# Active tectonics of the eastern Himalaya: New constraints from the first tectonic geomorphology study in southern Bhutan


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## ABSTRACT

**How convergent systems distribute strain among frontal thrusts is a major concern regarding seismic hazard assessment. Along the 2500 km Himalayan arc, the seismic behavior of the Bhutan region is unknown, because it corresponds to the only portion of the arc where no evidence of major earthquakes has been reported. This can be due either to the fact that no active tectonic studies have been conducted or to continental shortening being absorbed by the Shillong plateau 150 km farther south. Analyzing offset fluvial terraces in south-central Bhutan shows that two major earthquakes ruptured the Himalayan frontal thrust during the last millennium, and that a comparable rate of Holocene deformation (~20 mm/yr) is accommodated across the Himalaya in Bhutan as in central Nepal. Thus, the propensity for great earthquakes in Bhutan is similar to what is observed in neighboring portions of the Himalaya arc. This in turn suggests that the shortening process beneath the Shillong plateau has little effect on how strain accumulates within the Bhutanese Himalaya.**


## INTRODUCTION AND TECTONIC SETTING

The Himalayan belt is one of the few on-land collision zones where great earthquakes with sizes comparable to those of oceanic subduction zones can occur. Over the past few centuries several major earthquakes (M > 8) have been documented both geologically and historically in the central and eastern Himalaya: in western Nepal (A.D. 1505, ~M8.7), in Bihar-Nepal (1934, M8.1), in Assam (1950, ~M8.4), and near the Shillong plateau (1897, ~M8.1) (Kumar et al., 2010; Lavé et al., 2005; Yule et al., 2006; Mugnier et al., 2013) (Fig. 1). In this context, the Bhutan Himalaya, which is located between the great Himalayan ruptures of 1934 and 1950, appears as an ~350-km-long section where no similar great earthquakes have ever been documented. A single historical account reports an earthquake in 1713, but its magnitude and accurate location are unknown (Ambraseys and Jackson, 2003). The occurrence of the 1897 event in the Shillong plateau attests to the accommodation of some amount of convergence in this region, and has been proposed to increase the interval between great earthquakes in the Bhutan Himalaya (Bilham and England, 2001). Gahalaut et al. (2011) also proposed that the stress shadow caused by this earthquake may be responsible for the low seismicity rate currently observed in Bhutan.

In terms of paleoseismicity, a study by Lavé et al. (2005) along the Main Frontal thrust (MFT) in central Nepal suggests the occurrence of a great medieval earthquake at ca. A.D. 1100, with an estimated vertical slip component of 7–7.5 m. From similar investigations east and west of Bhutan, Kumar et al. (2010) proposed that this medieval event may have broken an 800-km-long portion of the MFT, including Bhutan, with a magnitude approaching M9. However, a more recent study by Sapkota et al. (2013) in eastern Nepal documented two great earthquake ruptures contemporary with the 1934 and 1255 historical earthquakes, instead of a single, giant 11$^{th}$ century event.

In central Nepal and Arunachal Pradesh (east of Bhutan), tectonic geomorphology studies have determined Holocene slip rates along the MFT of 21 ± 1.5 mm/yr (Lavé and Avouac, 2000) and 23 ± 6.2 mm/yr (Burgess et al., 2012), respectively. In Nepal, a consistent shortening rate of ~18–20 mm/yr was measured by

