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Geological observations on large earthquakes along the Himalayan frontal fault near Kathmandu, Nepal

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ABSTRACT

The 2015 Gorkha earthquake produced displacement on the lower half of a shallow decollement that extends 100 km south, and upward from beneath the High Himalaya and Kathmandu to where it breaks the surface to form the trace of the Himalayan Frontal Thrust (HFT), leaving unruptured the shallowest ~50 km of the decollement. To address the potential of future earthquakes along this section of the HFT, we examine structural, stratigraphic, and radiocarbon relationships in exposures created by emplacement of trenches across the HFT where it has produced scarps in young alluvium at the mouths of major rivers at Tribeni and Bagmati. The Bagmati site is located south of Kathmandu and directly up dip from the Gorkha rupture, whereas the Tribeni site is located ~200 km to the west and outside the up dip projection of the Gorkha earthquake rupture plane. The most recent rupture at Tribeni occurred 1221–1262 AD to produce a scarp of ~7 m vertical separation. Vertical separation across the scarp at Bagmati registers ~10 m, possibly greater, and formed between 1031–1321 AD. The temporal constraints and large displacements allow the interpretation that the two sites separated by ~200 km each ruptured simultaneously, possibly during 1255 AD, the year of a historically reported earthquake that produced damage in Kathmandu. In light of geodetic data that show ~20 mm/yr of crustal shortening is occurring across the Himalayan front, the sum of observations is interpreted to suggest that the HFT extending from Tribeni to Bagmati may rupture simultaneously, that the next great earthquake near Kathmandu may rupture an area significantly greater than the section of HFT up dip from the Gorkha earthquake, and that it is prudent to consider that the HFT near Kathmandu is well along in a strain accumulation cycle prior to a great thrust earthquake, most likely much greater than occurred in 2015.

1. Introduction

The Mw 7.8 Gorkha (Nepal) earthquake of April 25 was followed on May 12 by an Mw 7.3 aftershock (Fig. 1). The sequence released a total seismic moment of ~7–8 × 10^{20} Nm (NCEDC, 2014). Geophysical studies show the sequence to be the result of thrust motion on an ~150 × 50–80 km^2 fault plane elongated along strike of the Himalaya and dipping northward at about 5–11° (Avouac et al., 2015; Elliott et al., 2016; Hayes et al., 2015). Coseismic slip on the fault plane reached a maximum of ~6 m (Hayes et al., 2015) and ~2.5 m when averaged over the fault plane. The earthquake ruptured on the lower half of a shallow decollement that extends 100 km south, and upward from beneath the High Himalaya to where it produces the trace of the HFT, leaving unruptured the shallowest ~50 km of the decollement (Angster et al., 2015). The presence of fault scarps in young alluvium along strike of the HFT in both Nepal and India attests to the occurrence of past earthquakes that have ruptured the up dip portion of the HFT (e.g., Bollinger et al., 2014; Kumar et al., 2006; Lave et al., 2005). Here geological observations presented at two sites along the HFT place limits on the timing and size of past earthquake surface rupture displacements up dip and to the west of the Gorkha rupture sequence.

The two sites, Tribeni and Bagmati, are located along the HFT where it strikes across the mouths of the Narayani and Bagmati Rivers (Fig. 1). The Bagmati site is located south of Kathmandu and

