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Vertical stretching and crustal thickening at Nanga Parbat, Pakistan Himalaya: A model for distributed continental deformation during mountain building

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[1] The localization of strain in the continental crust during compressional tectonics is examined using the active structures at the Nanga Parbat massif, an exhumed tract of Indian continental crust in the Pakistan Himalaya. This large-scale (~40 km wavelength) structure is considered to involve the whole crust. Thrusting at the modern surface places gneisses of the Indian continental crust onto Holocene deposits. At the Raikhot transect, the thrust zone carries a relatively narrow (2 km wide) shear zone within which minor structures are asymmetric and the deformation apparently noncoaxial. However, modeling of foliation and augen preferred orientation/ellipticity suggests that the bulk deformation is a combination of relatively small simple shear strains ($\gamma = 1$) with larger stretching strains. Heterogeneous stretching within the shear zone was accommodated by localized shearing on metabasic layers so that strain is partitioned. Outside this shear zone on the transect there is penetrative deformation throughout the Nanga Parbat massif. This broadly distributed deformation shows no asymmetry or evidence of rotation. Rather this deformation is better described as near pure-shear subvertical stretching. Augen ellipticities suggest subvertical stretches of greater than 200%. Consideration of plausible changes in crustal thickness during the amplification of the Nanga Parbat structure suggests the magnitude of vertical stretch decays with depth. Presumably these strains in the deep crust are more distributed but weaker than in the exposed middle crustal sections, assuming conservation of horizontal shortening displacement with depth. These studies suggest that penetrative vertical stretching through dominantly pure shear deformation is an effective mechanism for thickening the continental crust and that models which assume that simple shear zones penetrate the whole crust need not be of ubiquitous applicability. *INDEX TERMS:* 8025 Structural Geology: Mesoscopic fabrics; 8015 Structural Geology: Local crustal structure; 8102 Tectonophysics: Continental contractional orogenic belts; 8107 Tectonophysics: Continental neotectonics; 8159 Tectonophysics: Evolution of the Earth: Rheology—crust and lithosphere; *KEYWORDS:* continental tectonics, strain partitioning, Himalayas, Nanga Parbat

1. Introduction

[2] There are now good descriptions of the active deformation that affects the upper continental crust during orogenesis. Most of this strain is represented by seismogenic faulting together with aseismic deformations, principally represented by folds but also by minor structures such as pressure solution cleavage. Although it has long been recognized that seismogenic faulting passes down into aseismic creep [e.g., *Sibson*, 1977], the kinematics and distribution of these more distributed strains at depth have remained controversial. For some researchers, faults in the upper crust pass down onto kinematically equivalent zones of dominantly simple shear strain [e.g., *Ramsay*, 1980]. Indeed these types of models, in which deformation on a crustal scale is localized onto relatively narrow tracts of noncoaxial strain, have come to dominate understanding of collision mountain belts [e.g., *Coward*, 1994]. However, much geodynamic modeling of deformation of continental lithosphere argues for weak lower crust where deformation is broadly distributed [e.g., *Shen et al.*, 2001; *Thompson et al.*, 2001]. *Burg* [1999] points out that anastamosing relatively narrow zones of noncoaxial strain can combine to create thick zones of macroscopically distributed strain. Yet the implication remains that it is essentially simple shear that dominates the deformation kinematics. This contribution is

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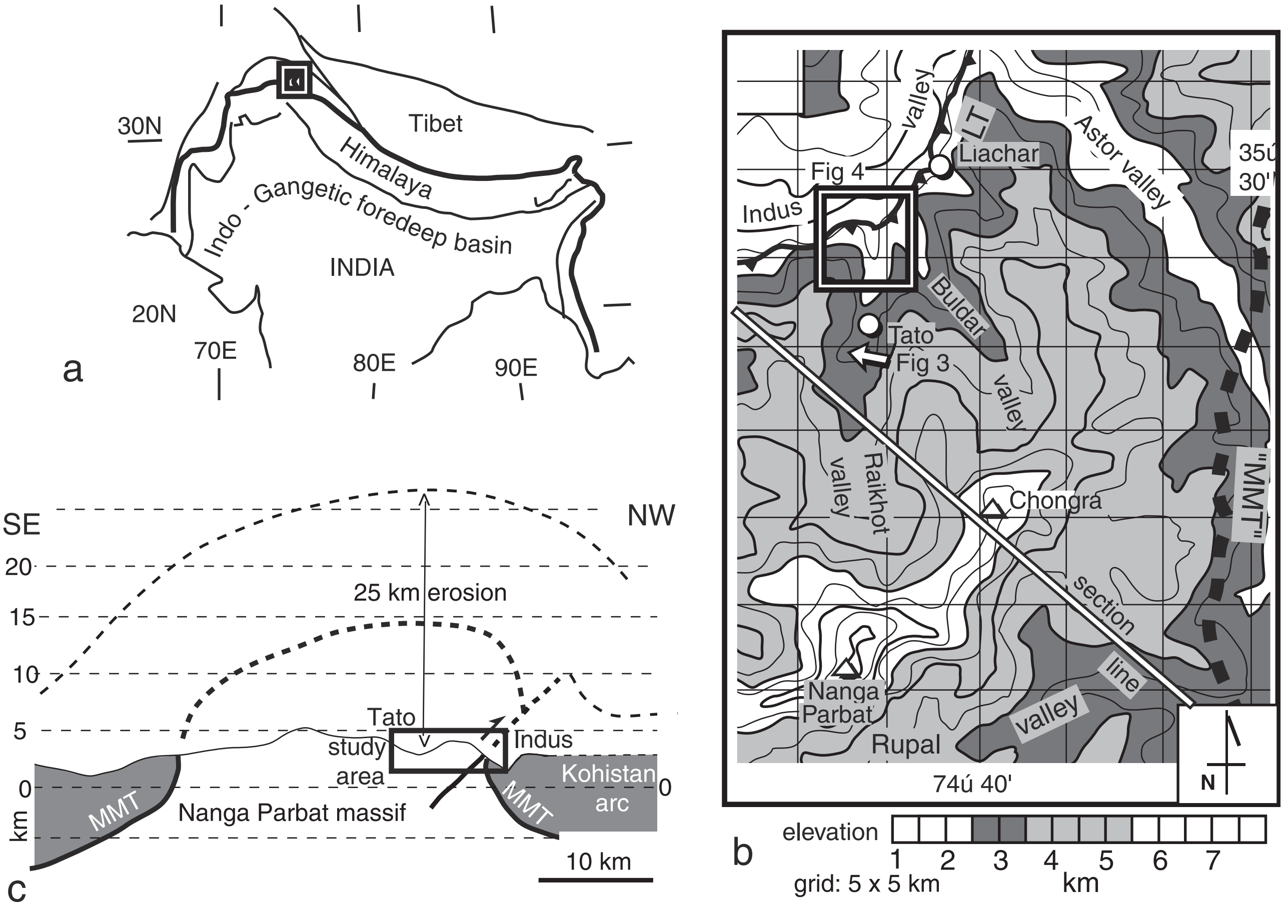


Figure 1. (a) Sketch location map for the Nanga Parbat massif in the NW Himalaya (boxed area). (b) Smoothed topographic map of part of the Nanga Parbat massif, around the eponymous mountain. The contour interval is 500 m. LT—Liachar Thrust; MMT—Main Mantle Thrust (the original contact between the massif (below) and the Kohistan arc terrane (above). For clarity, segments of the MMT which crop out in the Indus valley, in the immediate footwall to the Liachar Thrust are not shown [but see *Butler*, 2000]. (c) Simplified cross section through the massif (section line on Figure 1b) showing the form of the MMT. The upper dashed surface represents the now-deformed level of the approximated land surface prior to uplift of the massif, based on cooling histories of *Zeitler* [1985]. The unconventional orientation of the cross section and other profiles here (with N and W to the right) has been chosen to be consistent with the majority of field photographs.

aimed at providing new field observations that point to localized strain in the upper crust passing down into broadly distributed near-vertical stretching without throughgoing or anastamosing simple shear zones. Our study area is the Nanga Parbat massif of the NW Himalaya (Figure 1). As an area of active crustal thickening and exhumation, the massif offers insight on how deformation on localized thrust faults at the Earth's surface couples with more distributed strains at depth. The central questions for the Nanga Parbat massif are: to what extent is the deformation localized at depth and is deformation in the higher strain zones the result of dominantly simple shear or of a larger component of vertical stretching?

[3] As has long been recognized, the process of uplift and exhumation in dominantly dip-slip tectonic settings provides samples of the deeper structure that represents the roots to the superficial faults active during the latest part of the exhumation process [e.g., *Sibson*, 1977]. Consequently, kinematic studies of these tectonically exhumed roots can provide insight on the deformation style active at depth. Consequently we use structural data collected on a transect across the active deformation zone and project these into the subsurface on the assumption that deformation kinematics reflect the transport of material from levels deeper in the continental crust. Although our study methods are not original, their application to an area of active continental deformation, especially the Nanga Parbat massif, has general relevance for refining erosional thermo-mechanical models of orogenic tectonics. *Zeitler et al.* [2001] propose a so-called "tectonic aneurysm" model for Nanga Parbat. For these workers rapid denudation, leading to telescoping of near-surface geotherms, weakens the continental crust which in turn accelerates deformation, increasing uplift rate and erosion. This is a form of positive feedback which

