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Key Points:

- Geologic evidence for surface rupture on the Himalayan Frontal Thrust during the great *Mw* 8.4 Bihar-Nepal earthquake of 1934 remains lacking
- Whether or not the 1934 event produced surface rupture remains a puzzle

Supporting Information:

- Supporting Information S1

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New Observations Disagree With Previous Interpretations of Surface Rupture Along the Himalayan Frontal Thrust During the Great 1934 Bihar-Nepal Earthquake

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Abstract Reinvestigation reveals observations that do not support prior claims that the great *Mw* 8.4 Bihar-Nepal earthquake produced surface rupture along the Himalayan Frontal Thrust of Nepal. While it may be viewed as reasonable to suggest that the Main Himalayan Frontal Thrust was the source of the 1934 Bihar-Nepal earthquake on geophysical grounds, decisive and substantiating geological evidence that it produced surface rupture along the trace of the Himalayan Frontal Thrust remains lacking.

Plain Language Summary Great earthquakes on continents such as the *Mw* 8.4 Bihar-Nepal earthquake of 1934 are generally expected to produce ruptures along a fault trace where the causative fault intersects the ground surface. The 1934 earthquake for a long time remained enigmatic because surface ruptures were never reported until recently when investigators interpreted an outcrop along the Himalayan front to record such evidence. Our reinvestigation of the outcrop and presentation of new observations does not support their interpretation and so the enigma remains: there are no observations that clearly confirm that the 1934 earthquake produced surface rupture.

1. Introduction

The Sir Khola (river) of central Nepal crosses the trace of the Himalayan Frontal Thrust (HFT) at the foot of the Siwalik Hills (Figures 1 and 2). Previous study employing geomorphological mapping of fluvial surfaces and paleoseismological logging of river-cut cliffs and trench walls concludes that the great *Mw* 8.4 Bihar-Nepal earthquake of 1934 (Molnar & Deng, 1984) produced upward of 4–5 m of surface rupture throw at Sir Khola (Bollinger et al., 2014; Sapkota et al., 2013). The two studies at Sir Khola are the only published reports to claim geologic observations supporting the occurrence of surface rupture during this great earthquake and are now highly cited as definitive evidence that the source of the Bihar-Nepal earthquake was the HFT (Clarivate_Analytics, 2017). The location and length of surface rupture interpreted in the Sir Khola study are shown as the red line in Figure 1. Our unsuccessful efforts to find decisive and corroborative evidence elsewhere on the previously proposed length of the surface rupture led us to independently reexamine the Sir Khola site.

2. The Sir Khola Site

Erosion along an outward bend of the Sir Khola (river) has produced a steep cliff that exposes more than 50 m of sheared sand and siltstones of the Tertiary Siwalik group and younger fluvial sediments (Figures 2 and 3). It is the study of a portion of this cliff exposure that provided the principal observations for Sapkota et al. (2013) and Bollinger et al. (2014) to conclude the presence of the 1934 earthquake surface rupture. We reexcavated and cleaned the cliff exposure and also emplaced an additional excavation on the surface above the natural exposure (Figures 2 and 3). A photo and sketch of the cleaned cliff exposure are shown in Figure 4. The Siwalik beds are cut by north dipping thrust faults and shears. The northernmost shear and a splay emplace sheared Siwalik bedrock (*unit 1*) above packages of oxidized clast-supported fluvial gravel (*unit 2′*). The Siwaliks form a steep cliff below the intersection of the shear and splay with the surface. At the lower part of the cliff, the Siwaliks form an approximately horizontal platform on which rests in erosional contact a moderately sorted rounded pebble and small cobble

