Strain partitioning along the Himalayan arc and the Nanga Parbat antiform

Leonardo Seeber
Lamont-Doherty Earth Observatory of Columbia University, Palisades, New York 10964
Arnaud Pêcher
UJF Laboratoire de Geologie, 38031 Grenoble, France

ABSTRACT

Shortening along the Himalayan arc of continental convergence is approximately in the radial direction. If the underthrusting foot-wall block (India) is not deformed, the hanging-wall block (Tibet) needs to stretch along the arc, as suggested by radial grabens in southern Tibet. In contrast, the Nanga Parbat–Haramosh massif and the western Himalayan syntaxis are part of a 250-km-long antiform that strikes in the radial direction (northeast) and verges northwest. The Nanga Parbat antiform is the structural and topographic expression of arc-parallel shortening that compensates for arc-parallel extension in southern Tibet. This shortening is predicted to be as high as 12 mm/yr.

INTRODUCTION

The Himalayan front of continental convergence has a remarkably regular arcuate shape. This shape is manifested by structure and topography (Gansser, 1964; LeFort, 1975; Fielding, 1996; Bilham et al., 1997) and by seismicity (Baranowski et al., 1984; Seeber and Armbruster, 1984; Molnar and Lyon Caen, 1989). From south to north, the convergence front is characterized by three main kinematic elements (Fig. 1; Davis et al., 1983): (1) a foot-wall block (Indian craton) that dips gently northward below the sediment-filled Himalayan foredeep and generally has little internal deformation; (2) an accretionary wedge where thrusting and folding verge toward the foredeep; and (3) a hanging-wall block (Tibetan slab) that has prominent Neogene extension structures in both radial and arc-parallel directions (e.g., Burg et al., 1984; Gapais et al., 1992; Armijo et al., 1986). This pattern is prominently violated at the northwestern terminus of the arc where the western Himalayan syntaxis (Wadia, 1931; Calkins et al., 1975) and the Nanga Parbat–Haramosh massif (Treloar et al., 1991; Wheeler et al., 1995; Madin et al., 1989; Butler et al., 1989) are associated with folds and thrusts striking in the arc-radial direction, indicating arc-parallel shortening on the hanging-wall side of the Himalayan front.

Strain-partitioning is observed worldwide along tectonic boundaries where overall motion is oblique to the boundary (e.g., McCaffrey, 1992). Oblique motion is typically partitioned among strike-slip and dip-slip faults. Focal mechanisms of intermediate-magnitude earthquakes marking the Himalayan arc indicate slip in the radial direction on thrust faults parallel to the arc (Fig. 1; Baranowski et al., 1984). Assuming that the convergence direction at the Himalayan boundary is parallel to these slip vectors, such kinematics cannot alone account for convergence between rigid plates and require complementary deformation within at least one of the plates (Seeber and Armbruster, 1984; Armijo et al., 1986; Molnar and Lyon Caen, 1989; McCaffrey and Nabelek, 1998). Thus, the overall motion between India and Tibet is partitioned between distinct fault systems. This paper proposes an additional element to Himalayan strain partitioning by considering the Nanga Parbat massif and the Western syntaxis as a regional arc-parallel shortening structure that compensates, at least in part, for arc-parallel extension along the central portion of the arc.