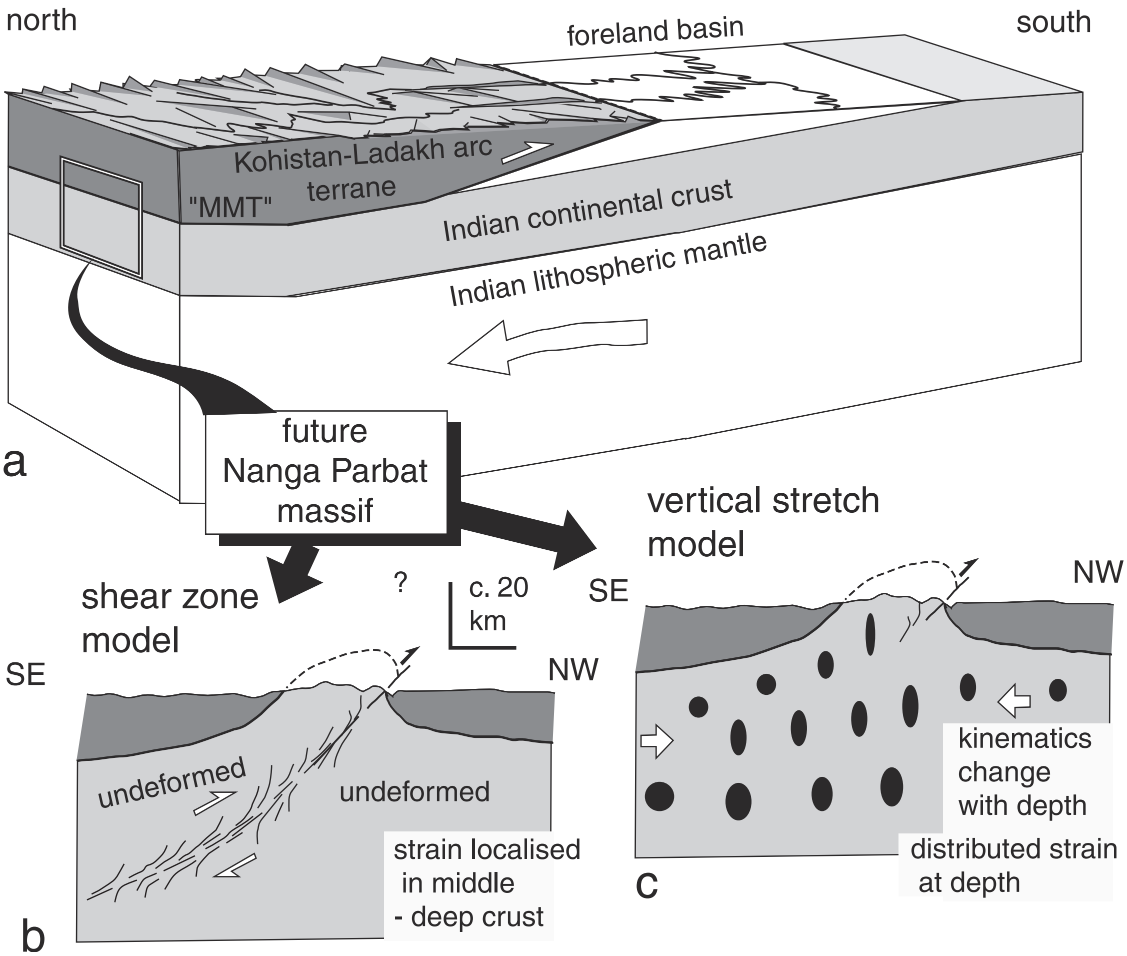


Figure 2. Schematic setting and models for the Nanga Parbat massif. (a) illustrates the position of the Nanga Parbat rocks—as part of the under-thrust Indian continental crust—prior to the formation of the modern massif. There are various kinematic models that may be invoked to explain the delivery of the Nanga Parbat rocks to outcrop. (b) shows the structure for the simple shear dominated model whereby a thrust at outcrop passes down into a zone of simple shear that, on the scale of the crust, is a belt of relatively localized strain. (c) illustrates a competing model where thrusting passes down into a broad zone of heterogeneously strained crust with a general vertical stretching, dominantly coaxial strain.

should lead to accelerating strain rates and progressively localized deformation. However, it has been known since at least the work of *England and Thompson* [1986] that the deformation kinematics (e.g., homogeneous vertical stretching versus overthrust duplication of crust) exerts a fundamental control on the dynamic thermal structure of the deformed crust. Consequently, to explore the geological predictions of ‘‘tectonic aneurysm’’ or other thermo-mechanical models it is necessarily to establish if structural kinematics vary with depth through the deforming crust. This represents the chief aim of this paper.

2. Field Area

[4] The Nanga Parbat massif is arguable one of the most intensely studied parts of the entire Himalayan-Tibet collision system. It lies at the NW termination of the arc of the Himalayan mountain belt (Figure 1). The massif itself represents exhumed levels of continental crust originally part of the Indian plate that were thrust under the southern margin of the Eurasian continent, as represented by the accreted arc terrane of Kohistan-Ladakh (Figure 2). The massif therefore offers a window on the style of deformation operating deep within the orogen. However, as a tract of old continental crust, the rocks of the Nanga Parbat massif record a long, polyphase deformational and metamorphic history only the youngest part of which is directly relevant to our study.

[5] Much of the recent studies that focus on metamorphic, igneous, geochronological and geophysical aspects are reviewed by *Zeitler et al.* [2001]. The structure at outcrop may be simply described as a half-window, open to the south within which are exposed once-buried rocks of the Indian continent exhumed from beneath a tectonically emplaced blanket of island arc rocks of the Kohistan-Ladakh terrane (Figure 1). In this part of the orogen, the original tectonic

contact (Indus suture) is generally termed the Main Mantle Thrust or "MMT" (reviewed by *DiPietro et al.* [2000]). Overall the structure is antiformal [*Coward*, 1985] so that the Nanga Parbat massif, composed of Indian cratonic basement, lies in the core (Figure 1c). Although Proterozoic in origin, rocks exposed within the massif have yielded monazite U-Pb ages of a few million years [e.g., *Zeitler et al.*, 1993]. The host gneisses include cordierite-bearing anatectic seams described by *Butler et al.* [1997]. *Whittington et al.* [1999] estimate the conditions under which these seams formed at 300 ± 40 MPa at 630 ± 50°C, a study that implies a steep near-surface geotherm. Relatively earlier metamorphic fabrics, overprinted by the seams, indicate deeper, higher temperature and pressure, conditions but under a more gentle geotherm. Additionally there are kilometer-sized plutons and a widespread network of meter-width veins of leucogranite. Petrological studies have established that these are the products of vapor-absent decompression melting [*George et al.*, 1993]. Rb-Sr geochemistry suggests that the leucogranites are younger than 5 Ma. Additionally, the deformation kinematics are consistent with emplacement during exhumation [e.g., *Butler*, 2000].

[6] While the consequences of active tectonics allied to rapid exhumation are evident within the massif, the onset of this tectonic regime is difficult to assess. Field relationships for the youngest granitic sheets within the Kohistan-Ladakh massif, which show no contamination from the Nanga Parbat massif [*George et al.*, 1993] show that the last movements on the MMT date at about 25 Ma. the formation of the massif and folding of the MMT are younger. However, some Ar-Ar ages for hornblendes in the massif have been interpreted as cooling through the 500°C closure temperature as early as 20 Ma [*Treloar et al.*, 2000]. These ages suggest an earlier age for the onset of the modern tectonic regime at Nanga Parbat and suggest that the recent cooling rates have been overestimated by many workers. We follow the interpretation of *Zeitler et al.* [2001] in regarding the Ar ages as maximum estimates of particular cooling ages. This is because studies on other polydeformed basement terranes [e.g., *Freeman et al.*, 1998] illustrate the dangers of uncritically using Ar ages in orogen studies. Radiogenic Ar derived from grain boundary fluids can combine with that produced within micas and amphiboles to yield apparent ages that are older than the true cooling age of the rock. Given the early Proterozoic protolith age of the Nanga Parbat gneisses such contamination should be expected. Our best estimate is that the current episode of deformation began no earlier than about 10–15 Ma.

[7] The summit of Nanga Parbat itself lies at 8125 m above mean sea level, while the Indus valley, some 25 km to the NNW, lies at an elevation of 1100 m. Pioneering fission track studies by *Zeitler* [1985] established a number of key features. First, the massif shows very young cooling ages in its heart, consistent with rapid, ongoing denudation. The cooling rates are asymmetric across the massif, implying faster denudation on its western margin. Drawn by these data, *Butler and Prior* [1988] established that the chief structure active during the recent exhumation of the massif is a contractional fault system, the Liachar Thrust (sometimes rather vaguely termed the Raikhot Fault [e.g., *Zeitler et al.*, 2001]), that runs near the base of the western flank of the massif. The discovery of a kilometer-wide zone of top-NW, asymmetric shear in the hanging wall to the Liachar Thrust led *Butler and Prior* [1988] to suggest that the superficial faults pass downwards into a simple shear zone. For these workers the tectonic construction of topography and the erosional exhumation of the massif relate to displacements on the Liachar Thrust and the kinematically-related Liachar Shear Zone (the deformation zone in the hanging wall to the Liachar Thrust). Subsequently, researchers have mapped out other deformation zones, apparently dominated by high simple shear strains, within the massif [e.g., *Edwards et al.*, 2000] and proposed that it is these structures that are key to understanding the tectonics [*Schneider et al.*, 1999; *Zeitler et al.*, 2001]. In this model, thrust faults at outcrop pass down onto zones of noncoaxial strain (Figure 2b) that stack crustal panels above each other. In contrast to this type of kinematic model, *Coward* [1985] interpreted the development of the Nanga Parbat massif as a crustal-scale buckle fold. Numerical modeling of this type of folding process by *Burg and Podladchikov* [2000] suggests that the asymmetry and faulting of the massif is a relatively late and subordinate process. There is therefore controversy as to the relative importance, in constructing the massif of localized, dominantly simple shear deformations on the one hand (Figure 2b), and distributed folding with near-vertical stretching on the other (Figure 2c).

[8] Here we are concerned with a structural transect leading into the Nanga Parbat massif from the "MMT" toward the summit area of Nanga Parbat (located on Figure 1b). This area not only includes the greatest range in elevation but also has outcrops of the granulites and leucogranites that have yielded some very young high temperature radiometric ages [*Zeitler et al.*, 1993]. The study presented here builds on the descriptions of the field area of *Butler* [2000]. This and related earlier studies show that the transect is dominated by chiefly dip-slip structural kinematics with an implicit direction of maximum compression lying on a NNW-SSE axis. On a large scale the Nanga Parbat massif has been regarded as accommodating oblique convergence through bulk right-lateral transpression, as predicted by models for the evolution of the Himalayan arc [e.g., *Coward et al.*, 1988]. Gently plunging N-S stretching lineations predicted by this model have been described from elsewhere in the massif [e.g., *Wheeler et al.*, 1995] but are largely absent from the chosen study area [*Butler*, 2000]. Consequently the transect is, in broad terms, structurally continuous. It includes accessible outcrops adjacent to the Indus, in the lower parts of the Raikhot and Buldar ravines and on path and track sections on the sides of the Raikhot valley. The hillsides provide near 100% outcrop obscured by almost no vegetation and steep enough to have retained only small volumes of unconsolidated deposits. General orientations and continuity of structure may be deduced by observations across the valleys and ground-truthed along paths. Additional data were collected higher in the Raikhot valley around the village of Tato. The

intervening ground was mapped at a reconnaissance level to provide general structural kinematic continuity.

[9] The dual attributes of structural continuity and a young, penetrative high temperature metamorphic/magmatic overprint through the massif are critical to our study. Faults and other structures that crosscut the peak metamorphic fabrics or which deform the leucogranites have formed relatively late in the exhumation of the massif. Given the age data it is likely that the absolute age of all faults within the transect are younger than 1 Myr. Active faults are described from along the Indus valley where fluvio-glacial deposits are cut by the Liachar Thrust [*Butler and Prior*, 1988; *Owen*, 1989]. Those ductile structures that are synchronous with the elevated geotherm or the coeval leucogranites, together with those that post-date them, are also synchronous with exhumation and the topographic growth of the massif. The bulk deformation is dip-slip (NNW-SSE contraction [*Butler*, 2000]). The critical assumption now is that the overall tectonics has not varied appreciably within our transect over the past few million years, a feature consistent with the geochronological data of *Zeitler* [1985; *Zeitler et al.*, 1993]. While not necessarily a steady state deformation (strain rates may be increasing), these data strongly suggest that exhumation is delivering samples of deformed rocks that are representative of deformation kinematics operating at depth today.

[10] The overall form of the massif may be estimated using the reconstructed shape of the base of the Kohistan terrane above the Indian continent (Figure 1c), based on reconnaissance mapping in the southern part of the massif [*Butler et al.*, 2000]. Background exhumation of Kohistan is estimated from the regional fission track studies of *Zeitler* [1985]. The surviving thickness of the Kohistan terrane to the west of Nanga Parbat has been estimated from gravity data as being about 15 km. This full thickness has been eroded from above the summit of Nanga Parbat, together with at least a few kilometers of Indian continental crust (e.g., the marginal cover sequences of the massif). Allowing for the elevation of Nanga Parbat, a minimum of 20 km of differential denudation has occurred from above those rocks in the heart of the massif. These currently lie at elevations of 3 km above sea level. Our cross section (Figure 1c) suggests ~25 km of exhumation has occurred across the heart of the massif.