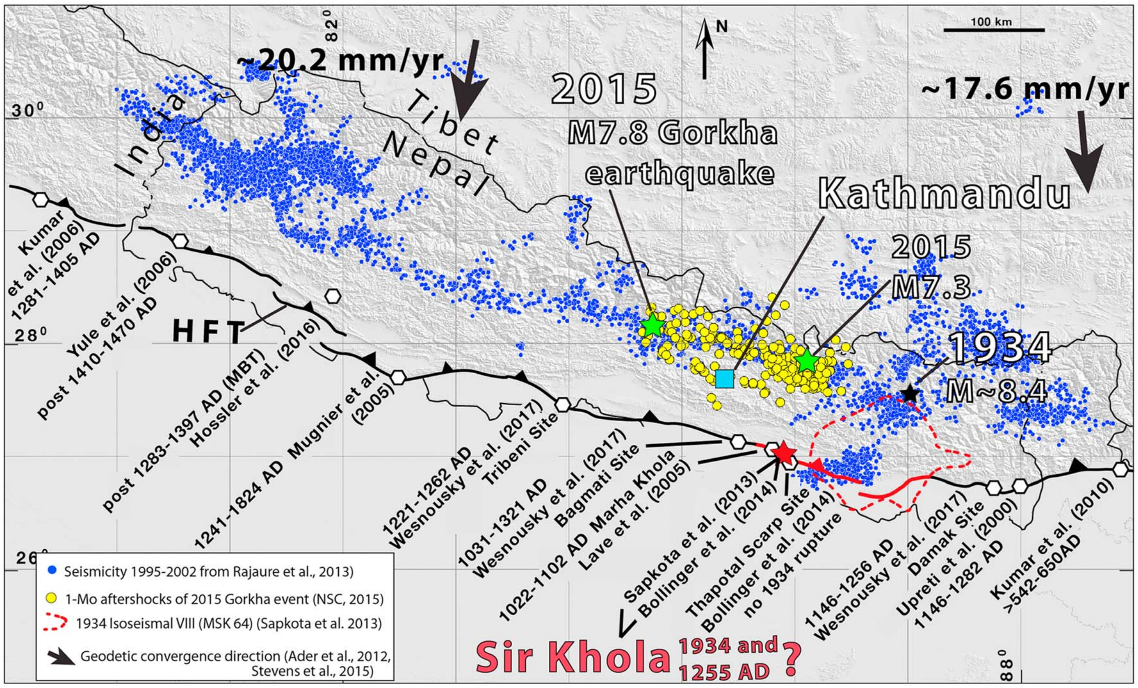

Figure 1. (a) Map of Nepal showing location of Sir Khola and age of surface rupture earthquakes reported at sites along the Himalayan Frontal Thrust (HFT). The length of surface rupture along the HFT for the 1934 event indicated in Sapkota et al. (2013) and Bollinger et al. (2014) is red. Additional citations in figure include Kumar et al. (2010, 2006), Yule et al. (2006), Hossler et al. (2016), Wesnousky, Kumahara, Chamlagain, Pierce, Karki, and Gautam (2017); Wesnousky, Kumahara, Chamlagain, Pierce, Reedy, et al. (2017), Lave et al. (2005), Upreti et al. (2000), Rajaure et al. (2013), Ader et al. (2012), NSC (2015), and Stevens and Avouac (2015).

fluvial gravel (*unit 3*). The fluvial gravel unit 3 is overlain by *unit 4*, generally massive and continuous horizons of silt and fine sand that reach a maximum thickness of ~1.5 m, absent of any coarser pebble fraction. The northern contact of the fluvial gravel unit 3 is an erosional buttress unconformity with the Siwalik cliff. The silt and fine sand of unit 4 are interpreted as flood (overbank) deposits. The northern limit of the unit 4 overbank deposits is interfingered with poorly sorted matrix-supported gravel containing numerous rounded pebbles that form a wedge shape (unit 4′). Unit 4′ is largely colluvium shed from the adjacent cliff. The entire exposure is capped by darker fine sand and silt taken to be soil developing on the overbank deposits and colluvium being shed from the scarp today (*unit 5*). The surface immediately adjacent to the exposure above units 3 to 5 and within ~0.5 m of the exposure has previously been disturbed by human activity. The two southernmost faults mapped in the exposure do not break and are capped by fluvial gravel (unit 3). The southernmost thrust fault is underlain by packages and beds of oxidized matrix-supported rounded gravel (unit 2) that show a distinctly greater fraction of coarse sands and silts and more oxidation in comparison to fluvial gravel unit 3. The upper part of unit 2 is composed of poorly sorted rounded cobble and pebble gravel. The lower part of unit 2 is much cemented rounded, well-sorted cobble, pebble and granule gravel with thin interbeds of massive coarse sand locally exhibiting bedding-parallel laminations. A higher-resolution image and log of this portion of the exposure are shown in Figure 5 and discussed below.

