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Neotectonics of the Nanga Parbat Syntaxis, Pakistan, and crustal stacking in the northwest Himalayas

Robert W.H. Butler [1], David J. Prior [2] and Robert J. Knipe [2]

[1] *Department of Earth Sciences, The Open University, Walton Hall, Milton Keynes MK7 6AA (U.K.)*
[2] *Department of Earth Sciences, The University of Leeds, Leeds LS2 9JT (U.K.)*

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The northwest termination of the Himalayan arc is marked by two large antiformal structures, termed syntaxes, and a NW-SE zone of intermediate depth earthquakes which have yielded both strike-slip and thrust-sense fault-plane solutions. This contribution presents new structural data from the Nanga Parbat area, the northern syntaxis, one of the fastest rising portions of the orogen (7 mm yr^{-1}). Our studies show uplift related to syntaxis growth to be accommodated by structures located along its western margin. Fault kinematics in the southern part of the margin indicate NW-directed thrusting along a shear zone and high level cataclastic faults, termed the Liachar thrust zone. This carries amphibolite facies basement rocks out onto Quaternary sediments. Further north along the western margin active faults are dominantly dextral strike-slip, oriented north-south (e.g. the Shahbatot fault). Overprinting relationships suggest that the strike-slip fault zone has migrated southwards into the NW-directed thrust zone. These relationships are consistent with the northwest termination of the arcuate Himalayan thrust belt at a lateral tip generating folding and radial thrust directions. Faulting patterns at Nanga Parbat suggest that this tip zone has migrated southwards. Active faulting is now concentrated in the northwest continuation of the Hazara (southern) syntaxis, along a seismogenic strike-slip and thrust zone. These deep level tips lie on the crustal stacking thrusts which cut through the higher level, SSE-directed thrusts of Pakistan.

1. Introduction

The complex relationship between continental compressional tectonics and plate motions has been realised for many years, most popularly by analysing seismic fault plane solutions and comparing these with global plate vectors (e.g. 1, 2). Arguably the finest illustration comes from the Himalayas, where the regional plate convergence vector between the Indian subcontinent and "stable" Eurasia is well established from studies of magnetic anomaly patterns on the Indian Ocean [3] and palaeomagnetism [4]. At present the convergence vector of India relative to Eurasia is oriented approximately NNW-SSE with a magnitude of approximately 4.5 cm y^{-1}. Palaeomagnetic [5] and structural studies [6] suggest that this bulk vector is partitioned with approximately 75% accommodated by deformation north of the suture (Tibetan plateau) and 25% on the south side where the Indian continental crust has been stacked up to form the Himalayas.

The geometry of crustal shortening in the Himalayas does not directly mirror the plate convergence. Fault plane solutions defined from seismic first motions [7] on intermediate-depth earthquakes show a radial pattern of thrusting around the Himalayan arc (Fig. 1). This arc follows the main topographic front where elevations decrease below 3 km, coinciding with a series of increased gradients on the antecedent rivers [8]. So there is a strong suggestion from geomorphology and seismicity that the topographic front in the Himalayas is a zone of active thrusting and that this faulting is radially oriented. This deformation zone is marked at outcrop by a belt of broad shear zones, the most notable being the Main Central Thrust (MCT) [9,10]. This ductile shear zone contains evidence from small-scale structures and stretching lineations of radial thrusting [11], parallel to the local fault plane solutions determined by seismicity. However, regional uplift data and metamorphic/ geochronological studies suggest that the MCT was active during the Miocene

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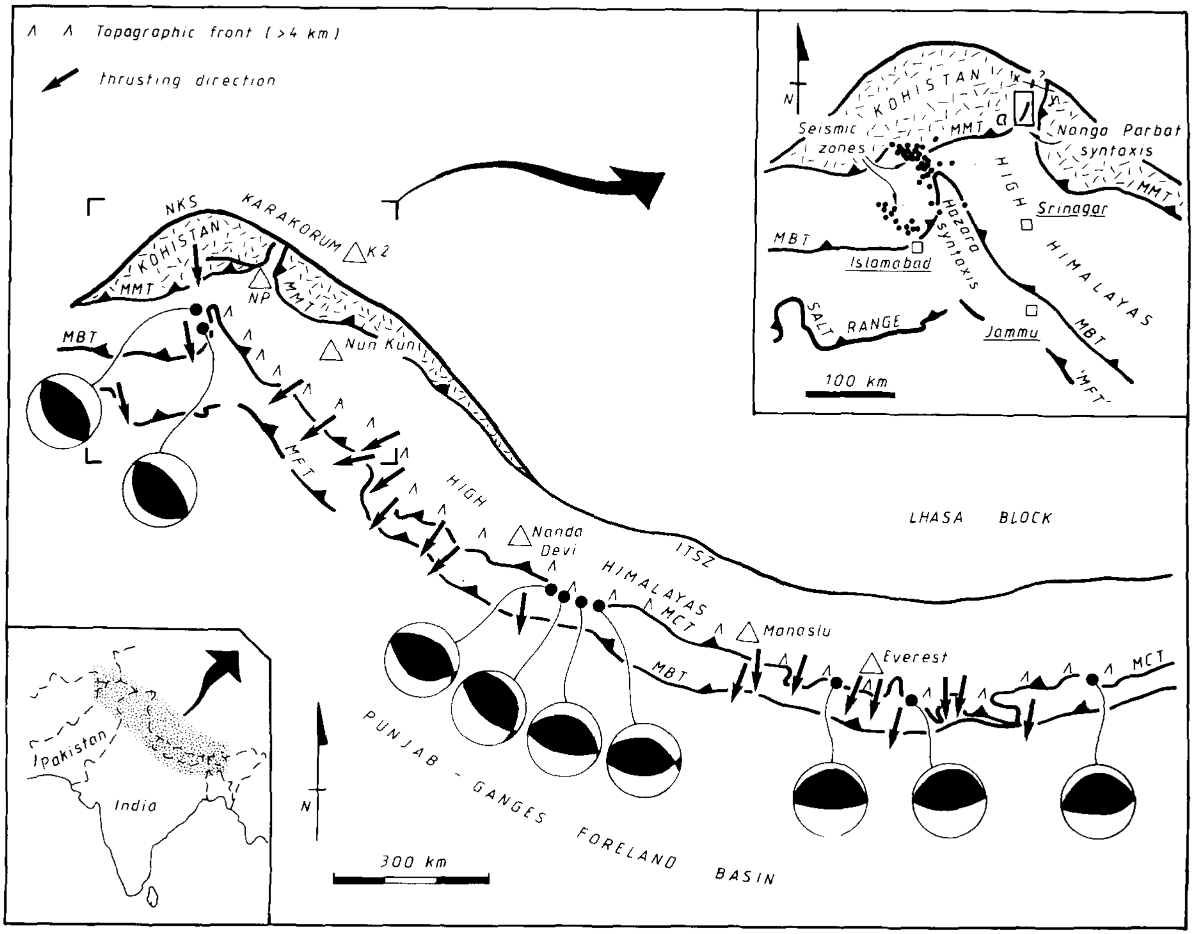

Fig. 1. Simplified tectonic map of the Himalayan collision belt and its location. Thrusting directions are from stretching lineations reported by Brunel [11], selected fault plane solutions from earthquakes [7,24,26,27]. Abbreviations for this and other figures: *MCT* = Main Central Thrust, *MBT* = Main Boundary Thrust, *MFT* = Main Frontal Thrust, *MMT* = Main Mantle Thrust, *ITSZ* = Indus-Tsangpo Suture Zone, *NKS* = Northern Kohistan Suture, *NP* = Nanga Parbat. Inset: detail of northwest termination of the Himalayan ranges in northwestern India and northern Pakistan. Seismic zones associated with syntaxis from Armbruster et al. [24]. *x-y* = line of fission track profile (Fig. 2); *a* = location of Fig. 3.

(15–20 Ma [10,12]). Therefore, the active seismicity probably comes from a deeper level thrust zone which eventually emerges further south in the foredeep basin (Fig. 1).

