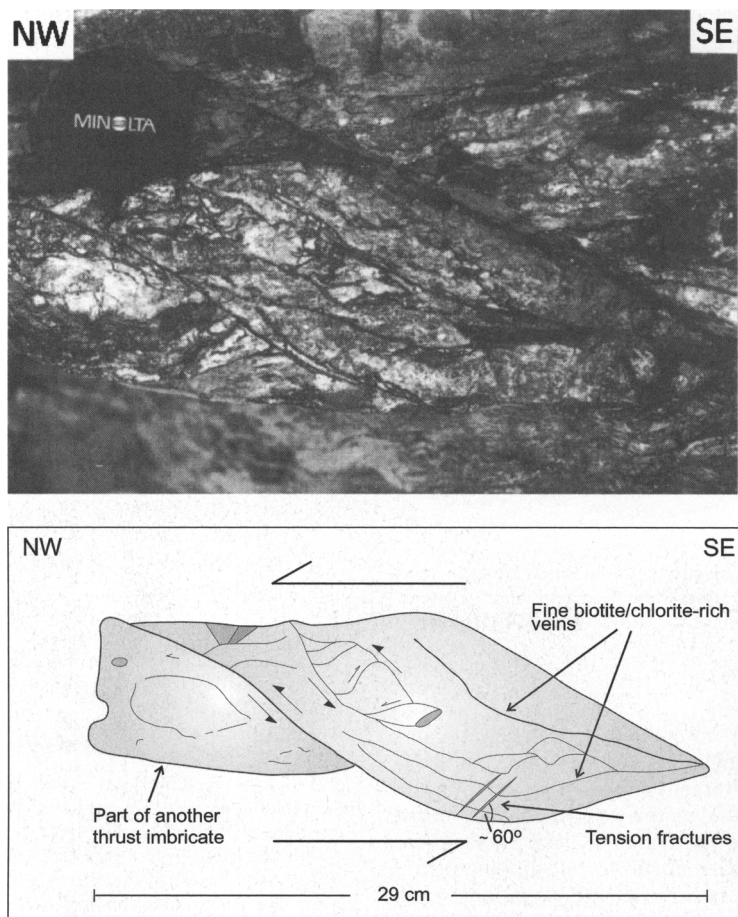


Fig. 10. Field photograph and sketch of a NW-vergent small-scale thrust duplex in the Besham basement gneisses on the KKH section through the MMT footwall.

have an S-C geometry and dip 22° more steeply to the NE than the mylonitic fabrics. Their frequency decreases abruptly downward with few present more than 60 m below the MMT. Mylonitic fabrics in the uppermost 5 m of the MMT footwall are deformed within a zone of north- to NNW-vergent thrust duplexes and NW-vergent folds with wavelengths of 5–10 cm. South-vergent, sheath folds that date from the thrusting of Kohistan onto India crop out above and below this zone of northerly-directed deformation (Fig. 10). North-dipping, top-side-north fractures, *c.* 30 cm long, and smaller north-vergent thrust duplexes occur within the imbricates (Fig. 10). Mineral lineations and chrysotile slickenfibres occur on 20–30% of the NE- to east-dipping mylonitic fabric surfaces in the uppermost 10 m of the MMT footwall. After

removing the effects of later folding, these indicate reactivation of the fabric planes as north-vergent brittle normal faults with dip-slip displacement toward the north. At greater depths, ENE-striking NNW-dipping tension fractures 1–4 cm long are abundant. The majority of these opened within quartzofeldspathic domains. The walls of some of the fractures are lined by biotite and, locally, chlorite and fracture tips coincide with the termination of north-dipping normal shear planes. This may indicate progression from ductile to semi-brittle conditions of deformation during late-stage, top-side-north stretching. At depths of >95 m into the MMT footwall north- and NNE-striking, planar and curvilinear faults, which dip at *c.* 60° to the north, cut the mylonitic fabrics. Striae on several of the fault planes indicate oblique, NE-directed

displacements along the faults. There is a clear similarity between the orientation and movement direction of these faults and the reactivated mylonitic fabric surfaces that crop out within the top 10 m of the MMT footwall. Gouge fabrics within some of the fault zones show that the faults accommodated north-directed normal displacements (Zeilinger *et al.* 2000).

Extensional microstructures from the MMT footwall. Basement gneisses from the Dubhair Khwar and MMT traverses contain identical microstructures. Mylonitic fabrics associated with Early Tertiary SSW-vergent thrusting are characterized by feldspar-rich, quartz-rich and

biotite-rich domains. Feldspar domains are composed of *c.* 18% antiperthitic feldspar porphyroclasts (0.5–4 mm) set in a matrix of albite and orthoclase with minor amounts of mica, quartz, epidote and titanite. Quartz domains are composed of *c.* 95% quartz and <5% white mica. The micas typically occur as fine-grained, intra-domainal zones with rare grains of sodic plagioclase typically aligned in the bulk foliation plane. Biotite domains are <100 μm thick and contain biotite grains <500 μm long with remnant amphibole and epidote set in a fine-grained biotite-rich matrix.

Top-side-north fabrics that displace the main top-side-SSW fabrics down to the north to NE

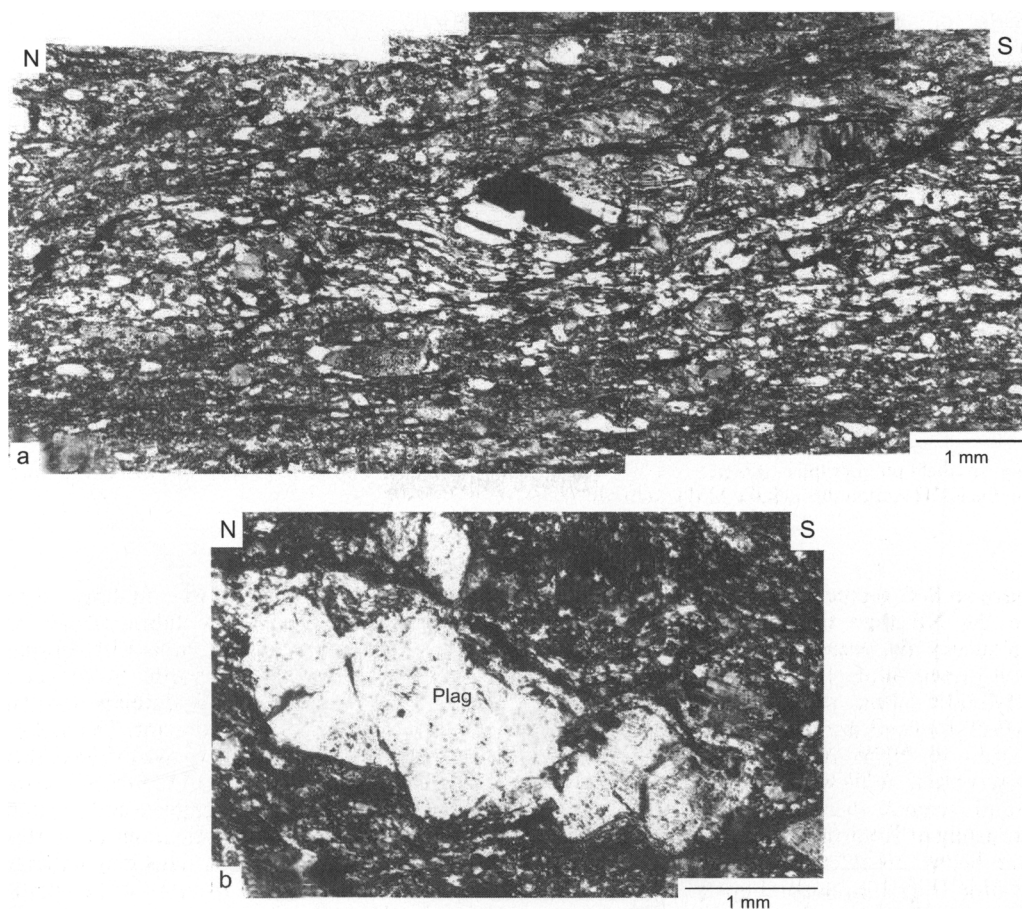


Fig. 11. Micrographs of top-side-north structures in the Besham basement gneisses on the immediate footwall of the MMT: (a) extensional biotite-rich shear bands displace the main top-to-the-SSW fabrics down to the north; (b) plagioclase porphyroblasts deformed by cataclastic micro-cracking and micro-faulting during extension produced disaggregated feldspar clasts with rotated domino fault blocks, jagged grain boundaries and extensional cleavage fractures.

are defined by phyllosilicate-rich shear bands, quartz *c*-axis fabrics and shear fractures within feldspar porphyroclasts (Fig. 11a). The shear bands are biotite-rich, ≤ 1 mm long and < 100 μ m wide and dip 20° more steeply to the north than the main mylonitic fabrics. They contain very fine-grained biotite together with chlorite and transect and extend the older foliation. Asymmetry across the shear bands gives a top-side-north sense of displacement. Chlorite nucleation and growth occurred within the shear bands as a result of breakdown of amphibole and biotite. Plagioclase porphyroblasts were deformed by cataclastic micro-cracking and micro-faulting during extension. This produced disaggregated feldspar clasts with rotated domino fault blocks, indicating top-side-NE sense of shear, jagged grain boundaries and extensional cleavage fractures (Fig. 11b). Aggregates of small elongate quartz grains within

Q-domains define a shape fabric oblique to the main SSW-vergent foliation, the sense of obliquity on which is consistent with a top-side-north to -NE sense of shear. Quartz fabrics are ductile and suggest deformation temperatures $> 350^\circ\text{C}$.

Traverses across the Banna Shear

The Banna Shear (Fig. 12) is a low-angle, north-dipping fault developed within Indian Plate rocks on the MMT footwall. The shear zone carries sillimanite-grade gneisses on its footwall and chlorite-grade metasediments on its hanging wall. Early fabrics on both footwall and hanging wall of the Banna Shear are consistent with south-directed shearing. Later north-vergent structures cut, and deform, the south-vergent fabrics on both the hanging wall and the footwall.

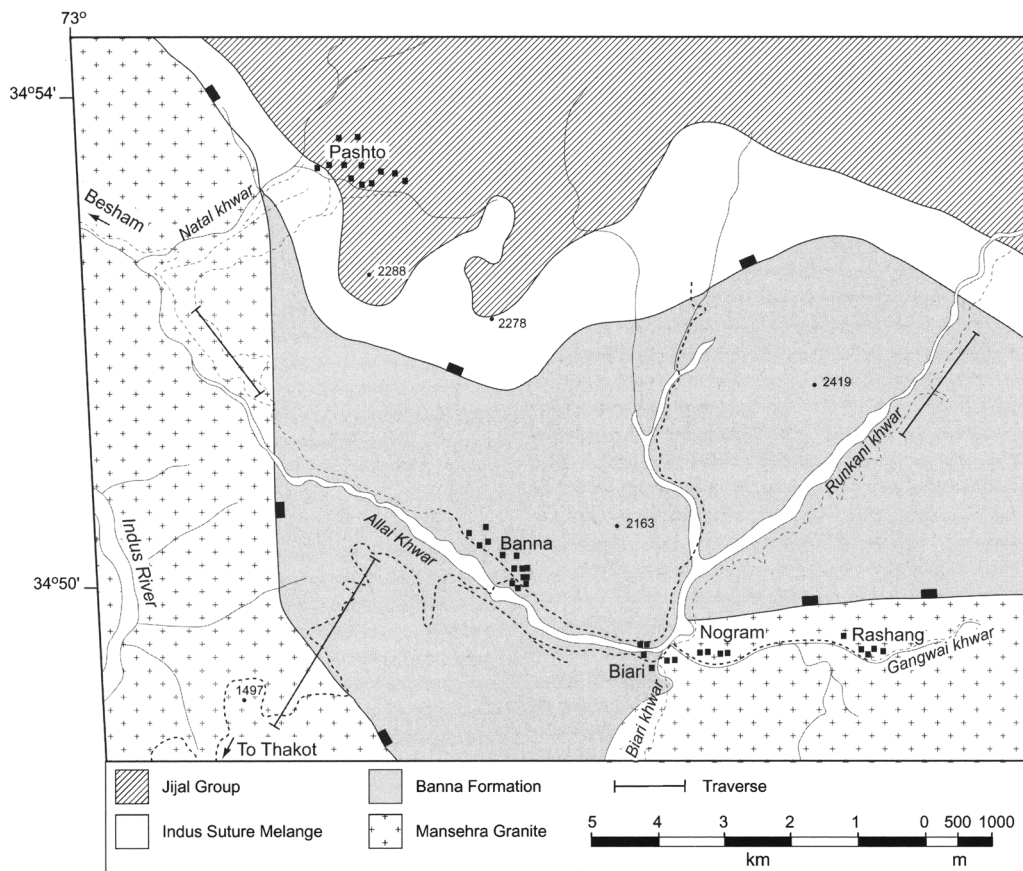


Fig. 12. Geological map of the MMT zone east of the Indus Valley, showing the location of the Banna Shear and the traverses described in the text.