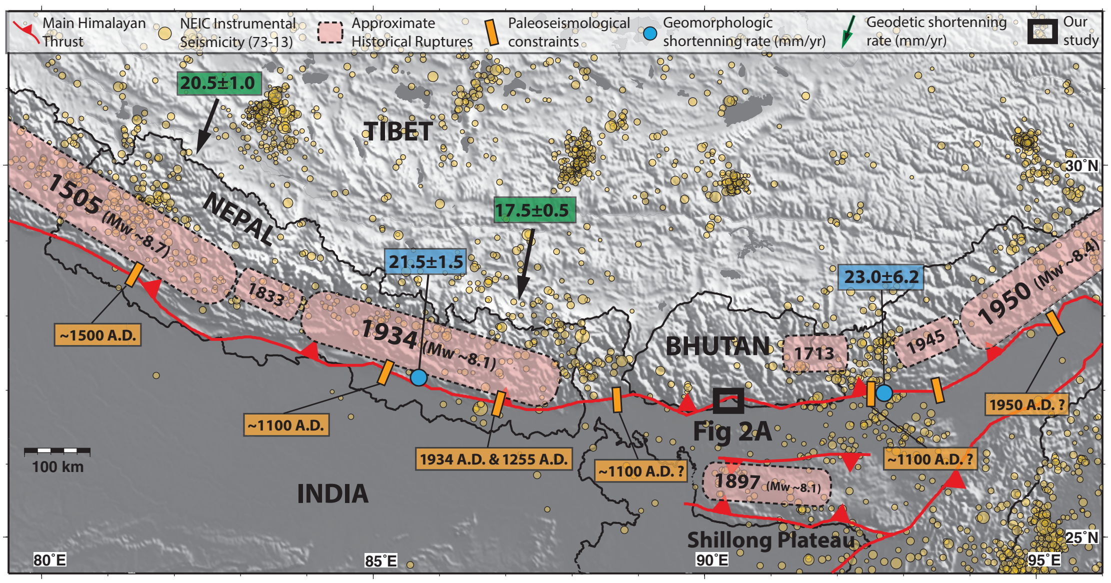


**Figure 1. Seismo-tectonic map of Central and Eastern Himalaya. Pink rectangles show historical events. Orange rectangles indicate ages of major surface-rupturing events (after Lavé et al., 2005; Yule et al., 2006; Sapkota et al., 2013; Kumar et al., 2010; Jayangondaperumal et al., 2011). Blue rectangles give Holocene shortening rates (after Lavé and Avouac, 2000; Burgess et al., 2012). Green rectangles provide geodetic slip rates (Ader et al., 2012). Black frame indicates location of our study. Yellow circles correspond to earthquake data recorded by the National Earthquake Information Center (NEIC) from 1973 to 2013.**


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GPS (e.g., Ader et al., 2012) (Fig. 1). This suggests that the interseismic loading accumulated beneath the High Himalaya on the Main Himalayan thrust (MHT, the down-dip continuation of the MFT and the main interface along which India underthrusts the Himalaya) is relaxed during large events that transfer the shortening to the emergent MFT (Cattin and Avouac, 2000; Mugnier et al., 2013).

The peculiar tectonic setting of the Bhutan Himalaya raises the question of whether its seismic behavior differs from what is occurring in Nepal. To answer this question, we carried out a tectonic geomorphology study in south-central Bhutan that yields the first estimate of the Holocene slip rate along the Bhutanese frontal thrust, and the first constraints on major seismic events that occurred during the past millennium.

## TECTONIC GEOMORPHOLOGY ANALYSIS

We focused our work in southern Bhutan at 90°–90.5°E within the Sarpang reentrant (Fig. 2A) where the topographic front is 15 km farther north compared to the rest of the region (Long et al., 2011). South of the topographic front, a ridge of hills rises above the surrounding alluvial fans. It spans 30 km laterally and ends at longitude 90.3°E (Fig. 2A). This structure uplifts and deflects the drainage network and illustrates the propagation of the deformation to the south (Yeats and Thakur, 2008). From the analysis of a 5-m-resolution digital elevation model (DEM) extracted from Pleiades satellite images and 1:25,000-scale aerial stereoscopic photographs, we selected two sites along the topographic front at the outlets of the Sarpang Khola and the Mao Khola rivers (Fig. 2B). In both areas, tectonic scarps and uplifted alluvial terraces attest to the accumulation of vertical deformation through time. Note that herein, terraces are named incrementally starting with the surface topographically closest to the active stream. The first site is located on the western part of the reentrant within the town of Sarpang; the second one on the eastern part north of the town of Gelephu. In the Sarpang area (Fig. 2B), abandoned terraces are preserved on both banks of the river. Two main terraces (T1 and T2) can be distinguished, and are affected to the south by an east-west–trending fault scarp perpendicular to the drainage. In the Gelephu area (Fig. 2C), we observe similar fluvial terraces, T1 and T2, plus an additional higher one named T3 preserved on the east bank of the river. Within the west bank, the east-west–trending scarp bounds the uplifted terraces T1 and T2. Within the east bank of the river, the scarp is found 1.5 km farther north and trends also east-west, cutting through the T1 terrace. There we assume that the two scarp segments are connected through a northeast-southwest section within the river bed. Further east, the trend of the scarp affecting T1 veers abruptly north-south and splits into two fault strands within T2 and T3 on the east bank of the river. Along that section, deformation is partitioned between a reverse fault located at the foot of the uplifted terraces and a right-lateral strike-slip fault forming the boundary between T2 and T3 (a similar feature was observed at the Kala Amb site of Kumar et al. [2010]).

