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# Seismic slip deficit in the Kashmir Himalaya from GPS observations

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# Seismic slip deficit in the Kashmir Himalaya from GPS observations

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[1] GPS measurements in Kashmir Himalaya reveal range-normal convergence of 11 ± 1 mm/yr with dextral shear of 5 ± 1 mm/yr. The transition from a fully locked 170 km wide décollement to the unrestrained descending Indian plate occurs at ~25 km depth over an ~23 km wide transition zone. The convergence rate is consistent with the lower bounds of geological estimates for the Main Frontal Thrust, Riasi, and Balapora fault systems, on which no surface slip has been reported in the past millennium. Of the 14 damaging Kashmir earthquakes since 1123, none may have exceeded $M_w = 7.6$. Therefore, either a seismic moment deficit equivalent to a $M_w \approx 8.7$ earthquake exists or the historical earthquake magnitudes have been underestimated. Alternatively, these earthquakes have occurred on reverse faults in the Kashmir Valley, and the décollement has been recently inactive. Although this can reconcile the inferred and theoretical moment release, it is quantitatively inconsistent with observed fault slip in Kashmir. **Citation:** Schiffman, C., B. S. Bali, W. Szeliga, and R. Bilham (2013), Seismic slip deficit in the Kashmir Himalaya from GPS observations, *Geophys. Res. Lett.*, *40*, 5642–5645, doi:10.1002/2013GL057700.

## 1. Introduction

[2] Between longitudes 75°E and 77°E, the Tibetan Plateau narrows to 500 km, and the convergence rate between the Tarim Basin and the Indian craton falls to ~16 mm/yr [*Zhang et al.*, 2004] (Figure 1). GPS measurements between the Indian plate, Pir Pinjal, and Zanskar regions of Indian Kashmir, following the 2005 Kashmir earthquake, reveal that 75% of this convergence (~12 mm/yr) is manifest in the southernmost 250 km of the mountains (Figure 1). Thus, the convergence rate in Kashmir is ~30% lower than the 16–18 mm/yr found in the central Himalaya and the contiguous Kangra region to the east [*Avouac*, 2003; *Banerjee and Bürgmann*, 2002; *Jade et al.*, 2004].

[3] Hitherto, it has been assumed that the northern edge of the Himalayan décollement west of the 1905 Kangra rupture follows the discontinuous 3.5 km elevation contour in the Pir Pinjal; however, the locus of maximum strain revealed by GPS measurements in Kashmir requires that this assumption be discarded. Instead, we find that interseismic locking occurs beneath the 3.5 km elevation contour at the SW edge of the Zanskar range, and we infer that a locked décollement underlies the Kashmir Valley and the Pir Pinjal with a total downdip width of 200 km in the west, narrowing eastward.

[4] The 270 km along-arc distance between the 1905 Kangra earthquake and the 2005 Kashmir earthquake has been termed the "Kashmir seismic gap" [*Khattri*, 1999] due to the historical absence of great décollement ruptures here. Although several damaging earthquakes have occurred since 1132 A.D., the absence of quantitative data prevents accurate conclusions concerning magnitudes or rupture areas [*Bilham et al.*, 2010; *Bilham and Bali*, 2013]. Four of the 13 known historical earthquakes before 1885 have been associated with several weeks of aftershocks suggesting that their magnitudes may have exceeded $M_w = 7$, but because none of these are described in historical sources from south of Kashmir, it is improbable that any have exceeded $M_w = 8$. Even for the best documented of these earthquakes (1555), $M_w \approx 7.6$ has been assigned based only upon the area of felt reports [*Ambraseys and Douglas*, 2004].

## 2. GPS Data

[5] We supplemented published GPS data from Afghanistan, Tibet, India, Pakistan, and China [*Bendick et al.*, 2007; *Khan et al.*, 2008; *Zhang et al.*, 2004] with data from Kashmir acquired from 2006 to 2012. Campaign points were occupied for 4–7 days, and continuous measurements were obtained at Raujari, Srinagar, Dras, and Kargil for more than 3 years. Trimble 5700 receivers with zephyr antennas were used throughout. The data were processed in Kashmir and in the U.S. with consistent results using GAMIT and GLOBK software [*King and Bock*, 1999] (see Text S1 in the supporting information for data and processing details). Range-normal velocities are shown in Figure 2. Data from some points were omitted because they exhibited clear evidence for local instability.