Along the road section from Thakot to Banna (Fig. 12), the hanging wall of the Banna Shear is characterized by fine-grained, greenschist-facies, graphitic and non-graphitic pelites, calc-pelites and marbles of the Banna Formation. Quartz and muscovite are ubiquitous and biotite is locally present in small amounts, often with chlorite. Microstructural relationships imply that both biotite and chlorite were stable during greenschist-facies development of the main south-vergent tectonic fabrics. The S_1 fabric is a weakly developed, ENE-striking cleavage oriented subparallel to bedding. S_1 was crenulated during D_2 producing an S_2 fabric co-planar to S_1 . Both F_1 and F_2 folds are south-vergent and relate to south-vergent deformation during the Early Tertiary. A series of folds and faults disrupt the greenschist-facies fabrics. Within the lowest 30 m of the hanging wall, chlorite-rich meta-sediments are crenulated by tight, north-vergent folds with axial planes that strike at *c.* 100° and dip at $45\text{--}50^\circ$ towards the south. Between 10 and 80 m above the Banna Shear, 10–100 cm long, north-dipping normal faults displace layering in graphitic phyllites (Fig. 13a), typically by a few centimetres, or reactivate earlier fabrics as brittle extensional surfaces. Between 90 and 130 m into the hanging wall, a series of south-dipping, north-vergent back-thrusts deform the metasediments (Fig. 13b). These brittle faults displace graphitic phyllite layers northwards by ≤ 3 cm. At 130 m into the hanging wall, marble layers are folded by north-vergent folds with amplitudes of <15 cm and axial planes that dip at *c.* 45° to the south. At 145 m above the Banna Shear marble layers exhibit ductile deformation across minor north-vergent extensional shear zones (Fig. 13c). Adjacent phyllite layers show brittle failure across similar north-dipping faults. A few metres structurally higher in the sequence, conjugate sets of north- and south-dipping faults displace marble horizons by about 1 cm. Of the two, the north-dipping faults are dominant suggesting evolution during top-side-north shearing.

A second traverse across the hanging wall of the Banna Shear follows the Rupkani khwar. Within this section, quartz-filled, brittle shear surfaces <1 m long cut the pelites of the Banna Formation. The shear surfaces dip at *c.* 30° to the NW and carry striae that plunge at 20° to the NNE, consistent with oblique, dip-slip normal faulting towards the NNE.

The footwall of the Banna Shear is formed of medium- to coarse-grained quartz-feldspar-biotite-muscovite-bearing gneisses of the deformed Mansehra Granite. A strong, sub-horizontal S-C fabric is defined by aligned mica

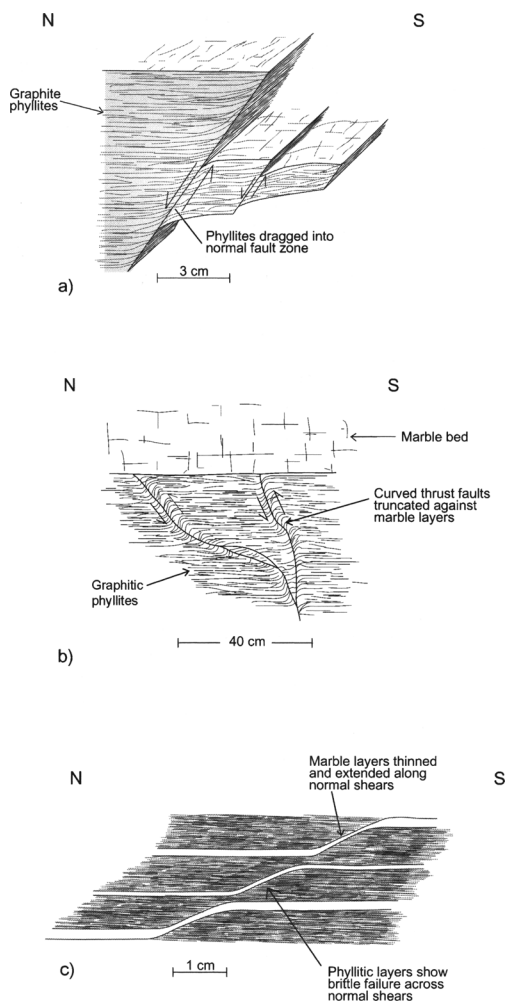


Fig. 13. Field sketches drawn from photographs of meso-scale north-vergent extensional structures developed in low-grade, chlorite-bearing metasediments on the hanging wall of the Banna Fault: (a) 10–100 cm long, north-dipping normal faults displace layering in graphitic phyllites typically by 1–2 cm; (b) south-dipping, north-vergent back-thrusts up to 100 cm long displace graphitic phyllite layers northwards by ≤ 3 cm; (c) marble layers exhibit ductile shearing across minor north-vergent extensional shear zones.

grains, elongate ribbon-like quartz domains and the aligned growth of recrystallized tails to feldspar megacrysts. Mineral lineations trend north-south. Muscovite S-C fabrics and asymmetry of feldspar tails both indicate a top-side-south shear sense for this fabric. Along the Banna-Thakot

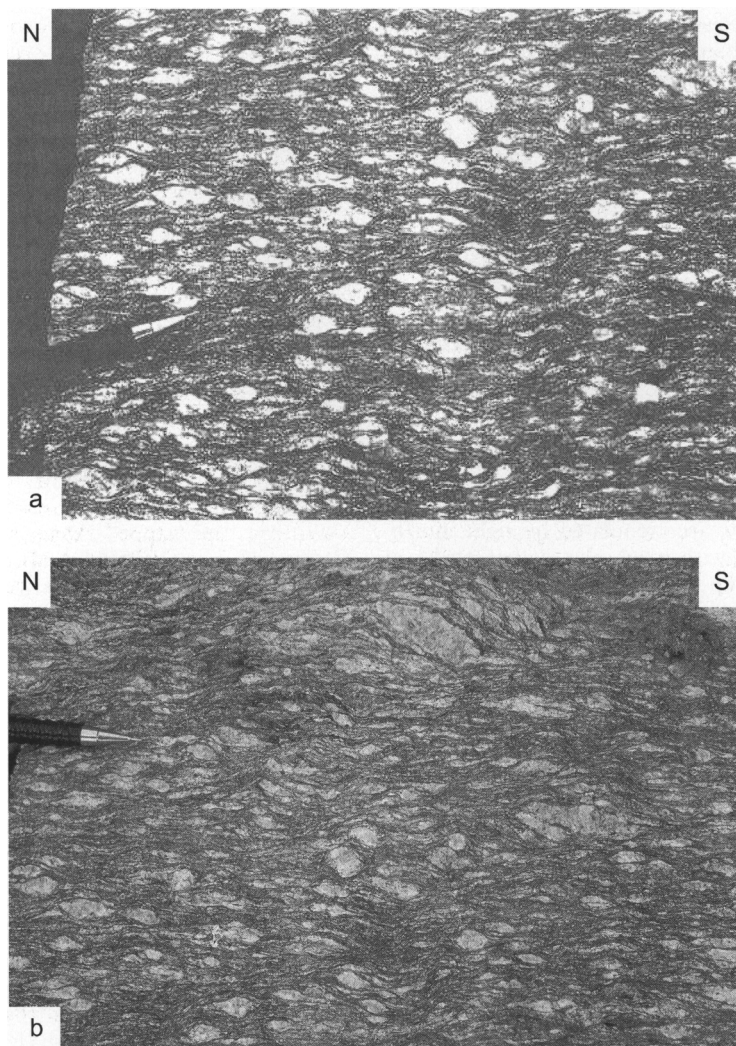


Fig. 14. (a, b) Field photographs of north-vergent ductile shears that cut earlier south-vergent shear fabrics in sillimanite-grade gneisses on the footwall of the Banna Shear.

traverse (Fig. 12), the granite gneiss on the immediate footwall of the Banna Shear contains abundant ductile north-vergent normal shears that cut the south-vergent fabrics (Fig. 14). As a consequence of its mica content, the shears developed within the gneiss are more prominent and numerous than those developed in the mica-poor basement gneisses on the MMT footwall. The ductile shears have an S–C' geometry. Common within the top 30 m of the footwall their abundance decreases downwards. Few north-dipping shears are preserved within the granite gneiss at >80 m into the footwall. Along the Banna to Besham

road section (Fig. 12) ductile, north-vergent shears are concentrated within the upper 100 m of the footwall. They measure a few centimetres long and displace the older fabrics by a few millimetres. With increasing depth the north-vergent extensional features become more brittle. Phyllosilicate-rich bands within the granite gneiss exhibit brittle failure across normal shears.

Along both traverses a variety of shear criteria and crystallographic fabrics within the gneiss document late-stage top-side-north- to NE-vergent stretching. Phyllosilicate-rich domains,

less than 4 mm long and 300 μm wide, carry fine-grained biotite and chlorite with minor muscovite and cross-cut the primary gneissic foliation. They define a shear band fabric with a top-side-north or -NE displacement sense. Within the granite gneiss extensional shear deformation was partitioned heterogeneously into zones of varying deformation intensity. Within many of these zones the early south-vergent fabrics are largely overprinted by an S-C fabric defined by oblique fine-grained biotite domains. Trails of aligned mica fish, ≤ 4 mm long, occur within zones of intense shearing (Fig. 15a). In places cataclasis and boudinage of muscovite, with subsequent migration recrystallization, resulted in formation of neoblastic biotite and chlorite (Fig. 15b). Elsewhere, intense cataclasis of muscovite, originally aligned parallel to south-vergent thrust fabrics, followed by migration recrystallization was accompanied by growth of fine-grained biotite and chlorite in north-dipping extensional C' shear bands (Fig. 15c).