The principal observation cited to claim evidence of 1934 surface rupture on the HFT by Sapkota et al. (2013) and Bollinger et al. (2014) (in interpretation of this same outcrop) is that the fluvial gravel we map as unit 3 is truncated at the fault and displaced downward ~2–3 m along the shear zone to correlate with a horizontal layer within our unit 2 (Figure S1 in the supporting information). Our reexamination of the outcrop leads to a contrary interpretation. Specifically, the unit 3 fluvial gravel is observed to form a cap and be continuous across the zone of shear that has emplaced Siwalik unit 1 upon the oxidized gravels of unit 2 (Figures 4 and 5). The observation is further confirmed by the exposure provided by emplacement of a trench immediately above the natural exposure (Figures 2, 3 and 6): the fluvial gravel extends continuously across the thrust. Additional photos of this relationship are given in Figure S2. The consequence of the observations is *clear*:

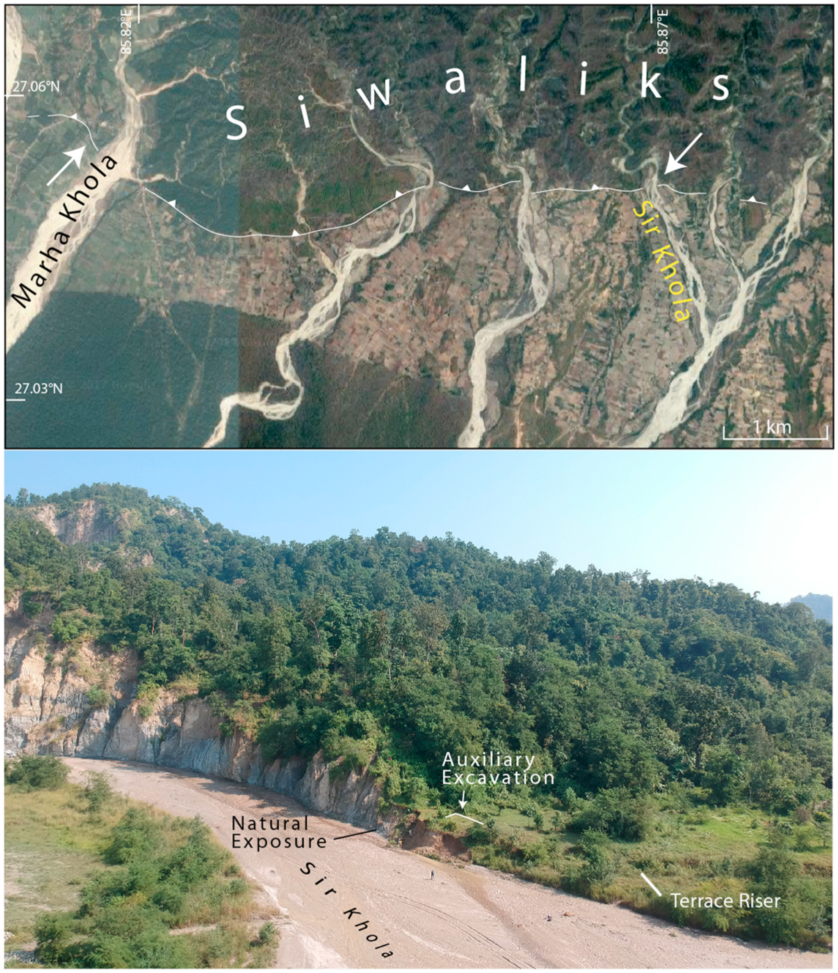

Figure 2. (upper panel) Arrows point to previously reported paleoearthquake investigations where the Himlayan Frontal Thrust (HFT, white line with triangles on hanging wall) is mapped to cross Sir Khola and Marha Khola. Here the HFT generally marks the boundary between young floodplain sediments and uplifted Siwalik beds. Satellite image is from Google. (lower panel) Oblique view toward northeast of Sir Khola natural exposure. Orientation of exposures shown in auxiliary excavation of Figure 6 is shown by white lines.

the primary evidence cited by Sapkota et al. (2013) and Bollinger et al. (2014) for the presence of 1934 surface rupture is not supported by these new observations.

