

GPS constraints on Indo-Asian convergence in the Bhutan Himalaya: Segmentation and potential for a $8.2 < M_w < 8.8$ earthquake.

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The seismogenic setting of Bhutan is unusual due to its lower-than-average 20th century seismic moment release (Drukpa et al., 2006), its absence of a reliable historical record, and its unusual location near the Shillong plateau where a great earthquake in 1897 resulted in ≈ 10 m of N/S shortening of the Indian plate to its south (Gahalaut et al., 2011). Despite these indicators that lower than normal convergence velocities should currently prevail, the GPS velocity between Shillong and Lhasa suggests that present day convergence in Sikkim and Bhutan occurs at velocities ≈ 20 mm/yr. GPS points between the Greater Himalaya and the Shillong Plateau measured in 2003-2012 permit us to quantify Bhutan's seismogenic potential.

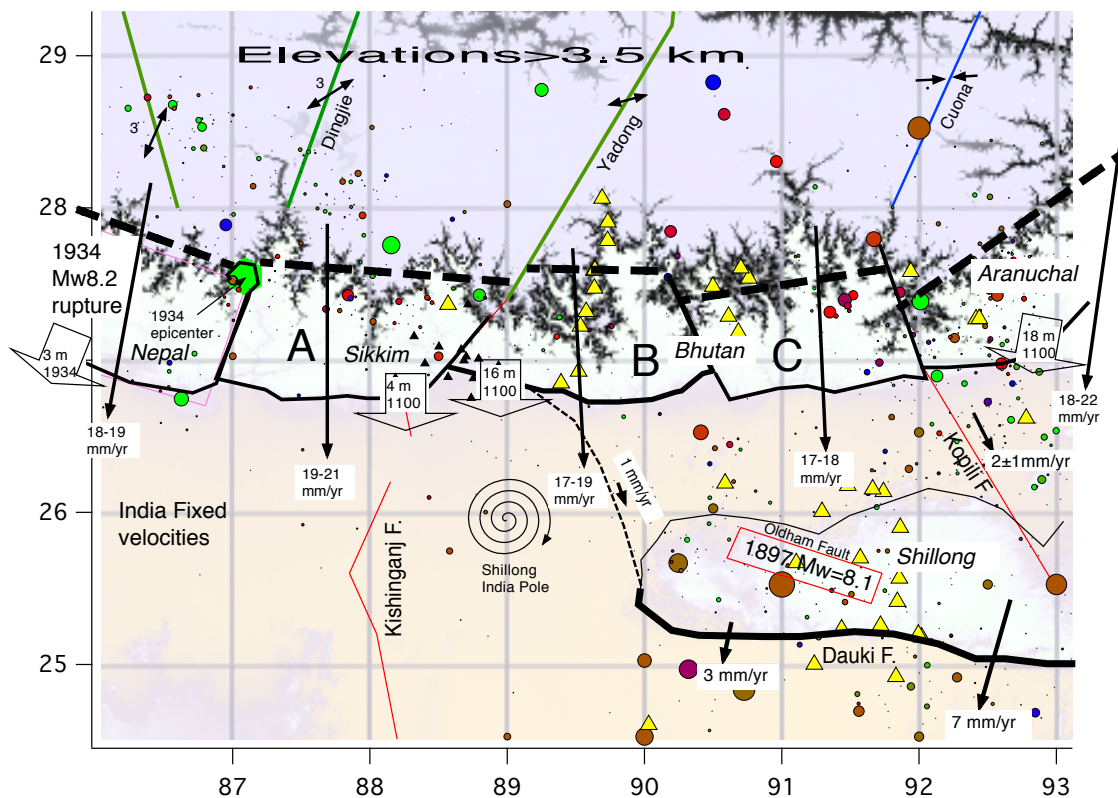


Fig. 1. Selected GPS points in Sikkim, Bhutan, Shillong (triangles), and rupture segments A, B and C discussed in the text. Thick dashed line is the inferred locking line south of which great ruptures propagate. Large arrows near the MFT are estimates of paleoseismic slip. Bold arrows indicate relative motions across major faults. Pole of rotation between Shillong Block and India implies slip increasing eastwards on the Dauki fault, and an ill defined boundary to the east (dashed) near Dhuki.

