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Short Note

Near-Surface Expression of Early to Late Holocene Displacement along the Northeastern Himalayan Frontal Thrust at Marbang Korong Creek, Arunachal Pradesh, India

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Abstract We present the results of a paleoseismic trench investigation of an 8-m scarp at the mouth of Marbang Korong Creek (27°58'26.0700" N 95°13'42.3000" E) within the meizoseismal area of the 1950 Assam earthquake along the northeast Himalayan Frontal Thrust (HFT) of India. Structural, stratigraphic, and growth-stratigraphy relations observed in the trench are interpreted to indicate that expression of the scarp is due to uplift and folding of near surface sediments in response to HFT displacement that reaches near the surface yet below the 5-m depth of the trench exposure. The most recent contribution to scarp growth dates to fault displacement post 2009 cal yr B.P. It remains a matter of speculation whether or not the most recent event deformation is a result of the great 1950 Assam earthquake that is reported on the basis of intensity data.

Online Material: High-resolution trench log 5 and table summarizing results and inputs of radiocarbon analysis of detrital charcoal samples.

Introduction

The rate of convergence between the Indian and Eurasian plates is about 50 mm/year (Fig. 1) (DeMets *et al.*, 1994; Banerjee and Bürgmann, 2002; Berger *et al.*, 2004). Between 10 and 20 mm/yr of the convergence is accommodated by thrusting along the Himalayan Frontal Thrust (HFT) and the remainder by deformation further inland and to the north (e.g., Tapponier and Molnar, 1977; Kumar *et al.*, 2010). The HFT extends ~2500 km, from Pakistan in the west to Pasighat, Arunachal Pradesh, India in the east. There have now been a number of paleoseismic investigations that have placed limits on the size and age of past earthquake displacements along the HFT (Kumar *et al.*, 2001; Lave *et al.*, 2005; Kumar *et al.*, 2006; Kumar *et al.*, 2010) (Fig. 1). Here we present the results of a trenching investigation across an 8-m high scarp at the mouth of Marbang Korong Creek intended to place limits on the past occurrence of large earthquakes along the HFT at the mouth of Marbang Korong Creek near Pasighat in Arunachal Pradesh, India. It is the easternmost of such studies that have thus far been attempted along the HFT. The resulting observations are put forth as a useful illustration of a significant scarp along the HFT that is due to folding of near surface sediments in response to displacement on the underlying thrust and the use of secondary growth stratigraphic relations to place bounds on past earthquake displacements. We initially place the study site in regional context, then describe the geomorphic characteristics of the site, followed by description and interpretation of the trench exposure. Finally, the results are placed in context of prior paleoseismic studies from the west of the study site.

Regional Tectonic Framework and Geomorphic Characteristics of the Study Site

The study site is located within the meizoseismal zone of the 1950, M_w 8.4 Assam earthquake (Fig. 1) (Poddar, 1950; Ambraseys and Douglas, 2004). The 1950 earthquake occurred near the eastern syntaxis of the Himalayan front where the major thrusts and rock units of the Himalaya take a sharp turn from northeast to southeast (Fig. 2). The HFT trends northeast-southwest and forms a boundary of the Siwalik Group sediments along the western flank of the eastern Himalayan syntaxis. The Mishmi Thrust is the corollary to HFT along the eastern flank of the syntaxis. Here the Siwalik Group sediments are absent and the Lesser and High Himalayan formations form the hanging wall of the northwest-southeast striking Mishmi Thrust (Kumar, 1997) (Fig. 2). The trench was excavated across an ~8-m high scarp in Holocene alluvium at the mouth of Marbang Korong Creek (Figs. 3 and 4). Here the scarp cuts perpendicular