The parallelism between active fault zones as defined by seismicity and earlier thrusts at outcrop breaks down in the northwestern Himalayas of Pakistan. In this area (Fig. 1) the thrusting direction [6] determined by small scale structures is towards the south-southeast, parallel to the local plate convergence vector. However, the band of intermediate-depth earthquakes continues around the arc, beneath the SSE-directed Pakistani thrust systems. Clearly then there is some interference between the long-term tectonic style expressed as geologic structures at the surface and the active tectonics defined by seismicity. The transition in surface geology from the radial Himalayan arc to the SSE-directed Pakistan thrust system is marked by two large re-entrants of major thrust structures viewed on the map (Fig. 1). These are the Nanga Parbat and Hazara syntaxes, major antiforms which expose structurally deep level rocks in their cores. The Hazara syntaxis uplifts foreland basin rocks from the footwall of the Main Boundary Thrust (MBT) [13]. The Nanga Parbat syntaxis exposes deeply buried Indian continental crust from beneath the principal Tethyan suture zone, locally called the Main Mantle Thrust (MMT) [10,14]. Both antiforms are amongst the largest in the world.

The structural setting of the two syntaxes is crucial in understanding how arcuate thrusting in the main Himalayas terminates. The Nanga Parbat syntaxis is particularly important because its recent uplift history has been documented by reconnaissance fission track studies [15]. These suggest uplift rates over the last 2–3 Myr of 7 mm yr^{-1}, the fastest yet recognised in the Himalayas, approximately one order of magnitude greater than the surrounding region. Structural studies which can illucidate the kinematics of the Nanga Parbat syntaxis therefore will be of paramount importance in understanding not only the large-scale evolution of the Himalayan arc but also how small areas of the mountain belt can experience very rapid differential uplift.

This contribution examines the patterns and kinematics of faulting associated with the development of the Nanga Parbat syntaxis. We will use simple field observations of diagnostic structures (so-called shear criteria [16]) to establish the sense of slip on faults and shear zones. These can be allied to stretching lineation and striation data which indicate the axis of slip on a fault plane, to fully define the local kinematics. Although we consider these datasets to represent palaeo-fault plane solutions they have advantages over geophysically determined solutions. Notably the fault or shear planes and their slip axis can be determined directly hence quasi-nodal planes can be constructed with precision. The sense of shear criteria determine which quadrants were in compression and which in extension. These data could be defined indirectly by well-designed and extensive seismic monitoring. However, structural studies also allow kinematic analysis of micro and aseismic faults and shear zones over tectonically significant time periods.

2. Geological framework and uplift of Nanga Parbat

The Nanga Parbat gneisses represent the most northerly exposure of Indian continental rocks and hence, of the rocks now exposed, were amongst the material most deeply buried beneath the overriding Asian continent during the early part of the collision history. This burial, achieved by movement on the MMT towards SSE, generated kyanite-garnet bearing metamorphic mineral assemblages indicating amphibolite facies conditions. Two distinct suites of metasediments have been recognised [17]. Within the main body of the gneisses lie a series of migmatised pelites, psammites and local marbles which show polyphase tectonic and metamorphic fabrics [18]. The foliations are cross-cut by meta-basic intrusions together with locally larger volumes of leucogranites and aplites. Although the leucogranite suites may well have been generated during Himalayan crustal thickening the earlier basaltic magmatism is difficult to explain in the present tectonic regime. The basic sheets cross-cut earlier metamorphic fabrics but are themselves now at amphibolite facies. Hence, it seems likely that they were emplaced prior to collision and that much of the metamorphism in the Nanga Parbat gneisses must predate this. These gneisses represent the old Indian basement [17].

The second suite of metasediments shows evidence for just one episode of amphibolite facies metamorphism and forms a veneer along the western margin of the syntaxis, in the footwall to the MMT. This is a well-differentiated sequence of psammites, pelites and marbles which we interpret as a possible Phanerozoic cover sequence to the Nanga Parbat basement gneisses [17]. Unfortunately the high degree of Himalayan metamorphism (local kyanite growth) has destroyed any fossil evidence to support this notion.

The hanging-wall (northern side) of the suture contains a remnant island arc complex, the Kohistan terrane [10,19], which docked with the rest of Asia in late Cretaceous times and so can be considered an integral part of the northern block with respect to the Tertiary (main Himalayan) collision [19]. The MMT is preserved as a zone of high-grade shearing with Asia over Nanga Parbat movement senses [17] at the eastern side of the syntaxis and on isolated parts of the western margin. Elsewhere along the western margin the early MMT structures are overprinted by new strains, commonly associated with retrogression of metamorphic mineral assemblages and cataclastic fault zones [20]. There are historical records of earthquakes [21] in the region (1840) although the area is seismically quiet at present. The antecedent

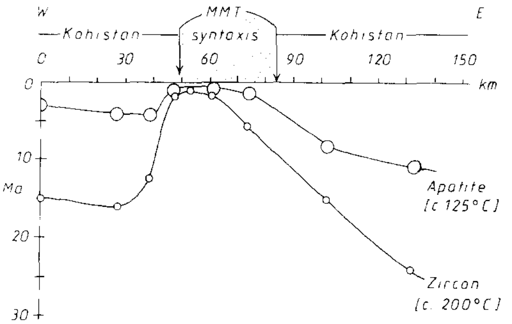

Fig. 2. Fission track profile across the Nanga Parbat syntaxis (x-y in Fig. 1), after Zeitler [15].

Indus river shows increased gradients across the syntaxis suggesting young tectonic activity.

2.1. Uplift of Nanga Parbat

Seminal fission track and $^{40}Ar/^{39}Ar$ studies by Zeitler [15] in northern Pakistan have shown regions of rapid cooling over the last 10–15 Myr compared with background rates. By erecting a preliminary geothermal model based on typical values of heat flow for orogenic belts, Zeitler [15] showed that the Nanga Parbat syntaxis had risen by 10–12 km in the last 10 Myr, at a rate over the last 2–3 Myr of 7 mm yr^{-1}. This compares with a background rate of about 1 mm yr^{-1} for the adjacent Kohistan region. Differential uplift is also indicated by the topographic elevations: Nanga Parbat itself is over 8026 m high while the adjacent Kohistan area rarely climbs above 4000 m. This uplift is strongly concentrated on the western margin of the syntaxis where the rate of cooling has been greatest, in contrast to much slower rates in the east (Fig. 2). We now present new structural data from the western margin of the syntaxis which is relevant to this uplift pattern.

3. Faulting on the western margin of the Nanga Parbat syntaxis

The kinematics and distribution of faults and shear zones on the western margin of the syntaxis help to constrain the tectonic controls on uplift [16,20]. Here we describe the geometry of faulting patterns from south to north (Fig. 3) together with field evidence for kinematic patterns. Research is continuing using metamorphic and microstructural techniques. A more detailed account of the various conditions of faulting, the variations in fault rock type with time and the cooling history of the western margin of the syntaxis will be reserved for a future publication.

3.1. The Raikhot–Liachar section

In this sector (Fig. 4) the MMT lies down in the base of the Indus valley where it is vertical, striking NE–SW. Foliation in both the Kohistan terrane and Nanga Parbat gneisses is parallel to the MMT. However, further southeast into the syn-

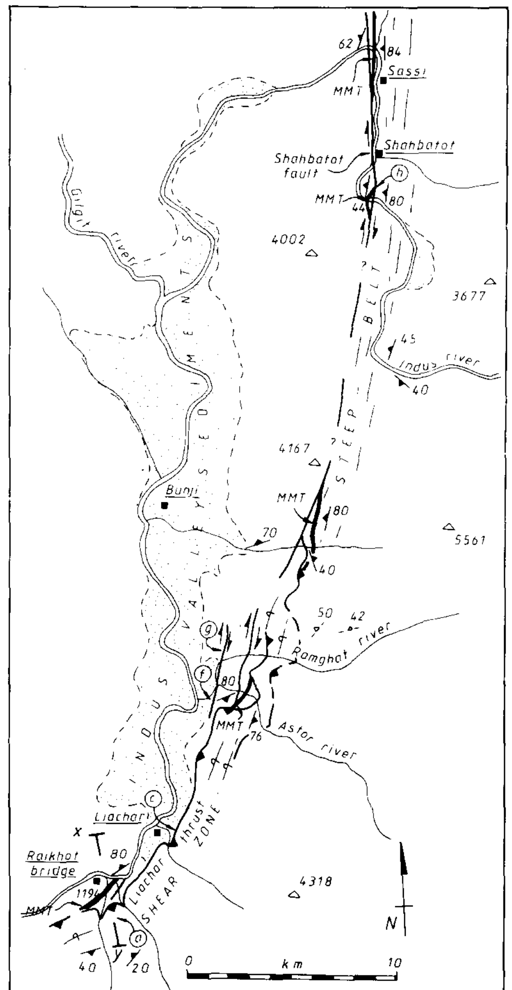

Fig. 3. Sketch map of western margin of the Nanga Parbat syntaxis, from Raikhot to Sassi, see Fig. 1 for location. Foliation orientations measured by authors or estimated for distance (pecked). Locations of other figures: x-y = Fig. 4, a = Fig. 6a, c = Fig. 6c, f = Fig. 9, g = Fig. 10, h = Fig. 11a, b.