3. Deformation Within the Nanga Parbat Massif

[11] The ideal simple shear zone model for exhumation of the Nanga Parbat massif predicts that, away from the Liachar Shear Zone, rocks of the massif were carried with little or no appreciable strain [e.g., *Zeitler et al.*, 2001]. Beyond about 2 km into the massif from the "MMT" the gneissic banding is generally steep and does not display the abundant shear criteria seen in the lower Raikhot valley. Therefore, for *Butler and Prior* [1988] the Liachar Shear Zone was less than 2 km across and the rest of the massif was simply translated "en masse" by displacements upon it. To test this prediction we studied the key outcrops used by *Whittington et al.* [1999] in their recognition of the young granulites. These crop out near the village of Tato in the Raikhot valley (Figure 1). The rocks consist of high-grade metasediments with abundant leucosome streaks. The structure generally appears relatively simple with steep banding coincident with psammitic and pelitic alternations together with calc-silicate bands. These migmatitic gneisses contain intrusive metabasic sheets which are mappable.

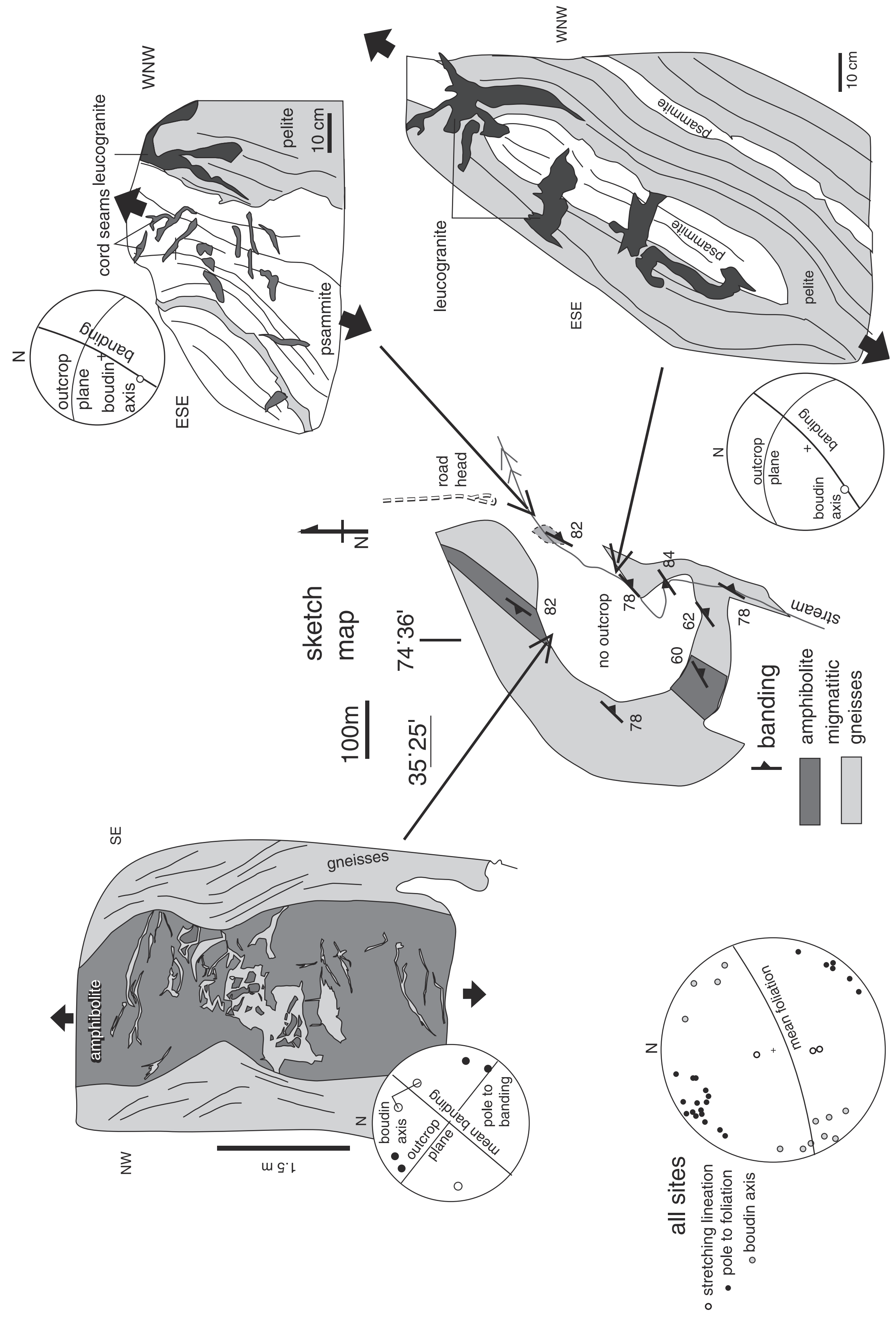
[12] The most striking feature of the rocks of the Tato area is layer boudinage (Figure 3). Psammites, amphibolites and calc-silicate layers are all necked implying broadly along-layer extension. We deduce that these lithologies were more competent than the surrounding pelites at the time of deformation. We were unable to detect any systematic asymmetry to the boudinage regardless of the amount of thinning or separation of boudins. Measured boudin axes plunge gently and are broadly orthogonal to the stretching lineation that is weakly developed on gneissose foliations (see stereonets on Figure 3). These observations are consistent with an approximately coaxial stretching with a maximum elongation aligned subvertically along the foliation. We found no evidence for stretches in or out of section. It is difficult to deduce the amount of finite elongation given the amount of ductile thinning of layers and the synkinematic intrusion of minor volumes of leucogranite. We have measured stretches from boudinaged calc-silicate layers within pelites which record elongations (as normalized against the original object length) of up to 30%. However, this represents only a minimum strain estimate.

[13] Although the amount of strain is difficult to determine at Tato, its timing may be well-established. Boudin necks commonly contain small volumes of cordierite-bearing anatectic zones concentrated in small shears [*Whittington et al.*, 1999]. These relate to the youngest anatectic episode in the massif which relates in turn to the elevated thermal structure during decompression. Therefore the boudinage is directly related to the exhumation of the massif. Similarly some of the leucogranites at Tato are spatially related to the boudins and are themselves stretched, indicating that leucogranite intrusion was coeval with the strain.

[14] The Tato area clearly indicates that rocks within the Nanga Parbat massif were not uplifted passively relative to the neighboring Kohistan-Ladakh terrane by translation upon a fault or shear zone. Rather they were actively participating in the crustal thickening through vertical stretching. It should be noted that we recognized similar layer boudinage through the Raikhot valley away from our Tato example. However, at these other sites it is difficult to demonstrate that the deformation is linked to exhumation as the cordierite-bearing seams, necessary to link structure to metamorphic conditions, crop out only at a few sites. Nevertheless it is highly likely that the boudinage elsewhere in the Raikhot valley correlates in time with our Tato examples.

4. Liachar "Shear Zone": Revisited

[15] Rocks from the margin of the Nanga Parbat massif, like those in the Tato area, show evidence for penetrative


WNW
ESE
leucogranite
cord seams
pelite
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10 cm
N
outcrop plane
boudin axis
banding
WNW
psammite
psammite
pelite
leucogranite
ESE
10 cm
N
outcrop plane
boudin axis
banding
road head
sketch map
N
74°36'
35°25'
100m
82
82
84
78
62
60
78
78
no outcrop
stream
banding
amphibolite
migmatitic gneisses
SE
gneisses
amphibolite
NW
1.5 m
N
boudin axis
outcrop plane
mean banding
pole to banding
all sites
stretching lineation
pole to foliation
boudin axis
N
mean foliation

deformation during exhumation. The structural geometry of the marginal area at Raikhot Bridge (Figure 4) is described by *Butler* [2000]. On the south bank of the Indus an early ductile contact between the Kohistan-Ladakh terrane and Indian continental crust of the Nanga Parbat massif itself is exposed, interpreted as the "MMT," that originally carried Kohistan onto rocks of the Indian continent. The "MMT" and the metasedimentary successions that lie to its east dip steeply to the NW. These "steep belt" rocks show ubiquitous evidence for near-vertical extension [*Butler*, 2000] with layer boudinage and steeply plunging mineral lineations. This belt of steep foliation and banding continues into the Nanga Parbat massif to include augen gneiss units. The "steep belt" is capped by a series of SE-dipping reverse faults (the Liachar Thrust zone) that in turn carry augen gneisses. These upper augen gneisses contain spectacular top-NW shear criteria [*Butler and Prior*, 1988; *Butler*, 2000], giving a synthetic relative sense of displacement parallel to that on the faults. These include asymmetric shears that overprint the foliation defined by aligned feldspar augen. These structures are strongly reminiscent of S-C fabrics [reviewed by *Hanmer and Passchier*, 1991], features that are commonly used to deduce penetrative noncoaxial deformation [e.g., *Alsop*, 1993]. The faults and the sheared gneisses constitute the Liachar Thrust and the Liachar Shear Zone of *Butler and Prior* [1988]. In this early study the principal deformation in the hanging wall to the Liachar Thrust was interpreted as simple shear, a deduction that led to the conclusion that it was localized shearing and faulting that uplifted the massif as a whole relative to neighboring Kohistan. However, this model does not explain the outcrop of the MMT in the footwall to the Liachar Thrust. Consequently deformation adjacent to the Liachar Thrust was interpreted as a "bend-in" strain deflecting the preexisting "MMT" into the subsequent Liachar shear zone. A range of structural data was collected along a transect leading into the Nanga Parbat massif from the Indus valley that we use here to test this simple shear hypothesis.

4.1. Strain Study

[16] The augen gneiss within the margin of the massif offers the chance to quantify kinematics. Recent studies of inclusions in deforming rocks [*Treagus and Treagus*, 2001] suggest that care must be taken in using initially elliptical or rheologically distinct objects to determine strain in deformed rocks. Field studies show that the augen in the steep belt (Figure 5a) are aligned parallel to the foliation defined by the penetrative foliation defined by aligned biotite. The biotite fabric generally passes to the edge of the feldspar augen, rather than systematically wrap it. This observation suggests that augen have acted as passive strain markers or that they grew after deformation. However, the presence of tails of quartz around the augen suggests that they were part of the rock prior to deformation, a feature described by *Butler et al.* [1997]. The issue of the initial shape of augen, addressed by *Treagus and Treagus* [2001], is more problematic. However, they suggest that only where initial ellipticity of inclusions exceeded 5 does the final ellipticity diverge significantly from the strain. This is a high threshold, equal to the mean value of observed final ellipticities, suggesting that initial ellipticities were rather less than 5. Consequently we believe that the augen shape should approximate to the shape of the finite strain ellipsoid.