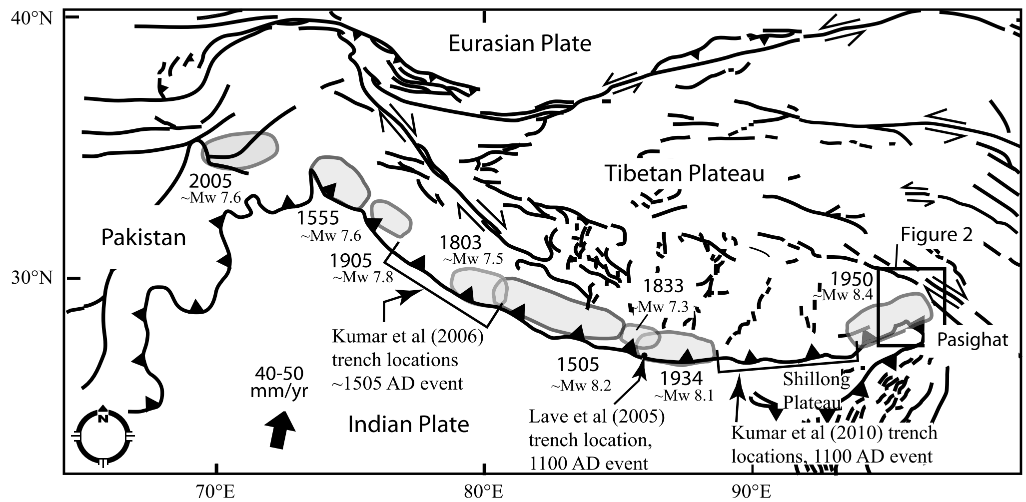

Figure 1. A simplified map of the Himalayan arc and the Tibetan Plateau showing distributions of active faults and historical earthquake rupture extents (after Kumar *et al.*, 2006). The HFT is shown by hachures on the hanging wall. The rupture extent determined from meizoseismal data of the 1505 central Himalayan earthquake ($M_w \sim 8.2$), the 1555 Kashmir earthquake ($M_w \sim 7.6$), the 1803 Kumaun-Garhwal earthquake ($M_w \sim 7.5$), the 1833 Nepal earthquake ($M_w \sim 7.3$), the 1905 Kangra earthquake ($M_w \sim 7.8$), the 1934 Bihar-Nepal earthquake ($M_w \sim 8.1$), the 1950 Assam earthquake ($M_w \sim 8.4$), and the 2005 Kashmir earthquake (M_w 7.6) are shown in gray with the year annotated. The location, reference, and age of most recent offset determined from previous trench studies are marked by arrows. Location of Figure 2 and area encompassing this study is marked by a rectangle.

to the flow of Marbang Korong Creek, and the associated uplift has produced a lower terrace surface (labeled LS in Fig. 3) that extends upstream from the scarp. Longer term uplift is recorded in the presence of a yet higher fluvial terrace surface (HS in Fig. 3), which is also truncated by the HFT. The HS surface is about 60 m above stream grade