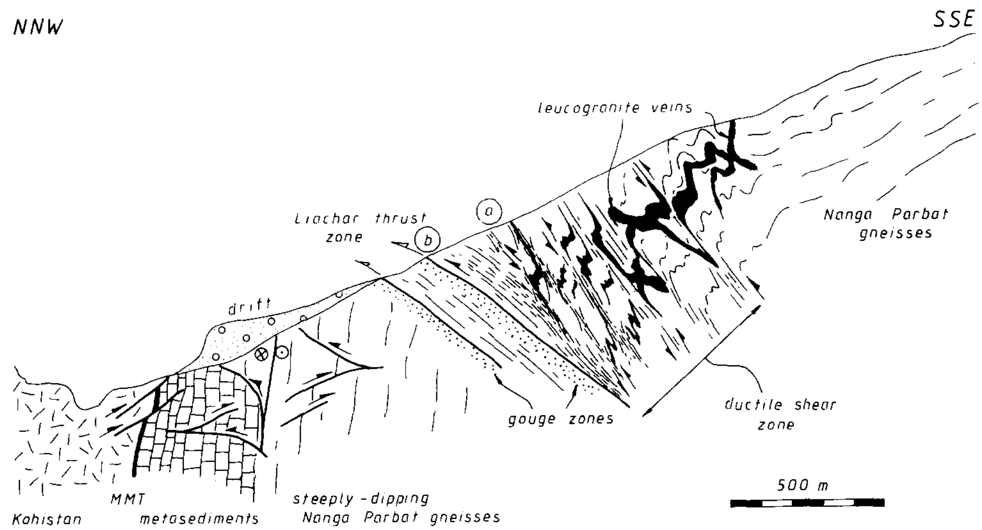

Fig. 4. Sketch geological cross-section (x-y in Fig. 3) through the Raikhot part of the syntaxis margin. Locations of other figures: a = Fig. 6a, b = Fig. 6b.

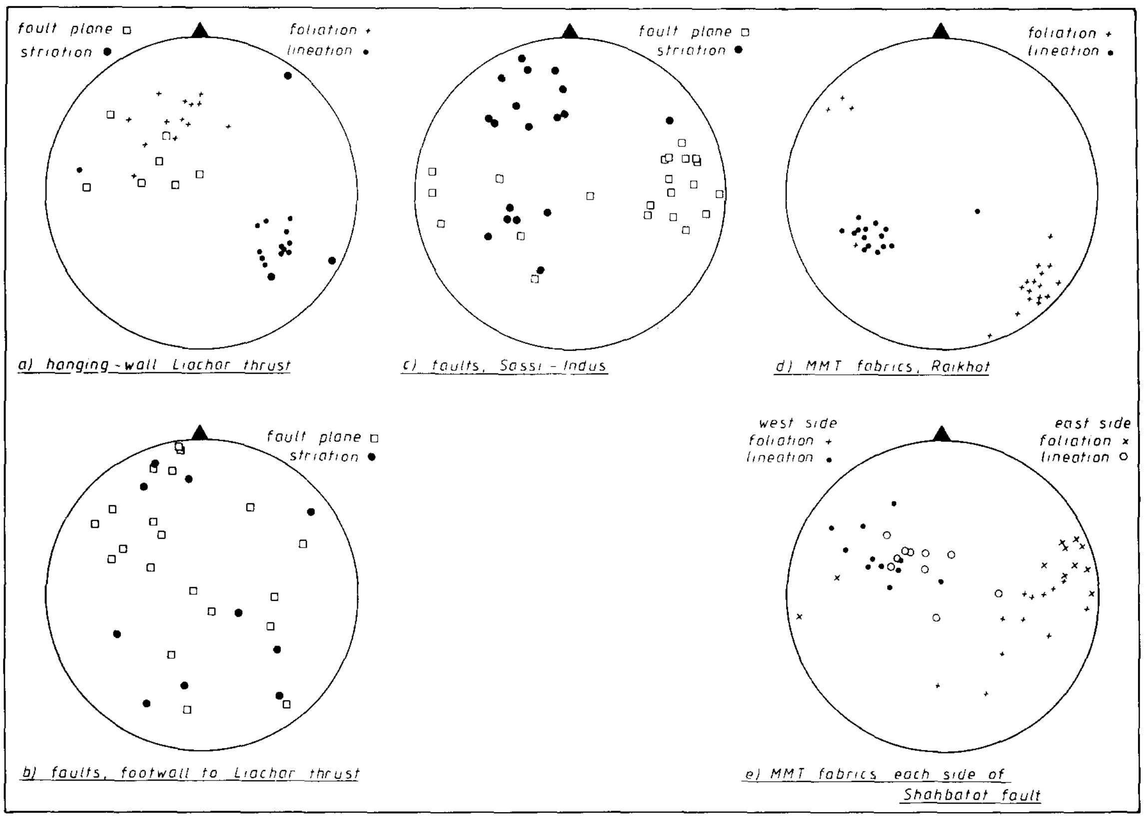

Fig. 5. Structural orientation data (lower hemisphere projections) for selected features from various locations along the western margin of the Nanga Parbat syntaxis. (a) Foliations and lineations within the shear zone in the hanging-wall to the Liachar thrust (Raikhot–Liachar sector), together with associated fault planes. (b) Fault plane and associated striation orientations in the footwall to the Liachar thrust at Raikhot. (c) Fault planes and associated striations from the MMT area at Sassi. (d) Foliation and lineation orientations on amphibolite-facies structures associated with the MMT at Raikhot. (e) Foliation and lineation orientations associated with amphibolite facies structures along the MMT at Sassi. Grouped for each side of the Shahbatot fault zone.

taxis the foliation within the Nanga Parbat gneisses dips moderately southeast (Fig. 4) and develops a prominent SE-plunging stretching lineation (Fig. 5a). Shear criteria, from rotated feldspar augen, shear bands (Fig. 6a) to large-scale offset of lithological markers indicate NW-directed thrusting [20]. This shear zone initiated at amphibolite facies but was active through biotite and chlorite grades