The Upper Kaghan Valley

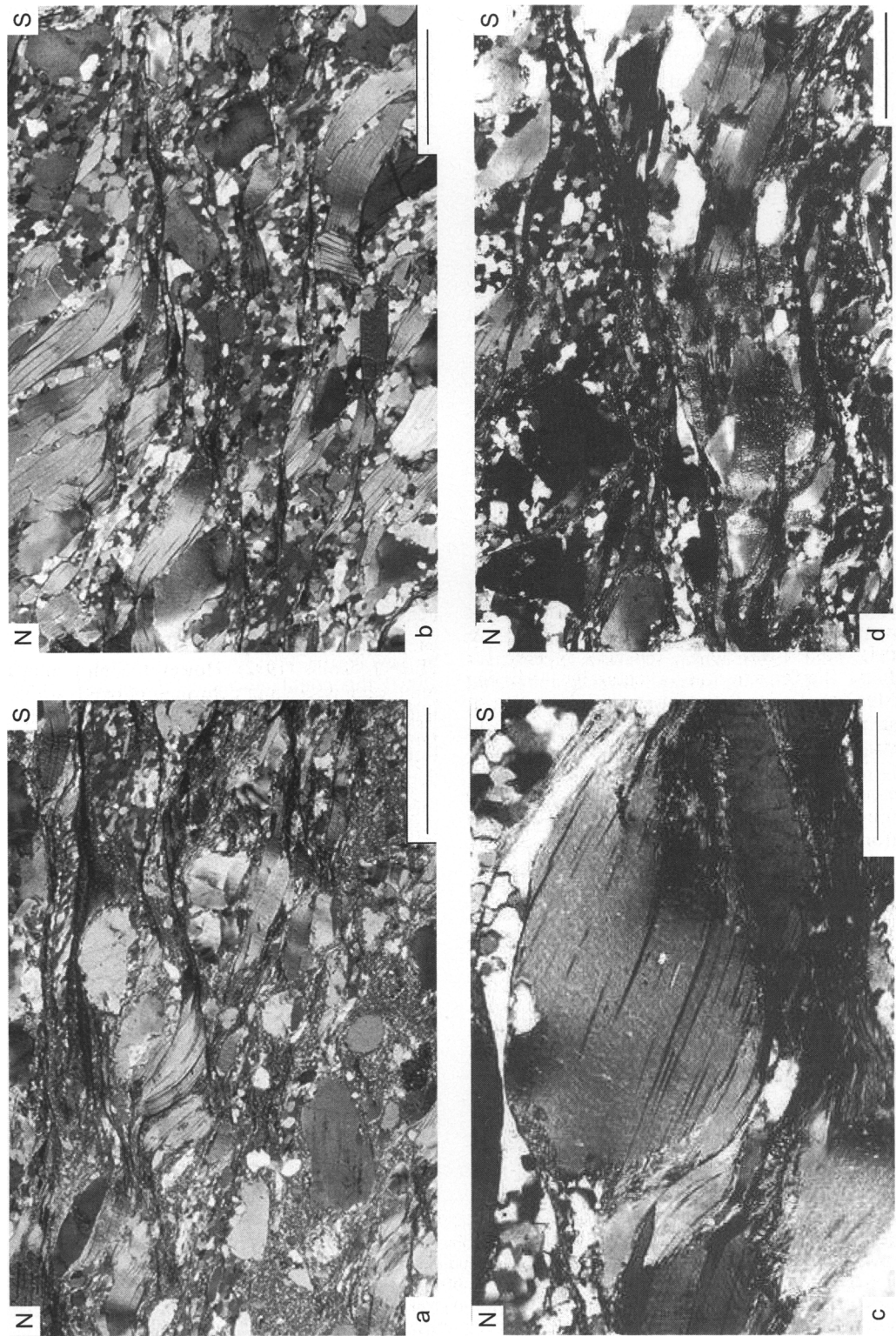
The Upper Kaghan Valley (Fig. 4) lies north of Naran. The rocks crop out on the hanging wall of the north-dipping Batal Fault (Chaudhry & Ghazanfar 1987), which separates greenschist-facies rocks on its footwall from kyanite- and sillimanite-grade amphibolite-facies rocks on its hanging wall. Further north, the Barrovian sequence is structurally overlain by coesite-bearing UHP eclogites (O'Brien *et al.* 2001; Treloar *et al.* 2003).

The Batal Fault is a south-vergent thrust zone (Chaudhry & Ghazanfar 1987; Greco 1989; Greco & Spencer 1993) operative during early stages of India-Asia collision. Our data show the thrust zone to be a steeply dipping sequence of mylonitic to sub-mylonitic rocks. The fault has been folded around a NNE-trending antiformal structure. Near Naran, the mylonitic fabrics strike NW, have a steep NE dip and carry a down-dip stretching lineation with an average trend and plunge of $054^\circ/37^\circ$ (Fig. 16). Although Greco & Spencer (1993) described the mylonitic protoliths as granitic, their mineral content (quartz-feldspar-biotite-muscovite $\pm$ chlorite $\pm$ garnet $\pm$ sillimanite or kyanite) suggests that they had a metasedimentary protolith.

Six samples have been analysed from the Batal Fault zone. KV.01 and KV.02 are dynamically recrystallized quartz veins that lie parallel to foliation in the quartz mica schists. KV.03, KV.04 and KV.05 are mylonitic quartz-feldspar-biotite-muscovite pelites and psammites with skeletal garnet grains. KV.06 is a

quartz-chlorite-muscovite rock with much of the quartz in ribbons. Quartz microstructures in all six samples indicate high-temperature regime 3 crystallization conditions (Hirth & Tullis 1992) with ubiquitous evidence for quartz grain boundary migration. This is also indicated in KV.04 by plastic deformation of plagioclase grains and grain boundary bulging of feldspars. On the basis of feldspar plasticity an absolute minimum deformation temperature of 450°C is indicated. All quartz *c*-axis fabrics from samples KV.01–KV.06 are Type II (Lister 1977) cross-girdle fabrics (Fig. 17) indicating approximately plane strain conditions (see review by Schmid & Casey 1986). Similar quartz *c*-axis fabrics, also measured by standard universal stage techniques, have previously been described by Greco (1989, fig. 4.26) 45 km along strike to the south of the Naran section in traverses across what could be regarded as the mapped extension of the Batal Fault zone (Greco 1989, fig. 4.24). Sense of fabric asymmetry in all our samples from the Naran section indicates top-side-SW sense of displacement during mylonite formation. Quartz *c*-axis fabric opening angles measured in the *x*-*z* plane range from 58 to 71° . By correlation with the quartz *c*-axis thermometry data of Kruhl (1998, fig. 2), combined with additional data reported by Law *et al.* (2004, fig. 7) and Morgan & Law (2004), this would indicate deformation temperatures of 460 – $560 \pm 50^\circ\text{C}$. The highest opening angles, and hence highest deformation temperature, are from sample KV.04, which also shows the most abundant microstructural evidence for plastic deformation of feldspar. These temperature estimates are in good agreement with deformation temperatures inferred from the quartz grain boundary migration microstructures (see Stipp *et al.* 2002, figs 2 and 4).

NE-dipping fabrics within the Batal Fault zone are deformed by centimetre-scale folds with SE-trending axes and SW-dipping axial planes. These NE-vergent folds are consistent with a top-side-NE shear sense and are interpreted as representing reactivation of the SW-vergent thrust-related shear surfaces of the Batal Fault. In this respect they are similar to the cascading top-to-the-NE folds described by Burg *et al.* (1996) on the footwall of the MMT to the NW of Naran. Burg *et al.* (1996) suggested the cascading folds to be located not just in the suture zone sequence that separates the Indian Plate rocks from the Kohistan arc sequence (their Bimbal Valley traverse), but also in Indian Plate rocks on the hanging wall of the Batal Fault. They also identified NW-vergent folds within the Batal Fault Zone and stated that these could be traced downward to structural levels below that of the



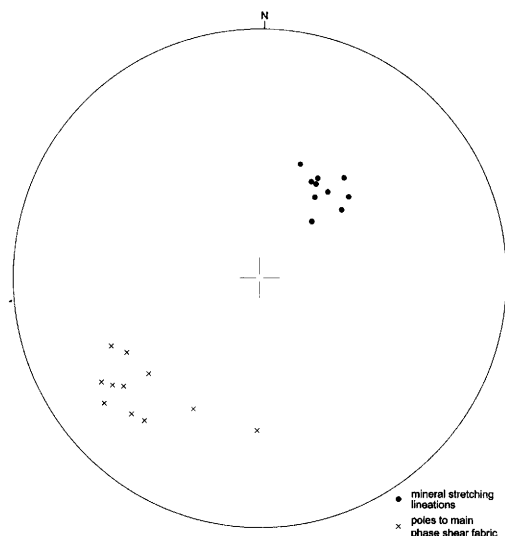


Fig. 16. Stereographic projections of S- and L-fabric orientations in the Batal Fault zone, SE of Naran in the Kaghan valley (see Fig. 4 for location).

fault. Our field data support the presence of a zone of distributed, late-stage, top-side-NE deformation throughout the area between the Batal Fault and the structurally overlying MMT and suggest that the early south-vergent structures were reactivated as top-side-north structures at greenschist-facies conditions.

The northernmost part of the Kaghan Valley contains evidence for both Eocene and Miocene top-side-north stretching. A field photograph from a road cut south of Besal (Treloar *et al.* 2003, fig. 2F) shows macroscopic evidence for top-side-north displacement. Treloar *et al.* (2003) argued that this top-side-north stretching occurred during mid- to Late Eocene cooling from UHP to greenschist-facies conditions and is related to the earliest stages of UHP eclogite exhumation during the Early Eocene.

The geology between Besal and the Babusar Pass has been described by Chaudhry & Ghazanfar (1987), Greco (1989) and Greco *et al.* (1989). The dominant structures are large-wavelength and -amplitude, approximately east-west-trending, folds (here termed F_{n+1}), folded by north- to NNE-trending folds (here termed F_{n+2}).

Fold interference yields Ramsay Type One patterns characterized by domal features as around Besal. The F_{n+1} folds deform the extensionally reactivated, south-vergent Early Eocene thrusts. Hornblende chronometers date cooling through the amphibolite-greenschist facies transition here at *c.* 41 Ma. The F_{n+1} deformation thus postdates 41 Ma. Numerous macro- and microscopic parasitic folds are co-planar and co-axial to the macroscopic F_{n+1} folds. Mineral lineations and quartz rods parallel the fold axes (Fig. 18). Originally oblate albite porphyroblasts near Lake Lalusar, which grew during breakdown of UHP phengite crystals at greenschist-facies conditions (Treloar *et al.* 2003), are folded around mesoscopic F_{n+1} fold hinges that plunge to the WNW.

Sample KV.10 is from a dynamically recrystallized, 1 m wide quartz vein aligned parallel to foliation in a marble layer 3.5 km south of Besal (Fig. 4). Lineations on the vein margins plunge at 55° toward 170° . Although the plunge is a function of later folding, the azimuthal direction, which is close to that of hornblende stretching lineations (Fig. 18) described by Treloar *et al.* (2003), documents the primary south-vergent thrust sense. Quartz vein microstructures indicate Regime 3 recrystallization conditions of Hirth & Tullis (1992). However, highly lobate grain boundaries and deformation bands within quartz grains may indicate later deformation under lower-temperature Regime 1 conditions. Temperature of deformation was probably lower than that along the Batal Thrust. No convincing microstructural shear-sense indicators are preserved within the plastically deformed quartz vein. Quartz *c*-axes define a partially developed cross-girdle fabric (Fig. 19a). Although the fabric asymmetry could indicate a top-side-north shear sense, all that can be safely deduced from the *c*-axis fabric is that the fabric indicates approximately plane strain conditions and that the mineral lineation is a principal extension direction and may document the primary south-vergent shear sense.

Sample KV.15, from a quartzite layer within crenulated garnet-mica-kyanite schists, was collected from crags 150 m above the valley floor, 4.5 km WNW of Besal (Fig. 4). Lineations on the margins of the layer plunge at 26° towards 115° ,

Fig. 15. Micrographs of north-vergent shear fabrics developed in the Mansehra granite gneiss on the footwall of the Banna Shear. (a, b) S-C fabric defined by oblique foliations within quartz aggregates, fine-grained biotite domains and mica 'fish' domains. (c) Cataclasis and boudinage of muscovite in mica fish, which, with subsequent migration recrystallization, resulted in formation of neoblastic biotite and chlorite. (d) Intense cataclasis of muscovite, followed by migration recrystallization, led to growth of fine-grained biotite and chlorite in north-dipping extensional C' shear bands. Scale bars represent 1 mm.