The locations and ages of several radiocarbon samples we collected are added to those reported by Sapkota et al. (2013) and Bollinger et al. (2014) and summarized and documented in Figures 4, 5, and S4. The ages of six samples taken from the hanging wall (S1, S2, SIR09-17, SIR09-13, SIR08-11, and SIR08-12) show similar ages which to the 95% confidence interval fall within range of 1420 Common Era (CE) to 1960 CE. The six samples are located within or above the unbroken fluvial gravel unit 3. It is most likely from these sample ages and their locations within unbroken units 3 and 4 that any displacement on underlying thrusts occurred before 1934 (Figure S4c). Radiocarbon ages collected from the coarse gravels of the footwall do not follow strict stratigraphic order. The ages of the lowest group of five samples (SIR09-01, 03, 04, 11, and and 15) range between 1130 Before Common Era and 2460 Before Common Era. A significantly younger age of 1660–1940 CE is reported for the sample SIR08-26 that is reported 0.6 m above the lower five. And then at the top of the footwall section, sample S4 taken from a faulted layer of silt yields an older age of 540–615 CE. Because the samples do not follow stratigraphic order, their assessment in the context of past fault displacements is necessarily interpretive and coupled with uncertainty. The gap in ages between the lowest four samples in the footwall and the immediately overlying (0.6 m above) sample SIR08-26 is ~3,000 years. In the absence of our viewing any significant

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Figure 3. Oblique view of Sir Khola study site showing reexamined natural exposure and location of an auxiliary trench on the surface above. Investigators on higher surface are viewing into excavation shown in Figures 2 and 6. Projection of fault observed in exposure to where observed in excavation is shown by arrow.

unconformities or horizons suggesting a long hiatus in deposition (e.g., soil or weathering horizon), it may be suggested that sample SIR08-26 was a decayed root rather than detrital charcoal and thus provided a radiocarbon age significantly younger than the deposit. Accepting this interpretation, it may only be said that the last displacement on the zone of shear in Figure 5 most likely occurred after 540–615 CE (age of sample S4) and before about 1420 to 1960 CE (the age range of the six samples taken from unbroken deposits of the hanging wall). A formal analysis of the radiocarbon data using OxCcal v4.32 (https://c14.arch.ox.ac.uk/OxCal/OxCal.html; Bronk, 2009) with the IntCal atmospheric curve of Reimer et al. (2013)