[6] Although the observed velocity field is consistent with uniform aseismic slip occurring below a locking line on a planar fault at 33 ± 10 km depth, this exceeds the mean depth reported elsewhere in the Himalaya for locking below the 3.5 km contour [*Avouac*, 2003]. Since the width of the surface velocity field can be broadened by partial seismic decoupling, we explored a range of models in which the transition from aseismic creep to full locking of the décollement tapers over a finite distance. Using boundary element methods [*Gomberg and Ellis*, 1993], we imposed an elliptically tapered decay in slip toward the tip of the subsurface dislocation over a downdip width from 5 to 300 km (Figures 1 and S1–S8 and Text S1). The best fitting models require 11 ± 1 mm/yr of convergence and 5 ± 1 mm/yr of dextral shear, where the transition from fully locked to fully decoupled creep occurs at a depth of 25 ± 4 km over a

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Additional supporting information may be found in the online version of this article.

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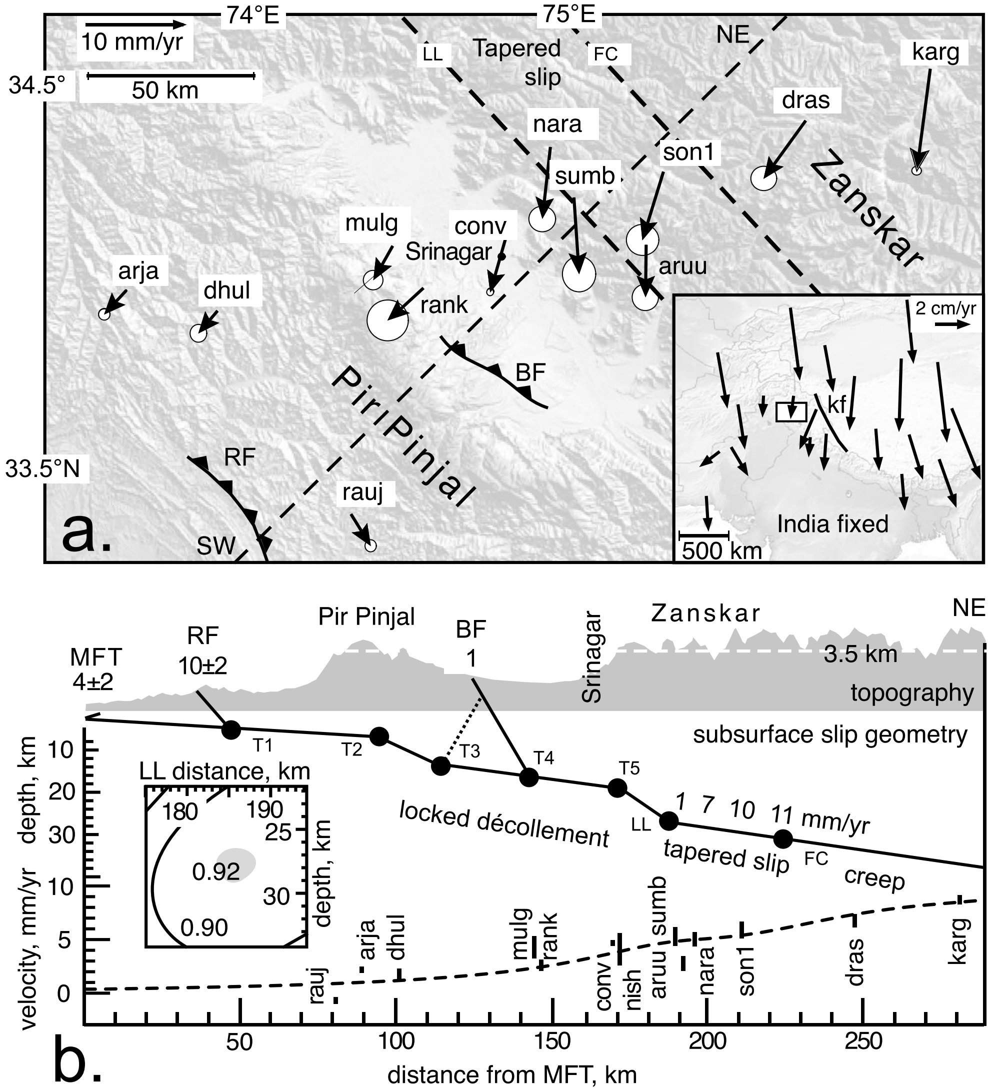