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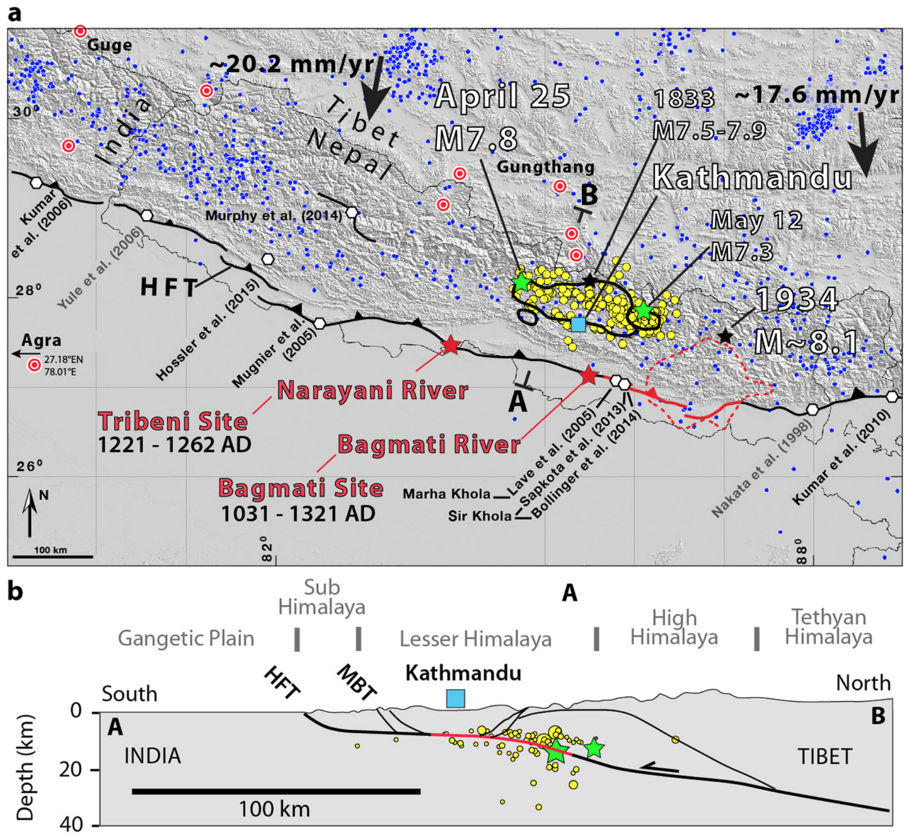

Fig. 1. (**a**) Locations (red stars) of Tribeni and Bagmati paleoseismic study sites along Narayani and Bagmati Rivers in Nepal. Green stars: Epicenters of 2015 Gorkha earthquake mainshock (M7.8) and largest aftershock (M7.3). Himalayan Frontal Thrust (HFT) is represented by solid black line with triangles on hanging wall. The extent of surface rupture along HFT during the Mw 8.4 1934 earthquake proposed by Bollinger et al. (2014) is colored red. Yellow dots: Epicenters of M > 4 aftershocks taking place within 1 day of Gorkha mainshock (National Seismological Center, Nepal; http://www.seismonepal.gov.np/index.php?action=earthquakes&show=recent). Blue dots: Locations of M > 4 earthquakes prior to Gorkha earthquake since 1968 taken from ANSS catalog (NCEDC, 2014). Black stars: Epicenters assessed from analysis of felt reports of prior large 1833 (M7.5–7.9) and 1934 (M ∼ 8.1) Bihar earthquakes from Bilham (1995) and Hough and Bilham (2008), respectively. Closed solid lines adapted from Hayes et al. (2015) delimit area of HFT that slipped in the Gorkha earthquake. Closed dashed red line: Area of isoseismal VIII (MSK64) for 1934 Bihar earthquake taken from Sapkota et al.'s (2013) interpretation of reports in Pandey and Molnar (1988). Thick black line with triangles: Location of Himalayan Frontal Thrust (HFT), triangles on hanging wall. White dots: Locations and citations of prior paleoseismological studies mentioned in text. Red dots: Locations of damage reported by Ambraseys and Jackson (2003) and used to interpret the occurrence of a ∼M8.3 earthquake in western Nepal on June 6, 1505. Arrows schematically illustrate GPS results of Ader et al. (2012) that show elastic strain equivalent to 17 to 20 mm/yr of convergence is accumulating beneath the High Himalaya. (**b**) Generalized cross-section extends along trend AB (shown in upper figure) is adapted from Lave and Avouac (2001) and shows approximate extent of rupture during Gorkha earthquake (red line) and relocated aftershocks reported in Hayes et al. (2015) (yellow circles). Convergence of the Indian and Eurasian plates has been accommodated by thrust motion along the Himalayan Frontal Thrust (HFT) and the Main Boundary Thrust (MBT), which coalesce into a single decollement beneath the High Himalaya and Tibet. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

directly up dip from the Gorkha rupture, whereas the Tribeni site is ∼50 km west of the Gorkha mainshock and located outside the up dip projection of the Gorkha earthquake rupture plane (Angster et al., 2015; Avouac et al., 2015; Hayes et al., 2015).