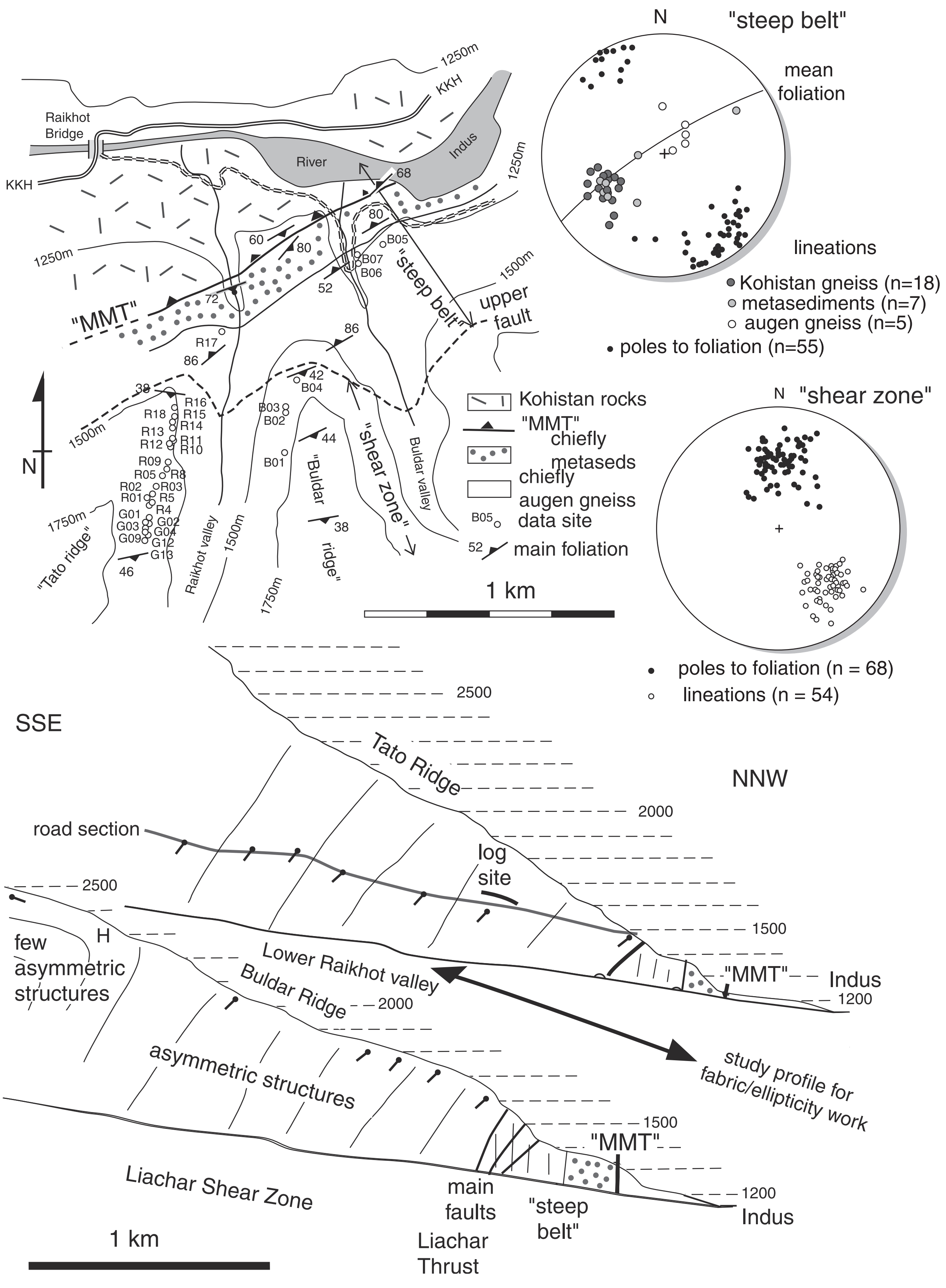
[17] For the simple shear model to be valid there should be a simple relationship between the shape of finite strain ellipsoids and the imposed simple shear strain [e.g., *Ramsay and Huber*, 1983]. The shear strain can be estimated by the angular deflection of preexisting or new foliation. In this study we use the shape of the augen to determine the orientation and intensity of the finite strain ellipse as seen in the principal strain plane that contains the finite mineral elongation direction.

[18] A series of sampling sites for our analysis was chosen into the massif, as indicated on Figure 4. The SE (internal) margin of our transect was determined by a change in lithology. The gneisses further into the massif are characterized by leucosome bands which are inappropriate as strain markers. Qualitative indicators of high simple shear strains, such as prominently asymmetric minor structures and S-C fabrics, are less well-developed in these more internal rocks.

[19] Within our transect we measured angular relationships between augen long-axis orientations and the biotite seams (which might be denoted "S" and "C" respectively in a conventional "shear zone"). Above the fault zone these two fabrics are demonstrably oblique (general 30°–40°; Figure 5b), in contrast to the relationship in the steep belt below. To test this qualitative deduction we measured fabric orientations using image analysis on oriented field photographs. Our analytical approach is as follows.

[20] Given the simple orientation of foliations and lineations within the augen gneisses we adopted a 2D approach to quantify the relationships between fabrics. Outcrop surfaces were chosen containing the stretching lineation and orthogonal to the intersection between "S" and "C" planes within the shear zone. Subvertical surfaces were used in the steep belt. These outcrop surfaces were then photographed and analyzed using the NIH Image package (http://rsb.info.nih.gov/nih-image). The apparent dip of biotite fabric and augen long axes were measured at 30+ sites in each photograph. The arithmetic mean orientation of the apparent dips was calculated together with the standard deviation. These data are plotted against distance through

Figure 3. (opposite) Selected outcrop-scale structures, typical of the deformation in the mid-upper the Raikhot valley within the Nanga Parbat massif. All come from a side valley to the west of the large moraine at the road head above Tato village, a site with excellent accessible and continuous outcrop. These relationships indicate layer-parallel boudinage, synchronous with exhumation related granitic seams and veins. All stereonets in this and other diagrams are equal angle, lower hemisphere projections. The sketched rock surface is oriented onto the stereonet for each outcrop.



1250m
KKH
Raikhot Bridge
KKH
River
Indus
1250m
68
80
60
80
B05
B07
B06
52
"steep belt"
1500m
upper fault
1250m
"MMT"
72
R17
86
86
42
B04
38
R18
R16
R15
R14
R13
R11
R12
R10
B03
B02
44
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R09
R05
R8
R02
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R5
R4
G01
G02
G03
G04
G09
G12
G13
46
B01
"Buldar ridge"
38
"shear zone"
Buldar valley
1750m
"Tato ridge"
Raikhot valley
1500m
1750m
N
Kohistan rocks
"MMT"
chiefly metaseds
chiefly augen gneiss
B05 data site
52 main foliation
1 km
N
"steep belt"
mean foliation
lineations
Kohistan gneiss (n=18)
metasediments (n=7)
augen gneiss (n=5)
poles to foliation (n=55)
N
"shear zone"
poles to foliation (n = 68)
lineations (n = 54)
2500
SSE
Tato Ridge
NNW
2000
road section
log site
2500
1500
H
few asymmetric structures
Lower Raikhot valley
"MMT"
Indus
1200
Buldar Ridge
2000
study profile for fabric/ellipticity work
asymmetric structures
1500
"MMT"
1200
Liachar Shear Zone
main faults
"steep belt"
Indus
Liachar Thrust
1 km

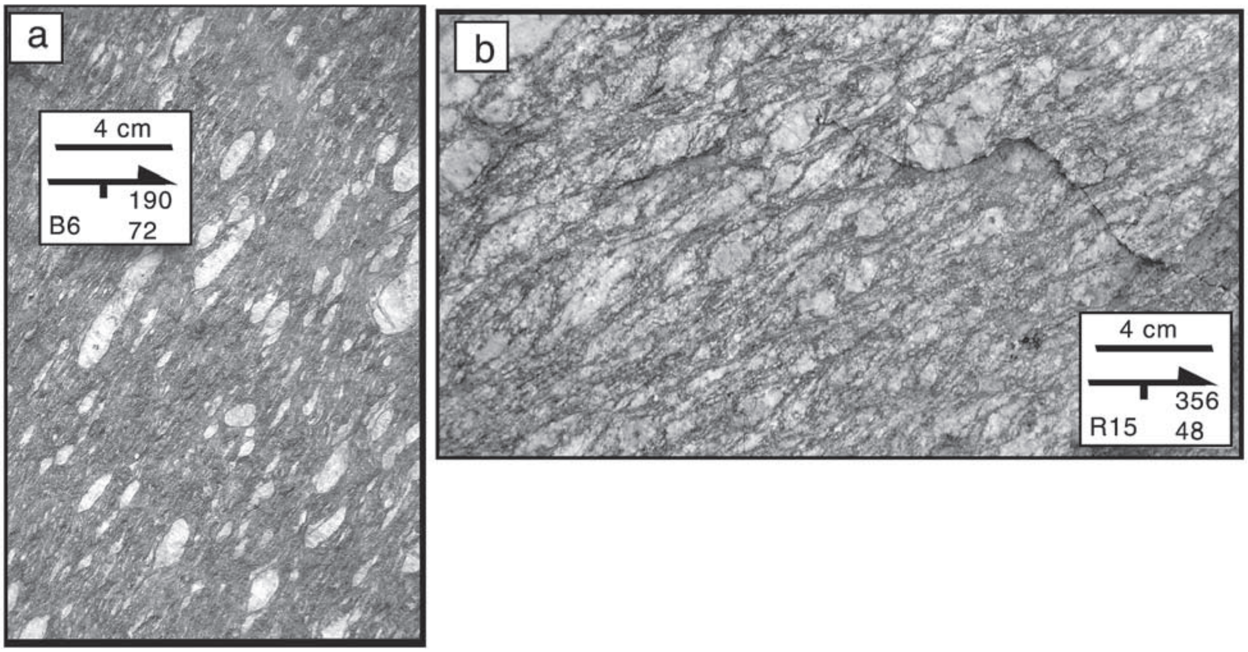

Figure 5. Examples of augen gneiss from the NW margin of the Nanga Parbat massif, lower Raikhot area. The location of the photographs can be established by matching the sample number with the location map (Figure 4). The orientation of the outcrop surface is indicated by a three figure strike (bearing from magnetic north in the direction arrowed) and a two figure dip value measured towards the viewer. (a) comes from the "steep belt." (b) comes from the "shear zone."

the margin of the massif (Figure 6). In all cases the true 3D orientations of representative augen and biotite foliations are measured at each site. All are consistent with the calculated mean orientations for the apparent dip populations in 2D.

[21] We also quantified the ellipticity of the augen fabrics using the NIH package. For each site the harmonic mean of the axial ratio of augen was calculated together with the standard deviation. Again we plot these against distance into the massif. Figure 6 also shows representative fabric relationships for different parts of the transect.

[22] Several observations may be drawn from our study. The foliation indicates two distinct domains within the transect. Within about 200 m of the "MMT" the augen and biotite foliations are statistically indistinguishable in orientation at individual sites. This parallelism is maintained regardless of the actual orientation of the fabric pairs, although they are generally steeply dipping. These sites are all from the steep belt, in the footwall to the Liachar faults. In marked contrast, the augen gneiss above the faults, over 400 m into the massif, show significant separations in the two foliations. The augen fabric is always steeper than the biotite fabric, though both dip into the massif. This pattern is consistent with the "S-C" interpretation of fabrics within the shear zone. The separation between "S" and "C" planes is generally about 30°. There is no evidence of cyclic generation of shear ("C") surfaces within the gneisses, as might be expected for long simple-shearing histories [e.g., *Alsop*, 1993]. Rather, for each locality, the c-plane shears appear to have formed at a single, late stage in the deformation.

[23] We now consider the ellipticity of the augen along the transect. Perhaps surprisingly, the domainal patterns seen in the orientations of the foliation are not replicated in the ellipticity data. Augen shape fabrics generally have an axial ratio of about 5. There is no systematic increase of ellipticity into the presumed shear zone from the steep belt. Theoretically we might expect variations in the intensity of the ellipticity of augen, if this attribute is a good proxy for strain intensity, if the Liachar Shear Zone displays heterogeneous simple shear.

4.2. Testing the Shear Zone Model

[24] We now use the strain data above to test the shear zone model for deformation on the margin of the Nanga

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Figure 4. (opposite) Structure in the lower Raikhot-Indus confluence area. The sketch map (modified after *Butler* [2000]), shows the Liachar Thrust zone and the steep belt in its footwall (to the NE). This includes the subvertical "MMT" (Main Mantle Thrust). The Liachar Shear Zone (labeled) lies in the hanging wall to the upper fault in the Liachar Thrust zone. Sample sites for the strain study are labeled. The two sections are subparallel, based on observations on either wall of the lower Raikhot valley running up to the Tato and Buldar ridges (labeled on the map).