**Figure 1.** (a) India-fixed velocities with 95% error ellipses showing location of tapered décollement slip. MFT = Main Frontal Thrust, RF = Riasi fault, BF = Balapora fault, LL = locking line, FC = fully creeping, kf = Karakoram fault. SW/NE dashed line indicates the cross section in Figure 1b. (b) Schematic cross section showing location of faults, published slip rates (mm/yr), hypothetical rupture termination points T1–T5, LL, and FC used in Table 1 and location of tapered slip. Inset shows $R^2$ values (percentage of variance explained by the model) for varying the depth and horizontal position of the end point (LL) of tapered slip along the line of section in Figure 1a. See supporting information for details.

downdip width of ~23 km. None of our elastic models permit significant creep (<1 mm/yr) beneath the Kashmir Valley.

[7] A remarkable feature in the data is the presence of ~6 mm/yr of dextral shear parallel to the Zanskar range which, although weakly constrained to the same maximum strain gradient as the convergence signal (Figure S8), suggests that an oblique slip deficit (N175°W) is developing along the SW edge of the Zanskar Range at 12.5 ± 1 mm/yr. With the exception of the Karakoram fault [*Jade et al.*, 2004], no prominent dextral faulting has been reported nearby, and it appears probable to us that NW trending faults that have been identified south of the Zanskar may include a component of oblique slip.

## 3. Structure and Faulting

[8] Three significant fault systems accommodate convergence between the Zanskar range and the Indian craton (Figure 2).

[9] No surface faulting has been reported from the Main Frontal Thrust (MFT) at the foot of the Pir Pinjal. Anticlinal structures here suggest that convergence in the past 15 kyr at 2–6 mm/yr has been accommodated by folding of surface sediments [*Vignon*, 2011].

[10] A 70 km long strand of the Riasi fault dips 45°NE on the SE flank of the Pir Pinjal (Figure 2) and has been interpreted to represent the southeast extension of the Balakot-Bagh fault [*Shah*, 2013; *Thakur et al.*, 2010; *Vignon*, 2011]. *Vignon* [2011] reported a N/S shortening rate of 10 ± 2 mm/yr near Riasi assuming an ~E/W strike and a 45° dip.

[11] The ~40 km long Balapora reverse fault dips ~60°NE near the surface and forms one of three conspicuous scarps that offset Karewa sediments in the SE Kashmir Valley [*Ahmad et al.*, 2013; *Shah*, 2013]. Paleoseismic investigations of the Balapora fault reveal a shortening rate of 0.3–1.3 mm/yr. The date of the most recent slip on the Balapora fault is

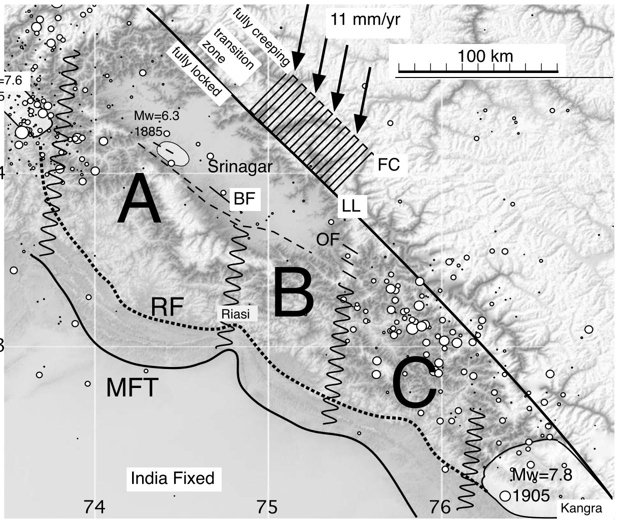

**Figure 2.** The Himalaya between the 2005 Kashmir and 1905 Kangra rupture zones. Segment boundaries (wavy lines) between areas A, B, and C are defined in text. Grid indicates region of tapered slip. Arrows indicate mean GPS India fixed vector. Symbols are as denoted in Figure 1. Dashed lines indicate inferred surface faults [*Shah*, 2013]. OF = Oldham fault [*Bilham et al.*, 2013]. Seismicity 1973–2013 from the USGS/PDE Global Catalog (http://earthquake.usgs.gov/research/data/pde.php).