2. Observations

2.1. Tribeni

Displacement on the HFT has here elevated fluvial terraces above the Narayani River (Fig. 2a). The youngest two uplifted terrace surfaces are T1 and T2 and truncated on the west by the HFT. We excavated two trenches across the HFT where it bounds each of the respective surfaces (Fig. 2a). The scarp that truncates the T1 surface and across which the trench B was excavated is interpreted to be the result of displacement during the most recent surface rupture earthquake. Coarse stratigraphy and lack of organic material for dating compromised the utility of Trench B (Supplementary Material, Section S1, Figs. S1, S2, and S3). Vertical separations across the scarps bounding the younger T1 and the relatively older and higher T2 surface are ∼7 and ∼14 m, respectively. We focus attention here on the exposure across the multiple-event T2 scarp.

The photo in Fig. 3a of the trench site prior to excavation illustrates the character of the HFT scarp where it truncates the T2 surface. A sketch of the exposure is presented in Fig. 4a. Strands of the HFT cut and deform sedimentary layers in the lower western portion of the trench. The stratigraphy of the hanging wall is defined by a sequence of fluvial beds inclined westward at an angle of ∼20°, rolling to yet steeper angles near the fault contact, to form a dip panel truncated by several strands of the HFT that dip east. The main basal strand of the fault zone is approximately planar and dips at ∼30° in the exposure, while the upper strand that bounds unit 4 dips at about 20° at the base of the exposure and lessens to <10° at its upward extent. The basal unit 1 of the dip panel is coarse rounded river gravel most likely deposited by an earlier course of the adjacent Narayani River. It is overlain conformably by an alternating sequence of fine sand and silty fine sand beds (units 2 and 3) earlier deposited as flood and overbank deposits of the Narayani River. Strata on the footwall below the east dipping strands of the fault are the same, though individual beds of unit 2 on the foot and hanging wall are not observed to match. The upper portion of the shear zone (unit 4) is composed of faulted, sheared, and rotated layers and blocks of sediment similar to unit 2. The basal portion of the shear zone (unit 5) is very

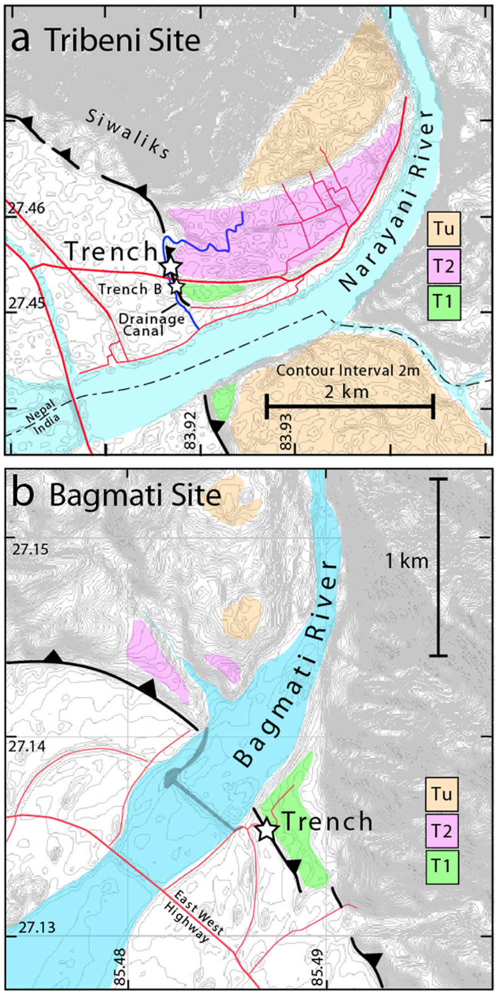

Fig. 2. Location of (**a**) Tribeni and (**b**) Bagmati trench sites (stars) each on 2 m contour base map (constructed from SRTM 1 Arc-Second Global data downloaded from http://earthexplorer.usgs.gov). T1 and T2 at each site are fluvial terrace deposits of relatively increasing age that are truncated and uplifted by displacement on the Himalayan Frontal Thrust (thick line with triangles on hanging wall). Possibly correlative and higher older surfaces are labeled Tu. Locations of trenches are labeled and marked by stars. The meandering blue line on T2 north of the Narayani River at Tribeni marks course of small drainage that has been deflected by human emplacement of a levee to produce a drainage canal that runs parallel to the fault scarp which marks trace of Himalayan Frontal Thrust. Waypoints of Tribeni Trench and Trench B are 27.454183°N, 83.916620°E and 27.451748°N, 83.917412°N, respectively, and the trench at Bagmati 27.134254°, 85.487735°. The elevation difference between the footwall of the Bagmati trench (∼135 m) and current river level (∼127 m) is ∼8 m. The elevation difference between the footwall of the Tribeni trenches (∼120 m) and current river level (∼120 m) is 6 m. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