NANGA PARBAT ANTIFORM

The Nanga Parbat–Haramosh massif is a distinct topographic, lithologic, and structural feature on the hanging-wall side of the Himalayan front at the western termination of the arc. The massif exposes high-metamorphic-grade Indian shield gneisses reworked by at least one Himalayan phase of metamorphism and deformation (e.g., Zeitler et al., 1989; Wheeler et al., 1995). Structurally, the massif is an antiform (e.g., Treloar et al., 1991). This antiform strikes north to northeast and verges west to northwest, in sharp contrast to regional trends, which generally mimic the southeasterly strike and southwesterly vergence of the Himalayan thrust front at the western terminus of the arc (Figs. 1 and 2). Horizontal and west-northwest maximum-stress directions we derived from mesoscopic faults in Quaternary (Jailpur sandstone) and older (Kohistan complex) foot-wall rock of the Raikot fault (Fig. 2) are consistent with the vergence direction inferred from the large-scale structure of the antiform. North of Nanga Parbat, the antiform terminates abruptly against the Main Karakorum thrust (Butler et al., 1992; Pêcher et al., 1996). Southwest of Nanga Parbat, the antiform continues beyond the massif and is approximately aligned with the northeast-trending antiform associated with the western Himalayan syntaxis (Calkins et al., 1975; Searle and Asif Khan, 1996; Edwards and Kidd, 1997). We consider these antiforms to be part of a single 250-km-long structure from the western terminus of the Himalayan front to the Main Karakorum thrust (Fig. 2). We postulate that the northwest-directed shortening observed at Nanga Parbat and at the syntaxis is characteristic of this entire structure, which is referred to here as the Nanga Parbat antiform.

The Indian crystalline foot-wall block of the Main Mantle thrust in the Tethyan Himalayas and the clastic foot-wall block of the Main Boundary thrust are exposed along the northern and southern portions of the Nanga Parbat antiform, respectively (Fig. 3). The northeast-trending Nanga Parbat antiform merges with the southeast-trending folds of the Himalayan front via a sharp right-angle bend (Calkins et al., 1975). There are no surface expressions of these active northeast-trending structures southwest of this intersection (Fig. 2). This suggests that the Nanga Parbat antiform is rooted on the main Himalayan detachment thrust fault (Fig. 3).

The structural high along the Nanga Parbat antiform correlates with a topographic ridge that includes prominent peaks, e.g., Haramosh (7397 m) and Nanga Parbat (8123 m) within the crystalline massif, and Jamgarh (4734 m) near the syntaxis (Fig. 2). This correlation between structure and topography, accelerating cooling rates during the Neogene (Zeitler et al., 1989), evidence of late Quaternary deformation (e.g., Shroder et al., 1989), and intense seismicity (Seeber et al., 1997) reflect ongoing rapid uplift and transport to the northwest of the Nanga Parbat–Haramosh massif.

The Nanga Parbat antiform is asymmetric (e.g., Treloar et al., 1991). Along the Indus River gorge, the antiform is cut by the Raikot fault (Butler