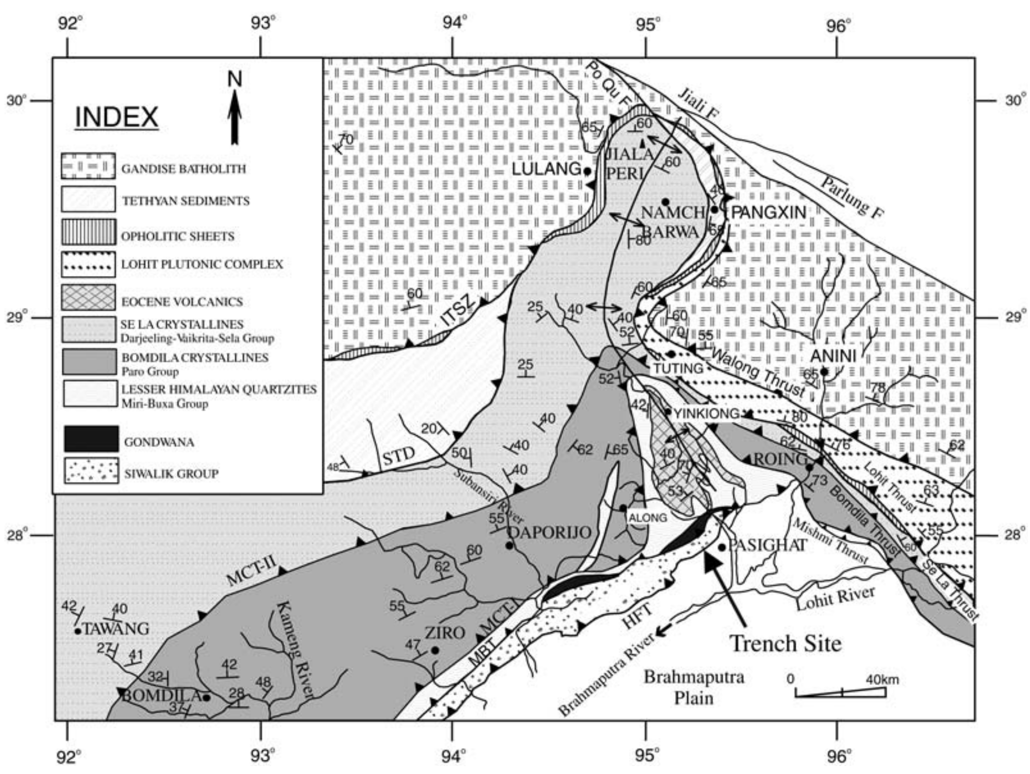

Figure 2. Map of the eastern syntaxis of northeastern Indian Himalaya showing major faults and geologic terranes of the Himalaya (modified after Choudhuri *et al.*, 2009). Trench site of this study is marked by a large arrow and located across the HFT. The HFT marks the contact between Siwalik rocks of the Sub Himalaya to the north and Quaternary sediments of Brahmaputra floodplains to the south. Indus-Tsangpo Suture zone, ITSZ; South Tibet Detachment, STD; Main Central Thrust, MCT; Main Boundary Thrust, MBT; Fault, F.

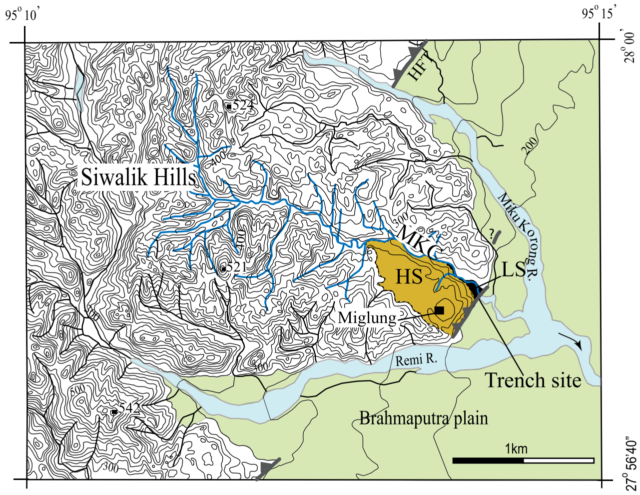

Figure 3. Location of Marbang Korong Creek (MKC) trench site on Survey of India 20-m contour interval topographic sheet. Trace of the HFT is shown by thick gray lines with teeth. The thrust truncates and has progressively uplifted the higher (HS) and lower (LS) fluvial terrace surfaces. The trench was placed across the HFT where it cuts the LS surface. The color version of this figure is available only in the electronic edition.

and observable in the digital elevation model of Figure 4. The HS terrace surface is capped by subangular to subrounded boulder gravels. The LS terrace surface is composed of subrounded and rounded pebbles to boulder gravels with lenses of brown silty sand. The present day catchment of Marbang Korong Creek is confined to the Sub Himalaya (Fig. 3).