fine sand lacking bedding. Unit 6 is the highest, youngest, and only unfaulted layer in the exposure. It is generally massive, except near its base where discontinuous lenses of rounded pebbles are present, and displays an erosive lower contact above the fault zone. Unit 6 thus aggraded subsequent to the deformation that caused the shear zone and accompanying dip panel. In this regard, the base of unit 6 marks a deformation event horizon. Unit descriptions are further documented in Supplementary Table S1 and a photo log of the exposure is provided in Supplementary Fig. S4.

Detrital charcoal samples present in units both above and below the event horizon were collected for radiocarbon analysis. The ages and sample locations are depicted in Fig. 4a. Supplementary Table S2 records the original laboratory analysis for each sample. The ages are also plotted graphically in Fig. 5a in stratigraphic order of the beds from which they were collected. The ages of samples immediately above and below the event horizon are nearly identical. Application of OxCal v4.2.4 (https://c14.arch.ox.ac.uk/oxcal/OxCal.html, Bronk, 2009) to the observed sequence of ages places the age of a scarp forming event at between 1221 AD and 1262 AD (labeled 'Displacement Horizon' in Fig. 5a). Surveyed profiles of the scarp and trench exposure show that vertical separation across the dip panel and scarp is ∼13–14 m, and the presence of the lower T1 terrace bounded by the same scarp (Fig. 2a) suggests that it is the result of two or more earthquakes. When viewing the trench exposure (Fig. 4a), at least 5 to 6 m of the entire vertical separation across the scarp may be attributed to that occurring between 1221 AD and 1262 AD: Sediments on the footwall are flat-lying, which rules out any contribution to the observed scarp from faulting further west of the exposure, and undeformed dip panel is observed to extend vertically 5 to 6 m to the east. The ∼7 m vertical separation observed across the scarp bounding the lower T1 surface at Trench B (Figs. 2a and S1 and S2) is considered to have occurred at the same time.

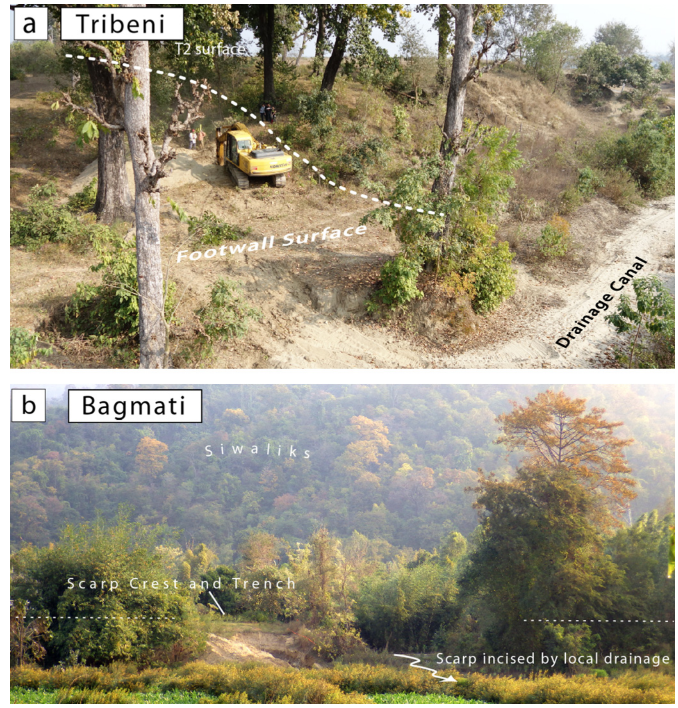

Fig. 3. Photos illustrate character of scarps excavated at Bagmati and Tribeni sites. (**a**) View is southeastward and taken from levee bounding drainage canal that is deflected along the scarp at Tribeni (see Fig. 2a). Dashed white line approximates scarp profile and location of trench. (**b**) Southeastward view of trench site at Bagmati shows it to be adjacent to local drainage that cuts approximately perpendicular to and incises scarp. Dashed line marks crest of scarp where hidden in trees.

