# Convergence across the northwest Himalaya from GPS measurements

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[1] Horizontal velocities of 26 Global Positioning System (GPS) stations in the northwest Himalayan region provide new constraints on the partitioning of India-Eurasia convergence and elastic strain accumulation about the locked Main Frontal Thrust (MFT). The northwest-striking Karakorum fault slips at 11 ± 4 mm/yr and contributes to east-west extension of southern Tibet and westward motion of the northwest Himalaya towards Nanga Parbat, rather than playing a role in eastward extrusion of Tibet. Crustal shortening across the Himalaya occurs within a zone centered about 100 km north of the Siwalik Foothills and the MFT. Model inversions of the GPS data indicate that the MFT is locked over a width of ~100 km. Comparison with geologic MFT-slip-rate estimates suggests that this zone is building up a slip deficit at a rate of 14 ± 1 mm/yr and will eventually fail in future great earthquakes. *INDEX TERMS:* 1206 Geodesy and Gravity: Crustal movements—interplate (8155); 1243 Geodesy and Gravity: Space geodetic surveys; 8102 Tectonophysics: Continental contractional orogenic belts

## 1. Introduction

[2] The topography, geologic structure and earthquakes of the Himalaya are a consequence of the collision and continued convergence of India and Eurasia. Global Positioning System (GPS) measurements [*Paul et al.*, 2001] indicate that the recent India-Eurasia angular velocity is 14% slower than the geologic NUVEL-1A plate motion model [*DeMets et al.*, 1994]. Based on the geodetic plate-motion model, India-Eurasia plate convergence rates increase from 37 to 44 mm/yr from west to east along the Himalaya. However, only as much as 50% of the total convergence occurs within the Himalayan arc itself. The remainder involves distributed continental deformation across a several-thousand-km-wide zone [*England and Molnar*, 1997; *Holt et al.*, 2000; *Wang et al.*, 2001].

[3] GPS measurements in the Nepal Himalaya suggest a Himalayan shortening rate of ~20 mm/yr [*Bilham et al.*, 1997; *Jouanne et al.*, 1999; *Larson et al.*, 1999]. The direction of shortening indicated by focal mechanisms [*Molnar and Lyon-Caen*, 1989] and GPS data [*Paul et al.*, 2001] rotates along the Himalaya to remain in a near arc-perpendicular orientation, consistent with east-west hanging wall extension of southern Tibet [*Armijo et al.*, 1986; *Larson et al.*, 1999]. The GPS measured velocities are consistent with models of interseismic elastic strain accumulation north of the locked, >100-km-wide Himalayan thrust system in Nepal [*Bilham et al.*, 1997; *Cattin and Avouac*, 2000]. No historic great earthquakes have been documented along a >600-km-long stretch of the fault system from northwest India to central Nepal, between the rupture zones of the 1905 Kangra and the 1934 Bihar-Nepal events [*Khattri*, 1987]. If the whole Himalayan thrust system is locked over widths comparable to those found in Nepal, there is potential for several M > 8 earthquakes along the Himalaya, now [*Bilham et al.*, 2001].

[4] GPS measured interseismic convergence rates complement longer-term estimates from structural cross-section restorations and geomorphic evidence. The MFT is the southernmost, youngest and currently most active member of the Himalayan fold and thrust belt. A 21 ± 1.5 mm/yr shortening rate inferred from folded fluvial terraces along the MFT in Nepal [*Lavé and Avouac*, 2000] suggests that little convergence across the Nepal Himalaya is accommodated by other structures to the north. Cross-section restorations of the folded and thrusted Tertiary Siwalik molasse yield shortening rates of 14 ± 2 mm/yr across the Kangra reentrant (near 76° E) and 11 ± 5 mm/yr across the Dehra Dun reentrant (77.5° E) [*Powers et al.*, 1998] (Figure 2). *Powers et al.* [1998] use seismic and borehole data to find that the MFT decollement dips 2.5°N under the Kangra reentrant and 6°N beneath the Dehra Dun reentrant. *Wesnousky et al.* [1999] and *Kumar et al.* [2001] determined Holocene MFT slip rates of ≥13.8 ± 3.6 mm/yr and 9.6 +7.0/−3.5 mm/yr, respectively, from uplifted fluvial strath terraces near Dehra Dun. *England and Molnar* [1997] conclude from a review of published studies that convergence rates increase from 10 ± 2 mm/yr across the Pakistan Himalaya west of 74°, to 17 ± 8 mm/yr in northwest India between 74°–78° E and as much as 25 ± 10 mm/yr east of 88° E.