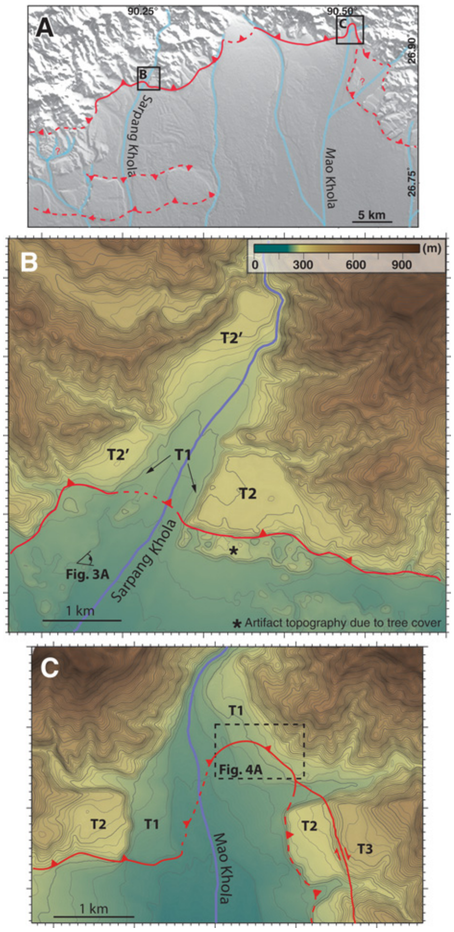


**Figure 2. A: Shaded SRTM3 (Shuttle Radar Topography Mission) topography of Sarpang reentrant in central Bhutan with drainage (blue) and active thrust faults (red). B, C: Detailed topographic maps of Sarpang and Gelephu sites showing uplifted river terraces. Dashed red line corresponds to our interpreted fault trace.**

### Sarpang Area

Figure 3A shows a perspective view of the east bank of the Sarpang Khola where we focus our study. The lower and youngest affected terrace, T1, is preserved along the riverbed of the Sarpang Khola (Fig. 3A). Figure 3B shows the riser of terrace T1 made of cobble and boulder layers topped with a sand unit. The terrace is affected by an ~4-m-high fault scarp perpendicular to the flow of the river. Within the hanging wall, immediately north of the scarp, one observes the slightly folded strath horizon of terrace T1 above a highly fractured bedrock unit (Baxa Formation). These features suggest that the Baxa Formation overthrusts the Quaternary deposits.

Terrace T2 is delimited to the south by an abrupt east-west topographic front perpendicular to the flow of the Sarpang Khola, defining a cumulative fault scarp of several tens of meters in height that corresponds to the eastward extension of the east-west–trending scarp affecting terrace T1. Topographic profiles of T2 across this scarp from a kinematic GPS survey and the 5-m-resolution DEM allow estimating a cumulative offset of 53.4 ± 2.2 m (Fig. 3C). This corresponds to a minimum tectonic offset, as the footwall can be partially buried by colluvium and alluvium; this applies to all tectonic offsets measured in this study. At the eastern foot of the cumulative scarp we observe a smaller scarp of 4.4 ± 0.5 m, comparable to the one affecting terrace T1 (Fig. 3D).

The abandonment age of the fluvial terrace T2 was determined by in situ–produced cosmogenic $^{10}$Be from the measurement of $^{10}$Be concentrations along a depth profile. Three stratigraphic units are observed in the pit: (1) an upper 0.5-m-thick sandy unit, (2) an intermediate clayey sand unit with angular pebbles (colluvium) radiocarbon-dated at A.D. 795 ± 105, and (3) a lower 1.5-m-thick sand unit with decimetric cobbles (debris flow). The colluvial nature of the intermediate layer and its young age attest to the burial of the underlying terrace. To model $^{10}$Be concentrations at depth, we account for burial since A.D. 795 ± 105 and obtain an exposure age of 6400 ± 1300 yr ($2\sigma$ uncertainty) for terrace T2 (see details in the GSA Data Repository[1]).