It seems unlikely, though cannot be strictly ruled out, that two earthquake displacements on the faults exposed in the trench occurred very closely spaced in time (<50 yrs) to produce the ∼13–14 m of vertical separation across the fault. We speculate that the 1221–1262 event is the youngest surface displacement recorded at Tribeni and an older rupture is recorded higher up on the T2 scarp (Fig. 4a, lower). The speculation is driven by observations that (1) no additional colluvium is observed on the scarp above the growth stratigraphy (Fig. 4a) which could be expected with sudden growth of the scarp from a fault displacement younger than the 1221–1262 event and higher up on the scarp, (2) there are to our knowledge no historical accounts since 1255 AD (Pant, 2002) that describe the extent and degree of damage we would expect for an earthquake with the large coseismic offsets interpreted in the Tribeni trench, and (3) analogue sand-box models that show thrust fault development is commonly charac-

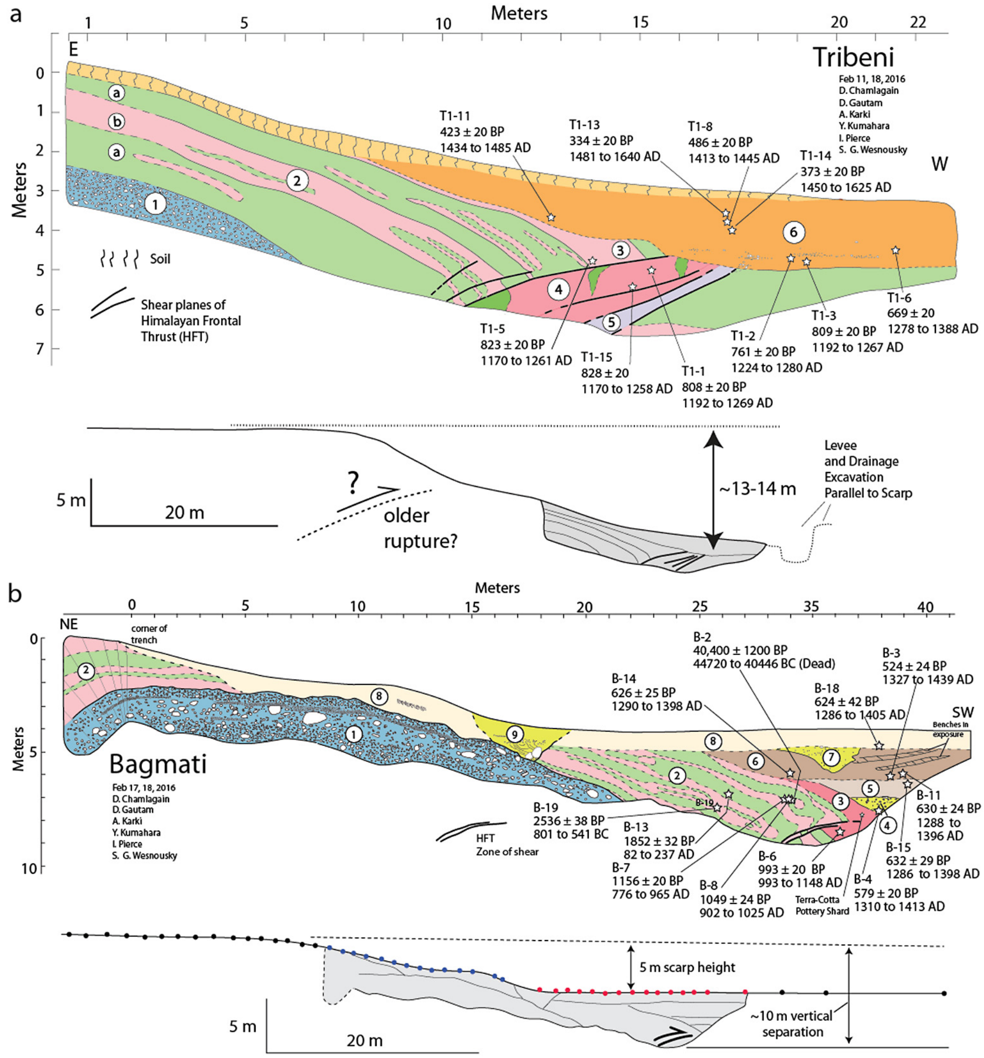

Fig. 4. Trench logs at (**a**) Tribeni and (**b**) Bagmati. Location of trenches relative to profile of scarp across which they are excavated shown below each log. Numbers in circles are unit numbers. Detrital charcoal samples dated with radiocarbon are labeled and plotted with radiocarbon and corrected age bounds, each reported to 95% confidence limits (Supplementary Table S1). At Bagmati, blue and red dots mark upper and lower portions of trench log, respectively. Logistics related to property ownership required that the upper portion of trench be excavated, logged and filled prior to excavating, logging, and filling the lower portion of trench. Aspects of property ownership also limited the southwestward extent to which the trench was excavated. Scarp profiles at Tribeni and Bagmati measured with GPS receiver and Total station vertical accuracy of ~0.5 m and ~<3 cm, respectively. Profile at Tribeni is average of several profiles across the scarp nearby because of stream incision adjacent to trench site. Supplementary Materials include further description of units (Table S2) and Photo Logs of each exposure (Figs. S3, S4, S5, and S6). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

terized by in-sequence propagation of forward thrusts (e.g., Ellis et al., 2004).

2.2. Bagmati

Here displacements on the HFT have truncated and uplifted fluvial deposits at the mouth of the Bagmati River. The youngest uplifted terrace deposits are labeled T1 and T2 in Fig. 2b, and the star marks the location where we excavated a trench across the fault scarp. The scarp bounding the younger T1 surface is ~5 m high whereas scarp heights along the older T2 surface are generally 10–15 m or greater. A photo of the scarp truncating the T1 surface at the trench site is shown in Fig. 3b. The trench log is shown in Fig. 4b, and Supplementary Figs. S5 and S6 provide photo logs of the exposure. The deformation style and sediment types are similar to those observed at Tribeni. The HFT is observed to displace and deform sedimentary layers in the lowest southwestern portion of the trench. The stratigraphy of the hanging wall is defined by a sequence of