[5] Additional convergence is accommodated by the northwest-striking, ~700-km-long, right-lateral Karakorum fault (Figure 1). *Avouac and Tapponnier* [1993] infer a slip rate of 32 ± 8 mm/yr from offset Quaternary landforms. *England and Molnar* [1997] and *Holt et al.* [2000] suggest rates of ~10 mm/yr based on regional strain field models and *Murphy et al.* [2000] determined a 6 mm/yr geologic slip rate of the southern Karakorum fault, since 11 Ma.

## 2. GPS Measurements and Analysis

[6] Beginning in 1995, we established a GPS network in northwest India across the rupture zone of the 1905 Kangra earthquake and the western portion of the adjoining seismic gap segment. Repeat measurements of 26 sites spanning at least 2 years allow us to compute reliable site velocities (Figures 1 and 2). All the stations were occupied for 4–5 days during each measurement epoch using Trimble 4000 SSE/SSi receivers. Two permanent GPS stations have been operating at Dehra Dun (WIH2) and Naddi near Dharmsala (NADI), since the end of 1998.

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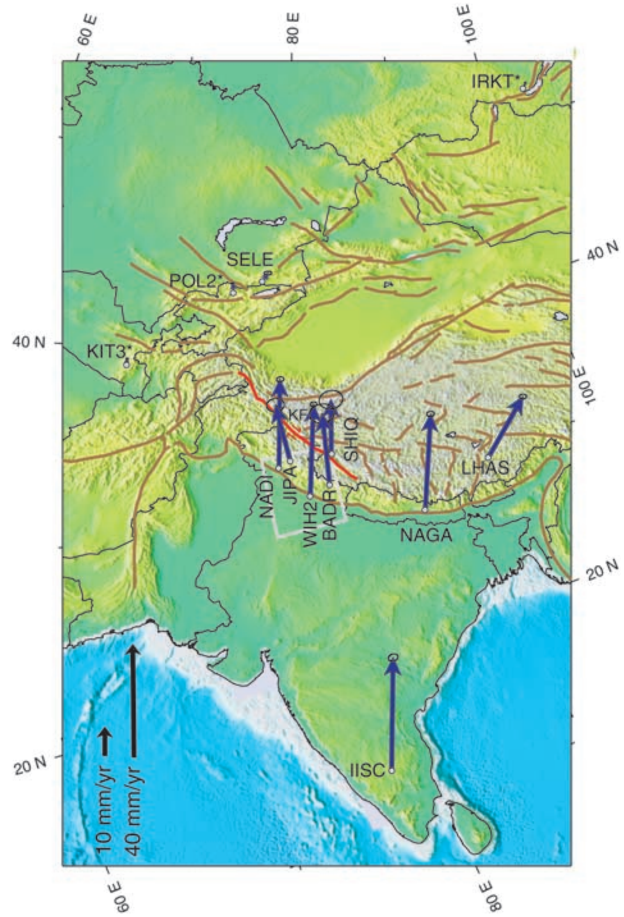


**Figure 1.** Surface relief map of the Indian subcontinent and central Asia showing velocities of a subset of regional GPS stations in Eurasian reference frame (blue arrows tipped with 95% confidence ellipses). Regional faults are drawn in brown and the Karakorum fault (KF) is highlighted in red. The map is drawn in an oblique Mercator projection chosen such that vertical lines and velocity vectors are aligned parallel to relative India-Eurasia plate motion using the pole of angular rotation of *Paul et al.* [2001]. The gray box indicates outline of detailed map shown in Figure 2.