probably >1 kyr [*Meigs et al.*, 2012]. *Vignon* [2011] interpreted the Balapora fault as a wedge thrust overlying a SE dipping antithetic fault (dashed line in Figure 1b). It is possible that the slip of the Balapora fault primarily records flexure of the Kashmir Basin [*Burbank and Johnson*, 1983] and thus provides a misleading measure of the convergence between the Zanskar range and the descending Indian plate.

[12] The lower range of these combined shortening rates (15 ± 5 mm/yr) is consistent with our observed oblique convergence rate of 12.5 ± 1 mm/yr (Figure 1), but since none of these faults are reported to have slipped in the past 900 years, a current slip deficit of >11 m may exist.

## 4. Discussion: Rupture Scenarios

[13] In Figure 2, we identify several possible rupture segments in the region between the 2005 Kashmir $M_w = 7.6$ earthquake and the 1905 Kangra $M_w = 7.8$ earthquake. The locking zone beneath the Zanskar range is considered the northern limit of décollement rupture, and the southern limit follows the foothills of the Pir Pinjal. We consider slip from the locking line to the surface Balapora and Riasi fault systems and to the MFT and partial slip on the décollement terminated at the base of these faults (Figure 1b, T1–T5).

[14] We invoke two broad tectonic features that may act to arrest along-strike rupture (Figure 2). The segment boundary between A and B is suggested by the river drainage in the SE Kashmir Valley and by the reentrant near Riasi that is typical of folding associated with a sea mount being underthrust beneath an accretionary wedge [*Schiffman et al.*, 2011]. The segment boundary between B and C is identified by the abrupt westward reduction of seismic productivity between Kishtwar and the Kashmir Valley and a suite of normal faults along the crest of the range that separates these two regions [*Schiffman et al.*, 2011; *Bilham et al.*, 2013].

[15] We next consider the rupture of each of these fault patches in isolation, or contiguously in unison, applying scaling laws, guided by observed slip in great Himalayan earthquakes [*Kumar et al.*, 2006] to anticipate fault slip for each combination of along-strike length and downdip width. The resulting matrix of $M_{\max}$ values from $7.3 > M_w > 9.0$ is shown in Table 1.

[16] We note that $M_{\max}$ for very few segment combinations calculated in Table 1 are compatible with the historical record of inferred $M_w \leq 7.6$ earthquakes. In particular, there is no precedence for a $M > 8$ multisegmented along-strike rupture of the entire region between Kangra and Muzaffarabad. The summed seismic moment, assuming that all 13 pre-1885 earthquakes were $M_w = 7.6$, amounts to $3.8 \times 10^{28}$ dyn cm, whereas the cumulative seismic moment since the 1123 earthquake for the entire décollement (A, B, and C in Figure 2) is $\approx 1.3 \times 10^{29}$ dyn cm, with a slip deficit of 11 m and a moment deficit equivalent to a single $M_w = 8.7$ earthquake. Since no creep is manifest SW of the locking line, we would conclude that one or more earthquakes with $8.2 < M_w < 8.6$ are either missing from the 900 yearlong historical earthquake record or will occur in the future.

[17] This calculation, however, follows the traditional view that the décollement from the locking line to the MFT represents the active plate boundary and makes no allowance for the possibility that reverse faults in the Kashmir Valley have transiently "short-circuited" the 11 mm/yr convergence signal in the past millennium. Thus, supposing that the Balapora system of thrust faults extends throughout segments A–C and that the décollement to its SE has been recently inactive, the anticipated seismic moment release for the past 900 years for this 270 × 50 km$^2$ area would be