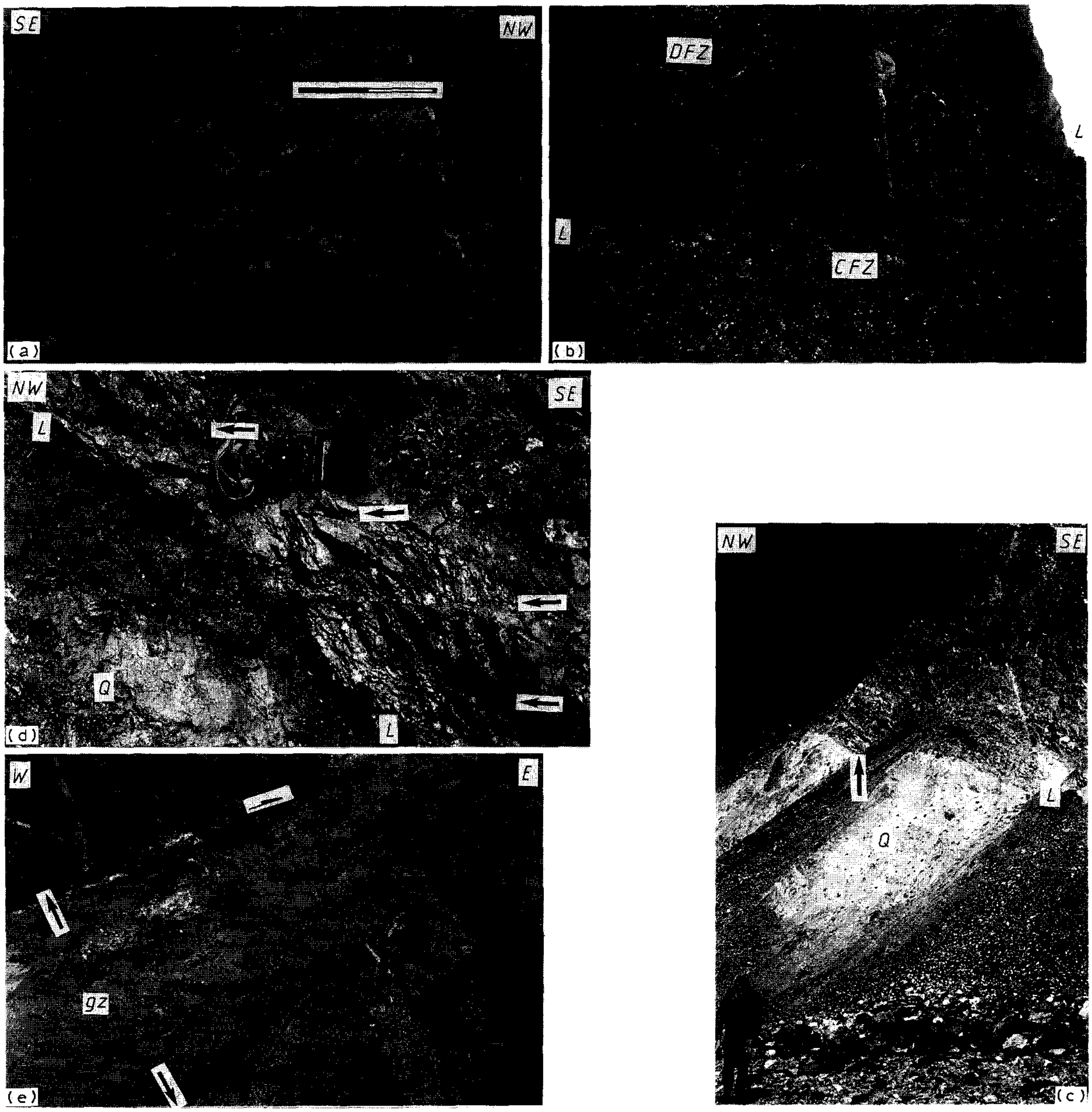

Fig. 6. Details of fault zone characteristics and kinematic indicators. (a) Shear bands and asymmetric feldspar augen in the amphibolite facies shear zone above the Liachar thrust. Scale bar 10 cm, location on Figs. 3 and 4. (b) Detail of the cataclastic fault zone (*CFZ*), a splay from the Liachar thrust, and its abrupt upper boundary (*L*) with the amphibolite facies ductile fault zone (*DFZ*). Outcrop on ridge above Raikhot bridge (see Fig. 4). (c) A view of the lower part of the Liachar thrust (*L*) in its type area (see Fig. 3) where it over-rides Quaternary sediments (*Q*). The visible cliff height is about 30 m. Arrow points to location of (d). (d) Detail of the Liachar thrust (*L*: arrowed in (c)). Riedel shears [28] are arrowed; they imply NW-directed faulting. (e) Cataclastic SE-directed fault zone in the Ramghat valley (near *g* in Fig. 3), marked by a 1 m gouge zone (*gz*).

in some parts. It is carried on a zone of cataclastic faulting (Fig. 6b), with prominent gouges and penetrative fracturing. This is termed the Liachar thrust [20] and it represents fault activity at the highest crustal levels. In its type area around Liachar village the thrust zone over-rides Quaternary Indus valley sediments (Fig. 6c) which otherwise mask the steep MMT zone. This cataclastic Liachar thrust shows the same kinematics as the ductile shear zone it carries [20]. Small-scale riedel shear [20] fractures link across onto the lowest fault plane and show clear NW-directed offsets (Fig. 6d). So in the Liachar–Raikhot area the Nanga Parbat syntaxis has been carried up from crustal levels suitable for the growth of amphibolite facies assemblages (ca. 550–650 ° C) to the present topographic surface [20,21]: this is more than adequate to explain the uplift path of the Nanga Parbat gneisses defined by fission track and $^{40}Ar/^{39}Ar$ studies [15]. Note that the asymmetric uplift induced by thrusting also provides an explanation for the fission track profile across the syntaxis (Fig. 2).

The MMT and associated foliations now found in the footwall to the Liachar thrust at Raikhot are steeply dipping (Fig. 5d). The early stretching lineation associated with movements on the MMT now plunges southwest in contrast to its regional NNW plunge azimuth [10,19]. We consider the steepening of the MMT and the deflection of the early lineations to represent substantial flattening strains associated with the early growth of the syntaxis [20].

This steep belt in the footwall to the Liachar thrust contains a complex suite of fault zones (Fig. 5b) with a wide range of orientations. The most obvious features are N–S trending gouge and breccia zones which contain gently plunging mineral lineations indicating strike-slip. However, in this region there are very few suitable kinematic indicators so the sense of slip on these strike-slip faults has not been resolved. There are also steep, N–S trending zones of penetrative fracturing and shatter which do not show significant offset (Fig. 7). These could represent tips to the strike-slip faults, where seismic damage has been localised. Additional fault zones with only minor (1–2 m) offsets occur in the footwall to the Liachar thrust. These have both NW- and SE-directed thrust senses, cutting the steep, high-grade MMT structures. We interpret these as forming at higher crustal levels, accommodating later parts of the strain which steepens up the MMT. These fault zones are generally overprinted by the steep strike-slip fault zones and their associated shattering.

Fig. 7. Photograph (profile view, looking northeast) of a vertical strike-slip fault zone (NE–SW trending) within the Liachar thrust zone. The strike-slip fault shows only minor lateral offsets and is associated with shattering and the development of prominent joints parallel to the principal fault strand.

3.2. The Ramghat–lower Astor section

The Liachar thrust can be traced northwards above the Indus valley from Liachar village to above the mouth of the Astor gorge (Fig. 3). Here the hanging-wall structure is more complex than above Raikhot, with two shear zones developed within the Nanga Parbat gneisses (Fig. 8. These structures deflect the early banding into tight syn-

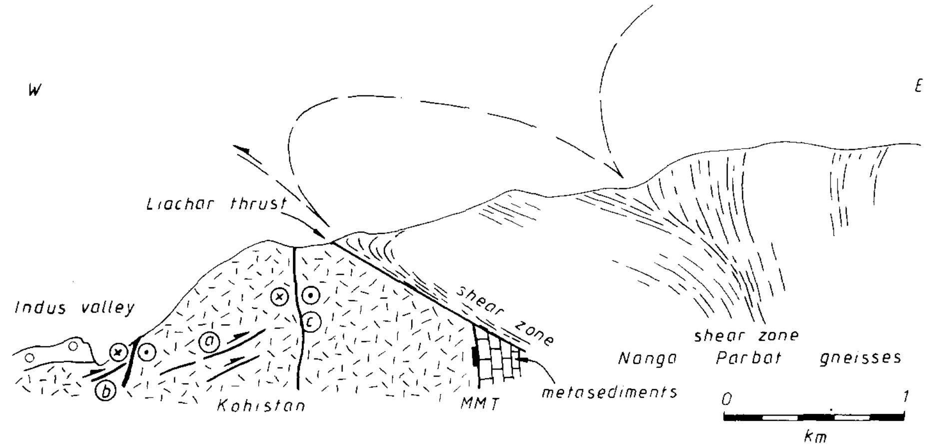

Fig. 8. Sketch cross-section through the western margin of the Nanga Parbat syntaxis, exposed along the ridge between the Ramghat and Astor valleys (Fig. 3). *MMT* = Main Mantle Thrust. *a* = location of Fig. 6e, *b* = Fig. 9, *c* = Fig. 10.

forms, reminiscent of the "pinched-in" synclines of cover sediments found at some Alpine basement massifs [22]. High on the hillside there is only minor cataclastic faulting. However, there are other cataclastic faults lower in the structure, in the footwall to the Liachar thrust zone. A continuous section is provided by the Ramghat valley (Fig. 8). This shows a suite of cataclastic faults which dip northwest, towards the Indus valley. The host rock is a complex suite of basic intrusions including gabbro and a suite of pegmatites, bearing igneous hornblendes, which are offset by the cataclastic faults. These offsets imply SE-directed thrust movements. The fault rocks are poorly consolidated gouges (Fig. 6d) and were clearly generated at about the same crustal level as the cataclastic parts of the Liachar thrust further south.