[7] The GPS data were processed using the GAMIT/GLOBK software package. GAMIT uses the GPS carrier phase and pseudorange observables to estimate three-dimensional relative positions of ground stations together with satellite orbits, atmospheric zenith delays, and earth orientation parameters. GLOBK is a Kalman filter used to compute site velocities within a rigorously defined reference frame. In addition to the GPS data collected from our study area, we processed data from a number of permanently operating stations in the region (IISC, KIT3, POL2, SELE, LHAS, and NAGA; Figure 1). We combined our own solutions with daily solutions of global IGS stations processed and archived at the Scripps Orbital and Permanent Array Center (SOPAC). The Eurasia reference frame was defined by applying translation and rotation parameters that minimize the horizontal velocities of sites assumed to lie within the stable plate interior. In this process, we account for effects of post-glacial rebound and plate boundary deformation on some sites, using the same set of reference stations and constraints as *Kogan et al.* [2000]. All together, 735 daily solution files were combined to compute velocities of 63 sites. We increased the formally computed velocity uncertainties by a factor of 2, as our formal uncertainties do not account for correlated errors in the data. We integrate our analysis with results from GPS sites within the Indian plate interior near Delhi (JNUC from *Paul et al.* [2001]) and in western Tibet about 20 km northeast of the Karakorum fault (SHIQ near Shiquanhe from *Wang et al.* [2001]).

## 3. GPS Results

[8] Figure 1 shows the computed GPS velocities with respect to Eurasia in an oblique Mercator projection about the angular rotation pole of India-Eurasia motion computed by *Paul et al.* [2001]. Thus, convergence-parallel features or velocities are aligned with the map border. Station IISC near Bangalore moves towards Eurasia at 40 ± 1 mm/yr, consistent with the *Paul et al.* [2001] plate motion model. Northeast-directed shortening across the Himalaya of 15 ± 2 mm/yr occurs between JNUC and JIPA, our northernmost

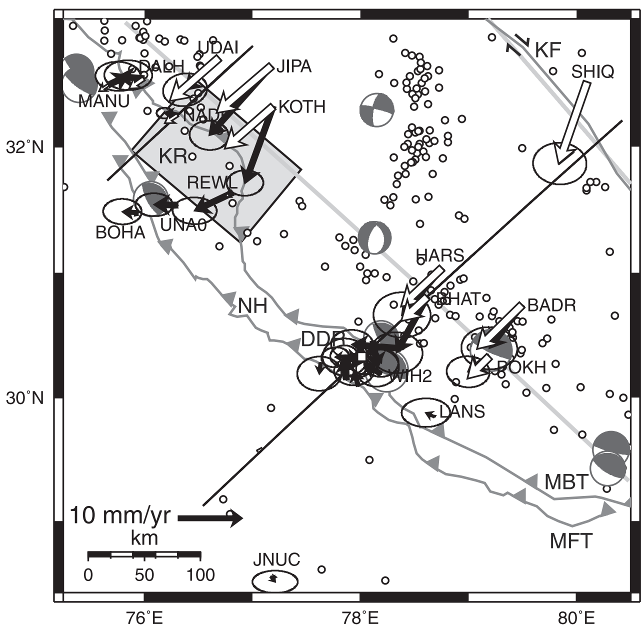


**Figure 2.** Fault and seismicity map of study area with observed (solid black arrows tipped with 95% confidence ellipses) and modeled (white open arrows) GPS site velocities relative to station WIH2 (indicated by white square) in Dehra Dun. Bold gray lines indicate the surface projection of dislocations used to model the data. Earthquakes of $M \geq 4$ from 1970–2001 (from CNSS catalog) are shown as small circles and focal mechanisms (from Harvard CMT catalog) are shown in gray shade. The inferred extent of the $M_s$ = 7.8, 1905 Kangra earthquake rupture plane (rectangle near Kangra reentrant) is from *Bilham* [2001]. Two northeast-striking lines indicate the section lines onto which the GPS velocities are projected in Figure 3. KR: Kangra reentrant, NH: Nahan salient, DDR: Dehra Dun reentrant, KF: Karakorum fault, MBT: Main Boundary Thrust, MFT: Main Frontal Thrust (thrust traces adapted from *Powers et al.* [1998]).

site in the northwest India network (Figure 2). Relative to our northern sites SHIQ has a Karakorum-fault parallel motion of about 10 mm/yr (Figure 2). East-west extension of 5 ± 3 mm/yr occurs across a seismically active graben system and the Karakorum fault between JIPA and SHIQ (Figure 2). We note that while stations in the southern Himalaya move parallel to the expected Indian plate motion, the northern stations in our network (e.g., JIPA and BADR in Figure 1) have a more westerly motion. In southeast Tibet, LHAS moves eastward of the India-Eurasia convergence direction. Thus, east-west extension across south Tibet between JIPA and LHAS is 20 ± 2 mm/yr and involves both westward and eastward extrusion.