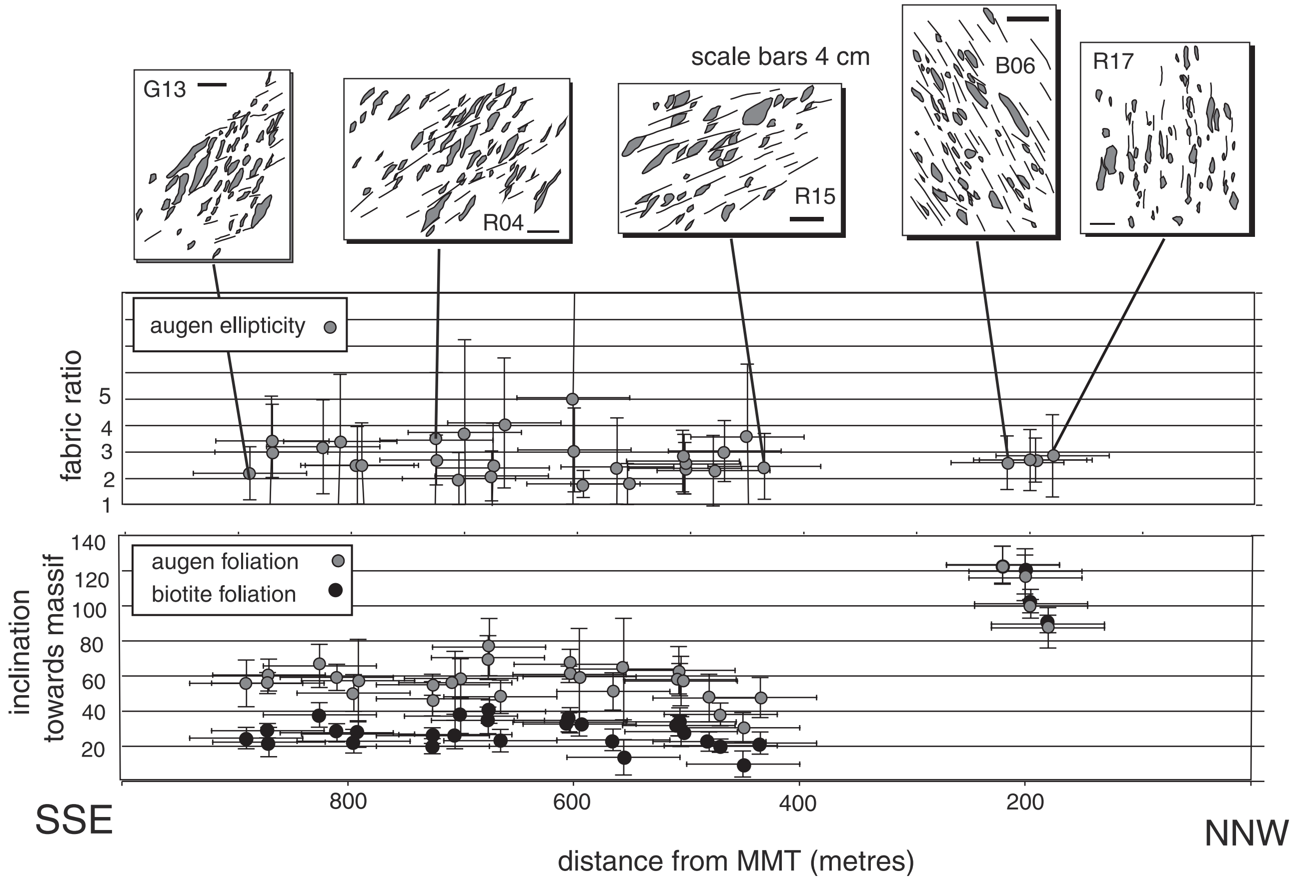
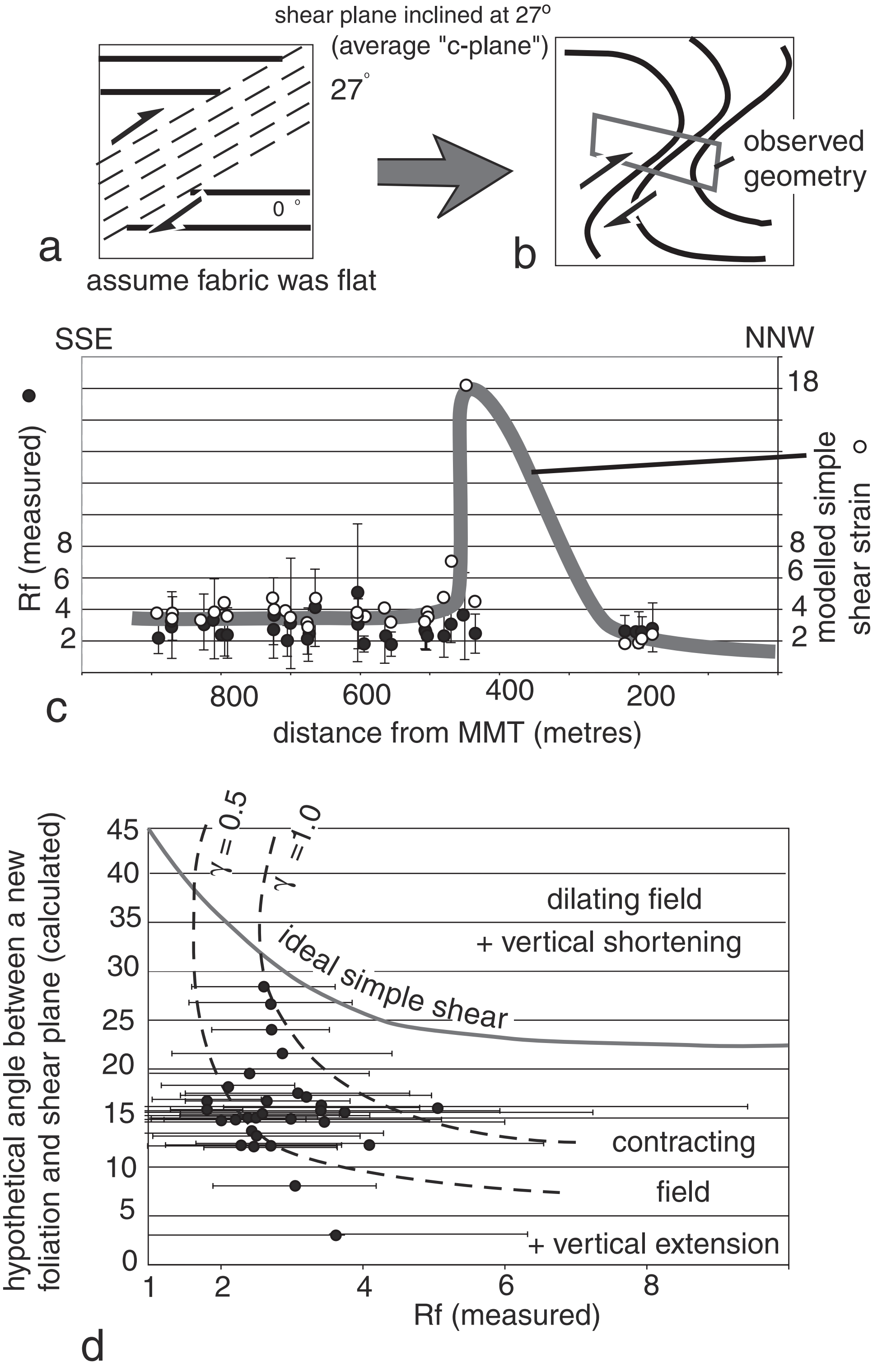


Figure 6. Fabric profile into the Nanga Parbat massif. The uncertainties on the location of sample sites relate to different projections onto the line of section. The bars on orientations/ellipticity are calculated single standard deviations in the sample populations. Some representative fabric relationships (with sample sites labeled, see Figure 3 for locations) are shown for comparison.

Parbat massif. There are several different strategies that might be used. However, the range in orientation of augen foliation is too great to be explained solely as a product of dip-slip simple shear on a shear plane of any single orientation. Consequently we infer that the augen foliation must have existed prior to shearing and that simple shear has intensified and reoriented this fabric. This inference is supported by the generally high angle between "S" and "C" fabrics. However, if the augen ellipticity is largely the result of simple shear, its intensity should correlate with the amount of deflection of its long axis orientation. However, despite over 100° variation in the amount of dip of the long axes between sites on our transect, the ellipticity is surprisingly constant. We confront this issue by applying a simple model to our data (Figure 7).

[25] We assume that, prior to the formation of the Nanga Parbat structure, the augen fabric was parallel to the "MMT". This in turn is thought to have been very gently dipping prior to the growth and uplift of the massif. We further assume that the finite shear plane that reworks the augen fabric dips at 27° into the massif (Figure 7a). This orientation is the arithmetic mean dip of the biotite fabrics ("c-planes") on our transect. We now assume that the augen foliation acts as a passive marker of the heterogeneous simple shear generating the measured orientation of augen long axis orientation across our shear zone (Figure 7b). There is a simple geometric relationship between the magnitude of imposed simple shear and the orientation of foliation, as plotted on Figure 7c. This shows that, in general, the orientation of augen long axes into the massif can be modeled with shear strains of between 2 and 5. Higher strains are required to explain the gently dipping augen foliations between 400 and 500 m into the massif, with shear strains locally as high as 18.

[26] These data can then be used in comparison with ellipticity. Figure 7d has been configured from *Ramsay and Huber* [1983, Figure 3.20], whereby the orientation of a hypothetical new foliation, calculated on the basis of the inferred shear strain in Figure 7c, is plotted against the measured ellipticity. For ideal simple shear there is a simple relationship between these two attributes. Our data do not conform with this ideal behavior. Rather they systematically fall in *Ramsay and Huber's* [1983] "contracting field." Qualitatively, the measured ellipticity is too low for the amount of simple shear inferred from the fabric orientation.


shear plane inclined at 27°
(average "c-plane")
27°
0°
a
assume fabric was flat
observed geometry
b
SSE
NNW
Rf (measured) ●
modelled simple shear strain ○
18
8
6
4
2
800
600
400
200
c
distance from MMT (metres)
γ = 0.5
γ = 1.0
45
40
35
30
25
20
15
10
5
0
dilating field
+ vertical shortening
ideal simple shear
contracting
field
+ vertical extension
hypothetical angle between a new foliation and shear plane (calculated)
1
2
4
6
8
Rf (measured)
d

[27] Before abandoning the simple shear model we should address two issues. First, have we underestimated the ellipticity? If the augen behaved rigidly in a deforming matrix this is possible. However, in general the external (matrix) foliation does not show the patterns expected for such partitioning behavior on the scale of hand-specimens [e.g., *Ildefonse et al.*, 1992]. Alternatively by selecting different orientations of initial foliation and shear plane, could we calculate lower values of simple shear? This is unlikely because our data are discrepant by tens of degrees from that predicted by the ideal simple shear model. Further, the shear zone cannot be steeper than about 35° (8° greater than our model) given the dips of augen fabric in the transect. A hypothetically lower angle to the shear plane would imply higher shear strains than our model. Consequently we have adopted a conservative approach. The penetrative simple shear model does not explain the ellipticity of the augen foliation, the Liachar "shear zone" is not, in fact, primarily a zone of simple shear.