Sikkim GPS data (Mukul et al., 2008; Mullick et al., 2009) and new data presented here can be explained by a convergence velocity of ≈ 20 mm/yr with a locking line at 20 km depth. No evidence for creep is manifest south of the locking line. Our preferred solutions suggest 7°N dip similar to the centroid solution for a 2009 $M_w=6.1$ earthquake in E. Bhutan. Velocities in central and eastern Bhutan are 17-19 mm/yr, and in the Aranuchal Himal they increase to 18-22 mm/yr.

Given the foregoing values for velocity, dip and depth we searched for the probable northern limit of the locking line, and hence the down-dip width of the Himalayan décollement in Sikkim and Bhutan (Table 1). In E. Bhutan we use the 2009 earthquake as a proxy for the locking line. Analytic locations for the locking line approximately follow the 3.5 km contour (Avouac, 2003).

We next proceed to determine the maximum magnitude earthquake that could occur in the Bhutan Himalaya at the present day assuming that a historical earthquake with 18 m of slip may have occurred c.1100 as recorded in trenches at 88.8°E and 92.8°E (Kumar et al., 2011), or in 1713 (Ambraseys and Jackson, 2003) as recorded in Tibetan histories.

The size of a future (or historical) earthquake depends on its along-strike length, for which we have no observational data. However, the Sikkim-Bhutan Himalaya is bounded by prominent along-arc changes of strike that we invoke to suggest favorable locations for rupture termination or initiation (King & Nabelik, 1985). In the west, at 87° , a 10° change in strike of the Himalaya occurs between the 1934 rupture zone (Feldl, 2005) and the almost east-west 500-km-long Sikkim-Bhutan segment (A-B-C). An abrupt 20° change in strike of the Himalayan-arc occurs in 91.7°E in eastern Bhutan at the start of the 400-km-long, $\text{N}70^\circ\text{E}$ striking, Aranuchal Pradesh segment close to the intersection of the inferred Kopilli fault.

Between these two major segment boundaries we identify A) the E.Nepal-Sikkim segment west of the Gish fault (Mukul et al., 2008), Yadong rift and Kishinganj Fault (Ni and Barazangi, 1984). The west end of the Shillong plateau is invoked to separate segments B) and C) on the basis that the 1897 earthquake may have reduced stress in segment C (Bilham and England, 2001; Gahalaut et al., 2011). Our analysis suggests that there is weak evidence to suggest a slightly narrower décollement there (Table 1).

Table 1. Décollement widths, depths and anticipated maximum M_w earthquakes in Sikkim and Bhutan inferred from GPS convergence rates assuming no rupture since 1713, or c. 1100.

	E. Nepal/ Sikkim	W. and Central Bhutan	*E.Bhutan
latitude locking line	27.65°N	27.6°N	27.33°N
width décollement	94 km	99 km	≈ 70 km
along-arc rupture	150 km	150 km	150 km
1713 & 6 m of slip	$M_w=8.3$	$M_w=8.3$	$M_w=8.2$
c.1100 & 18 m slip	$M_w=8.5$	$M_w=8.5$	$M_w=8.4$
18 m segments A, B&C	$M_w=8.5$	$M_w=8.7$	
18 m segments AB&C	$8.8 < M_w < 8.9$		

* constrained by the epicenter of the 21/9/2009 Bhutan $M_w=6.1$ earthquake

We conclude that if no great earthquake has ruptured this entire region since 1100 AD a cumulative slip deficit of ≈ 18 m could be released in single $8.8 < M_w < 8.9$ earthquake. The current 18 m slip deficit is disconcertingly similar to slip estimated to have occurred in paleoseismic trenches near Bhutan (Kumar et al, 2011), suggesting that the failure all or part of the Bhutan décollement soon would not be unexpected. An alternative interpretation based on a possible intervening great earthquake in 1713 (for which we have no paleoseismic evidence) suggests that a $M_w \approx 8.2$ earthquake, similar to the 1934 event could repeat at the present time in any of the

segments we have identified. The apparent absence of creep suggests that, given our current state of knowledge, a future great earthquake is inescapable.

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