fluvial beds that are near horizontal at the northeast limit of the exposure and then bend downward ~25° to form a dip panel that is truncated by the HFT. The HFT dips northeastward at ~30° near the base of the trench and lessens to <10° at its shallowest extent. The basal unit (1) of the dip panel is coarse rounded river gravel most likely sourced from the Bagmati River. It is capped by an alternating sequence of fine sand and silty fine sand beds (units 2 and 3) interpreted to be flood and overbank deposits of the Bagmati River. The beds of the dip panel are overlain by a sequence of unfaulted horizontal beds (units 4, 5, and 6) that accumulated subsequent to displacement on the HFT and creation of the dip panel. The lowest of the units (4) is comprised of pebbles and small cobbles enriched in sand at its base and displays an erosive lower contact. The higher flat-lying units (5 and 6) are very fine silty and clay bearing sand, which are viewed as growth stratigraphy accumulating as the result of erosion and sediment transport from the adjacent drainage (Fig. 3b), subsequent to creation of the dip panel. Local flood events from the adjacent drainage also appear responsible for the gravel-filled channel units (7 and 9). Likewise, the significant erosion of unit 2 along the higher reaches of the dip panel may be attributed to development of the adjacent drainage subsequent to development of the scarp.

Detrital charcoal was present and sampled from layers of the dip panel and overlying growth stratigraphy. The results are plotted in stratigraphic sequence in Fig. 5b and the original radiocarbon laboratory analyses summarized in Table S2. But for sample B-2 that was radiocarbon dead, the radiocarbon ages follow stratigraphic order. Units 2 and 3 (containing samples B-19, 13, 8, 7, and 6) were deposited prior to deformation and creation of the dip panel while units 4 to 8 (containing samples B-4, 15, 11, 14, 3, and 18) were deposited subsequently. The deformation event horizon thus falls between the beds of units 3 and 4 containing samples B-6 and B-4, respectively, and so marks the time of surface rupture and scarp formation. Application of OxCal v4.2.4 (https://c14.arch.ox.ac.uk/oxcal/OxCal.html, Bronk, 2009) places fault rupture and creation of the scarp at between 1031 AD and 1321 AD (Fig. 5b). The surface scarp height at the trench is ∼5 m. The vertical separation resulting from tectonic deformation is more aptly described as 10 m when fill on the footwall wall that occurred subsequent to faulting and tilting of the dip panel is taken into account (Fig. 4b). In these regards, 10 m of vertical uplift occurred across the scarp during the period 1031 AD and 1321 AD. Limits imposed upon excavating further to the west and deeper prevented exposing the dip panel to its deepest extent and the full thickness of the growth stratigraphy on the footwall. That the dip panel continues below the lowest most exposed fault strand requires that there is at least one more fault strand below the base of the exposure, that the 10 m measure of vertical separation is a minimum, and permits that the dip panel is the result of more than one displacement between 1031 AD and 1321 AD.