The SE-directed thrust can be traced across to the Astor valley (Fig. 9). In this section, low on the hillside, the thrusts climb over Quaternary valley fill which has been trapped between the uplifted fault block and the bed rock of the valley side. This section (Fig. 8) contains other faults which run N–S and are vertical, the same trend as the strike-slip faults at Raikhot. One particularly prominent fault is marked by about 3 m of gouge which separates the valley wall to the east from unconsolidated screes, debris flow and alluvial deposits (Fig. 9). A splay from this gouge zone cuts up into these sediments indicating recent fault activity. So both steep faults and moderately dipping SE-directed thrusts have operated during Quaternary times.

Deformation within the 3 m gouge was presumably dominated by grain boundary sliding mechanisms since the grain size is many orders of magnitude smaller than the width of the fault zone. This fault gouge appears to have evolved almost homogeneously so that kinematic indicators are not developed at the hand-specimen scale. However, the slip sense can be established from a splay in the adjacent Ramghat section to the north. The SE-directed gouge thrust zones are cut by several steep fault zones which link across to the major fault at the mouth of the Astor valley (Fig. 9). These steep fault zones contain gently plunging mineral fibres, grooves and slickensides suggesting strike-slip. To correlate these faults with regional structural models it is critical to determine the shear sense on the strike-slip fault zones. The sense of offset can be defined by riedel shear arrays (Fig. 10) when viewed from above. These imply dextral slip sense.

Both the strike-slip faults and thrusts in the Ramghat–lower Astor section obscure the MMT. This can be found in an isolated window between a NW-directed splay from the Liachar thrust and a strike slip fault which cuts it. It is not evident in the Ramghat valley.

3.3. The Sassi-Indus section

The margin of the Nanga Parbat syntaxis is marked by a steep fault zone which can be found

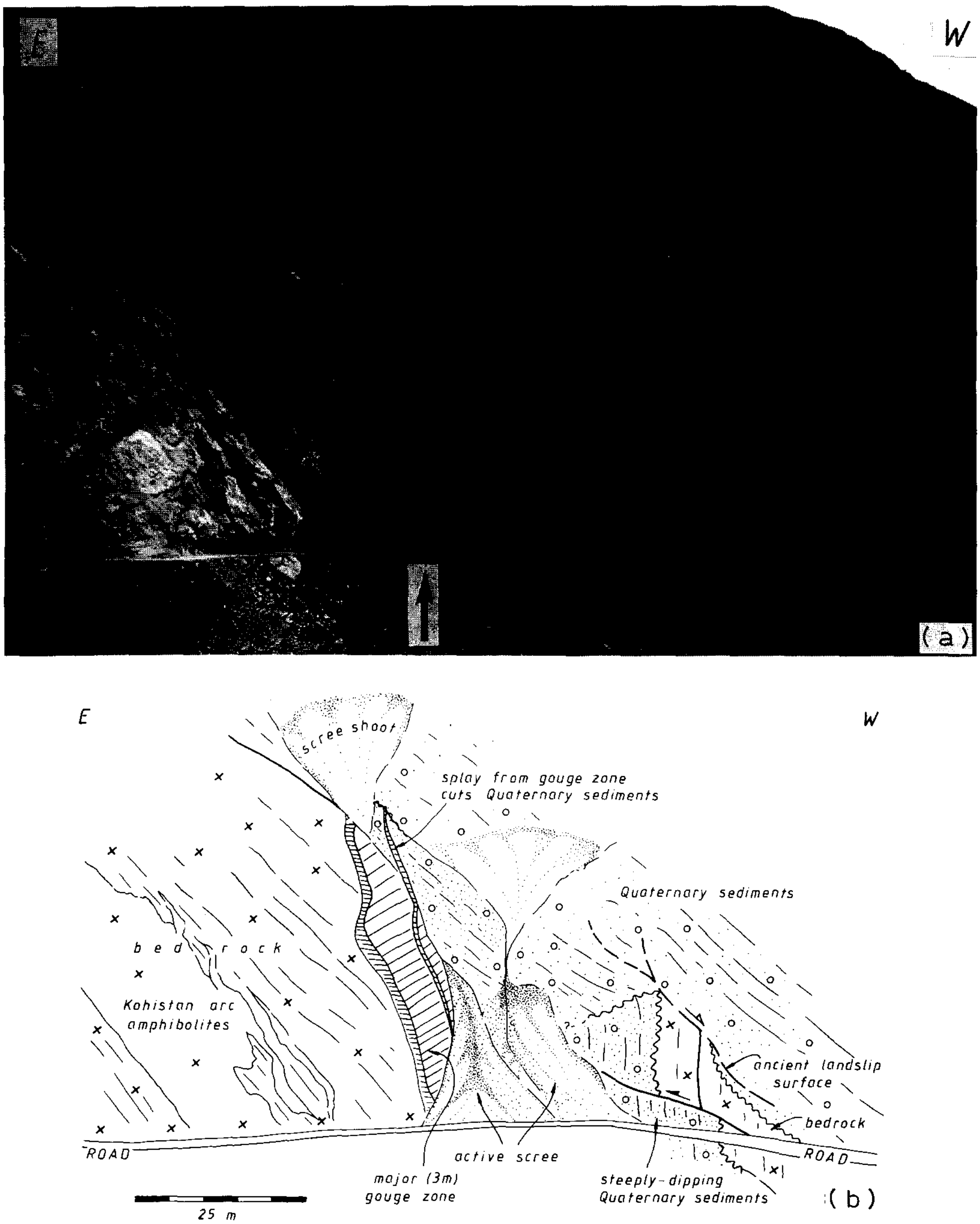

Fig. 9. (a) View of the relationships between bedrock (Kohistan complex gneisses and metagabbro) and Quaternary Indus valley sediments in the lower Astor Valley, near its confluence with the Indus (*f* in Fig. 3). The major gouge zone is arrowed. (b) Interpretation of the above, based on detailed field observations.

in the upper Bunji valley and again in the Indus around Sassi (Fig. 3). This separates Kohistan rocks which dip moderately west from a steep belt in the east containing Nanga Parbat gneisses together with local slices of the MMT and Kohistan units. There is no equivalent structure to the Liachar thrust in these northern areas. The only discrete shear zone, which shows a NW-directed

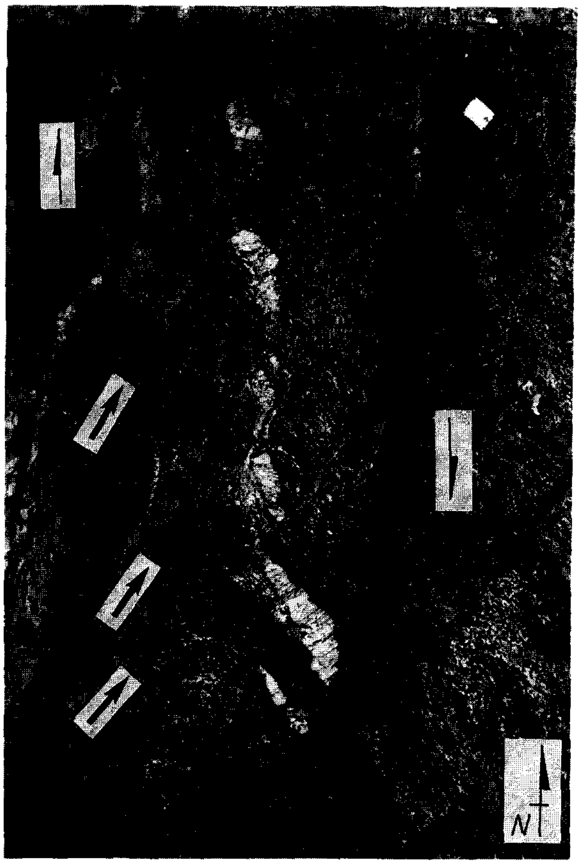

Fig. 10. Riedel shears [28] (arrowed) on a dextral strike-slip splay in the Ramghat valley (*g* in Fig. 3).

thrust sense, lies on the south side of the Bunji valley where it plunges northwards beneath the steep belt (Fig. 3).

The steep fault which bounds the belt of sub-vertical foliation of the syntaxis from gently dipping Kohistan rocks can be traced crossing the Indus valley at Sassi. Several good profiles through it occur up on the hillsides (Fig. 11). The small-scale fracture patterns and shear fabrics (Fig. 11b) indicate dextral offsets. This major strike-slip fault is termed here the Shahbatot fault after the village on the Indus through which it passes.