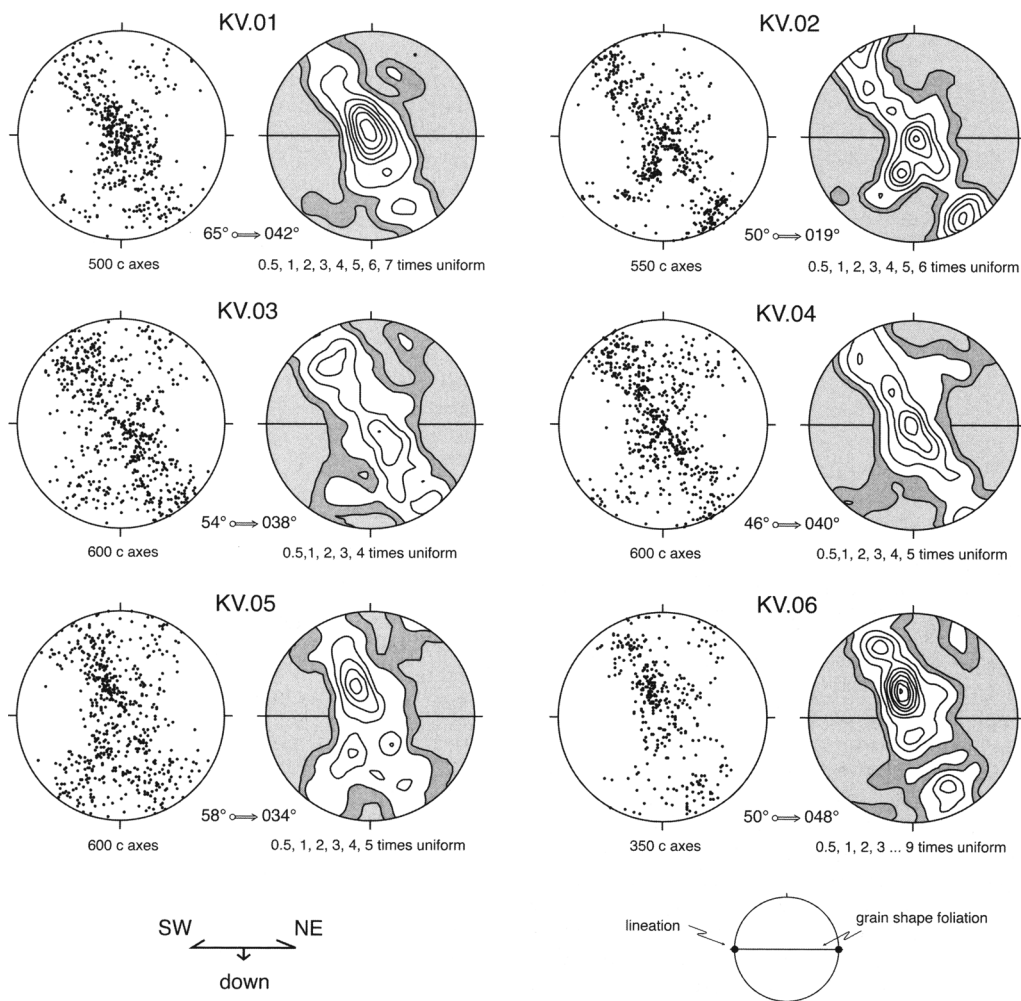


Fig. 17. Quartz *c*-axis fabrics from roadside exposures of plastically deformed and dynamically recrystallized metasedimentary rocks in the Batal Thrust Zone (see Fig. 4 for location). All fabrics are equal area projections on *xz* surfaces cut perpendicular to foliation and parallel to lineation. All fabrics are viewed towards the NW. Plunge and trend of lineation are indicated. Data were derived using optical universal stage analysis.

parallel to the crenulation lineation in the enveloping schists. Muscovite laths define a banding parallel to the compositional layering. There are no convincing microstructural shear-sense indicators in either the quartzite or the schist. Quartz microstructures indicate Regime 3 recrystallization conditions (Hirth & Tullis 1992), but with superposition of deformation bands at a very high angle to foliation. The sample shows a very strong crystallographic preferred orientation. Quartz *c*-axes define a fabric transitional between a Type II cross girdle fabric intersecting in the sample *y* direction and a small circle fabric

of large opening angle centred about the lineation (Fig. 19b). This fabric pattern indicates plane strain with a slightly constrictional deformation (Schmid & Casey 1986). There is no fabric asymmetry that can be used as a shear-sense indicator, although the fabric pattern shows that both the mineral lineation and the crenulation hinges parallel the principle extension direction of 115° . This is parallel to the plunge direction of refolded, oblate albite porphyroblasts from near Lalusar Lake. These directions parallel the axial trends of the F_{n+1} folds and are probably related to their evolution.

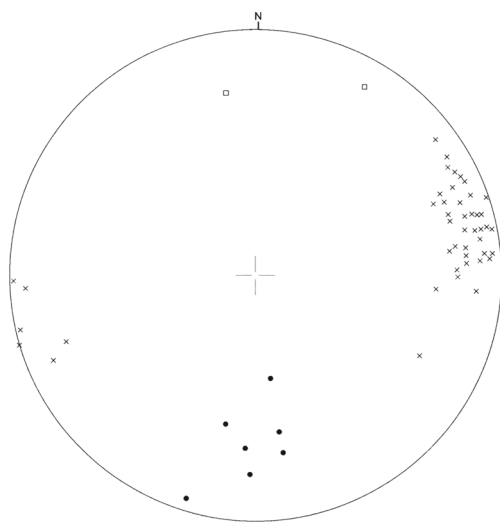


Fig. 18. Stereographic projections of linear fabrics from the northern Kaghan Valley. ● mineral stretching lineations from S of Besal; × mineral stretching lineations and axes from between Besal and Babusar Pass; □ mineral stretching lineations associated with late stage N-directed slip on calcite veins.

The Babusar Pass marks the north end of the Kaghan Valley. The MMT crops out just north of the Pass. A sequence of strongly foliated Indian Plate quartz-feldspar-mica-graphite schists and marbles are exposed at the Pass and along the ridge crest to the west. Marble units are intercalated with garnet-chlorite-bearing schists and metamorphosed mafic volcanic tuffs that contain hornblende, retrogressed to actinolite, and garnet. An early foliation is preserved in mafic boudins within marbles. The foliation in the schists and marbles is folded about ENE–WSW-trending subhorizontal fold hinges. Pervasive mineral lineations on foliation surfaces in schists and marble parallel the local fold hinges. Two sets of co-axial folds and crenulations are present. The first set has steep, NNW-dipping axial planes and is probably synchronous with the folds described from near Besal further south. The second has hinge planes that dip at 20–30° to the SSE. Inter-limb angles for the latter are typically 45–90°. Folds verge toward the NNW with long limbs dipping gently (20–30°) to the NNW, and short limbs dipping more steeply (40–70°) to the SSE. The geometry of the second set of folds is similar to that of the cascading folds described near Naran by Burg *et al.* (1996) and is consistent with top-side-north stretching. Calcite veins separate foliation surfaces on the NNW-dipping fold limbs. Mineral lineations on these plunge

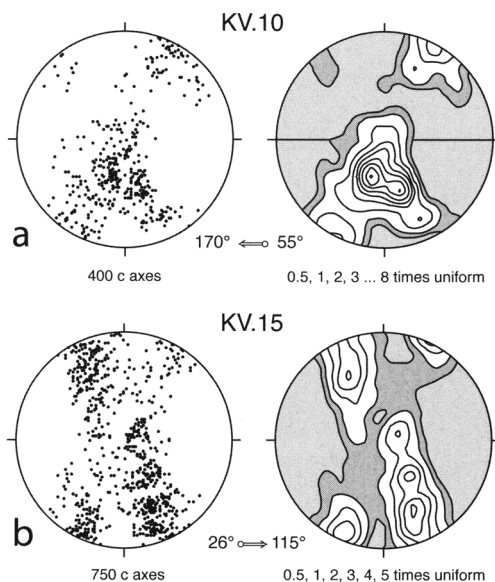


Fig. 19. Quartz *c*-axis fabrics from the Besal area, northern Kagan Valley (see Fig. 4 for location details): (a) *c*-axis fabric from coarse-grained dynamically recrystallized quartz vein (KV.10) in road cut south of Besal; equal area projection on *xz* surface viewed towards the west; (b) *c*-axis fabric from quartzite (KV.15) located c. 4.5 km WNW of 'Highway Lodge' at Besal; equal area projection on *xz* face viewed towards the NNE. Plunge and trend of lineation for each sample are indicated. Data were derived using optical universal stage analysis.

at 26° towards 350° and post-date the pervasive subhorizontal ENE–WSW-trending lineation developed in the schists. A top-down-to-NNW shear sense is indicated in the calcite veins by: obliquity between elongate calcite grains and vein margins; bending of calcite grains lamellae adjacent to planar zones of fine-grained calcite (<5 µm), which presumably represent zones of localized shear within veins; asymmetric trails of fine-grained calcite and graphite surrounding quartz clasts in fine-grained zones; and shear bands in fine-grained zones.

Samples KV.18 to KV.24 were collected from folded schists along the ridge crest at Babusar Pass. Axial planes dip shallowly to the SSE. Quartz *c*-axis fabrics from KV.23 and KV.24 (Fig. 20) confirm the subhorizontal ENE–WSW-trending lineation to be a true stretching lineation oriented parallel to the principal extension direction associated with penetrative deformation. Few unequivocal microstructural shear-sense indicators were found within the schists. Weakly developed shear bands in KV.23 (S: 052°/44°NW, L: 246°/12°) indicate a dextral sense of

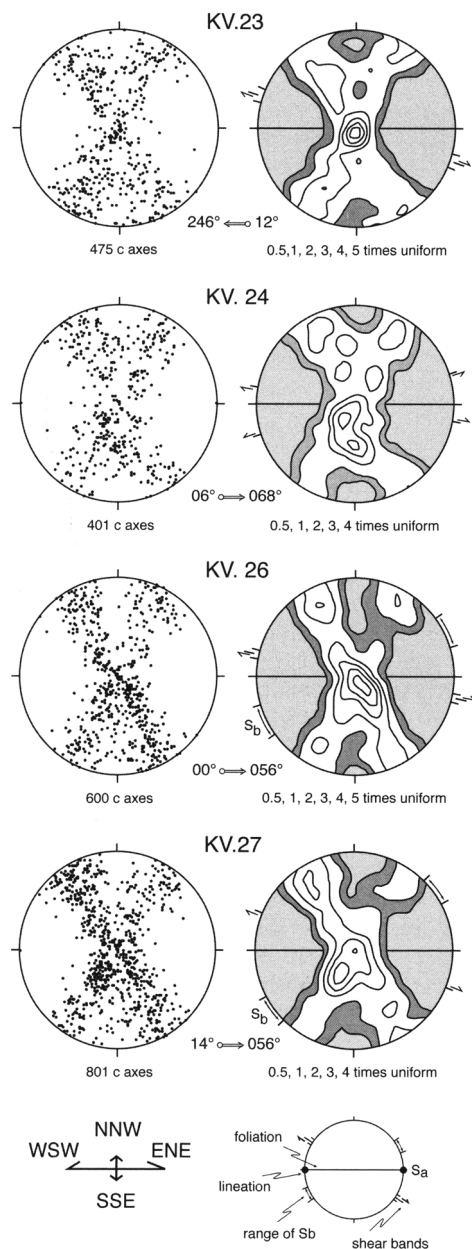


Fig. 20. Quartz *c*-axis fabrics from Babusar Pass area. Samples KV.23 and KV.24 were collected from the ridge crest due west of the summit of Babusar Pass; samples KV.26 and KV.27 were collected 2 km due north of Babusar Pass (see Fig. 4 for location details). All fabrics are equal area projections viewed geographically downwards onto *xz* surfaces. S_a , macroscopic foliation; S_b , alignment of elongate recrystallized grains in quartz-rich domains. Plunge and trend of lineation are indicated for each sample. Data were derived using optical universal stage analysis.

relative motion between the Indian Plate and Kohistan rocks when viewed geographically downward. This shear sense is compatible with the asymmetry in the quartz *c*-axis fabric data for KV.23, but the degree of fabric asymmetry is small. The skeletal asymmetry of the *c*-axis fabric from KV.24 (S: 060°/46°SE; L: 068°/06°) also indicates a dextral sense of relative motion between the Indian Plate and Kohistan viewed geographically downward. Weakly developed shear bands in KV.24 locally indicate both dextral and sinistral shear senses. Weakly developed shear bands and asymmetric amphibole tails on garnet grains in KV.19 (a mafic boudin within a marble unit; S: 070°/20°NNW; L: 070°/00°) also indicate a dominant dextral shear sense, although some asymmetric tails indicate the opposite shear sense.