5. A Two-Stage Model

[28] Figure 7 suggests that the finite strain within our transect through the margin of the massif is best explained by a combination of simple shear and subvertical stretching. The amount of simple shear required to explain the ellipticity is generally less than 1. Therefore the vertical stretching dominates the strain. However, our modeling approach cannot distinguish between a two stage process of stretching followed by simple shear and a continuous compressive strain. Field observations are consistent with the two stage process, in that trails on the augen are deflected into the biotite shears. It is these shears that provide the only indication within the augen gneiss for noncoaxial strain. Consequently we suggest that the bulk strain through the margin of the massif is dominated by subvertical stretching fabrics, locally intensified by simple shear. These deductions are consistent with our observations from the Tato area, well within the massif, outlined above (Figure 4). The strain intensity is apparently higher at the margins than in the exhumed deeper portions represented by Tato, although direct comparison is difficult because our strain measurements involve different methods.

[29] Continuing with our assumption that augen ellipticity is a good proxy for the intensity of the finite strain ellipse, our measured variations on the margin of the massif imply that the vertical stretching was heterogeneous. This raises serious problems of strain compatibility. Strain variations are compatible in simple shear deformations but in coaxial strains such variations necessarily generate discontinuities [e.g., *Ramsay*, 1980].

5.1. Evidence for Partitioning

[30] The augen gneiss units through the western margin of the massif, within the Liachar "shear zone" are not homogeneous (Figure 8). The augen gneisses are transected by seams of amphibolite and mixed amphibolite/biotite schist. These are presumed to represent the deformed equivalents of suites of metabasic sheets that are found throughout the Nanga Parbat massif [*Treloar et al.*, 2000]. Away from the Raikhot transect these amphibolite sheets retain thicknesses of several meters (e.g., Figure 3). Similar thicknesses are found, albeit rarely, on the Raikhot transect. These thicker, presumably less deformed examples, are necked (Figure 8c), suggesting that when they deformed, the amphibolites had a higher bulk viscosity than the surrounding augen gneiss. Only rarely are necked amphibolites fully boudinaged with separation of boudin bodies. Structural continuity is retained by thin seams of aligned hornblende and biotite. At inferred higher strain states the entire amphibolite sheet is represented by a few centimeters of schistose hornblende and biotite (e.g., Figure 8b). At these stages the biotite shear foliations in the augen gneiss intensifies and deflects into the seams. So in these situations we deduce that the seams have a lower bulk viscosity than the surrounding augen gneiss. Apparently the metabasic sheets evolve rheologically during deformation, exhibiting strain softening, presumably by recrystallization of its mineral components.

[31] We infer that, at least during the later stages of deformation, the amphibolite-biotite schist seams acted as soft layers within the deforming gneisses, effectively forming ductile strain discontinuities. But these seams were also acting early in the shear zone's history as evidenced by boudinaged amphibolites being crosscut by leucogranites (Figure 8c). However, in general few leucogranites within the Raikhot transect cross more than a few seams. Many are deflected into the seams. Using the leucogranites as relative time markers, we infer that the amphibolite-biotite schist seams acted as strain discontinuities during much the history of the deformation in the Raikhot transect. It was these throughgoing features that localized the shear strains necessary to retain strain compatibility during heterogeneous stretching in the augen gneiss.

[32] For the accommodation of heterogeneous pure shear, the effective partitioning of deformation requires the zones

Figure 7. (opposite) Modeling structural fabric patterns into the massif in terms of simple shear. (a) shows the assumed initial state with banding initially flat, modified into a shear zone with shear plane inclined at 27° (mean "C"-plane biotite foliation). (b) is the resultant (observed) geometry of banding. The transformation from state (a) to state (b) carries an implicit shear strain for each observed augen foliation orientation. This is shown in (c) together with measured ellipticity (Rf) across the transect. We also show a qualitative curve for shear strain variation into the Liachar shear zone implicit in the model. (d) Comparison of mean augen long axis and mean ellipticity (Rf) for each sample site, plotted in terms of the angle made by a hypothetical new foliation with the shear plane [after *Ramsay and Huber*, 1983]. The data all plot off the ideal simple shear curve, but within the combined strain field of simple shear plus vertical extension (the contracting field of *Ramsay and Huber* [1983]). Values for the simple shear component are contoured.

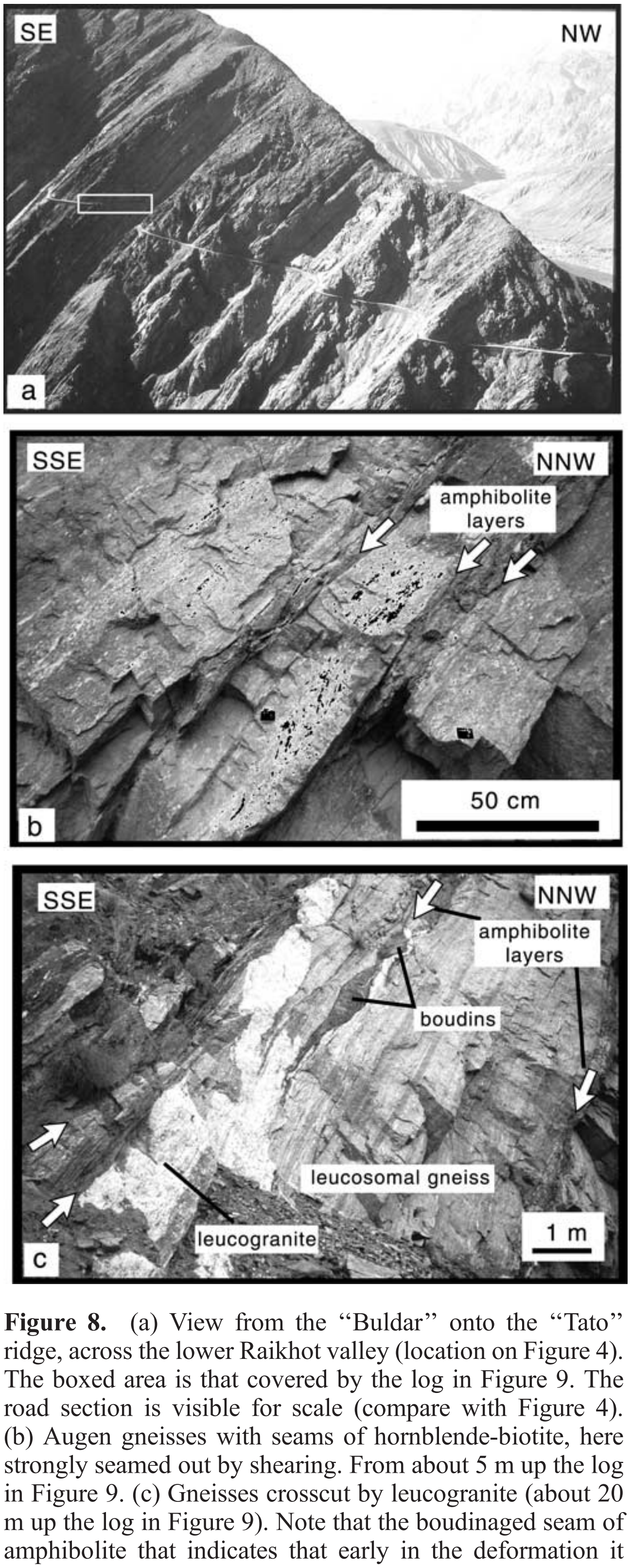


Figure 8. (a) View from the “Buldar” onto the “Tato” ridge, across the lower Raikhot valley (location on Figure 4). The boxed area is that covered by the log in Figure 9. The road section is visible for scale (compare with Figure 4). (b) Augen gneisses with seams of hornblende-biotite, here strongly seamed out by shearing. From about 5 m up the log in Figure 9. (c) Gneisses crosscut by leucogranite (about 20 m up the log in Figure 9). Note that the boudinaged seam of amphibolite that indicates that early in the deformation it was more competent than the surrounding gneisses, apparently behaving similarly to the amphibolite sheets in the Tato area (Figure 3).

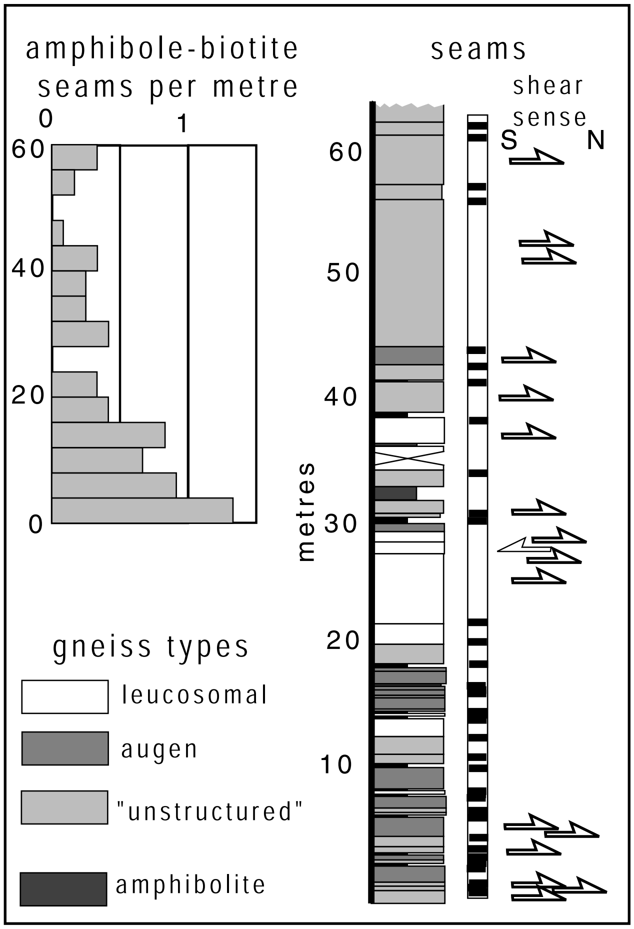


Figure 9. Representative structural log of shear sense, gneiss type and hornblende-biotite seams (see Figure 4 for location). The thicknesses are true for the layers, although it was logged obliquely through inclined layers encountered on the road section. The distribution of seams through the section is highly variable—as indicated on the density histogram, (sample window 4 m).

upon which the simple shear is localized at a length-scale appropriate to the gradients in intensity of the pure shear. To quantify this we present data from a logged section (Figure 9) of a representative part of the shear zone. The seams are subparallel and may be traced through the visible height of the outcrop (several hundred meters). All but one of these seams, where the shear sense is recognizable, show consistent top to the NNW kinematics. Spacing is highly variable but averages at about one seam for three meters across strike. Given the continuity of the outcrop the aspect ratio of the panels of augen gneiss between the seams is in the order of 100:1 or greater in the dip/shear direction.