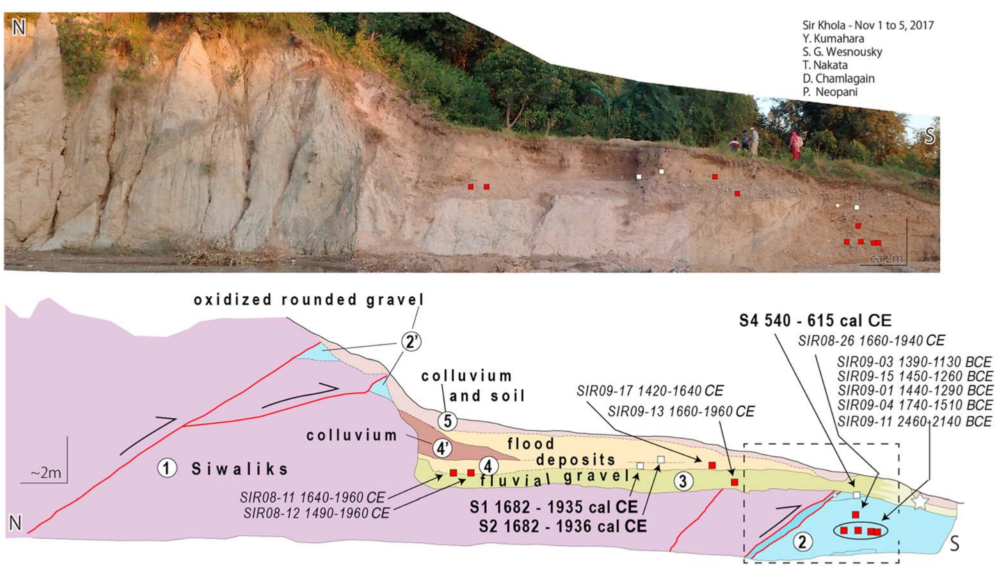

Figure 4. Photo and sketch of southernmost extent of natural exposure. Dashed box outlines area of detailed photo and log in Figure 5. Radiocarbon sample locations and ages from this study are marked by small white boxes and bold text, respectively. Radiocarbon samples collected in prior study of Sapkota et al. (2013) and Bollinger et al. (2014) are depicted by small red boxes and italicized text, respectively. Locations of red boxes are stratigraphically correct though not precisely located on this log because details of this exposure differ in detail from that studied by Sapkota et al. (2013) and Bollinger et al. (2014). Exact location of the red symbols is documented in supporting information Figure S1. Slumping of fluvial gravel of unit 3 along terrace riser occurs near star and within adjacent lighter shade of green that is used to color unit 3. CE = Common Era; BCE = Before Common Era.

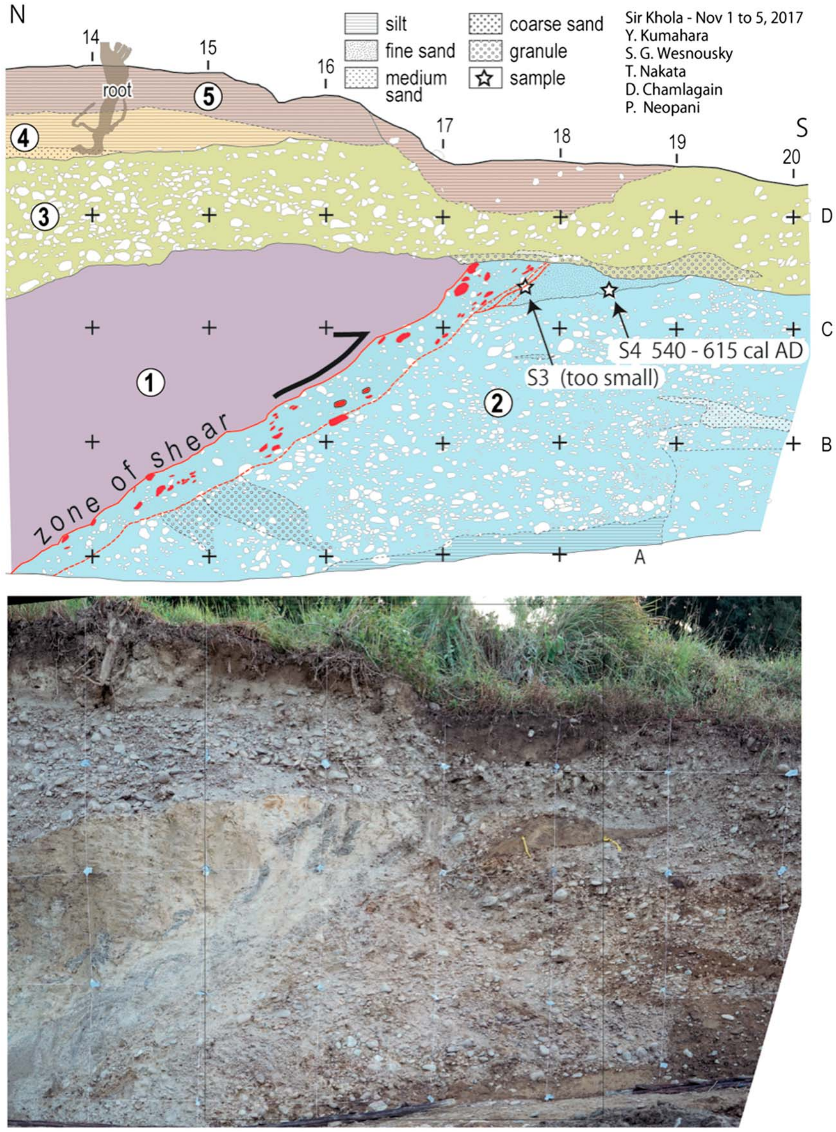

Figure 5. Enlarged photo and log illustrates capping of shear by fluvial sand and gravel. Location shown by dashed box in Figure 4. Clasts in exposure each drawn individually in log to illustrate texture. Clasts rotated with long-axis oriented along shear zone are red. Additional photos of exposure are shown in Figure S4. CE = Common Era.