Hubbard & Spencer (1990) and Hubbard *et al.* (1995) suggested that meso- and micro-scale structures in rocks of both the Indian Plate and the Kohistan arc at Babusar Pass, together with the preferred crystallographic orientation of quartz, indicate a top-side-WSW shear sense associated with the pervasive WSW–ENE-trending mineral lineation. These structures include asymmetric pressure shadows, shear bands and preferred quartz grain shape orientations. The quartz *c*-axis fabric data described here (Fig. 20) are not consistent with the data of Hubbard & Spencer (1990). There are two possible reasons for this. First is a reference frame problem with reporting shear senses at Babusar Pass. This is because the main fabrics are folded about the WSW–ENE-trending co-axial stretching lineation, and may thus dip to the NNW, the SSE or be vertical. Descriptions of shear senses in terms of top-to-the-ENE or -WSW thus become meaningless when traced across a fold axis. When traced from one limb to an adjacent one, and always viewed from above onto the *xz* plane, a single original shear sense (Fig. 21a) after folding of foliation about a gently dipping hinge surface may appear to be sinistral (top-side-WSW) on the NNW-dipping limb, sinistral where foliation is vertical, and sinistral (but now top-side-ESE) on the SSE-dipping limb (Fig. 21b). At Babusar Pass, where folding has occurred about gently to moderately, SSE-dipping hinge surfaces, it is more useful to express shear senses in terms of either a dextral or sinistral sense of relative motion between the Indian Plate and Kohistan rocks when viewed geographically downward. That the primary fabrics are refolded around the meso-scale late folds at Babusar Pass suggests a further complication. The regional-scale, upright, large-amplitude ENE–WSW-trending F_{n+1} folds described above have fold axes and

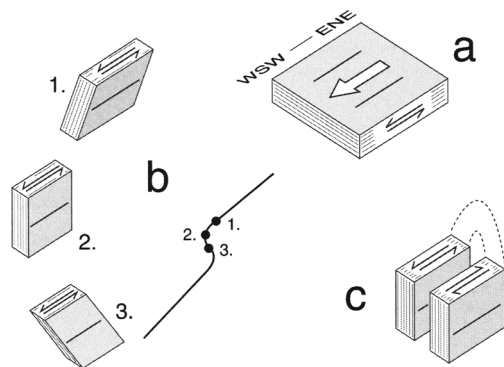


Fig. 21. Schematic diagrams illustrating the effects of folding about WSW–ENE-trending lineation on shear senses reported on xz surfaces. (a) Original planar foliation with top-to-the-WSW sense of shear on lineation as reported by Hubbard & Spencer (1990) and Hubbard *et al.* (1995) for the Babusar Pass area. (b) Folding about a hinge surface dipping gently to the SSE results in change in top-to-the-WSW 'upper over lower' shear sense (Hubbard & Spencer 1990; Hubbard *et al.* 1995) from top-to-the-WSW on NW-dipping fold limb (case 1) to top-to-the-ENE on the SE-dipping limb (case 3). Viewed geographically downwards onto the xz surface, however, a constant sinistral shear sense is observed. (c) Isoclinal folding about a hinge surface dipping steeply to the NNW results in opposite shear senses being observed on xz surfaces from adjacent fold limbs when viewed geographically downwards. However, results from our study (Fig. 20, sample KV.27) indicate the same (dextral) shear sense on both limbs, indicating that penetrative shearing outlasted isoclinal folding.

axis-parallel lineations subparallel to those of the late-stage, cascading folds at Babusar Pass. Quartz c -axis data reviewed above show that the F_{n+1} folds were not plane strain structures, as there was significant extension along their axes. The Hubbard & Spencer data would suggest that these major folds, which postdate the Eocene but predate extension along the MMT, had a sinistral sense of transpressive shear.

Samples KV.26 and KV.27 were collected 200 m east of the road, 2 km north of Babusar Pass. According to Chamberlain *et al.* (1991, fig. 2) these samples should be part of the Kohistan sequence. However, the samples are quartz–biotite–muscovite schists with euhedral garnet and are instead retrogressed, greenschist-facies Indian Plate rocks. Both samples are strongly foliated and lineated. Foliation is tightly to isoclinally folded on a centimetre to millimetre scale about gently plunging WSW–ENE-trending fold hinges with hinge surfaces dipping steeply to the NNW. A strong linear fabric is

produced by quartz rods oriented parallel to fold hinges. A spaced ($c. 10$ cm) crenulation cleavage, oriented parallel to hinge surfaces, locally overprints the main foliation. Both the vergence of the folded main foliation and the sense of down-dip offset along spaced crenulation cleavage planes indicate a top-down-to-NNW shear sense. The presence of chlorite on the cleavage planes indicates a low metamorphic grade during crenulation development. The main foliation and the crenulation cleavage are locally cross-cut by NNE-dipping listric faults or shear bands which can be traced for over 1 m down dip and have a typical spacing of 10–30 cm. The sense of foliation deflection into these structures indicates a top-down-to-NNE shear sense. Mean strike and dip of five of these metre-scale extensional structures is $117^{\circ}/46^{\circ}$ NE. These structures, together with the lineated calcite veins described above, document a phase of north-directed extension that post-dates development of the crenulation cleavage and its associated WSW–ENE-trending lineation.

Sections from samples KV.26 and KV.27 were cut perpendicular to the main foliation and parallel to a lineation defined by quartz rods (i.e. the xz section). The section from KV.26 is from a domain of NNW-dipping foliation. That from KV.27 cuts across both limbs of an isoclinal, centimetre-scale antiformal fold. The lineation developed on a foliation surface on KV.26 that dips $056^{\circ}/70^{\circ}$ NE is horizontal and trends towards 056° . The lineation on KV.27 plunges at 14° towards 056° on a vertical foliation surface that strikes 056° . When viewed downward onto xz surfaces, both shear bands and recrystallized quartz grain shape alignment (S_b) oriented oblique to main foliation (S_0) indicate an unequivocal dextral shear sense (Fig. 20). This is the same as that recorded in samples KV.23 and KV.24 to the west of Babusar Pass. Quartz c -axis fabrics from KV.26 and KV.27 are fairly symmetric in terms of skeletal outline, although the asymmetry of density distribution in both these fabrics could be interpreted to indicate a sinistral shear sense (Fig. 20). The difference in shear sense between the microstructures and the c -axis fabrics is unusual but could indicate a flip in shear sense with the c -axis fabric asymmetry probably recording the most recent motion. Quartz c -axis fabrics from samples KV.26 and KV.27 (Fig. 20) confirm the subhorizontal ENE–WSW-trending rodding lineation to be a true stretching lineation oriented parallel to the principal extension direction associated with penetrative deformation. As at Babusar Pass, and further south at Besal and Lake Lalusar, fold hinges are oriented parallel to this extension

direction. To the north of the Pass folding is much tighter and generally associated with steeply dipping hinge surfaces. If isoclinal folding about subhorizontal hinges and steeply dipping hinge surfaces post-dated penetrative deformation, then opposite shear senses should be observed in *xz* sections on adjacent fold limbs (Fig. 21c). However, the same shear sense is indicated by both shear bands and oblique recrystallized grain shape alignment on adjacent fold limbs in KV.27, suggesting that along fold hinge straining outlasted isoclinal folding. The microstructural and *c*-axis data from small-scale east–west-trending structures implies that the large-wavelength and -amplitude east–west-trending folds are characterized by along-axis stretching. This is an important observation as it implies that regionally developed large-wavelength and -amplitude folds that deform the Early Eocene fabrics are not plane strain structures but exhibit evidence for pre-Miocene orogen-parallel stretching.

In the Upper Kaghan Valley the MMT zone crops out just north of Babusar Pass as a moderately north-dipping structure. Here, it separates two distinct sets of structures. On the footwall the main structures in the Indian Plate are a series of approximately east–west-trending upright folds with wavelength and amplitudes measurable in terms of tens of kilometres. These upright folds deform early Eocene thrusts and shear fabrics that accommodated exhumation to mid-crustal levels of the coesite eclogites (O'Brien *et al.* 2001; Treloar *et al.* 2003). The crenulations described from Besal and the Babusar Pass are co-planar to, and co-axial with, these large-scale structures and probably developed synchronously with them. The upright Eocene folds are characterized by along-axis stretching. Such folds are not found in the rocks of the Kohistan

Arc that crop out on the hanging wall of the MMT. Large-amplitude folds in the Indian Plate rocks are truncated by the MMT north of Saleh de Bainkh (Fig. 22). Here Indian Plate rocks and bedding parallel fabrics dip steeply south and are cut by the north-dipping MMT (Treloar *et al.* 2003). In contrast, the MMT hanging wall just north of Babusar Pass carries hillside-sized, mesoscopic to macroscopic flat-lying northward-cascading folds (Fig. 23). These folds have subhorizontal axial planes that dip gently towards the SE or SSE and axes that trend approximately east–west.

Summary of the structural and thermal evolution of the internal zones of the Indian Plate of North Pakistan

Data presented here, and elsewhere, allow construction of a structural history for the northern part of the Indian Plate during Eocene to Miocene collision with the Kohistan Island Arc. (1) South-vergent thrusts accommodated subduction of the leading edge of the Indian Plate beneath Kohistan along the Main Mantle Thrust. This was accompanied by prograde metamorphism along a path of increasing pressure. Both the UHP coesite-bearing eclogites and the Barrovian sequences reached metamorphic peaks at about 47 Ma. (2) Buoyancy forces caused rebound of the UHP rocks, bringing them back to mid-crustal levels, where they are flanked by normal faults above and thrust faults below. Imbrication of the Barrovian sequence occurred on the footwall of the thrusts that accommodated uplift of the UHP rocks. (3) Eocene fabrics were folded about large-wavelength and -amplitude, WSW–ENE-trending folds characterized by along-axis stretching. (4) Early Miocene upper

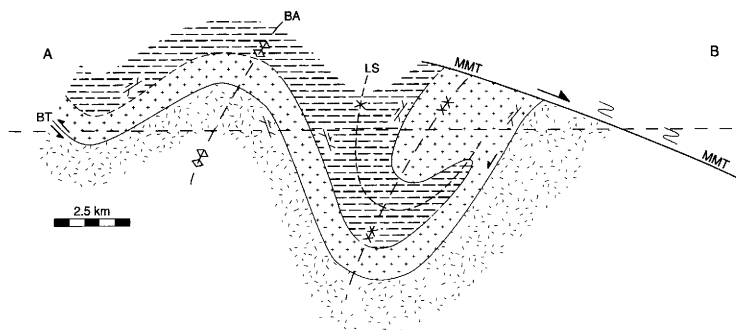


Fig. 22. Structural section, viewed towards the WNW, across the northern part of the Indian Plate and the MMT in the upper Kaghan Valley; line of section is indicated in Figure 4.

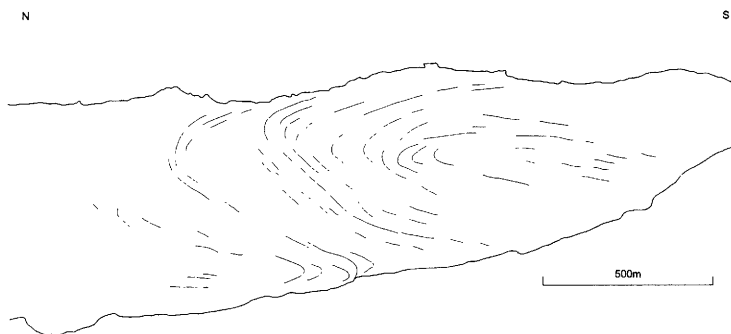


Fig. 23. Large-scale cascading folds developed on the MMT hanging wall at Babusar Pass. (Sketch drawn from a mosaic of field photographs.)

crustal stretching caused reactivation of the MMT zone as a top-side-north ductile to brittle shear zone. This brought rocks metamorphosed at UHP and mid-crustal conditions back to near the surface. In the Indus Valley, Early Miocene stretching is documented by a range of north-vergent ductile structures overprinted by north-vergent brittle structures. In the Kaghan Valley it is documented dominantly by north-vergent cascading folds and by excision of upright, large-wavelength folds in the Indian Plate by reactivation of the MMT. Thermo-chronological data show that cooling on the MMT footwall was much more rapid than that on the hanging wall, suggesting that differential uplift across the MMT zone during the early Miocene can be measured in terms of up to 10 km. The MMT zone is thus best described as a complicated, long-lived structure (originally with a thrust sense and latterly with a top-side-north extensional sense) that separates the Kohistan arc to the north, on its hanging wall, from the Indian Plate to the south on its footwall.