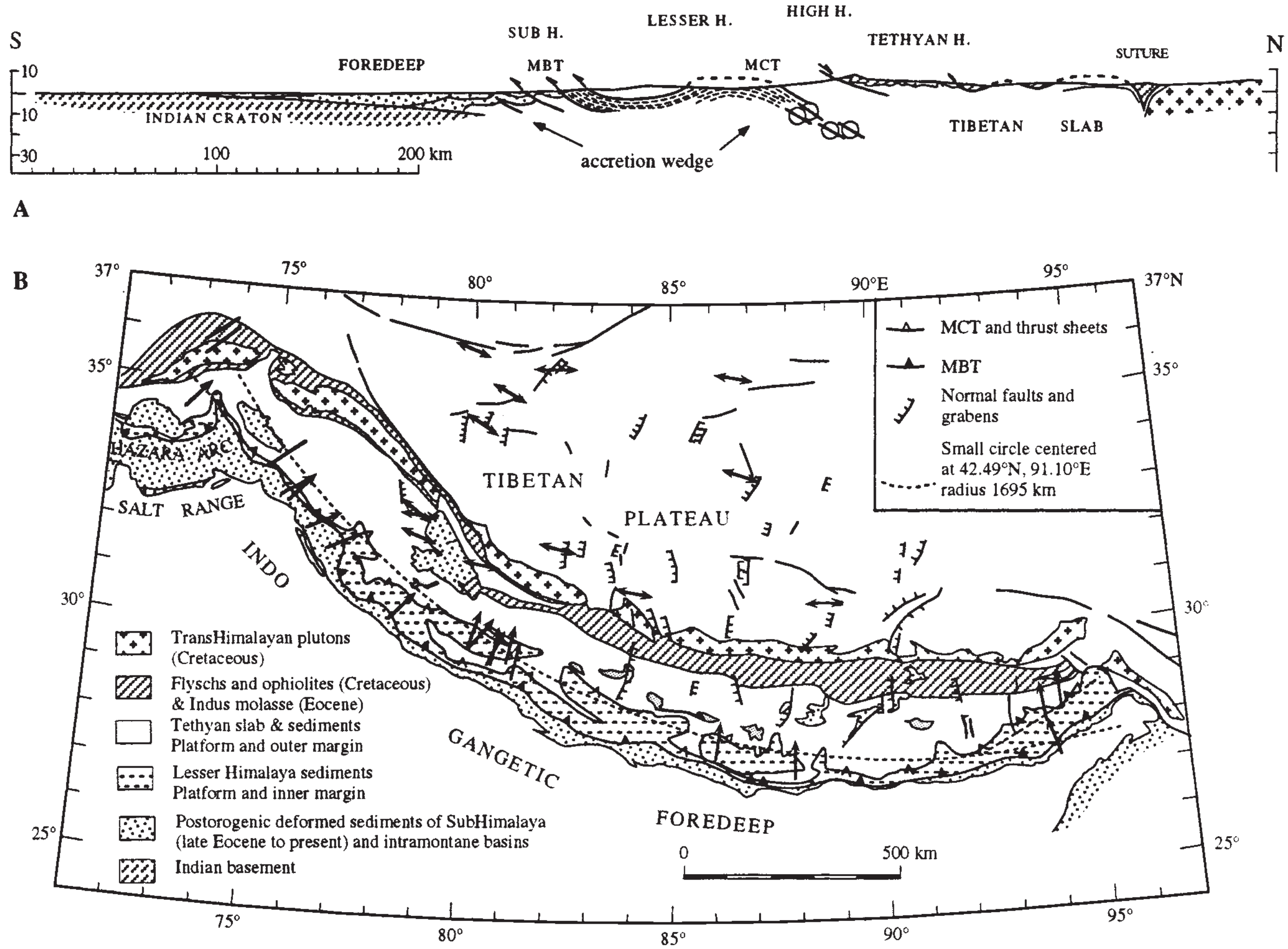

Figure 1. A: Main geologic features and kinematics of seismogenic faults in the Himalayan arc. Single arrows or segments represent slip vectors with shallow or intermediate dips, respectively, in nearly pure thrust focal mechanisms. Double arrows represent T axesof mechanisms with predominant normal faulting. B: Schematic section (1 × 1) through central portion of the arc includes four representative thrust nodal planes. Redrawn from Seeber and Armbruster (1984). MCT—Main Central thrust; MBT—Main Boundary thrust; H—Himalayas.

et al., 1989). This fault strikes north to northeast, parallel to the axis of the antiform, and dips southeast, below the antiform (Fig. 3). It is primarily a reverse fault, as suggested by stress directions (Fig. 2), although dextral and sinistral components are found locally (e.g., Seeber et al., 1997). Shroder et al. (1989) determined a 5 mm/yr late Quaternary dip-slip rate, similar to the estimated uplift rate of the massif (Zeitler at al., 1989). The geometry suggests that the Nanga Parbat antiform is genetically related to the Raikot fault and that shortening is the fundamental cause of the structure. This shortening is directed northwest, meaning that vergence and hanging-wall transport is to the northwest, as compared to a southwest direction of shortening along the Himalayan front in Kashmir (Calkins et al., 1975) and along its buried extension, the Indus Kohistan seismic zone (Fig. 2; Seeber and Armbruster, 1984). Tectonic models of the Nanga Parbat antiform need to account for the singularity of the structure in terms of attitude and kinematics. They also need to account for the rapid uplift of the massif.