Trench Observations

A log of the trench exposure is shown in Figure 5a. A photo-mosaic of the exposure is provided in Ⓔ Figure S1, available as an electronic supplement to this paper. The extent and depth of the 26-m long and ~5-m deep trench, shown in relationship to the scarp profile, are shown in Figure 5b. The oldest bed (unit 1) in the exposure is highly fractured Siwalik bedrock sandstone present in the lowest northern portion of the exposure. The Siwalik beds are overlain by unit 2, a package of rounded to subrounded cobble and pebble gravel with distinct sand lenses and fabric that shows bending of the deposits and increasing southeastward dip to ~30° SE. Units 1 and 2 are broken by faults F1, F2, and F3, which dip steeply to the northwest. The bounding strands of F1 and F2 show normal displacement and form a small tilted graben-like structure. The top of the graben is filled with silty fine and medium sand (unit 2a). In the footwall, the gravel of unit 2 is overlain unconformably by two packages of bedded fine sand that are labeled units 3 and 4 on the trench log (Fig. 5). The lower of the two units (unit 3) dips at about 10° to the southeast and is unconformably overlain by the horizontal beds of unit 4. Layer boundaries in unit 4 are marked by incipient soil horizons, suggesting brief hiatuses of deposition during growth of the unit.

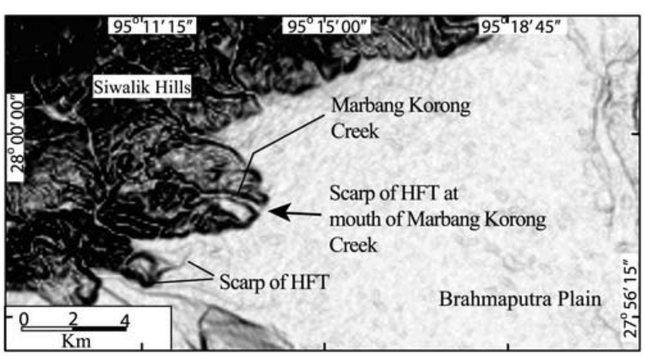

Figure 4. Ninety-meter SRTM (http://glcf.umiacs.umd.edu/data/srtm/) image of the study area showing the scarp at the mouth of Marbang Korong Creek and the flat surface of the uplifted HS terrace mapped in Figure 3 are visible. A solid arrow indicates HFT scarp at the mouth of creek and location of a trench site.

A thrust fault is not exposed in the trench. Yet there are a number of observations that indicate that the normal faults (F1 to F3), unconformities, and dipping strata are the result of displacements along an underlying thrust fault that is close to the surface, and that were we able to excavate deeper we would have encountered the trace of the thrust fault. The tectonic nature of the scarp is embodied in the observation that the scarp across which the trench is excavated strikes parallel to the range front and perpendicular to Marbang Korong Creek. The truncation and relatively greater uplift of the older HS and younger LS terraces show that the fault has been active through the Quaternary. The southeast dipping beds of unit 2, which form the scarp, and the extensional faults (F1-F3) that are present near the crest of the scarp (Fig. 5) are similar to those that have been observed in trenches further to the west along the HFT where the underlying thrust fault is directly seen to reach to or very close to the surface (Kumar *et al.*, 2001, 2006). The dipping beds of unit 2 are thus interpreted to represent the dip panel of a fold related to displacement on an underlying thrust fault that extends to near the surface and the normal fault strands near the scarp crest to reflect extension from bending that has produced the dip panel (e.g. Kumar *et al.*, 2006; Jayangondaperumal *et al.*, 2010). The fine sands of units 3 and 4 are interpreted to be sediments that accumulated as flat-lying beds (growth strata) along the scarp from periodic flooding of adjacent creeks and rivers. Unit 4 is horizontal and sits unconformably on the southeast dipping beds of unit 3. Tilting of unit 3 is thus interpreted to be a result of warping, associated with an earthquake, subsequent to formation of a fault scarp at the site and prior to deposition of the currently flat-lying unit 4 beds. A schematic illustration of the interpreted development of the trench stratigraphy and structure is shown in Figure 6.