Principal stretch direction parallel to east–west trending fold hinges

The Upper Kaghan Valley (Fig. 4) is marked by a series of gently plunging east–west trending folds (with amplitudes varying from metre to kilometre scale) in which quartz petrofabric analysis indicates the principal stretching direction to be oriented parallel to fold hinges (Figs 19 and 20). This parallelism between east–west trending fold hinges and the principal extension direction is recorded only at relatively high structural levels of the Indian Plate sequence, above the Batal Thrust and below the MMT. In the Batal Thrust zone itself, the principal stretching

direction plunges down-dip towards the NNE, and is perpendicular to the hinges of the cascading folds. This suggests that the relationship between the principal stretching direction and fold hinges is likely to be due to structural position within the orogenic wedge. Similar relationships between structural position and the orientation of principal stretching directions relative to orogenic strike have been identified in other collisional orogens, and have also been predicted on the basis of analogue and numerical modelling studies. For example, in the European Alps Ramsay (1981) identified a vertical distribution between stretching perpendicular to the orogenic strike at deeper structural levels and stretching parallel to orogenic strike at higher structural level. A similar geometry was reported from analogue models by Merle (1998, pp. 96–102).

One potential explanation for this domainal distribution of principal stretching directions was suggested by Platt (2000, fig. 10), who argued that during oblique plate convergence involving a viscous wedge, strike-parallel motion is concentrated near the rear of the wedge, or adjacent to the backstop, whereas motion in the frontal part of the wedge is essentially perpendicular to orogenic strike. In this numerical model, the strike-parallel component of flow increases upward from the base of the wedge. In the case of the Himalayan arc, it is clear from earthquake first motion fault-plane data, GPS-derived velocity fields and stretching lineations in the frontal parts of the arc that transport directions are perpendicular to strike (e.g. Bouchez & Pêcher 1981; Baranowski *et al.* 1984; Brunel 1986; Molnar & Lyon-Caen 1989; Grasemann *et al.* 1999; Larson *et al.* 1999; Bendick & Bilham 2001; Jade *et al.* 2004). However, within the orogenic hinterland of the Himalaya there is much evidence for the presence of along-arc strike-parallel extension

(e.g. Pêcher 1991; Pêcher *et al.* 1991; Coleman 1996; McCaffrey & Nabelek 1998; Seeber & Pêcher 1999; Murphy & Copeland 2005). This close geometric relationship between arc curvature and the observed distribution of arc-perpendicular (radial) and arc-parallel stretching suggests a more direct relationship between degree of orogenic curvature and local stretching directions than that implied in models involving oblique plate convergence. Murphy & Copeland (2005, fig. 10) have suggested a mechanism for western Nepal that explains arc-normal contraction in the foreland and arc-parallel extension in the hinterland that is directly linked to degree of orogenic curvature. Their model predicts that with foreland-directed growth of the orogenic wedge, parts of the orogen pass with time from being located in domains undergoing arc-normal contraction to domains undergoing arc-parallel extension. Together, the two work to maintain the arcuate shape of the orogen.

By analogy, for northern Pakistan we can identify a temporal sequence from thrust-directed crustal thickening in the Early Eocene in what is now the hinterland, to a period, probably during the Oligocene, when the hinterland was being internally deformed by upright east-west trending folds with along-axis stretching, while simultaneously being carried southward along underlying south- to SW-vergent thrusts characterized by strike-normal (i.e. thrust transport-parallel) stretching. Our kinematic data (Fig. 20) suggest a dextral sense of shear along these fold axes. This period of crustal thickening came to an end during the early Miocene, when the upper part of the system went into overall extension and the upright folds were truncated by normal faults developed within the Main Mantle Thrust zone.

Exhumation: causes and mechanisms

Two phases of exhumation, separated by a long standstill with minimal apparent exhumation, are indicated for the metamorphic rocks, including the UHP rocks, of the northern part of the Indian Plate in Pakistan. Although both the Late Eocene and Early Miocene phases of extension are synchronous with continued convergence, the driving force for each is different although there are similarities in the structures that accommodate extension. Eocene exhumation was the result of buoyancy driven uplift of felsic UHP rocks. Structures that accommodated this uplift have been described by Treloar *et al.* (2003) and a mechanism for it by Chemenda *et al.* (1996, 2000). Although the north-dipping Eocene structures that structurally overlie the UHP rocks

have a top-side-north extensional geometry, they did not develop within a regime of lithospheric extension. Lithospheric shortening was continuing and the structures with extensional senses are the result of vertical thickening driven by buoyant uplift of the UHP rocks which contributed to thickening of the developing orogenic pile.

Here we assess potential causes and mechanisms of Miocene upper crustal, orogen-perpendicular stretching. In the NW Himalaya such stretching could be a function of one of three possible processes: (1) over-steepening of the thrust wedge driven by changes in rate of accumulation to the base of the wedge; (2) slab break-off, which could cause over-steepening of the thrust wedge; (3) extrusion driven by channel flow. Because top-side-north stretching in the NW Himalaya occurred at the same time in the main Himalayan chain, there is no reason to invoke driving mechanisms in the central Himalaya that are different from those proposed for the NW Himalaya. For instance, if channel flow models that apparently explain upper crustal extension in the central Himalaya (Beaumont *et al.* 2001, 2004; Jamieson *et al.* 2004) do not obviously work for the rest of the Himalaya they are probably fundamentally flawed. Some models are assessed below although the assessment is based on the assumption that processes in the NW Himalaya are at least as important as those in the main Himalaya.

A large amount of published data relate to the concept of the thrust wedge. The Coulomb wedge model, outlined by Platt (1993), is a scenario that may be applicable to the Himalaya. In this model the taper of the wedge is a function of the angle of internal friction of the material within the wedge and the coefficient of friction along the base of the wedge. Features that affect the internal angle of friction include changes in pore pressure and the presence of melt. A stable orogenic wedge will not deform unless the balance between tractional forces at its base and gravitational forces related to wedge thickening is disturbed for some reason. The underplating of material to the base of the wedge is a consequence of continental collision and, unless compensated for elsewhere, will cause an increase in the angle of taper of the wedge. One way of maintaining the taper in such a situation would be by initiating extension at the rear of the wedge. The Coulomb model thus provides a mechanism through which underplating can occur synchronously with exhumation at higher structural levels. Harris & Massey (1994) suggested that weakening of the wedge through crustal anatexis might yield a similar result. The Coulomb wedge model is an attractive one to use to explain Early Miocene extension along the

entire Himalayan chain. England & Molnar (1993) explored various scenarios in which extension along the Himalayan chain might be explained by changes within the wedge or along its base. The main problem with this analysis is that there is no real continuity along the length of the chain from Nepal to Pakistan. Hence, changes in the internal constitutive force in the Nepalese Himalaya, largely driven by melting, are not apparent in the NW Himalaya. Similarly, although abrupt reductions in the tractive strength of the basal detachment can be documented in the NW Himalaya where the basal thrusts cut down into salt horizons (Coward *et al.* 1988), the same cannot be shown in the central Himalayan chain. Hence, it is unlikely that simple thickening of the thrust wedge along the entire length of the Himalayan chain could have driven extension that was synchronous from Bhutan to Pakistan.

The second possibility is that exhumation of high-grade metamorphic rocks occurred as a result of channel flow. Beaumont *et al.* (2001, 2004) used numerical modelling to show that synconvergent extension in the main Himalayan chain could be the result of a form of toothpaste tectonics in which a ductile, melt-rich layer is squeezed out to the south. The South Tibetan Detachment Zone, with high-grade rocks below and low-grade rocks above, has a north-side down sense of normal displacement. Key elements of the model are a high plateau in the hinterland, a steep mountain front and elevated mid-crustal temperatures with rocks in the channel rheologically weakened by the presence of melt. Although the requirements might be met in the central Himalaya they are not in the NW Himalaya in North Pakistan. None of the key elements used to model channel flow in the central Himalaya are recognized in the NW Himalaya, where there is no evidence that a high plateau existed in the hinterland or that a steep mountain front was present during the early Miocene and where, unlike in the central Himalaya, no Himalayan age migmatites have been brought to surface. As synconvergent extension was operative synchronously in both the NW Himalaya and the central Himalayan, this suggests that the channel flow model may not be the ultimate solution. We note that the high Moho temperatures of 704 °C used in the models of Beaumont *et al.* (2001, 2004) are unreasonable and probably imply the model to be invalid even in the central Himalaya.

A third possibility is that upper crustal stretching at the top of the Himalayan thrust stack in Pakistan was driven by slab delamination and associated rollback. Maheo *et al.* (2001)

argued the case for slab break-off north of the Indus suture on the basis of enhanced heat flows recorded in metamorphic rocks and the emplacement of alkaline mafic rocks and lamprophyres into the Asian crust. They suggested that slab break-off commenced at 25 Ma, or just before initiation of Miocene exhumation along the length of the Himalayan chain. Royden's (1993a) analysis of the mechanics of retreating and advancing subduction boundaries is relevant here. Orogenic belts that form at retreating boundaries are generally characterized by low mountains and the development of extensional back-arc basins. However, as subduction boundaries may switch from retreating to advancing and back again the characters of their supra-structure may change with time. In the case of the Himalaya, it is clear that the partitioning of shortening between thrusting in the main Himalayan chain, thickening of Tibet and lateral extrusion of Tibet has not been constant. The main effect of slab break-off will be to change the balance between slab pull and overall plate convergence. High slab pull will encourage retreating subduction boundaries and upper plate extension (Royden 1993a,b). In contrast, slab break-off will decrease the negative buoyancy, and hence tractive force, of the subducting slab, thus reducing the force exerted by the slab, and hence encourage subduction advance and hence increase shortening in the upper plate. Theoretically, this should lead an increase in the height of the mountain chain. However, feedbacks within the system are obvious. If the Late Oligocene–Early Miocene Himalayan mountain front can be viewed as a Coulomb wedge, increasing the shortening across the wedge would have a dramatic effect, regardless of the presence or otherwise of melt within it. Initiating addition of material to the base of the wedge, as a result of instigating activity along new, foreland-directed thrusts on the wedge base, will cause oversteepening of the wedge, which will drive extension in its upper parts. Hence, reducing the tractive force on the base of the system as a result of slab break-off may initiate wedge collapse simply as a result of the increased compression that results.

Since the Miocene the Pakistani Himalayan topographic high has been reduced by erosion rather than extension. Although thrusting has continued at the base of the wedge, growth of high mountains has been stopped by the presence of the Eocambrian salt layer within which the basal thrusts are now located. As a result, critical taper of the wedge is now maintained by out-of-sequence thrusting at the rear of the wedge, rather than thickening at its frontal base.

Conclusions

Two main phases (Eocene and Miocene) of exhumation of UHP and medium-pressure rocks are evident in the Pakistan Himalaya. The Eocene event is the function of buoyant uplift of upper crustal material rapidly buried to >100 km depth. Although flanked above by top-side-north ductile shears this uplift involved no real extension but instead contributed to the overall thickening of the subducting Indian Plate.

Top-side-north shear zones, developed in the upper part of the Indian Plate in North Pakistan during the Early Miocene, document a major phase of upper crustal, orogen-perpendicular, stretching. This occurred synchronously with upper crustal stretching in the central Himalaya. The structures described here are documented by clear metamorphic breaks (greenschist- or blueschist-facies rocks structurally overlying sillimanite-grade rocks) and by distinct breaks in cooling history across the major structures. In addition, they cause significant structural discontinuities best documented by the way that upright large-amplitude and -wavelength folds are cut by the north-dipping MMT. The combination of macro-, meso- and microscopic structures with a general top-side-north (hinterland-directed) sense of motion, metamorphic breaks and P - T - t data suggest that the top-side-north shear zones within the Pakistan Himalaya have a true extensional sense and support the notion that the thrust wedge was collapsing northward. They are not hinterland-directed back-thrusts.