To date the deposition of terrace T1, we collected charcoal samples within a 70-cm-deep pit dug into the sand unit found on top of terrace T1 within the hanging wall. Two sub-units can be distinguished. Two charcoals within the upper sub-unit yield modern dates and are interpreted as being anthropic (the terrace surface has been reworked for construction purposes). The two charcoals collected within the lower sub-unit give consistent dates of A.D. 1520 ± 100 and A.D. 1570 ± 80. We interpret them as corresponding to the depositional age of terrace T1 (see details in the Data Repository).

### Gelephu Area

Figure 4 focuses on our study area on the east bank of the Mao Khola, near Gelephu. At this site, the terrace T1 can be subdivided into two sub-terraces (T1a and T1b) that are both affected by an ENE-WSW–trending fault scarp. Note that T1a and T1b are found on both sides of the scarp (due to river incision). We surveyed

[1]GSA Data Repository item 2014152, details on dating and uncertainties, is available online at www.geosociety.org/pubs/ft2014.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

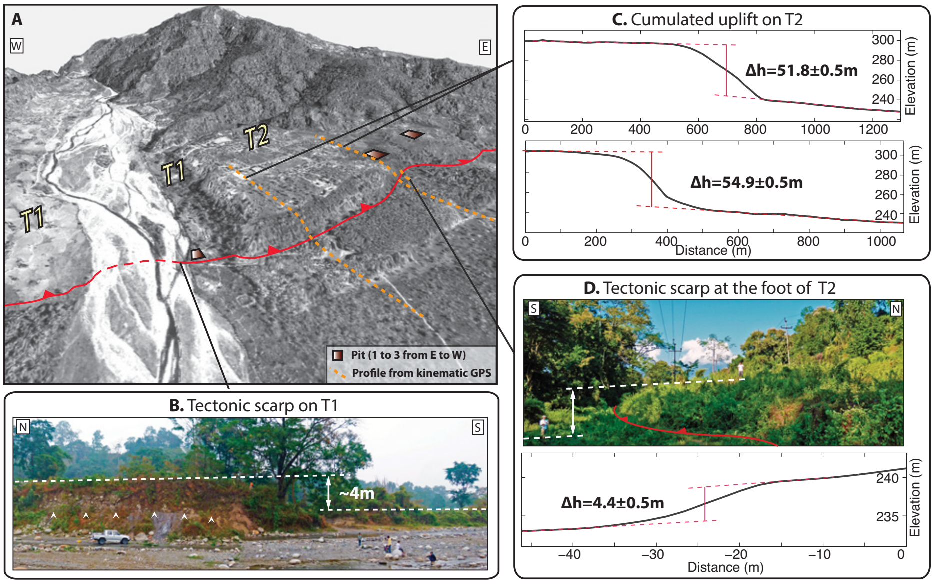


Figure 3. A: Perspective view to northeast of Sarpang Khola east bank (Pleiades satellite image). Red and orange lines define trace of fault and profiles across terrace T2, respectively. B: Fault scarp affecting T1 terrace. C: Topographic profiles across T2. D: Photo and topographic profile of fault scarp at foot of T2.

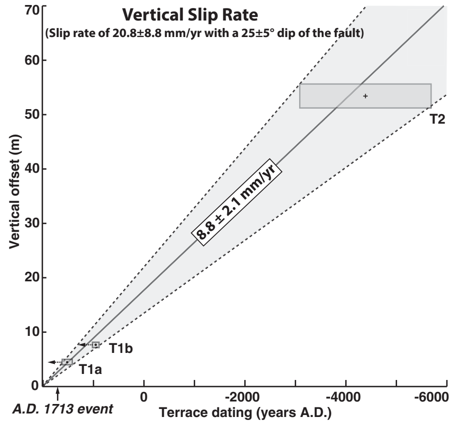


Figure 5. Vertical slip rate along Bhutanese frontal thrust (black line) and its uncertainties (dashed lines). Rectangles represent error on ages and elevations of terraces, respectively. Arrows within T1a and T1b rectangles indicate that the seismic event affecting each terrace is younger than their respective depositional age.