Detrital charcoal samples P4 and P6 taken from the deformed unit 2 (Fig. 5 and Ⓔ Table S1 in the electronic supplement to this article) give calibrated ages of 10,608–10,112 cal yr B.P. and 11,752–10,681 cal yr B.P., respectively. Assuming the fluvial deposits of unit 2 were originally

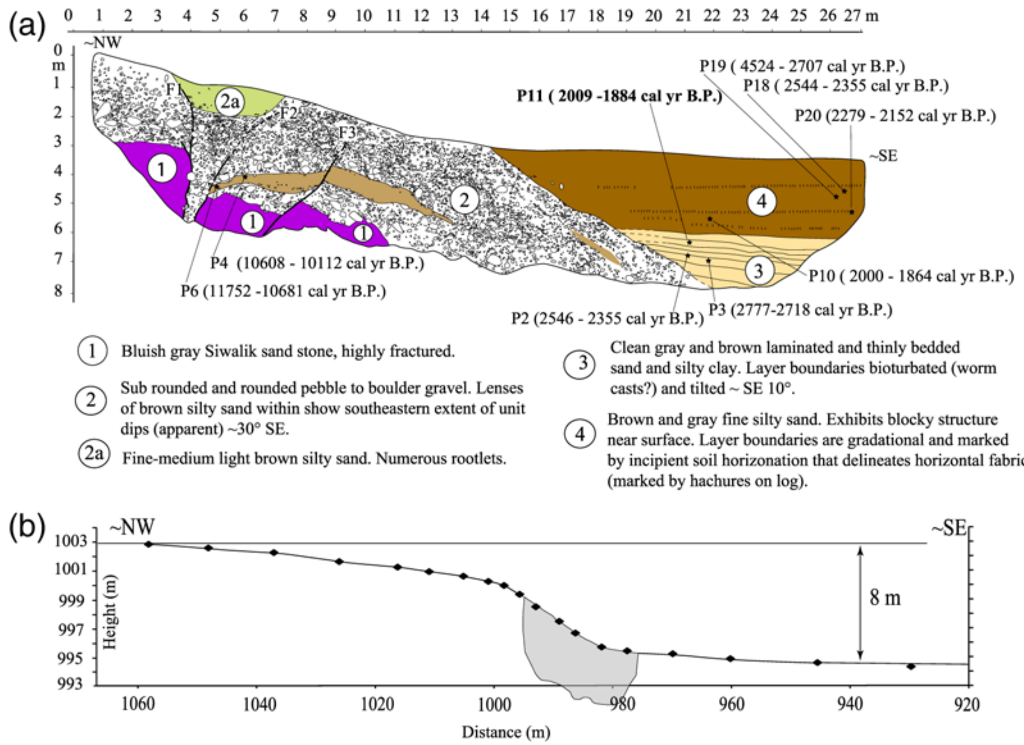

Figure 5. (a) Log of the eastern wall of Marbang Korong Creek trench. Numbers in white solid circles denote the major stratigraphic units observed in the trench. Secondary bending faults are marked as F1 to F3. Small stars connecting solid line to text show location of radiocarbon samples, sample numbers and calibrated ^{14}C accelerator mass spectrometry (AMS) ages in cal yr B.P. Horizontal and vertical scales are the same. (Ⓔ See Figure S1 for photo-mosaic of the trench exposure available as an electronic supplement to this paper.) (b) Profile based on survey using electronic surveying total station across the lower terrace scarp on which trench was excavated. The area of the trench in relation to the scarp profile is shaded. The color version of this figure is available only in the electronic edition.

horizontal, the radiocarbon ages place the formation of the dip panel and a scarp at the site to be subsequent to 10,112 cal yr B.P. (Fig. 6, Stage 1). The youngest of three radiocarbon samples taken from unit 3 is 2009–1884 cal yr B.P. (sample P11). Tilting of unit 3 must have taken place after this date (Fig. 6, Stage 2). Four radiocarbon samples taken from the overlying unit 4 provide no useful upper bound on tilt timing of unit 3. Ages for the samples of P10, P18, P19, and P20 are not stratigraphically consistent and samples P18 and P19 have yielded ages older than those of samples taken from underlying unit 3. The ages appear to indicate that deposition of some or all of the charcoal samples in this trench are reworked from older deposits and the ages are thus older than the deposits from which they are collected.