[9] The GPS velocity field in northwest India indicates that much of the ~15 mm/yr of Himalayan shortening is localized within a ~100 km-wide zone that follows the southern edge of the higher Himalaya and roughly coincides with a belt of active microseismicity along the range (Figures 2 and 3). There is little deformation across the Siwalik foothills and the surface trace of the MFT, which shows that the faults that apparently accommodate most of the Quaternary Himalayan shortening [*Powers et al.*, 1998] did not slip appreciably during the observation period. This pattern is similar to the distribution of deformation observed along the Nepal Himalaya and agrees with models of elastic strain accumulation north of the interseismically locked Himalayan thrust system described next.

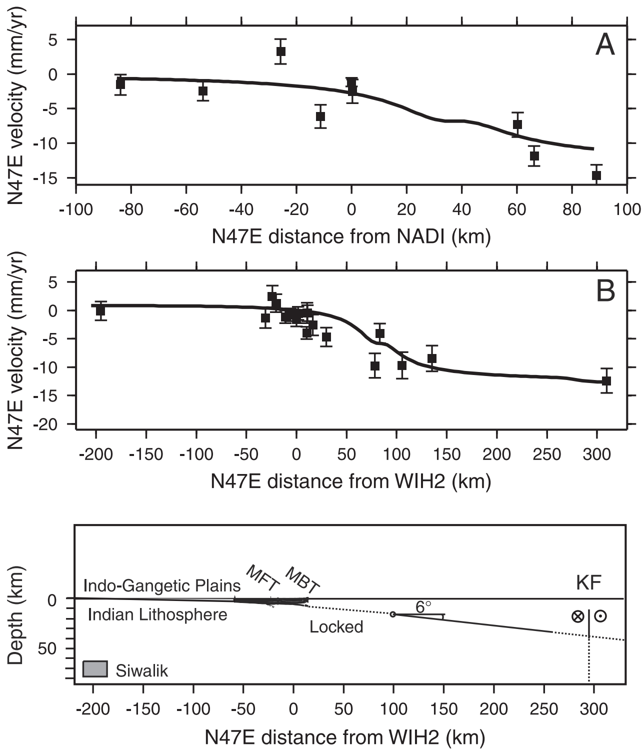


**Figure 3.** Cross-section of arc-perpendicular velocities relative to WIH2 projected onto two section lines through (a) Kangra and (b) Dehra Dun reentrants (see Figure 2 for location). Squares with 1-sigma error bars are observed site velocities and solid lines are predicted arc-normal velocities along profiles from the model shown in Figure 2. (c) Schematic structural cross-section along the Dehra Dun profile shown in Figure 2.

## 4. Modeling the Northwest Himalaya GPS Velocities

[10] Assuming that the 1995–2000 GPS velocity field across the northwest Himalaya is dominated by interseismic elastic strain accumulation about major locked faults by adjacent aseismically slipping fault segments [e.g., *Larson et al.*, 1999], we model the deformation using uniform-slip dislocations in an elastic, homogeneous and isotropic half-space [*Okada*, 1985]. The model faults reach far below Tibet to avoid edge effects from the northern tip of the finite dislocations, even though deformation below Tibet is likely to be accommodated by more widely distributed shear in the lower crust and upper mantle [*Royden et al.*, 1997]. We use both ''trial-and-error'' forward modeling and inversion methods to evaluate model parameters. We further constrain the model parameters by incorporating information about the geometry of the fault system provided by geologic studies [*Powers et al.*, 1998]. The agreement of model predictions and data is formally evaluated by the weighted residual sum of squares $WRSS = (d_{obs} - d_{\mathrm{mod}})^T \cdot \mathrm{cov}^{-1} \cdot (d_{obs} - d_{\mathrm{mod}})$, where $d_{obs}$ and $d_{\mathrm{mod}}$ are the observed and modeled horizontal velocity components, respectively, and $cov$ is the data covariance matrix. Our aim in using these simple models is to gain an improved understanding of fault slip rates and the width of the locked megathrust in the northwest Himalaya that represents the source area of future large earthquakes in the region.