It is unlikely that channel flow, as described from the central Himalaya, caused Early Miocene upper crustal stretching, as the boundary conditions for channel flow are not present in the NW Himalaya. The structures present would, however, be consistent with upper crustal stretching caused by collapse of the south-vergent Pakistani thrust wedge. Collapse would be encouraged by overthickening of the wedge as a result of the Indian Plate going into overall compression as the tractive force on the base of the wedge reduced during slab break-off.

P.J.T. says: Mike Coward introduced me to the NW Himalaya and I will always be grateful to him for that. Working with Mike was exciting, stimulating and always a pleasure. Our initial work was funded by an NERC Research Grant (GR3/6113). Subsequent fieldwork was supported by Royal Society grants. K.V. acknowledges an NERC research studentship tenable at Kingston University. R.D.L. acknowledges National Science Foundation Grants EAR 950625 and 0207524 that supported field and laboratory work. We thank

J.-P. Burg and M. P. Searle for their reviews of an earlier version of this manuscript, and R. W. H. Butler for editing.

References

- BAIG, M. S., SNEE, L. W. & LAFORTUNE, R. J. 1989. Timing of pre-Himalayan orogenic events in the northwest Himalaya. *Kashmir Journal of Geology*, **6**-7, 29-39.
- BARANOWSKI, J., ARMBRUSTER, J. G., SEEGER, L. & MOLNAR, P. 1984. Focal depths and fault-plane solutions of earthquakes and active tectonics of the Himalaya. *Journal of Geophysical Research*, **89**, 6918-6928.
- BEAUMONT, C., JAMIESON, R. A., NGUYEN, M. H. & LEE, B. 2001. Himalayan tectonics explained by extrusion of a low-viscosity crustal channel coupled to focused surface denudation. *Nature*, **414**, 738-742.
- BEAUMONT, C., JAMIESON, R. A., NGUYEN, M. H. & MEDVEDEV, S. 2004. Crustal channel flows: 1. Numerical models with applications to the tectonics of the Himalayan orogen. *Journal of Geophysical Research B: Solid Earth*, **109**(B06406), 1-29.
- BENDICK, R. & BILHAM, R. 2001. How perfect is the Himalayan arc? *Geology*, **29**, 791-794.
- BERTHE, D., CHOUKROUNE, P. & JEGOUZO, P. 1979. Orthogneiss, mylonites and non-co-axial deformation of granites: the example of the South Armorican Shear Zone. *Journal of Structural Geology*, **1**, 31-42.
- BOUCHEZ, J.-L. & PÉCHER, A. 1981. Himalayan Main Central Thrust pile and its quartz-rich tectonites in central Nepal. *Tectonophysics*, **78**, 23-50.
- BRUNEL, M. 1986. Ductile thrusting in the Himalayas: shear sense criteria and stretching lineations. *Tectonics*, **5**, 247-265.
- BURCHFIELD, B. C. & ROYDEN, L. H. 1985. North-south extension within the convergent Himalayan region. *Geology*, **13**, 679-682.
- BURCHFIELD, B. C., ZHILIANG, C., HODGES, K. V., YUPING, L., ROYDEN, L., CHANGRONG, D. & JIENE, X. 1992. *The South Tibetan Detachment System, Himalayan Orogen: Extension Contemporaneous with and Parallel to Shortening in a Collisional Mountain Belt*. Geological Society of America, Special Papers, 269.
- BURG, J. P., BRUNEL, M., GAPAIS, D., CHEN, G. M. & LIU, G. H. 1984. Deformation of leucogranites of the crystalline Main Central sheet in southern Tibet (China). *Journal of Structural Geology*, **6**, 535-542.
- BURG, J.-P., CHAUDHRY, M. N., GHAZANFAR, M., ANCZKIEWICZ, R. & SPENER, D. A. 1996. Structural evidence for backsliding of the Kohistan arc in the collisional system of NW Pakistan. *Geology*, **24**, 739-742.
- CHAMBERLAIN, C. P., ZEITLER, P. K. & ERIKSON, E. 1991. Constraints on the tectonic evolution of the northwestern Himalaya from geochronologic and petrologic studies of Babusar Pass. *Journal of Geology*, **99**, 829-849.

- CHAUDHRY, M. N. & GHAZANFAR, M. 1987. Geology, structure and geomorphology of upper Kaghan Valley, NW Himalaya, Pakistan. *Geological Bulletin, Punjab University*, **22**, 13–57.
- CHEMENDA, A. I., MATTAUER, M. & BOKUM, A. N. 1996. Continental subduction and a mechanism for exhumation of high-pressure metamorphic rocks: new modelling and field data from Oman. *Earth and Planetary Science Letters*, **143**, 173–182.
- CHEMENDA, A. I., BURG, J.-P. & MATTAUER, M. 2000. Evolutionary model of the Himalaya–Tibet system: geopoem based on new modelling, geological and geophysical data. *Earth and Planetary Science Letters*, **174**, 397–409.
- COLEMAN, M. E. 1996. Orogen-parallel and orogen-perpendicular extension in the central Nepalese Himalayas. *Geological Society of America Bulletin*, **108**, 1594–1607.
- COWARD, M. P., BUTLER, R. W. H., CHAMBERS, A. F. *et al.* 1988. Folding and imbrication of the Indian crust during Himalayan collision. *Philosophical Transactions of the Royal Society of London, Series A*, **326**, 89–116.
- DAVIES, J. H. & VON BLANKENBURG, F. 1995. Slab break off: a model of lithosphere detachment and its test in the magmatism and deformation of collisional orogens. *Earth and Planetary Science Letters*, **129**, 85–102.
- DESMONS, J., COMPAGNONI, R. & CORTESOGNO, L. 1999. Alpine metamorphism of the western Alps: II. High-*P/T* and related pre-greenschist metamorphism. *Schweizerische Mineralogische und Petrographische Mitteilungen*, **79**, 111–134.
- DIPIETRO, J. A. 1991. Metamorphic pressure–temperature conditions of Indian plate rocks south of the Main Mantle Thrust, Lower Swat, Pakistan. *Tectonics*, **10**, 742–757.
- DIPIETRO, J. A. & ISACHSEN, C. E. 2001. U–Pb zircon ages from the Indian Plate in northwest Pakistan and their significance to Himalayan and pre-Himalayan geologic history. *Tectonics*, **20**, 510–525.
- DIPIETRO, J. A. & LAWRENCE, R. D. 1991. Himalayan structure and metamorphism south of the Main Mantle Thrust, Lower Swat, Pakistan. *Journal of Metamorphic Geology*, **9**, 481–495.
- ENGLAND, P. C. & HOUSEMAN, G. A. 1988. The mechanics of the Tibetan Plateau. *Philosophical Transactions of the Royal Society of London, Series A*, **326**, 301–319.
- ENGLAND, P. & MOLNAR, P. 1993. Cause and effect among thrust and normal faulting, anatexis melting and exhumation in the Himalaya. In: TRELOAR, P. J. & SEARLE, M. P. (eds) *Himalayan Tectonics*. Geological Society, London, Special Publications, **74**, 401–411.
- FOSSEN, H. 2000. Extensional tectonics in the Caledonides: synorogenic or postorogenic. *Tectonics*, **19**, 213–224.
- FOSTER, G. L., VANCE, D., ARGLES, T. W. & HARRIS, N. B. W. 2002. The Tertiary collision-related thermal history of the NW Himalaya. *Journal of Metamorphic Geology*, **20**, 827–844.
- GARZANTI, E., CRITELLI, S. & INGERSOLL, R. V. 1996. Paleogeographic and paleotectonic evolution of the Himalayan Range as reflected by detrital modes of Tertiary sandstones and modern sands (Indus transect, India and Pakistan). *Geological Society of America Bulletin*, **108**, 631–642.
- GEBAUER, D. 1999. Alpine geochronology of the Central and Western Alps: new constraints for a complex geodynamic evolution. *Schweizerische Mineralogische und Petrographische Mitteilungen*, **79**, 191–208.
- GRASEMANN, B., FRITZ, H. & VANNAY, J. C. 1999. Quantitative kinematic flow analysis from the Main Central Thrust Zone (NW Himalaya, India); implications for a decelerating strain path and the extrusion of orogenic wedges. *Journal of Structural Geology*, **21**, 837–853.
- GRECO, A. 1989. *Tectonics and Metamorphism in the Western Himalayan Syntaxis Area (Azad Kashmir, NE-Pakistan)*. Mitteilungen aus dem Geologischen Institut der Eidgenössischen Technische Hochschule und der Universität Zürich, Neue Folge, **274**.
- GRECO, A. & SPENCER, D. A. 1993. A section through the Indian Plate, Kaghan Valley, NW Himalaya, Pakistan. In: TRELOAR, P. J. & SEARLE, M. P. (eds) *Himalayan Tectonics*. Geological Society, London, Special Publications, **74**, 221–236.
- GRECO, A., MARTONITTI, G., PAPRITZ, K., RAMSAY, J. G. & REY, R. 1989. The crystalline rocks of the Kaghan Valley (NE Pakistan). *Eclogae Geologicae Helveticae*, **82**, 629–653.
- GRUJIC, D., CASEY, M., DAVIDSON, C., HOLLISTER, L., KUNDIG, K., PAVLIS, T. & SCHMID, S. 1996. Ductile extrusion of the Higher Himalayan crystalline in Bhutan: evidence from quartz microfabrics. *Tectonophysics*, **260**, 21–43.
- HARRIS, N. B. W. & MASSEY, J. 1994. Decompression and anatexis of Himalayan metapelites. *Tectonics*, **13**, 1537–1546.
- HIRTH, G. & TULLIS, J. 1992. Dislocation creep regimes in quartz aggregates. *Journal of Structural Geology*, **14**, 145–160.
- HUBBARD, M. S. & SPENCER, D. A. 1990. WSW-trending deformation between Babusar Pass and Toshe Gali area, northern Pakistan. *Geological Bulletin, University of Peshawar*, **23**, 101–110.
- HUBBARD, M. S., SPENCER, D. A. & WEST, D. P. 1995. Tectonic exhumation of the Nanga Parbat massif, northern Pakistan. *Earth and Planetary Science Letters*, **133**, 213–225.
- JADE, S., BHATT, B. C., YANG, Z. *et al.* 2004. GPS measurements from the Ladakh Himalaya, India: preliminary tests of plate-like or continuous deformation in Tibet. *Geological Society of America Bulletin*, **116**, 1385–1391.
- JAMIESON, R. A., BEAUMONT, C., MEDVEDEV, S. & NGUYEN, M. H. 2004. Crustal channel flows: 2. Numerical models with implications for metamorphism in the Himalayan–Tibetan orogen. *Journal of Geophysical Research B: Solid Earth*, **109**(B06407), 1–24.
- KANEKO, Y., KATAYAMA, I., YAMAMOTO, H. *et al.* 2003. Timing of Himalayan, ultrahigh-pressure metamorphism: sinking rate and subduction angle of the Indian continental crust beneath Asia. *Journal of Metamorphic Geology*, **21**, 589–599.