**Table 1.** Estimated $M_{\max}$ Associated With Segmental or Complete Slip of the Kashmir Seismic Gap [*Khattri*, 1999][a]

| Segment | Width | A = 100 km | B = 70 km | C = 100 km | A + B = 170 km | B + C = 170 km | A + B + C = 270 km |
|---|---|---|---|---|---|---|---|
| LL-BF | 50 | 7.7 (2) | 7.6 (2) | - | 8.0 (2) | - | - |
| LL-RF | 135 | 8.3 (6) | 8.1 (6) | 8.3 (6) | 8.6 (10) | 8.6 (10) | 8.8 (15) |
| LL-MFT | 170 | 8.5 (10) | 8.4 (10) | 8.4 (10) | 8.7 (15) | 8.6 (15) | 8.9 (20) |
| FC-MFT | 200 | 8.6 (12) | 8.5 (12) | 8.5 (12) | 8.8 (15) | 8.5 (15) | 9.0 (25) |
| FC-RF | 170 | 8.5 (10) | 8.4 (10) | | 8.7 (15) | | |
| T5-BF$_{\text{surface}}$ | 30 | 7.5 (2) | 7.4 (2) | | | | |
| T3-RF$_{\text{surface}}$ | 25 | 7.8 (5) | 7.7 (5) | 7.8 (5) | 8.4 (7) | | |
| LL-T3 | 20 | 7.4 (2) | 7.3 (2) | | | | |
| LL-T4 | 30 | 7.8 (5) | 7.7 (5) | 7.7 (5) | | | |

[a] Estimated $M_{\max}$ values are calculated for rupture between downdip features L1-FC in Figure 1b and along-strike segments in Figure 2. Slips in parentheses (m) are from scaling laws. Not all combinations of slip and rupture area are considered. The width of the décollement (column 2, in km) halves eastward. Maximum slip (23 m) has been reported in the western Himalaya [*Kumar et al.*, 2006], but no paleoseismic slip has been recorded from the Pir Pinjal MFT.

$4.4 \times 10^{28}$ dyn cm, close to that inferred above. However, this would require branches of the Balapora fault system each to have slipped 2–4 m in 13 earthquakes distributed along the range, for which there is no evidence. No surface faulting in the past millennium has yet been reported on any faults in the Kashmir Valley.

## 5. Conclusions

[18] We report range-normal convergence of $11 \pm 1$ mm/yr and dextral shear of $5 \pm 1$ mm/yr beneath the Zanskar range, with total oblique convergence of 12.5 mm/yr at ~N175°W. A 23 km wide transition zone on the Himalayan décollement separates a fully locked 170 km wide décollement from the unrestrained descending Indian plate at 25–30 km depth. No creep occurs beneath the Kashmir Valley. Geological slip rates reported on the Balapora, Riasi, and MFT faults in the past 15–40 kyr are quantitatively consistent ($0.8 \pm 0.5$, $10 \pm 2$, and $4 \pm 2$ mm/yr, respectively) with our observations, and therefore, it is probable that these faults absorb the entire long-term convergence signal.

[19] Since no surface slip is reported to have occurred in the past millennium, we may conclude that a slip deficit of ~11 m exists. If the entire décollement, or ~250 km of the Riasi fault, were to slip 11 m slip between 74 and 76°E, it would result in a $8.5 < M_w < 8.7$ earthquake. The maximum slip recorded on the MFT to the east is ~23 m [*Kumar et al.*, 2006]; hence, $M_{\max}$ for a Kashmir gap-filling earthquake could be $8.8 < M_w < 9.0$. Although the recurrence interval for such earthquakes would be ~1200 years on the Riasi fault and >1800 years on the MFT, no quantitative evidence for such a large earthquake is currently known in Kashmir's history.

[20] However, if we consider that the plate boundary has been recently short-circuited by reverse faults in the Kashmir Valley and that the Riasi fault and the frontal fold system have been inactive in recent history, then 14 $M_w \approx 7.6$ earthquakes would be sufficient to satisfy the lower anticipated cumulative moment release. Arguing against this alternative interpretation, of the 14 damaging earthquakes that have occurred in 1123–1885, only the 1555 earthquake is believed to have been $M_w \sim 7.6$; none have resulted in observed surface slip, and it is possible that the faults in the Kashmir Valley are secondary features that do not actively participate in underthrusting of the Indian plate. Since 1555, damaging earthquakes have been reported in the Kashmir Valley with a mean recurrence interval of $29 \pm 27$ years, and it is now 128 years since the most recent ($M_w = 6.5$ in Baramula). The absence of a recent damaging earthquake suggests that a $6.5 < M_w < 7.6$ earthquake in the valley should be anticipated, and a much larger earthquake, though of low probability, cannot yet be excluded.

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