Discussion and Conclusions

The observations we have collected indicate that displacement on the HFT formed a fault scarp at Marbang Korong Creek subsequent to 10,112 cal yr B.P. The subsequent earthquake contributed to development of the scarp after 2009 cal yr B.P. (Figs. 5 and 6). Scarps of similar size have been observed and interpreted to be the result of a single displacement at sites elsewhere to the west along the HFT (Kumar *et al.*, 2006, 2010). It is thus tempting to suggest that the scarp was primarily formed in a single large earthquake post 10,112 cal yr B.P. followed by an earthquake event post 2009 cal yr B.P. Yet the observed tilting of the unit 3 beds in the absence of surface faulting shows that scarp growth has occurred by incremental warping and raises the possibility of multiple events (between 10,112 cal yr B.P. and 2009 cal yr B.P.). Unfortunately, the exposed structure, stratigraphy, and depth of the trench do not allow a unique assessment of the number of events between 10,112 cal yr B.P. and 2009 cal yr B.P. Hence an estimate of the recurrence time of scarp forming events at this site does not seem warranted. Withstanding the uncertainty in timing of earthquakes, this note serves to document that large scarp forming earthquakes occur and extend to the eastern limits of the HFT and, given another site and introduction of larger excavation equipment to the area of study, paleoseismology holds the potential to evaluate the possibility that the tilting of sediments that occurred post 2009 cal yr B.P. is the result of the historical 1950 Assam earthquake (Poddar, 1950; Ambraseys and Douglas, 2004).

Data and Resources

Figure 4 was created using 90-meter Shuttle Radar Topographic Mission (SRTM, http://glcf.umiacs.umd.edu/data/srtm/) and Figure 3 was created using a Survey of India (SOI) 20-m contour interval topographic sheet.

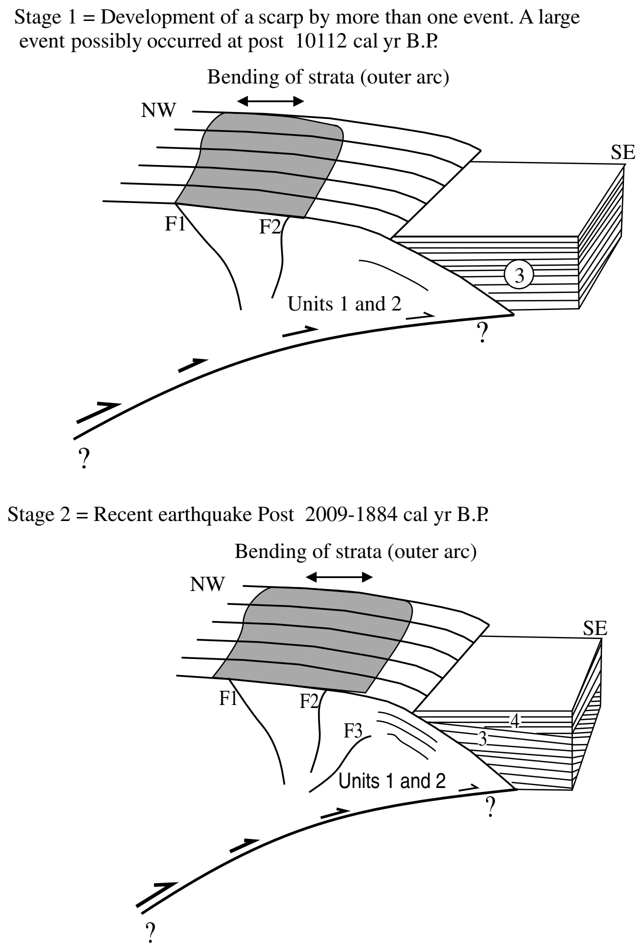

Figure 6. Schematic view of development of Marbang Korong Creek fault scarp and trench stratigraphy. Stage 1 depicts the development of preexisting scarp by more than one earthquake. F1 and F2 normal faults formed as a result of bending. Stage 2 shows cumulative and recent earthquake related initiation of F3 bending normal fault, unconformities, and dipping strata as a result of tectonic displacements along an underlying thrust fault that reaches the surface. Decreasing length of the arrows depict decrease in slip on fault surface as it reaches near surface. Numbers denote the major stratigraphic units observed in the trench. See Discussion and Conclusions section.

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