- KRUHL, J. H. 1998. Reply: Prism- and basal-plane parallel subgrain boundaries in quartz: a microstructural geothermobarometer. *Journal of Metamorphic Petrology*, **16**, 142–146.
- LARSON, K., BÜRGMANN, R., BILHAM, R. & FREYMUELLER, J. 1999. Kinematics of the India–Asia collision zone from GPS measurements. *Journal of Geophysical Research*, **104**, 1077–1093.
- LAW, R. D., SEARLE, M. P. & SIMPSON, R. L. 2004. Strain, deformation temperatures and vorticity of flow at the top of the Greater Himalayan Slab, Everest massif, Tibet. *Journal of the Geological Society, London*, **161**, 305–320.
- LISTER, G. S. 1977. Crossed-girdle *c*-axis fabrics in quartzites plastically deformed by plane strain and progressive simple shear. *Tectonophysics*, **39**, 51–54.
- MAHEO, G., ROLLAND, Y., GUILLOT, S. & PÉCHER, A. 2001. Metamorphic and magmatic evidences for slab break-off process below NW Himalaya. *Journal of Asian Earth Sciences*, **19**, 43–44.
- MCCAFFREY, R. & NABELEK, J. 1998. Role of oblique convergence in the active deformation of the Himalayas and southern Tibet plateau. *Geology*, **26**, 691–694.
- MERLE, O. 1998. *Emplacement Mechanisms of Nappes and Thrust Sheets*. Kluwer, Dordrecht.
- MOLNAR, P. & LYON-CAEN, H. 1989. Fault plane solutions of earthquakes and active tectonics of the Tibetan Plateau and its margins. *Geophysical Journal International*, **99**, 123–155.
- MORGAN, S. S. & LAW, R. D. 2004. Unusual transition in quartzite dislocation creep regimes and crystal slip systems in the aureole of the EJB pluton, California: a case for anhydrous conditions created by decarbonation of adjacent marbles. *Tectonophysics*, **384**, 209–231.
- MURPHY, M. A. & COPELAND, P. 2005. Transtensional deformation in the central Himalaya and its role in accommodating growth of the Himalayan orogen. *Tectonics*, **24**(TC4012), doi:10.1029/2004TC001659.
- NAJMAN, Y., PRINGLE, M., GODIN, L. & OLIVER, G. 2001. Dating of the oldest continental sediments from the Himalayan foreland basins. *Nature*, **410**, 194–197.
- O'BRIEN, P. J., ZOTOV, N. LAW, R. D., KHAN, M. A. & JAN, M. Q. 2001. Coesite in Himalayan eclogite and implications for models of India–Asia collision. *Geology*, **29**, 435–438.
- PARRISH, R. R., GOUGH, S., SEARLE, M. P. & WATERS, D. 2003. Extremely rapid exhumation of the Kaghan UHP terrane, Pakistan from U–Th–Pb measurements on accessory minerals. *Geological Society of America, Annual Meeting, Seattle, Abstracts*, 229–7.
- PATRIAT, P. & ACHACHE, J. 1984. India–Eurasia collision chronology and its implications for crustal shortening and driving mechanisms of plates. *Nature*, **311**, 615–621.
- PÉCHER, A. 1991. The contact between the Higher Himalaya crystallines and the Tibetan sedimentary series—Miocene large-scale dextral shearing. *Tectonics*, **10**, 587–598.
- PÉCHER, A., BOUCHEZ, J. L. & LE FORT, P. 1991. Miocene dextral shearing between Himalaya and Tibet. *Geology*, **19**, 683–685.
- PIVNIK, D. A. & WELLS, N. A. 1996. The transition from Tethys to the Himalaya as recorded in NW Pakistan. *Geological Society of America Bulletin*, **108**, 1295–1313.
- PLATT, J. P. 1993. Exhumation of high pressure rocks: a review of concepts and processes. *Terra Nova*, **5**, 119–133.
- PLATT, J. P. 2000. Calibrating the bulk rheology of active obliquely convergent thrust belts and forearc wedges from surface profiles and velocity distributions. *Tectonics*, **19**, 529–548.
- PLATT, J. & VISSERS, R. L. M. 1989. Extensional collapse of thickened continental lithosphere: a working hypothesis for the Alboran Sea and Gibraltar arc. *Geology*, **17**, 540–545.
- RAMSAY, J. G. 1981. Tectonics of the Helvetic Nappes. In: MCCLAY, K. R. & PRICE, N. J. (eds) *Thrust and Nappe Tectonics*. Geological Society, London, Special Publications, **9**, 293–310.
- REDDY, S. M., WHEELER, J. & CLIFF, R. A. 1999. The geometry and timing of orogenic extension: an example from the western Italian Alps. *Journal of Metamorphic Geology*, **17**, 573–589.
- REDDY, S. M., WHEELER, J., BUTLER, R. W. H. *et al.* 2003. Kinematic reworking and exhumation within the convergent Alpine Orogen. *Tectonophysics*, **365**, 77–102.
- RING, U., BRANDON, M. T., WILLETT, S. D. & LISTER, G. S. 1999. Exhumation processes. In: RING, U., BRANDON, M. T., WILLETT, S. D. & LISTER, G. S. (eds) *Exhumation Processes: Normal Faulting, Ductile Flow and Erosion*. Geological Society, London, Special Publications, **154**, 1–27.
- ROWLEY, D. B. 1996. Age of initiation of collision between India and Asia: a review of the stratigraphic data. *Earth and Planetary Science Letters*, **145**, 1–13.
- ROYDEN, L. H. 1993a. The tectonic expression of slab pull at continental convergent boundaries. *Tectonics*, **12**, 303–325.
- ROYDEN, L. H. 1993b. Evolution of retreating subduction boundaries formed during continental collision. *Tectonics*, **12**, 629–638.
- RUBATTO, D. & HERMANN, J. 2001. Exhumation as fast as subduction? *Geology*, **29**, 3–6.
- SCHMID, S. M. & CASEY, M. 1986. Complete fabric analysis of some commonly observed quartz *c*-axis patterns. In: HOBBS, B. E. & HEARD, H. C. (eds) *Mineral and Rock Deformation Laboratory Studies: the Paterson Volume*. American Geophysical Union, Geophysical Monographs, **36**, 263–286.
- SEARLE, M. P. 1999. Extensional and compressional faults in the Everest–Lhotse massif, Khumbu Himalaya, Nepal. *Journal of the Geological Society, London*, **156**, 227–40.
- SEARLE, M. P. 2003. *Geological map of the Everest massif, Nepal and South Tibet, Scale 1:100 000*. Department of Earth Sciences, Oxford University.
- SEARLE, M. P., SIMPSON, R. L., LAW, R. D., PARRISH, R. R. & WATERS, D. J. 2003. The structural geometry, metamorphic and magmatic evolution of the Everest massif, High Himalaya of Nepal–south Tibet. *Journal of the Geological Society, London*, **160**, 345–366.

- SEEBER, L. & PÉCHER, A. 1999. Strain partitioning along the Himalayan arc and the Nanga Parbat antiform. *Geology*, **26**, 791–794.
- SMITH, H. A., CHAMBERLAIN, C. P. & ZEITLER, P. K. 1994. Timing and duration of Himalayan metamorphism within the Indian Plate, Northwest Himalaya, Pakistan. *Journal of Geology*, **102**, 493–508.
- STIPP, M., STÜNITZ, H., HEILBRONNER, R. & SCHMID, S. M. 2002. Dynamic recrystallization of quartz: correlation between natural and experimental conditions. In: DE MEER, S., DRURY, M. R., DE BRESSER, J. H. P. & PENNOCK, G. M. (eds) *Deformation Mechanisms, Rheology and Tectonics: Current Status and Future Perspectives*. Geological Society, London, Special Publications, **200**, 171–190.
- TONARINI, S., VILLA, I., OBERLI, F., MEIER, M., SPENCER, D. A., POGNANTE, U. & RAMSAY, J. G. 1993. Eocene age of eclogite metamorphism in the Pakistan Himalaya: implications for India–Eurasian collision. *Terra Nova*, **5**, 13–20.
- TRELOAR, P. J. 1997. Thermal controls on early-Tertiary, short-lived, rapid regional metamorphism in the NW Himalaya, Pakistan. *Tectonophysics*, **273**, 77–104.
- TRELOAR, P. J. & O'BRIEN, P. 2003. What do coesite eclogites tell us about the earliest stages of India–Asia collision? *Geological Society of America, Abstracts with Programs*, **35**(6), 95.
- TRELOAR, P. J. & REX, D. C. 1990a. Cooling, uplift and exhumation rates in the crystalline thrust stack of the North Indian Plate, west of the Nanga Parbat syntaxis. *Tectonophysics*, **180**, 323–349.
- TRELOAR, P. J. & REX, D. C. 1990b. Post-metamorphic cooling history of the Indian Plate crystalline thrust stack, Pakistan Himalaya. *Journal of the Geological Society, London*, **147**, 735–738.
- TRELOAR, P. J., BROUGHTON, R. D., WILLIAMS, M. P., COWARD, M. P. & WINDLEY, B. F. 1989a. Deformation, metamorphism and imbrication of the Indian Plate, south of the Main Mantle Thrust, North Pakistan. *Journal of Metamorphic Geology*, **7**, 111–125.
- TRELOAR, P. J., COWARD, M. P. & WILLIAMS, M. P. 1989b. Metamorphism and crustal stacking in the North Indian Plate, North Pakistan. *Tectonophysics*, **165**, 167–184.
- TRELOAR, P. J., COWARD, M. P., WILLIAMS, M. P. & KHAN, M. A. 1989c. Basement cover imbrication south of the Main Mantle Thrust, North Pakistan. In: MALINCONICO, L. L. & LILLIE, R. J. (eds) *Tectonics of the Western Himalaya*. Geological Society of America, Special Papers, **232**, 137–152.
- TRELOAR, P. J., REX, D. C., COWARD, M. P. *et al.* 1989d. K/Ar and Ar/Ar geochronology of the Himalayan collision in NW Pakistan: constraints on the timing of collision, deformation, metamorphism and uplift. *Tectonics*, **8**, 891–909.
- TRELOAR, P. J., COWARD, M. P., CHAMBERS, A. F., IZATT, C. N. & JACKSON, K. C. 1991. Thrust geometries, interferences and rotations in the north-west Himalaya. In: McCLAY, K. R. (ed.) *Thrust Tectonics*. Chapman and Hall, London, 325–342.
- TRELOAR, P. J., O'BRIEN, P. J., PARRISH, R. R. & KHAN, M. A. 2003. Exhumation of early Tertiary, coesite-bearing eclogites from the Pakistan Himalaya. *Journal of the Geological Society, London*, **160**, 367–376.
- VANNAY, J.-C. & GRASEMANN, B. 2001. Himalayan inverted metamorphism and syn-convergence extension as a consequence of a general shear extrusion. *Geological Magazine*, **138**, 253–276.
- VINCE, K. J. 1997. *Miocene-aged extension within the Main Mantle Thrust Zone, Pakistan Himalaya*. PhD thesis, Kingston University.
- VINCE, K. J. & TRELOAR, P. J. 1996. Miocene, north-vergent extensional displacements along the Main Mantle Thrust, NW Himalaya, Pakistan. *Journal of the Geological Society, London*, **153**, 677–680.
- VISSERS, R. L. M., PLATT, J. P. & VAN DER WAL, D. 1995. Late orogenic extension of the Betic cordillera and the Alboran domain. *Tectonics*, **14**, 786–803.
- WHEELER, J. & BUTLER, R. W. H. 1994. Criteria for identifying structures related to true crustal extension in orogens. *Journal of Structural Geology*, **16**, 1023–1027.
- WILLIAMS, M. P. 1989. The geology of the Besham area, North Pakistan: deformation and imbrication in the footwall of the Main Mantle Thrust. *Geological Bulletin, University of Peshawar*, **22**, 65–82.
- WINSLOW, D. M., CHAMBERLAIN, C. P. & ZEITLER, P. K. 1995. Metamorphism and melting of the lithosphere due to rapid denudation, Pakistan Himalaya. *Journal of Geology*, **103**, 395–408.
- ZEILINGER, G. 2002. *Structural and geochronological study of the lowest Kohistan complex, Indus Kohistan region in Pakistan, NW Himalaya*. PhD thesis, EH Zurich.
- ZEILINGER, G., BURG, J.-P., CHAUDHRY, N., DAWOOD, H. & HUSSAIN, S. 2000. Fault systems and paleo-stress tensors in the Indus Suture Zone (NW Pakistan). *Journal of Asian Earth Sciences*, **18**, 547–559.
- ZEITLER, P. K. 1985. Cooling history of the NW Himalaya. *Tectonics*, **4**, 128–151.
- ZHU, B., KIDD, W. S. F., ROWLEY, D. B., CURRIE, B. S. & SHAFIQUE, N. 2005. Age of initiation of the India–Asia collision in the east-central Himalaya. *Journal of Geology*, **113**, 265–285.