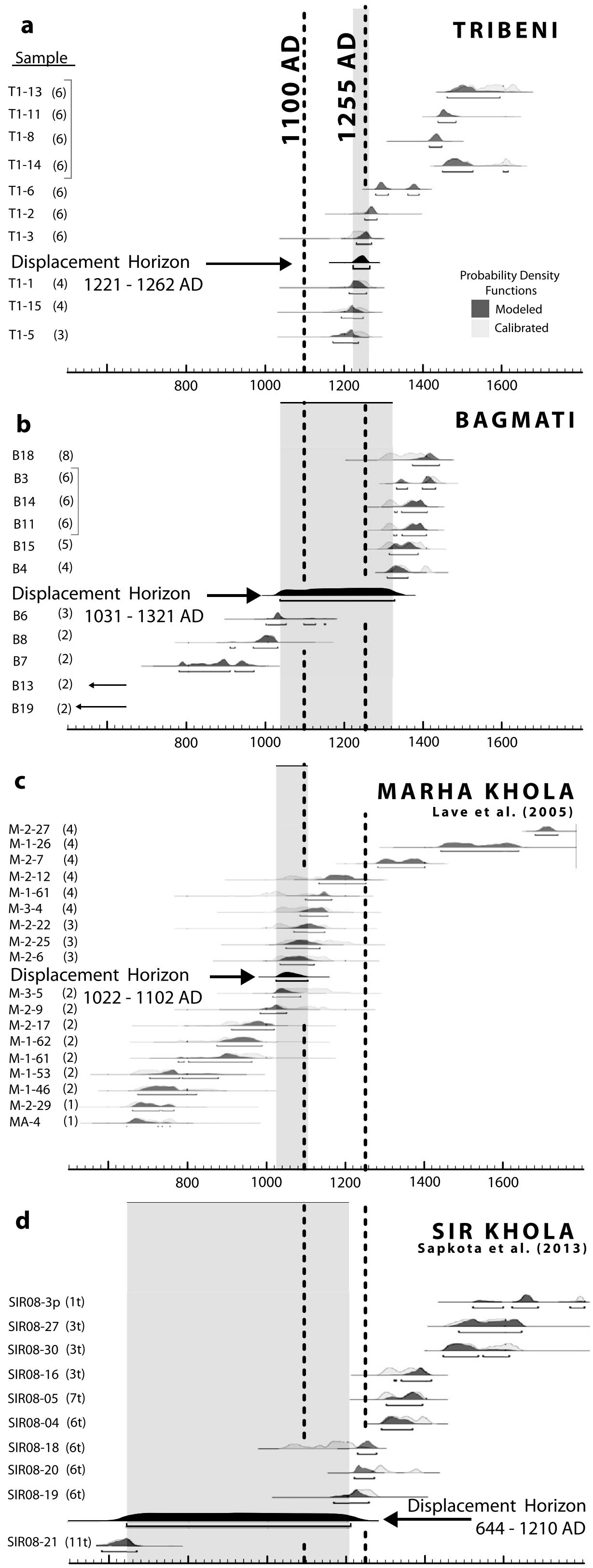

Fig. 5. Radiocarbon ages of detrital charcoal samples in conjunction with structural and stratigraphic relationships exposed in trenches limit the time of last large earthquakes to produce surface rupture. Individual corrected and modeled ages of each sample are presented in stratigraphic order as probability density distributions determined with OxCal v4.2.4 (https://c14.arch.ox.ac.uk/oxcal/OxCal.html, Bronk, 2009) with the IntCal13 atmospheric curve of Reimer et al. (2013). Each sample number and stratigraphic unit number (in parentheses) is labeled and correlate to respective trench logs from which they were taken. Observations collected in this study at (a) Tribeni and (b) Bagmati are compared to results reported in prior nearby studies at (c) Marha Khola (Lave et al., 2005) and (d) Sir Khola (Sapkota et al., 2013), and arranged to progress eastward from a to d. Grayed areas encompass temporal bounds on event at each site. Thick vertical dashed line corresponds to years 1100 AD and 1255 AD discussed in text.