[11] We find that a first-order model that predicts the general character of the GPS velocity field consists of a single 6°N-dipping, 133° striking dislocation whose southwestern edge at 15 km depth follows the zone of highest displacement gradient (Figures 2 and 3). Whereas the strike and horizontal location of the model dislocation are relatively well constrained by the data, we find significant tradeoff between the locking depth and best-fit slip rate. A free geometry inversion favors a locking depth of only 5 km (WRSS = 288), inconsistent with the geometry inferred from geologic and seismic evidence [*Powers et al.*, 1998]. Extrapolating the detachment dips found by *Powers et al.* [1998] back to the inferred transition zone suggests locking depths in the range of 10–20 km. We evaluate the best-fitting slip rate for these depths finding rates increasing from 13.1 mm/yr (WRSS = 299) to 14.9 mm/yr (WRSS = 354) as locking depths increase from 10 to 20 km. Our best estimate of northwest Himalayan thrusting is 14 ± 1 mm/yr given a locking depth of 15 km. The width between the surface trace of the MFT along the Siwalik foothills and the model-dislocation edge is approximately 100 km.

[12] We also include the Karakorum fault in our model inversions as a vertical dislocation slipping below a locking depth of 10 km following the mapped trace of the fault (Figure 2). A Karakorum fault slip rate of 11 mm/yr matches the observed velocity of SHIQ, and a range of 7 to 15 mm/yr produces predicted velocities within one standard deviation of the observation.

## 5. Discussion and Conclusions

[13] Our measurements shed new light on the regional accommodation of India - Eurasia convergence and constrain

the slip rate and locking width of the MFT. The extension of south Tibet involves both eastward motions of points in southeast Tibet relative to the Indian convergence azimuth [*Larson et al.*, 1999], as well as westward motion of points in the northwest Himalaya (Figure 1). Thus, the Karakorum fault contributes to westward motion of points in the northwest Himalaya, rather than to the large-scale eastward extrusion of Tibet. This result is consistent with models in which arc-parallel extension is accommodated by significant east-west shortening in the western Himalaya syntaxis [*Seeber and Pecher*, 1998]. The velocity of a single GPS station (SHIQ) located ~20 km to the northeast of the southern Karakorum fault [*Wang et al.*, 2001] suggests a slip rate of ~11 ± 4 mm/yr, which is consistent with the lower range of geologic slip-rate estimates for the Karakorum fault. It is possible that some slip is transferred to a thrust belt and the right-lateral Karakorum-Jiali fault zone which diverge from the Karakorum fault at ~34° N [*Armijo et al.*, 1986].

[14] Our best-fit slip rate for the (currently locked) MFT of 14 ± 1 mm/yr is consistent with geologic studies [*Powers et al.*, 1998; *Wesnousky et al.*, 1999, *Kumar et al.*, 2001]. This comparison assumes that the elastic strain accumulating interseismically along the Higher Himalaya will ultimately be relieved by slip of the MFT to near its surface trace along the Siwalik foothills. In Nepal it was found that geologic slip rate estimates along the MFT range front faults are in fact very close to those inferred from the GPS deformation field [*Larson et al.*, 1999; *Lavé and Avouac*, 2000]. As field studies provide more precise estimates of geologic slip rates and our geodetic measurements improve, we will be able to more confidently determine if other structures such as the MBT are also active.

[15] Similar to conclusions drawn from GPS measurements in Nepal our results indicate a locked ~100-km-wide detachment fault. Thus the seismic gap between the rupture zones of the 1905 Kangra and 1934 Bihar-Nepal earthquakes will likely be filled by one or more major earthquakes. Ongoing densification and improved precision of GPS measurements will eventually allow us to determine in greater detail variations in locking width and strain accumulation patterns, and thus the seismic potential along the Himalaya.

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