STRAIN PARTITIONING ALONG THE HIMALAYAN ARC

The Himalayan convergence front is arcuate, spanning about 2500 km and 60° (Fig. 1). The central two-thirds of the boundary is remarkably circular and has a radius of 1700 km (Seeber and Armbruster, 1984; Bilham et al., 1997). The India-Asia plate-tectonic velocity is approximately to the north and varies little in direction along the Himalayan arc. However, the uniformity of the shortening structures along the arc (e.g., Gansser, 1964) suggests thrusting perpendicular to the local strike of the front. These kinematics are confirmed by earthquake focal mechanisms that show radial convergence along the arc (Fig. 1; Baranowski et al., 1984; Ni and Barazangi, 1985; Molnar and Lyon Caen, 1989). The difference between the expected rigid-plate motion and the observed kinematics along the convergence front requires extension of the Tibetan slab (Tibet) normal to the convergence direction, assuming that the Himalayan foot-wall block (India) is internally undeformed (Fig. 4; e.g., Molnar and Lyon Caen, 1989). A variety of deformation patterns in Tibet can accommodate such extension, but only arc-parallel extension would not change the shape of the arc (Seeber and Armbruster, 1984). A number of Quaternary grabens that cut across the Himalayan front into southern Tibet (e.g., Armijo et al., 1986; Ni and Barazangi, 1985) may account for such extension. These structures tend to be in the radial direction and are most prominent in southern Tibet, as expected with fan-like arc-parallel extension.

Assuming very simple geometry and kinematics (a flat Earth and irrotational motion of India), the rates of shortening across the Himalayan front and the rate of arc-parallel escape (relative to the arc) are **IA**cosθ and **IA**sinθ, respectively, where **IA** is the velocity vector between India and the center of the arc, and θ is the angle between any point along the arc and the point where **IA** is normal to the arc (Fig. 4). These kinematic relations are valid only if the arcuate shape and radius of the convergent front is invariant and if the slip vectors of the intermediate-size thrust earthquakes in Figure 1 reflect the long-term relative motion between India and Tibet. A small part of the India-Tibet nonradial motion may be absorbed in the accretionary prism and may not be represented by the earthquake data (Figs. 1A and 4; Seeber and Armbruster, 1984).

Radial convergence along the Himalayan arc appears to be coupled with arc-parallel escape of hanging-wall material toward the arc termini (e.g., Ni and Barazangi, 1985). As long as the angle between the plate vector and the local convergence vector increases along the arc toward the termini, the escape velocity is expected to increase, leading to distributed extension in southern Tibet (Fig. 4). This arc-parallel extension needs to be compensated by shortening. One candidate is arc-parallel shortening of the hanging-wall block at the arc termini, where the kinematic requirement for arc-parallel escape comes to an abrupt end. We propose that the Nanga Parbat antiform manifests such shortening and is one of the key elements of strain partitioning along the Himalayan arc.

If Tibet-India velocity **IA** ≈ 20 mm/yr (Bilham et al., 1997), then at the western terminus of the front (θ ≈ 40°) the arc-parallel escape velocity **IA**sinθ ≈ 12 mm, similar to the Himalayan convergence rate near the terminus. The escape velocity would be higher if Tibet has an overall motion to the east relative to Asia (e.g., Armijo et al., 1986), but would be lower if part of the arc-parallel motion is taken up in the wedge. The slip rate of 5 mm/yr on the Raikot fault (Shroder et al., 1989) is consistent with a 12 mm/yr escape velocity because additional shortening is probably absorbed by folding of the Nanga Parbat antiform and by other structures northwest of the antiform (Seeber et al., 1997).