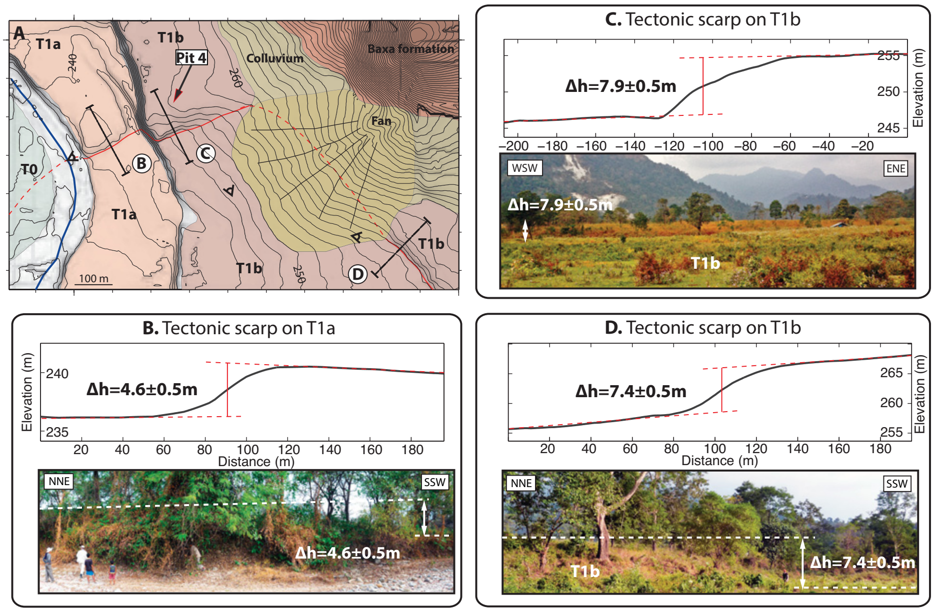


Figure 4. A: Map of T1 terrace flight observed on Mao Khola east bank (see location in Fig. 2C). Contour lines are every 2 m; red line corresponds to fault trace. B, C, D: Profiles and photos of fault scarps affecting T1a and T1b (see black lines on A for their locations). Note debris fan burying scarp.

this area using kinematic GPS to build a high-resolution DEM with high vertical accuracy (Fig. 4A). The map shows that the fault scarp is buried under a debris fan where its strike changes from ENE-WSW to NW-SE. The vertical offset of terrace T1a is 4.6 ± 0.5 m (Fig. 4B). The vertical offset of terrace T1b is 7.9 ± 0.5 m (Fig. 4C) across the ENE-WSW scarp, and 7.4 ± 0.5 m (Fig. 4D) across the NW-SE scarp.

We used radiocarbon and in situ–produced $^{10}$Be to date the deposition of terrace T1b. The 2-m-deep soil pit dug into the terrace surface shows two main depositional units, both clast supported and topped by sandy-silty horizons. A brown organic-poor modern soil has developed in the silty upper part of the first (upper) unit. Two radiocarbon dates obtained from a bulk sample collected in the sands that topped the second (lower) unit yield close dates of A.D. 955 ± 65 and A.D. 1150 ± 100. Considering the oldest dated sample (A.D. 955 ± 65) as reworked, we retain A.D. 1150 ± 100 as the date constraint for T1b (see details in the Data Repository).

## Holocene Slip Rate along the Bhutanese Frontal Thrust

Combining the mean offset of 53.4 ± 2.2 m across terrace T2 in Sarpang and its $^{10}$Be age of 6400 ± 1300 yr yields a mean vertical slip rate of 8.8 ± 2.1 mm/yr along the Bhutanese frontal thrust for the Holocene period (Fig. 5). Offsets and ages obtained near Sarpang on terrace T1 and near Gelephu on terrace T1b are consistent with this estimate (Fig. 5). From this vertical slip rate, we estimate the slip rate along the thrust fault: we calculate a dip angle of ~20° for the thrust at the surface using the horizontal shift of the fault trace between the terraces T1a and T1b at the Gelephu site. However, this value may be an underestimate because of lateral incision at the foot of the scarp affecting T1a. At the Sarpang site, where we calculated the vertical slip rate, Long et al. (2011) reported structural measurements of dip bedding of ~30°. Considering both values, we use a dip of 25° ± 5° together with mean vertical slip rate of 8.8 ± 2.1 mm/yr to calculate a Holocene slip rate along the fault of 20.8 ± 8.8 mm/yr (see details in the Data Repository).