places the event horizon at between 592 and 1671 CE (Figure S4c). The bracketing range of ages is broad and encompasses the 1255 CE age of a large earthquake shaking event in Kathmandu (Pant, 2002) and the age of large surface rupture paleoearthquakes previously reported nearby elsewhere along strike of the HFT to the east and west of Sir Khola (Figure 1). If one desires to attribute the last displacement at Sir Khola to a historical earthquake, it is reasonable to attribute it to the 1255 CE earthquake and not 1934. In this regard, the locations and ages of radiocarbon samples collected from the site may likewise not be construed as substantive and definitive evidence of surface rupture in 1934 at Sir Khola.

The lack of a fault scarp and folding in young sediments above the trace of the HFT at Sir Khola (supporting information Figure S3) is conspicuous and inconsistent with all other paleoearthquake trench sites that have reported evidence of earthquakes occurring in the last century (e.g., Kumar et al., 2006, 2010; Lave et al., 2005; Mugnier et al., 2005; Wesnousky, Kumahara, Chamlagain, Pierce, Karki, & Gautam, 2017; Wesnousky, Kumahara, Chamlagain, Pierce, Reedy, et al., 2017; Yule et al., 2006). Each is invariably associated with a fault scarp produced by displacement on the HFT commensurate with the size of an earthquake on the same order

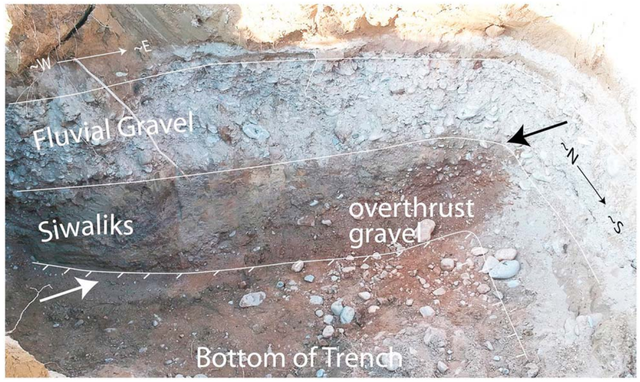

Figure 6. Exposure in auxiliary trench shows shear plane overlain by Siwaliks (between arrows) truncated by continuous exposure of river gravels. Location of intersection of thrust fault with capping fluvial gravel with respect to natural exposure is shown by arrow in Figure 3. The dip of the thrust in this exposure is northerly and into photo, and the apparent dip exposed in outcrop is to the west. Location of basal thrust contact of Siwaliks is between large arrows. If displacement on the thrust were to have displaced the fluvial gravel, it would have occurred along trend of the arrow at upper right. Length of E-W exposure about 1.5 m. Additional views are shown in Figure S2.

as the *Mw* 8.4 Bihar-Nepal earthquake. Likewise, an *Mw* 8.4 earthquake would be expected to produce surface ruptures along a fault extending from tens to hundreds of kilometers in length (e.g., Blaser et al., 2010; Leonard, 2010, 2014; Strasser et al., 2010; Wesnousky, 2008). Yet trenches excavated across the HFT within tens to hundreds of meters on either side of the Sir Khola site (Sapkota et al., 2013), and at the Marha Khola (Lave et al., 2005) and Thapatol scarps (Bollinger et al., 2014), which are located within ~5 to 7 km and also spatially bracket the Sir Khola site, do not show any displacement that is decisively associated with the 1934 earthquake. Our findings remove these inconsistencies and reopen the question of whether, as would generally be expected for such a large continental earthquake, the 1934 Bihar-Nepal event did indeed produce primary surface ruptures.

3. Conclusion

It is our view that there has yet to be found any definitive observation for surface rupture on the HFT during the great *Mw* 8.4 Bihar-Nepal earthquake of 1934. In this regard, while it may be viewed as reasonable to suggest on geophysical grounds that the Main Himalayan Frontal Thrust was the source of the 1934 Bihar-Nepal earthquake, substantiating geological evidence that it produced surface rupture along the trace of the HFT remains lacking.

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