[33] The seams do more than act as strain discontinuities between the strained panels of augen gneiss. Disorganized heterogeneous vertical stretching, even if plane strain, predicts variable shear senses on the seam discontinuities. This is not a general observation: Only one part of our logged transect (Figure 9), representative of less than 1% of the logged rock volume, shows top SSE shear sense. The

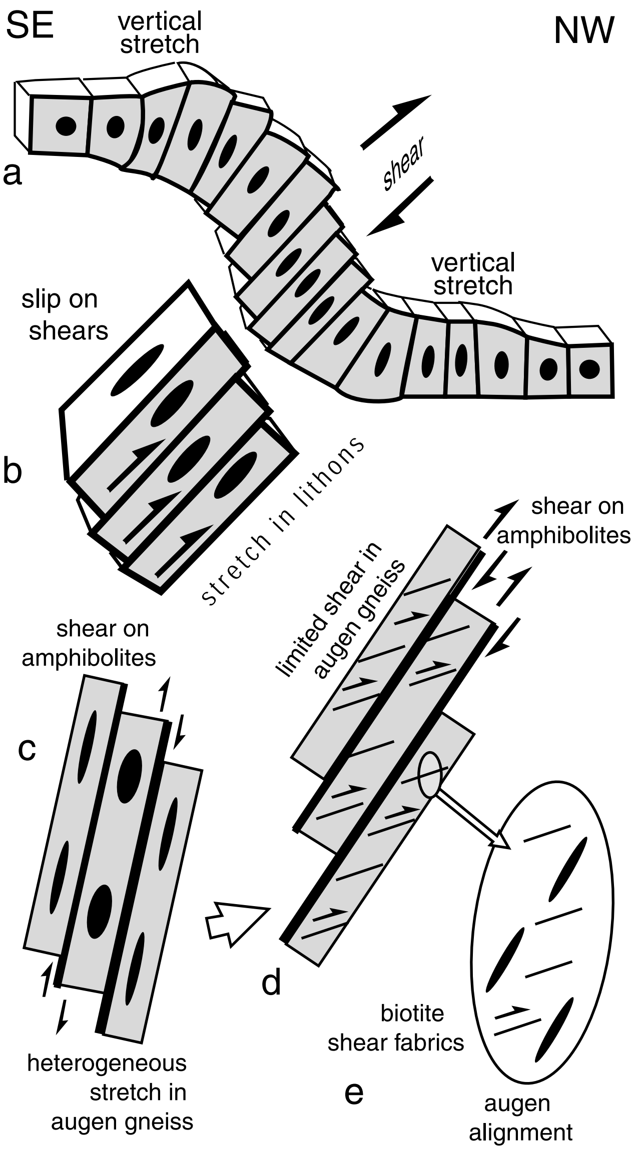


Figure 10. A qualitative model for partitioning heterogeneous layer elongation on the NW margin of the Nanga Parbat massif. (a) illustrates the regional subvertical stretching passing into a restricted zone that also contains simple shear. (b) shows how this may be achieved by localized shear, rotation and stretch. Our envisaged evolution of these structures is sketched (c)–(d), with the observed fabric relationship (e.g., shear zone part of Figure 7) sketched in (e).

rest is consistently top NNW. Therefore the strain is organized and asymmetric. This suggests a bulk top NNW shear sense, with simple shear strongly partitioned onto the amphibolite-biotite seams (Figure 10).

5.2. Strain Model

[34] The bulk strain within the Lower Raikhot transect is strongly partitioned, with dominantly down-dip heterogeneous stretching in the augen gneiss coupled across seams of presumed dominant simple shear. The overall structure thus has a strong planar anisotropy at the scale-scale—an attribute visible from afar (Figure 8a). However, away from this transect, for example in the Tato area (Figure 3), this type of planar anisotropy, together with evidence for strain partitioning, is absent. The amphibolite sheets are necked but the thinned portions of the amphibolites are not drawn out. Similarly there is no evidence for throughgoing strain discontinuities within the augen gneisses below the fault zones near Raikhot Bridge.

[35] There is a correlation then between development of asymmetric "S-C" type fabrics and the presence of amphibolite-biotite seams, our inferred strain discontinuities. We propose a two-step model. For any given rock volume the deformation initiates as broadly coaxial vertical stretching. Strain softening of the amphibolite sheets generates throughgoing soft zones. These permit greater strain heterogeneity within the augen gneiss. This strain is asymmetric and may, during the later stages, begin to approximate to net simple shear. It is this gradual change that presumably heralds the transition in behavior from broadly distributed vertical stretching at depth to strongly localized thrusting at the surface along the Liachar thrust (Figure 11). However, the simple shear behavior is restricted to a tract less than 2 km wide. The Nanga Parbat rocks within this zone, like those outside, show evidence for substantial stretching along layering.

6. Strain Through the Crust: Depth-Dependent Kinematics

[36] We can use the data on strain intensity at Nanga Parbat to deduce how kinematics may vary through the continental crust at this site. Fundamental to our approach here is that rocks at outcrop today are representative of the deformation active today at depth. Faulting at outcrop is strongly localized to a tract a few hundred meters across. Dominantly noncoaxial strain, representing deformation that occurred directly beneath the zone of faulting, is localized to a zone less than 2 km wide. Heterogeneous, subvertical stretching occurs throughout our study area. In view of these variations we infer that strain is localized by different amounts at different levels in the crust. Although simple-shear dominant strain was active synchronously with the emplacement of some of leucogranite sheets on the transect (as reported by *Butler et al.* [1997]), much of this deformation post-dates leucogranite emplacement. This is evidenced by the biotite shear ("C") planes indicative of simple shear passing into the leucogranite sheets. There is little evidence for significant simple shear strains associated with structurally deeper levels.

[37] Near vertical stretching of the outcropping Indian continental crust may be estimated from the augen ellipticity on our strain transect (Figure 6). Above the Liachar Thrust, where there has been some modification by simple shear, the finite ellipticity varies from ratios of 3 to 8. Where there has been no modification (i.e. below the Liachar Thrust), the ratios are about 5. These values imply substantial elongation (e) of 1.25.

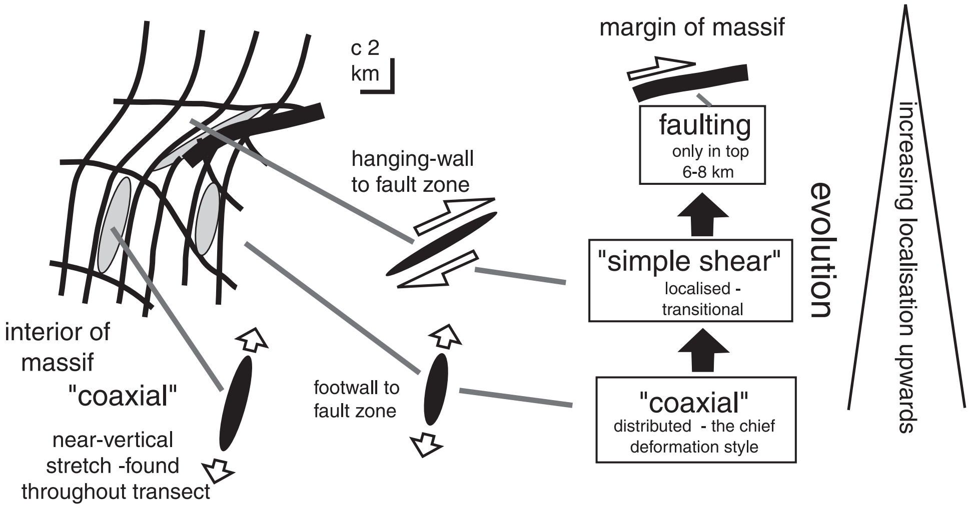


Figure 11. Qualitative view of the inferred transition from faulting through shearing to stretching strains with depth. Individual tracts of gneiss at outcrop today are considered to have passed up through these different structural domains and therefore show an evolution as indicated.

[38] Many workers [e.g., *Burg and Podladchikov*, 2000] assume that the Himalayan syntaxes involve deformation of the whole crust. Certainly the wavelength of these structures is suggestive of whole crustal involvement. The question now is whether the strain values (e_s) estimated for rocks at outcrop at Nanga Parbat could be representative of the strain on a crustal scale (e_c). The depth to the Moho beneath Nanga Parbat is rather poorly constrained. The best recent estimate, using the gravity field together with sparse wide angle seismic data [*Caporali*, 2000], places it at about 70 km. Assuming erosion of approximately 25 km of rock from above the massif, of which about 10 km was Indian continental crust, the finite crustal thickness (l_1) is about 80 km. If we apply the estimate of vertical stretching (e_s = 1.25 as estimated above) the original thickness of the Indian crust (l_0) prior to the development of the Nanga Parbat massif may be estimated at about 35 km. This figure is consistent with estimates of crustal thickness of the Indian continent in the foreland south of the Himalayas. Therefore a largely homogeneous vertical stretching of about 1.25 necessary to have achieved the observed strain axial ratios of about 5, acting through the whole thickness of the crust beneath Nanga Parbat, is consistent with estimates of crustal thickening based on comparison of the modern and original thickness of this crust.

[39] Despite the attractions of the above calculations, they are unlikely to be valid. The strains within the massif represent deformation acting not on the original Indian continental crust but on material that had already been involved in the Himalayan collision. 35 km is probably a gross underestimate of the thickness (l_0) of Indian continental crust in the Himalayas that existed prior to the formation of the Nanga Parbat massif. In Pakistan we can estimate this value away from the massif. The Moho is believed to lie at a depth of approximately 60 km, with the upper 12 km or so constituting the Kohistan-Ladakh arc terrain. Thus away from the massif the Indian continental crust has a thickness (l_0) of about 48 km. Using this figure, the required strain (e_c) to create reconstructed crustal thickness (l_1) of Indian crust at Nanga Parbat of 80 km is 0.67, equating to a strain axial ratio of about 2.8.

[40] Using the more plausible values of crustal thickening associated with the formation of the Nanga Parbat syntaxis it is clear that the strains recorded at outcrop at Nanga Parbat are too high to be applied to the complete crustal thickness (Figure 12). We infer therefore that if the whole crust experienced vertical stretching, the magnitude of this strain (e_s) must decrease from the values recorded for the upper parts of this crust (i.e. 1.25) to substantially lower (e.g., 0.5 or less) in the lower crust. If we assume that these strains must integrate at their respective crustal levels to achieve the same horizontal shortening (i.e. achieve a plane strain balance), then the lower strains in the lower crust must be correspondingly more widely distributed than the higher strains in the upper crust. If this view is accepted, the kinematics and localization of deformation may be considered to be depth-dependent. This description is consistent with the general “tectonic aneurysm” model of *Zeitler et al.* [2001] where strain becomes progressively more localized up through the crust.

[41] Varying coaxial strains generates additionally noncoaxial strain components [e.g., *Ramsay*, 1980]. In this context the abrupt transition from subvertical stretching to faulting is marked by a local shear zone of limited depth penetration. However, varying the amount of vertical stretching with depth, as predicted here, also generates significant noncoaxial strains, evident on Figure 12 as horizontally sheared gridlines. Therefore, although the bulk deformation within the crust at Nanga Parbat may be described as heterogeneous vertical stretching, in detail this strain is not coaxial. It will however, be dominated by high