The Shahbatot fault is not the only structure in the Sassi-Indus area to be related to the growth of the Nanga Parbat syntaxis. There are strong indications of east-west shortening, perpendicular to the strike-slip fault zone. The clearest examples are discrete reverse faults marked by zones of gouge and cataclasites which can show both east and west-directed offsets. Collectively these faults form a crude conjugate set which accommodate moderate amounts of vertical extension and east-west shortening. Unfortunately few of these contain clear striations to allow accurate kinematic determinations. However these faults show a geometric grouping (Fig. 5c), with the few recognisable striae plunging WSW. The striations on the major oblique and strike-slip faults (e.g. Shahbatot) plunge to the NW quadrant (Fig. 5c).

The strain intensification and rotation of the MMT into the margin of the syntaxis can be recognised in the differing orientations of MMT associated fabrics across the Shahbatot fault (Fig. 5e). The west side of the fault contains little modified MMT structures while on the east these early structures have been flattened and rotated into a steep orientation. We interpret this strain in a similar way to the steep dip of the MMT at Raikhot, as representing the early growth of the syntaxis. The Sassi-Indus section can be explained by the MMT being rotated during E–W compression followed by E–W compressional faulting and N–S dextral strike-slip.

3.4. Lateral changes in structural style

Apart from the distribution of strike-slip faulting there are important variations in compressional structural style along the western margin of the syntaxis. At Liachar compression is accommodated by thrusting. However, the MMT in the footwall to the Liachar thrust now has a vertical attitude suggesting a strong buckling component associated with this thrusting (Fig. 12). At Sassi in the north there is no indication of the Liachar thrust in the Indus gorge section. It may of course lie buried, cut out by the Shahbatot strike-slip fault. However, there is no indication of other major fault zones on the hillsides. It seems most likely that uplift along the northern Indus valley section occurred by buckle folding and E–W flattening. The transition between the thrust-fold geometries at Liachar and the kilometric buckle fold at Sassi apparently involves a series of ductile shear zones (Fig. 12) exposed along the Ramghat section.

Lateral variations in structural style render any quantitative modelling of uplift paths using the current fission track dataset [15] premature. Varying degrees of folding and thrusting will clearly

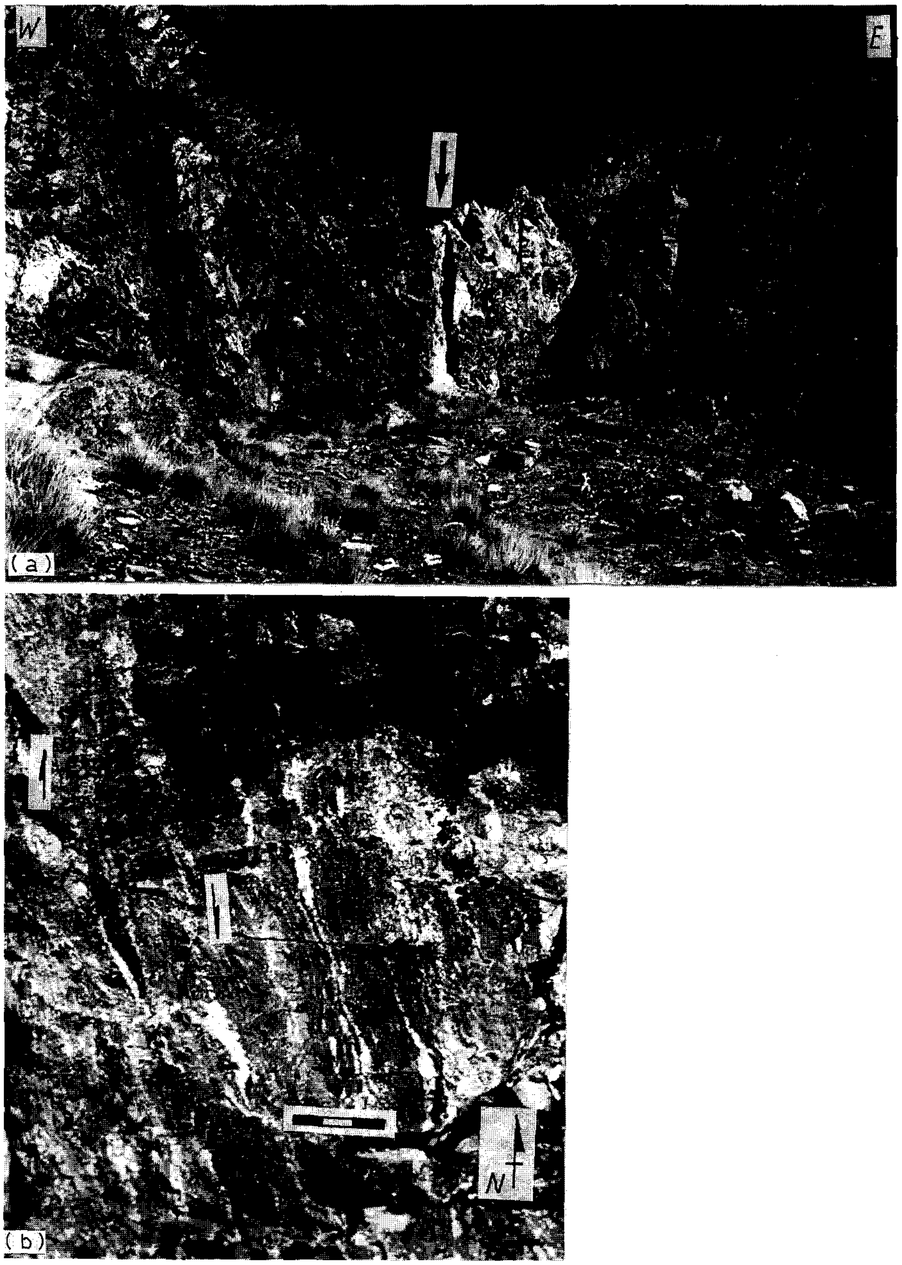

Fig. 11. (a) The Shahbatot fault (youngest cataclastic break arrowed) above the Indus near its type area (*h* in Fig. 3). Cliffs 20 m at their lowest point. (b) Biotite grade mylonites ca. 50 m west of the arrowed part of the Shahbatot fault (see (a)). Relict pods deflected into shear zone to give dextral shear sense. Scale bar 3 cm.

generate different *P-T* paths in the syntaxis so the fission track data should not be projected away from their specific structural location. This problem is compounded by strike-slip faulting on the margin of the massif. We might expect this to juxtapose rocks with different thermal histories. In any event, with the intense topographic relief we might expect a strong lateral component to heat

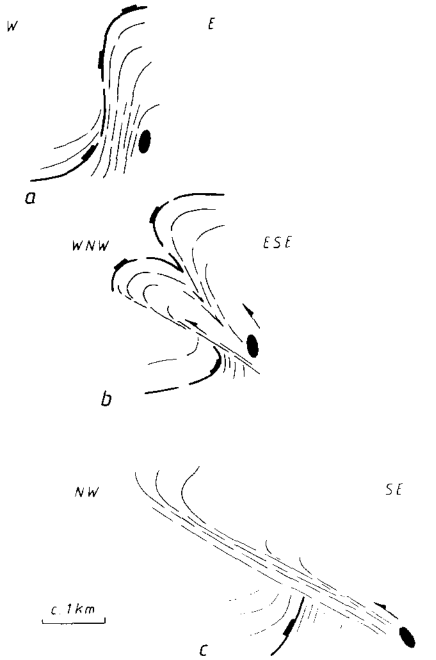

Fig. 12. Sketch sections illustrating the variation in styles of compressional structures along the western margin of the Nanga Parbat syntaxis. (a) Sassi, (b) Ramghat, (c) Raikhot. The brick-ornamented line represents the MMT.

flow so that thermal structure within the syntaxis will not be a simple function of uplift alone.