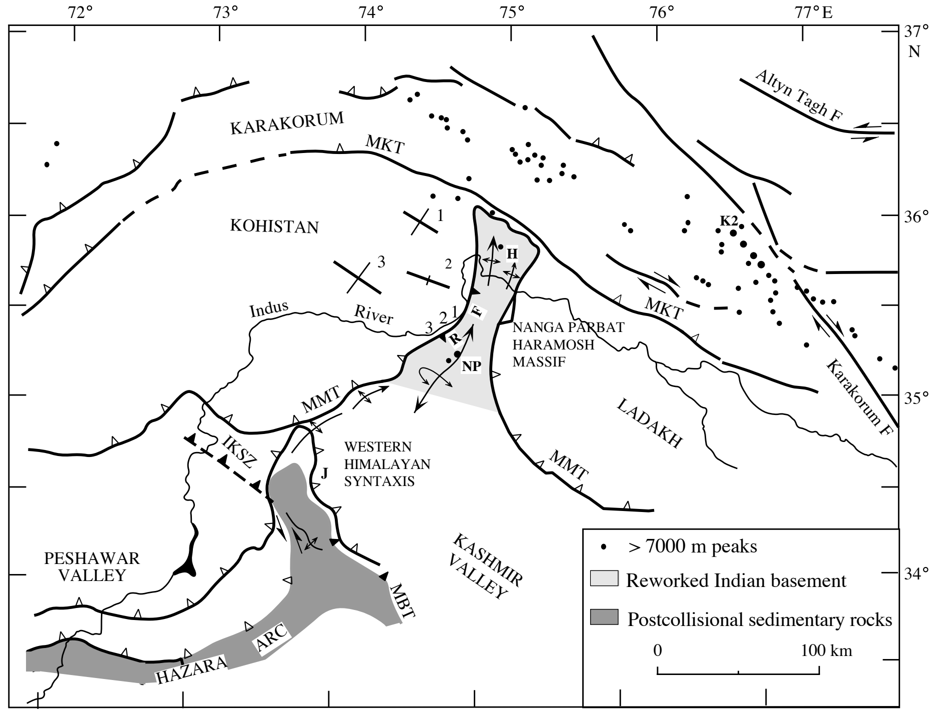

Figure 2. Main structural features of the western Himalayan terminus. The Nanga Parbat antiform strikes northeast across regional structural trends and terminates sharply at the Main Karakorum thrust (MKT) and at the Himalayan front, which is represented by the Main Boundary thrust (MBT) and by the Indus Kohistan seismic zone (IKSZ). Modified from Searle and Asif Khan (1996). Principal horizontal stress axes (deviatoric compression thick; deviatoric extension thin) were inverted from kinematics of mesoscopic faults in footwall of the Raikot fault (RF). Site 3 (15 faults) is in Quaternary Jailpur sandstone. Sites 1 (8 faults) and 2 (17 faults) are in Chilas complex. H, NP, and J are Haramosh, Nanga Parbat, and Jamgarh peaks. MMT is Main Mantle thrust.

SUMMARY AND CONCLUSIONS

The Nanga Parbat–Haramosh massif is part of a 250-km-long northeast-striking antiform, the Nanga Parbat antiform, with clearly defined terminations at the western Himalayan syntaxis to the south and at the Main Karakorum thrust to the north. A strain-partitioning model where radial convergence along the arcuate Himalayan front is coupled with arc-parallel extension in its hanging wall predicts arc-parallel shortening at the arc termini. This model accounts for the Nanga Parbat antiform as a compressional structure normal to the local trend of the Himalayan front. It predicts a dextral transpressional transfer zone at the sharp northern termination of the Nanga Parbat antiform and eastward, possibly connected with the Karakorum fault. It does not, however, require transcurrent motion along the western and eastern boundaries of the antiform. In the proposed kinematics, northwestward transport at the Nanga Parbat antiform may be more than half the convergence rate in the central Himalayas, or as much as 12 mm/yr. The very rapid uplift of the massif is therefore accounted for by