## Age Constraints on the Two Last Great Earthquakes in Bhutan

Our observations in the Sarpang and Gelephu areas show evidence for an ~4.5-m-high fault scarp affecting the most recent alluvial terrace T1 (see Figs. 3B, 3D, and 4B). We interpret this offset as the result of the latest surface-rupturing event along the Bhutanese frontal thrust. If we consider a 20° dip angle for this thrust at the surface, this vertical displacement would result from an ~13 m slip along dip. The radiocarbon age obtained for the deposition of terrace T1 in Sarpang indicates that the first event occurred after A.D. 1570 ± 80. This event may correspond to the A.D. 1713 event, the only historical earthquake reported for the region (Ambraseys and Jackson, 2003).

At Gelephu, T1b is affected by a fault scarp of ~8 m, which is about twice the height of the scarp affecting T1a (4.6 m). We consider that T1b has been displaced by two events with vertical components of ~4.5 m for the ultimate and of ~3.5 m for the penultimate. This yields an ~10 m slip for the penultimate event considering a 20° dip for the fault. Age constraints on T1b at Gelephu indicate that the penultimate event occurred after A.D. 1150 ± 100.

The displacements observed for these two Bhutanese events are similar to co-seismic displacements associated with the M8.1 1934 earthquake in eastern Nepal (Sapkota et al., 2013), suggesting the two last surface-rupturing events along the Bhutanese frontal thrust were great earthquakes with magnitudes that may have been above M8.

## DISCUSSION AND CONCLUSIONS

Our study across the Bhutanese frontal thrust brings new constraints on the active tectonics in the eastern Himalaya. A Holocene vertical slip rate of 8.8 ± 2.1 mm/yr was estimated. This yields a horizontal shortening rate of 20.8 ± 8.8 mm/yr considering a dip of 25° ± 5°. This estimate is consistent with shortening rates of 21.5 ± 1.5 mm/yr and 23.0 ± 6.2 mm/yr estimated in central Nepal (Lavé and Avouac, 2000) and in India east of Bhutan (Burgess et al., 2012), respectively. This suggests that the Himalayan convergence is also mainly accommodated on the MFT at the longitude of Bhutan. Drukpa et al. (2012) gave a preliminary slip rate estimate of ~20 mm/yr from new GPS observations, consistent with the slip rate estimated in this study. This estimate suggests that the deformation accommodated within the foreberg located in the Indian plain south of Sarpang might be small.

Furthermore, our observations document two major events with M > 8, cumulating ~8 m of vertical deformation, that have occurred since A.D. 1150 ± 100. The most recent event occurred after A.D. 1570 ± 80 and could correspond to the A.D. 1713 historical event. If so, the poorly constrained magnitude (Mw ~7) proposed by Ambraseys and Jackson (2003) for the 1713 event may be an underestimate. This is not inconsistent with Jackson's (2002, p. 147) report mentioning that "occurred [in Bhutan] the great terror of an earthquake that pulverized all houses and huts in every direction." The penultimate event occurred between A.D. 1150 ± 100 and A.D. 1570 ± 80. This age constraint is not inconsistent with a potential giant medieval earthquake at ca. A.D. 1100. However, the occurrence of two surface-rupturing events during the past millennium in Bhutan is similar to observations made by Sapkota et al. (2013) in eastern Nepal where two major earthquakes occurred in A.D. 1934 and A.D. 1255. We thus favor the interpretation of strain being accommodated into individual rupture events, along with the role of fault segmentation in limiting rupture size.

To conclude, the fact that a similar amount of Holocene deformation is accommodated along the MFT in Bhutan as in the neighboring parts of the arc suggests that there is no major lateral variation of the distribution of strain along the frontal thrust from central Nepal to east of Bhutan despite the presence of the Shillong plateau. Moreover, we confirm that most of the strain accumulated along this major convergent system is accumulated along the frontal thrust. The two surface ruptures observed in this study also show that the Bhutan Himalaya is able to generate great Himalayan events and that the continental shortening processes beneath the Shillong plateau have little effect in reducing their propensity. Thus, the size of rupture events in the Himalaya seems most likely related to the role of fault segmentation rather than major longitudinal variations of convergence rate.


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