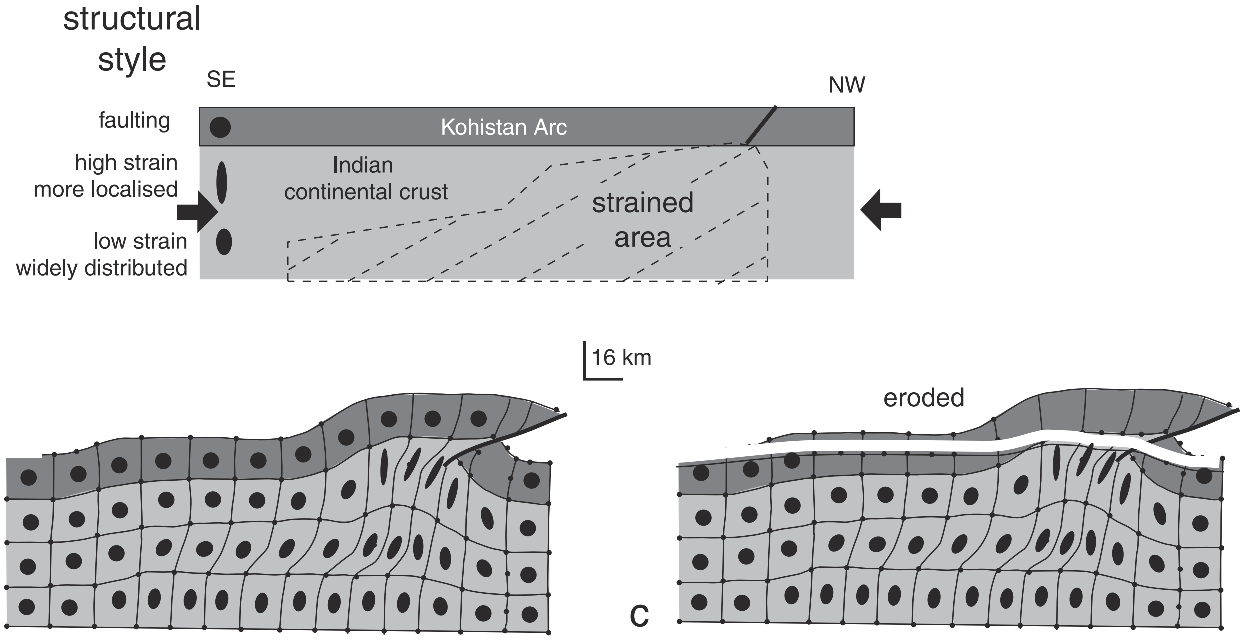


Figure 12. Schematic quasi-crustal scale model for deformation at and beneath the Nanga Parbat massif. (a) shows the inferred predeformational state and how structural style/localization will vary with depth. (b) shows the deformed state-without erosion. (c) Adds erosion to show the outcrop width of the Nanga Parbat massif. Note that the true structure should show isostatic loading effects, although erosion makes this far less that would be deduced from the state shown in (b).

simple shear components only when gradients in the variations of vertical stretching become pronounced.

7. Conclusions

[42] The Indian continental crust of the Nanga Parbat massif is penetratively deformed. Within our study area on the Raikhot transect this strain is dominantly subvertical stretching. Significant simple shear strains are recorded only at the NW margin of the massif, near the Indus valley, over an across strike distance of about 2 km. Modeling augen fabrics and foliations suggests that the maximum shear strain recorded by the augen gneiss within this zone is less than $\gamma = 1$. Simple integration therefore limits displacement across the shear zone to about 2 km. This is a minimum estimate as it does not include displacement across the high strain amphibolite-biotite shears. However these account for less than 1% of the rock volume, and are unlikely to account for substantially greater displacements.

[43] In the absence of high simple shear strains, the most important deformation within the massif is represented by near-vertical stretching. Boudin axes and ellipticity-foliation studies of augen gneisses strongly suggests that this stretching was achieved by dominantly coaxial strain paths. While the strain ratios estimated for vertical stretching approximately equal those found in the zone of apparent simple shear (i.e., about 5), this strain state occurs over a much wider area (over 10 km across strike) than do the apparent simple shear strains. Therefore the integrated effect of the coaxial vertical stretching outplays the simple shear as a mechanism by which the Indian continental crust at Nanga Parbat has thickened. This conclusion is in marked contrast with earlier studies [e.g., *Butler and Prior*, 1988; *Schneider et al.*, 1999] which assumed crustal thickening was controlled by discrete shear zones (c.f. Figure 1b). At least for the NW margin of the massif, the new interpretation presented here relegates the simple shear zone to be a kinematic transfer zone between the broadly distributed vertical stretching at depth and the localized Liachar Thrust at the surface. On a crustal scale it is the vertical stretching that dominates the deformation (Figure 1c). Consequently future work will focus on how these strains localize within the Himalayan collision system. Preliminary analysis of the relationship between observed strain intensity and the inferred increase in crustal thickness at Nanga Parbat suggest that deformation kinematics change with depth. Not only is faulting restricted to the top few kilometers of the crust, as is well recognized, the style of distributed strain also varies with depth. In the upper 20 km of crust the vertical stretch achieves values in excess of 200% (axial ratios of 5+). However, these high values are too high to explain the change in thickness of the Indian crust achieved by the Nanga Parbat structure. Therefore the magnitude of vertical stretching and the corresponding volume of deforming crust must vary with depth.

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References

Alsop, G. I., Sequential generation of listric shear bands during protracted ductile thrusting within the Ballybofey Nappe, northwest Ireland, *Irish J. Earth Sci.*, *12*, 1–2, 1993.

Burg, J.-P., Ductile structures and instabilities: Their implications for Variscan tectonics in the Ardennes, *Tectonophysics*, *315*, 251–267, 1999.

Burg, J.-P., and Y. Podladchikov, From buckling to asymmetric folding of the continental lithosphere: Numerical modeling and application to the Himalayan syntaxes, in *Tectonics of Western Himalaya and Karakoram*, edited by M. A. Khan et al., *Geol. Soc. Spec. Publ.*, *170*, 219–236, 2000.

Butler, R. W. H., Structural evolution on the western margin of the Nanga Parbat massif, Pakistan Himalayas: Insights from the Raikhot-Liachar area, in *Tectonics of Western Himalaya and Karakoram*, edited by M. A. Khan et al., *Geol. Soc. Spec. Publ.*, *170*, 51–75, 2000.

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

Butler, R. W. H., N. B. W. Harris, and A. G. Whittington, Interactions between deformation, magmatism and hydrothermal activity during active crustal thickening: A field example from Nanga Parbat, Pakistan Himalayas, *Mineral. Mag.*, *61*, 37–52, 1997.

Butler, R. W. H., J. Wheeler, P. J. Treloar, and C. Jones, Geological structure of the southern part of the Nanga Parbat massif, Pakistan Himalaya, and its tectonic implications, in *Tectonics of Western Himalaya and Karakoram*, edited by M. A. Khan et al., *Geol. Soc. Spec. Publ.*, *170*, 123–136, 2000.

Caporali, A., The gravity field of the Karakoram mountain range and surrounding area, in *Tectonics of Western Himalaya and Karakoram*, edited by M. A. Khan et al., *Geol. Soc. Spec. Publ.*, *170*, 7–23, 2000.

Coward, M. P., A section through the Nanga Parbat syntaxis, Indus Valley, Kohistan, *Geol. Bull. Univ. Peshawar*, *18*, 147–152, 1985.

Coward, M. P., Continental collision, in *Continental Deformation*, edited by P. L. Hancock, pp. 264–288, Pergamon, New York, 1994.

Coward, M. P., et al., Folding and imbrication of the Indian crust during Himalayan collision, *Philos. Trans. R. Soc. London, Ser. A*, *326*, 89–116, 1988.

Dipietro, J. A., A. Hussain, I. Ahmed, and M. A. Khan, The Main Mantle Thrust in Pakistan: Its character and extent, in *Tectonics of Western Himalaya and Karakoram*, edited by M. A. Khan et al., *Geol. Soc. Spec. Publ.*, *170*, 375–393, 2000.

Edwards, M. A., W. S. F. Kidd, M. A. Khan, and D. A. Schneider, Tectonics of the SW margin of the Nanga Parbat–Haramosh massif, in *Tectonics of Western Himalaya and Karakoram*, edited by M. A. Khan et al., *Geol. Soc. Spec. Publ.*, *170*, 77–100, 2000.

England, P. C., and A. Thompson, Some thermal and tectonic models for crustal melting in continental collision zones, in *Collision Tectonics*, edited by M. P. Coward and A. C. Ries, *Geol. Soc. Spec. Publ.*, *19*, 83–94, 1986.

Freeman, S. R., R. W. H. Butler, R. A. Cliff, and D. C. Rex, Direct dating of mylonitic evolution: A multidisciplinary geochronological study from the Moine thrust zone, NW Scotland, *J. Geol. Soc. London*, *155*, 745–758, 1998.

George, M. T., N. B. W. Harris, and R. W. H. Butler, The tectonic implications of contrasting post-collisional magmatism between the Kohistan island arc and the Nanga Parbat-Haramosh massif, Pakistan Himalaya, in *Himalayan Tectonics*, edited by M. P. Searle and P. J. Treloar, *Geol. Soc. Spec. Publ.*, *74*, 173–191, 1993.

Hanmer, S., and C. Passchier, Shear-sense indicators: A review, *Geol. Surv. Can.*, *90–17*, 72 pp. 1991.

Ildefonse, B., D. Sokoutis, and N. S. Mancktelow, Mechanical interactions between rigid particles in a deforming ductile matrix: Analogue experiments in simple shear, *J. Struct. Geol.*, *10*, 1253–1266, 1992.

Owen, L. A., Neotectonics and glacial deformation in the Karakoram mountains and Nanga Parbat Himalaya, *Tectonophysics*, *163*, 227–265, 1989.

Ramsay, J. G., Shear zone geometry: A review, *J. Struct. Geol.*, *2*, 83–89, 1980.

Ramsay, J. G., and M. I. Huber, *The Techniques of Modern Structural Geology, Volume 1: Strain Analysis*, 307 pp., Academic, San Diego, Calif., 1983.

Schneider, D. A., M. A. Edwards, W. S. F. Kidd, M. A. Khan, L. Seeber, and P. K. Zeitler, Tectonics of Nanga Parbat, western Himalaya: Synkinematic plutonism within the doubly vergent shear zones of a crustal scale pop-up structure, *Geology*, *27*, 999–1002, 1999.

Shen, F., L. H. Royden, and B. C. Burchfiel, Large-scale crustal deformation of the Tibetan plateau, *J. Geophys. Res.*, *106*, 6793–6816, 2001.

Sibson, R. H., Fault rocks and fault mechanisms, *J. Geol. Soc. London*, *133*, 191–213, 1977.

Thompson, A. B., K. Schulmann, J. Jezek, and V. Tolar, Thermally softened continental extensional zones (arcs and rifts) as precursors to thickened orogenic belts, *Tectonophysics*, *332*, 115–141, 2001.

Treagus, S. H., and J. E. Treagus, Effects of object ellipticity on strain, and implications for clast matrix rocks, *J. Struct. Geol.*, *23*, 601–608, 2001.

Treloar, P. J., M. T. George, and A. G. Whittington, Mafic sheets from Indian plate gneisses in the Nanga Parbat syntaxis: Their significance in dating crustal growth and metamorphic and deformation events, in *Tectonics of Western Himalaya and Karakoram*, edited by M. A. Khan et al., *Geol. Soc. Spec. Publ.*, *170*, 25–50, 2000.

Wheeler, J., P. J. Treloar, and G. J. Potts, Structure and metamorphic evolution of the Nanga Parbat syntaxis, Pakistan Himalayas, on the Indus gorge transect: The importance of early events, *Geol. J.*, *30*, 349–371, 1995.

Whittington, A. W., N. B. W. Harris, and R. W. H. Butler, Contrasting anatectic styles at Nanga Parbat, northern Pakistan, in *Himalaya and Tibet: Mountain Roots to Mountain Tops*, edited by A. Macfarlane, R. B. Sorkhabi, and J. Quade, *Geol. Soc. Am. Spec. Pap*, *328*, 129–144, 1999.

Zeitler, P. K., Cooling history of the NW Himalaya, *Tectonics*, *4*, 127–135, 1985.

Zeitler, P. K., C. P. Chamberlain, and H. Smith, Synchronous anatexis, metamorphism, and rapid denudation at Nanga Parbat (Pakistan Himalaya), *Geology*, *21*, 347–350, 1993.

Zeitler, P. K., et al., Crustal reworking at Nanga Parbat, Pakistan: Metamorphic consequences of thermo-mechanical coupling facilitated by erosion, *Tectonics*, *20*, 712–728, 2001.

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