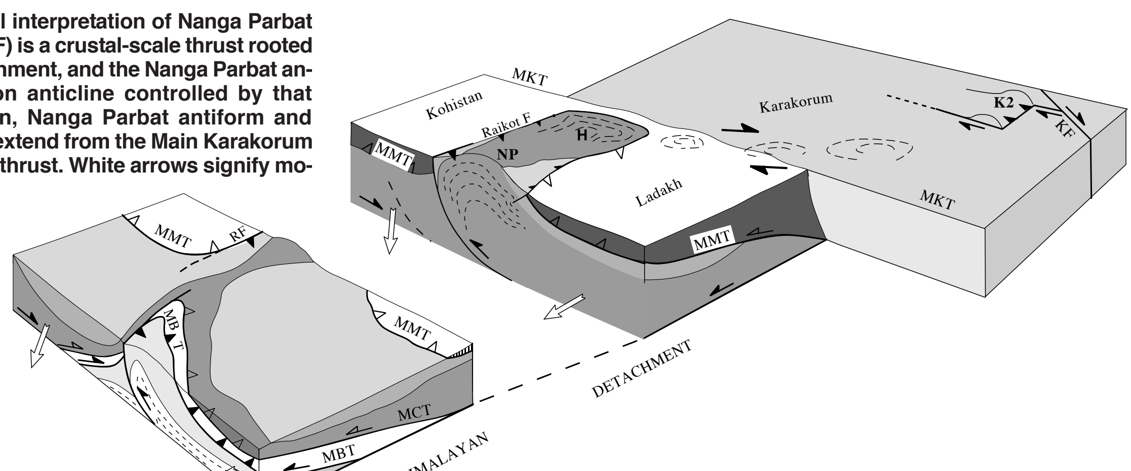

Figure 3. Tentative structural interpretation of Nanga Parbat antiform. The Raikot fault (RF) is a crustal-scale thrust rooted in the main Himalayan detachment, and the Nanga Parbat antiform is a fault-propagation anticline controlled by that thrust. In this interpretation, Nanga Parbat antiform and Raikot thrust (mostly blind) extend from the Main Karakorum thrust to the Main Boundary thrust. White arrows signify motion relative to footwall of Himalayan detachment. Thick and thin one-sided arrows signify sense of motion on inactive and active faults, respectively. MMT—Main Mantle thrust; MKT—Main Karakorum thrust; KF—Karakorum fault; MBT—Main Boundary thrust; MCT—Main Central thrust; NP—Nanga Parbat peak; H—Haramosh peak.

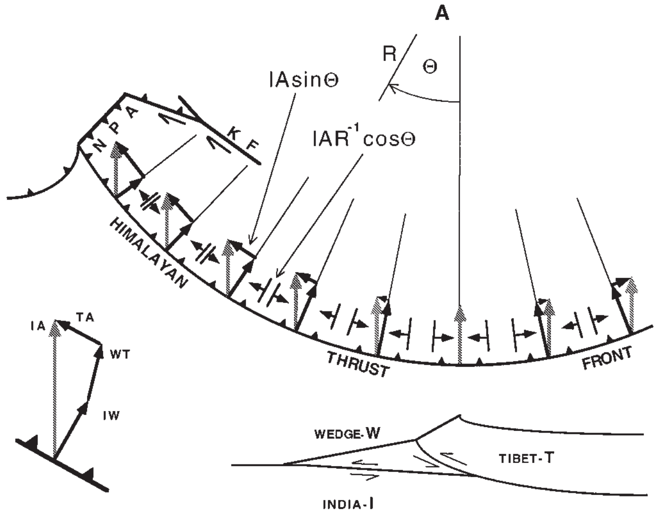

Figure 4. Kinematics for radial convergence along the Himalayan arc (invariant radius R on flat Earth). The velocity vector IA **between India (I) and center of arc (A) is assumed uniform along the arc and directed north.** IA = IW + WT + TA**, where accretionary wedge W and Tibetan hanging-wall T are tectonic elements interposed between I and A along the Himalayan thrust front. If the radial slip vectors of thrust earthquakes represent** IT**, then the "escape" velocity** TA ≤ IA sinθ**. This is a maximum value because the earthquake vectors may not account for some arc-parallel shear in the wedge. KF—Karakorum fault; NPA—Nanga Parbat anticline.**

thrust-related folding. Radial convergence coupled with arc-parallel extension in the hanging-wall block is a common feature of arcuate convergence zones (e.g., McCaffrey, 1992). Arc-parallel shortening at the arc termini may be just as common and is predicted north of the Namcha Barwa syntaxis at the eastern Himalayan terminus.

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