4. Interactions between strike-slip and thrusting

Although it is difficult to interpret the long term thermal evolution of the Nanga Parbat syntaxis we can consider the later episodes of faulting with a reasonable degree of confidence. It is likely that all the poorly consolidated gouge zones represent faulting at high crustal levels and therefore will be young. There is a relatively simple distribution of the two distinct styles of faulting and shearing along the western margin of the syntaxis. The southern sector around Riakhot involves thrusting, directed dominantly towards the northwest. The major structure here is the Liachar thrust zone. In the north, neglecting the major buckle fold and associated strains, the dominant structure is the strike-slip Shahbatot fault. A transition zone lies around the Ramghat-Astor gorge area where both strike-slip and thrust tectonics are operative, although those late gouge zones which lie on thrusts are directed into the syntaxis (i.e. southeast).

Using the kinematic data from the cataclastic faults from Sassi-Indus to Raikhot we can produce a map of palaeo-fault plane solutions (Fig. 13). Note however that this cannot represent the pure shear dominated flattening strains associated with the early growth of the syntaxis which is represented by the steep MMT. Nevertheless we can explore the larger-scale kinematic implications of the map. The critical feature is the distribution of the various faults and how they spatially relate to each other. This type of information is usually

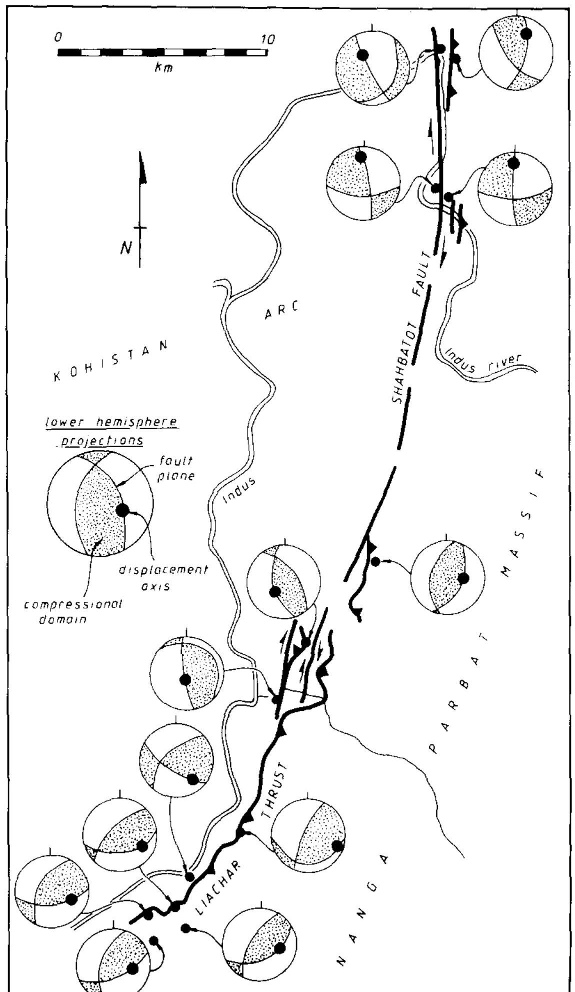

Fig. 13. Palaeofault plane solution map of western margin of the Nanga Parbat massif, based on structural kinematic indicators in fault zones recorded by the authors. The area of the map is as for Fig. 3.

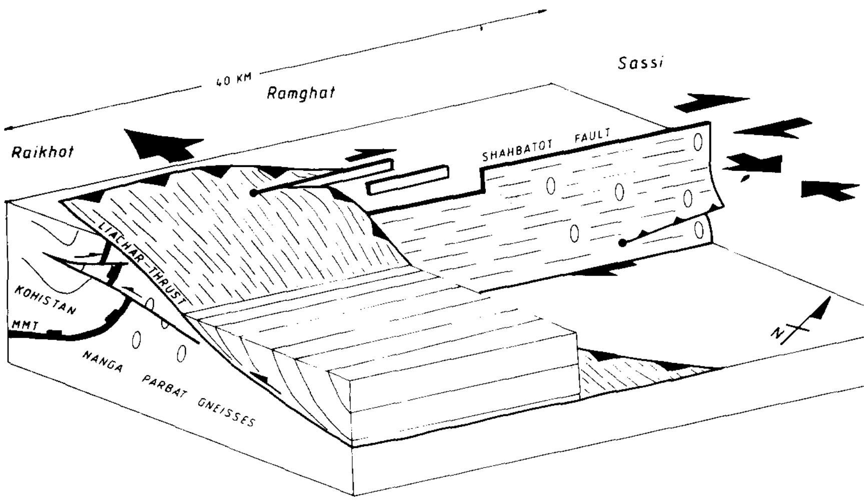

Fig. 14. Stylised block diagram showing the interpreted relationship between thrust and strike-slip fault zones along the western margin of the Nanga Parbat syntaxis. High-level cataclastic fault zones which form the pattern apparently migrated southwards with time so that strike-slip overprints thrusting.

available only from exceptionally detailed micro-seismic investigations on the few presently active faults. However, structural data can be gathered from seismically inactive faults and fault strands to provide a far more complete picture.

Since uplift has been fast in the Nanga Parbat area it is likely that all the gouge zones, generated within a few kilometres of the earth's surface, have been active over the same short time span. This

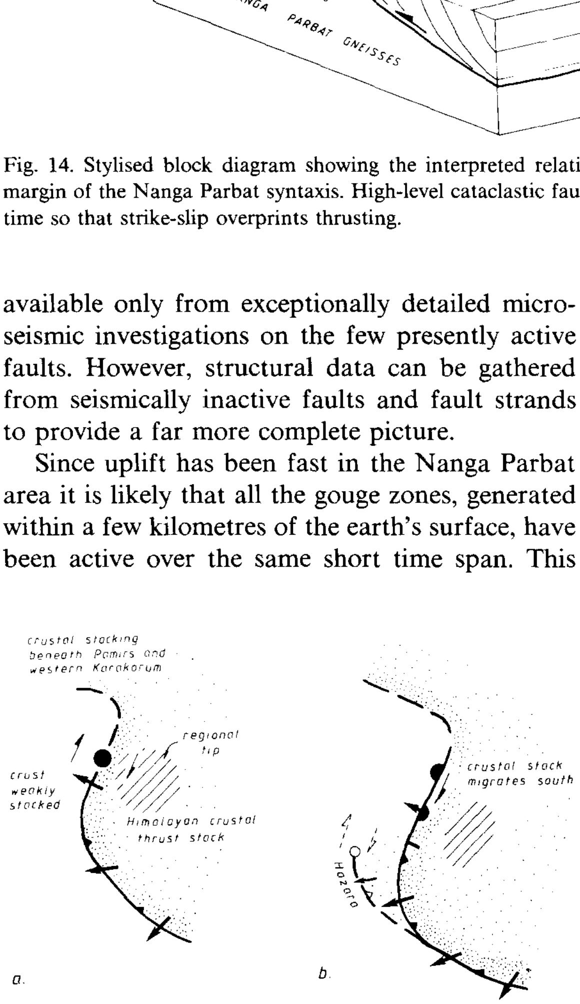

Fig. 15. A regional model (no scale intended) for the development of the Nanga Parbat massif by laterally inhibited crustal stacking beneath the High Himalayas, adjacent to weakly stacked crust beneath the northern Pakistan thrust systems. Such a pattern generates a dextral shear couple with clockwise rotates and radial thrusting. With time (b) this dextral wrench system will migrate south and may generate splays (e.g. Hazara syntaxis and the associated seismic zones, see Fig. 1) to the southwest.

pattern of neotectonic activity is indicated in Fig. 14. The present southern limit of strike-slip faulting lies in the Raikhot area where it is largely represented by shattering without appreciable offsets. This pattern is in contrast to the north sector where the Shahbatot fault appears to be a major structure, separating steep rocks in the core of the syntaxis from moderately dipping MMT structures on the flanks. These observations suggest that the strike-slip faulting has a longer history in the north than in the south, probably reflecting a north to south migration with time. The Shahbatot fault strikes N–S in its type area and is unlikely to bend in a continuous fashion around the syntaxis margin. A more plausible geometry is for a belt of en echelon strike-slip strands, which gradually step westwards (Fig. 15), collectively to form a releasing bend [23] on the dextral system. This broadening occurs around the Ramghat-Astor gorge sector where the areal extent of cataclastic faults is greatest.

5. Regional tectonics: seismicity and syntaxes

During the construction of the Tarbela dam in the northwest Himalayan foothills of Pakistan approximately five years of microseismic data were collected. These defined two belts of intermediate depth earthquakes, termed the Indus-Kohistan and Tarbela Seismic Zones [24]. The belts run NW–SE, oblique to surface thrust trends. They form the map continuations of the main Himalayan arc sweeping in from the southeast (Fig. 1). It is tempting therefore to relate the seismicity to the subsurface continuation of a deep main Himalayan thrust, one which is cutting up from mid-crustal levels [24]. However, there is a range of strike-slip and thrusting solutions on these active fault planes, as there was on the palaeofault zones at Nanga Parbat.

The main Himalayan arc presently terminates at the Hazara syntaxis, an analogous structure to the Nanga Parbat syntaxis. It too is a region of rapid uplift as indicated by locally increased stream gradients [8] and regionally anomalous topography. There have been no fission track studies to date which might confirm the geomorphological interpretation. Nevertheless, the syntaxis is an antiform [13], best explained as lying above the continuation of a main Himalayan thrust which is cutting up from mid-crustal levels [6].

In the frontal parts of mountain belts where structures involve synorogenic sediments, it is relatively commonplace for folds to develop at the lateral terminations of thrust [25]. They represent the change in deformation style from being highly localised along the thrust to distributed through the fold. On a regional scale both the Hazara and the Nanga Parbat syntaxes show this arrangement. The terminating thrusts are not those Himalayan structures at outcrop (MCT, MBT) but are deeper level fault zones which have been active in the recent past and stack the crust. How do the faulting patterns at Nanga Parbat relate to this model?

Dextral strike-slip along the western margin of the Nanga Parbat syntaxis is entirely consistent with the predicted distribution [6] of crustal shortening in the northwest Himalayas (Fig. 15). Thickening to the east of the syntaxis is indicated by enhanced topographic relief in these regions compared to the equivalent thrust systems to the west (Fig. 1). The thrust termination model predicts that dextral faulting should gradually overprint the marginal thrusts as the system evolves and migrates southwards. The pattern of fault activity at Nanga Parbat is consistent with this model.

It is likely then that the northwestern Himalayan syntaxes result from the lateral termination of major crustal thickening thrusts which operate beneath the main Himalayan arc. These thrusts are climbing through from beneath the higher level thrust systems of Pakistan to expose deep parts of the orogenic complex. There is a local obliquity between these two thrust systems so that the SSE-directed Pakistan thrust belts are overprinted by SW-directed crustal stacking structures. Clearly both thrust directions are related to the India–Asia collision and, on the scale of the mountain belt, are coeval. In older orogenic belts where lateral continuity of exposure has been lost these types of structural relationships may be misinterpreted as representing two distinct orogenic episodes. It may also be difficult to match particular parts of *P-T* paths to movements on specific thrust and fault zones. In the northwest Himalayas this is possible but a complete analysis of the thermal and uplift history of the Nanga Parbat syntaxis requires a rigorous collection of samples for radiometric and fission track analysis, tightly tied in to local structure. Studies of the continuing tectonic history of the region would be greatly enhanced by detailed microseismic monitoring, such as the prematurely curtailed experiments at Tarbella.

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References

1 J.A. Jackson and D.P. McKenzie, Active tectonics of the Alpine-Himalayan Belt between western Turkey and Pakistan, Geophys. J. R. Astron. Soc. 77, 185–264, 1984.

2 D.P. McKenzie and J.A. Jackson, A block model for distributed deformation by faulting, J. Geol. Soc. London 143, 349–353, 1986.

3 P. Patriat and J. Achache, India-Eurasia collision chronology has implications for crustal shortening and driving mechanism of plates, Nature 311, 615–621, 1984.

4 C.T. Klootwijk, A review of Indian Phanerozoic palaeomagnetism: implications for the India-Asia collision, Tectonophysics 105, 331–353, 1984.

5 J. Achache, V. Courtillot and Y.X. Zhou, Palaeogeographic and tectonic evolution of southern Tibet since middle Cretaceous time: new palaeomagnetic data and synthesis, J. Geophys. Res. 89, 10311–10339, 1984.

6 R.W.H. Butler and M.P. Coward, Crustal scale thrusting and continental subduction during Himalayan collision tectonics on the NW Indian plate, in: Tectonic Evolution of the Tethyan Region, A.M.C. Sengor, ed., NATO ASI Ser. C 259, 387–413, 1989.

7 L. Seeber, J.G. Armbruster and R.C. Quittmeyer, Seismicity and continental subduction in the Himalayan arc, Am. Geophys. Union, Geodyn. Ser. 5, 215–242, 1981.

8 L. Seeber and V. Gornitz, River profiles along the Himalayan arc as indicators of active tectonics, Tectonophysics 92, 335–367, 1983.

9 A. Gansser, The Geology of the Himalayas, John Wiley, London, 1964.

10 P. Le Fort, The Himalayan orogenic segment, in: Tectonic Evolution of the Tethyan Region, A.M.C. Sengor, ed., NATO ASI Ser. C 259, 289–386, 1989.

11 M. Brunel, Ductile thrusting in the Himalayas: shear sense criteria and stretching lineations, Tectonics 5, 247–265, 1985.

12 P. Le Fort, Metamorphism and magmatism during the Himalayan collision, in: Collision Tectonics, M.P. Coward and A.C. Ries, eds., Spec. Publ. Geol. Soc. London 19, 159–172, 1986.

13 P. Bossart, D. Dietrich, A. Greco, R. Ottiger and J.G. Ramsay, The tectonic structure of the Hazara-Kashmir syntaxis, southern Himalayas, Pakistan, Tectonics 7, 273–297, 1988.

14 R.A.K. Tahirkheli, The geology of Kohistan and adjoining Eurasian and Indo-Pakistan continents, Pakistan, Geol. Bull. Univ. Peshawar Spec. Issue 11, 1–30, 1979.

15 P. Zeitler, Cooling history of the NW Himalaya, Pakistan, Tectonics 4, 127–151, 1985.

16 P.R. Cobbold, D. Gapais, W.D. Means and S.H. Treagus, eds., Shear criteria in rocks, J. Struct. Geol. 9, 521–778, 1987.

17 R.W.H. Butler and D.J. Prior, Anatomy of a continental subduction zone: the Main Mantle Thrust in northern Pakistan, Geol. Rundsch. 77, 239–255, 1988.

18 P. Misch, Stable association wollastonite-anorthite and other calc-silicate assemblages in amphibolite facies crystalline schists of Nanga Parbat, northwest Himalayas, Contrib. Mineral. Petrol. 10, 315–356, 1964.

19 M.P. Coward, B.F. Windley, R.D. Broughton, I.W. Luff, M.G. Petterson, C.J. Pudsey, D.C. Rex and M.A. Khan, Collision tectonics in the NW Himalayas, in: Collision Tectonics, M.P. Coward and A.C. Ries, eds., Spec. Publ. Geol. Soc. London 19, 203–219, 1986.

20 R.W.H. Butler and D.J. Prior, Tectonic controls on the uplift of Nanga Parbat, Pakistan Himalayas, Nature 333, 247–250, 1988.

21 R.W.H. Butler, L. Owen and D.J. Prior, Flashfloods, earthquakes and uplift in the Pakistan Himalayas, Geol. Today 4, 197–201, 1988.

22 J.G. Ramsay, Stratigraphy, structure and metamorphism in the western Alps, Proc. Geol. Assoc. 74, 357–391, 1963.

23 R.H. Sibson, Earthquakes and lineament infrastructure. Philos. Trans. R. Soc. London Ser. A, 317, 63–79, 1986.

24 J. Armbruster, L. Seeber and K.H. Jacob, The northwestern termination of the Himalayan mountain front: active tectonics from microearthquakes, J. Geophys. Res. 83, 269–282, 1978.

25 C.D.A. Dahlstrom, Structural evolution in the eastern margin of the Canadian Rocky Mountains, Bull. Can. Pet. Geol. 18, 332–406, 1970.

26 L. Seeber and J.G. Armbruster, Seismicity in the Hazara arc in northern Pakistan: decollement versus basement faulting, in: Geodynamics of Pakistan, A. Farah and K. De Jong, eds., pp. 131–142, Geological Survey of Pakistan, Quetta, 1979.

27 J. Ni and M. Barazangi, Seismotectonics of the Himalayan Collision Zone: geometry of the underthrusting Indian plate beneath the Himalaya, J. Geophys. Res. 89, 1147–1163, 1984.

28 F.M. Chester, M. Friedman and J.M. Logan, Foliated cataclasites, Tectonophysics 111, 139–146, 1985.