3. Discussion: past and future rupture behavior

3.1. *Size of earthquake recorded at Tribeni*

The relationships in the trench at Tribeni (Fig. 4a), located southwest of Kathmandu and outside the up-dip projection of the 2015 Gorkha rupture (Fig. 1), are evidence that earthquake displacement has produced surface rupture resulting in a scarp of at least ∼5 m vertical separation between 1221 and 1262 AD (Fig. 5a). Uncertainties are large when trying to estimate the size of a past earthquake from a single measurement of vertical separation. In addition to being limited to a single observation, assumptions must be made bearing on the style of deformation and dip of causative fault for which, in this case, we cannot be certain that the dip observed in the trench exposure extends without change beneath the entire scarp. The dip of the shear zone is about 20°–30° at the base of the Tribeni trench. To approximate the fault displacement required to produce the dip panel and ∼5–7 m of vertical separation observed across the Tribeni scarp (Figs. 4a and Supplementary S2), we assume a 15°–45° range of dips to reflect uncertainty in our knowledge of the dip as it extends below the trench exposure, consistent with Andersonian mechanics (Anderson, 1951). When it is assumed the slip vector is perpendicular to the Tribeni scarp, the amount of slip on a fault dipping at an angle between 15° and 45° required to produce 5 to 7 m of vertical separation is between 7 m to 27 m, respectively. The strike of the scarp at Tribeni (∼160°) is oblique to the direction of convergence (∼190°) indicated by geodesy (e.g., Ader et al., 2012 and Fig. 1). If coseismic slip at the scarp shares the same obliquity, the required amount of slip to produce the 5 to 7 m vertical separation would approach double these values. These approximated values of slip viewed in the context of empirical scaling laws relating average coseismic slip, rupture length, and moment magnitude Mw constructed from data sets comprising hundreds of historical dip-slip earthquakes (Blaser et al., 2010; Leonard, 2010, 2014; Strasser et al., 2010), are commensurate to that expected for earthquakes of magnitude ranging between Mw ∼8.5 and >9.0 with rupture lengths of 400 km to >900 km. If the fault steepens to vertical dip beneath the scarp, the lesser measure of 5 m vertical separation should approximate the fault slip needed to produce the observed dip panel. In this case, the same empirical scaling laws point to a causative earthquake in the broad range of Mw ∼8.2 to 8.4 with a 200–350 km rupture length. The scaling laws are developed for estimates of average coseismic slip. It is possible that the slip at Tribeni was actually maximum along strike of the earthquake rupture, in which case the prior estimates of Mw and rupture length might be considered overestimates. This concern is tempered by the observation that our 5 m measurement of vertical separation is a minimum estimate of coseismic offset. So, while such estimates are coupled with large uncertainty, it is reasonable to consider that the last scarp producing earthquake at Tribeni was associated with a rupture that extended hundreds of kilometers along the HFT, a distance greater than that between Tribeni and Bagmati.

3.2. Extent of rupture east of Tribeni to Bagmati

The Bagmati trench site is located about 200 km east of Tribeni and directly up-dip of the 2015 Gorkha earthquake rupture (Fig. 1). The broader 1031–1321 AD temporal constraint on the timing of scarp formation at Bagmati encompasses the 1221–1262 AD age of most recent scarp formation at Tribeni (Fig. 5a and b). Given the temporal overlap and the prior discussion showing that the earthquake producing the Tribeni scarp may be considered to have produced surface rupture on order of hundreds of km in length along the HFT, it is reasonable to suggest that the Bagmati and Tribeni sites ruptured simultaneously between 1221–1262 AD. The large vertical separation observed across the scarp at Bagmati (>10 m) is consistent with the interpretation, albeit the Bagmati scarp may be the result of more than one earthquake during the period 1031–1321 AD, a topic we return to later in the discussion.

3.3. Extent of rupture east of Bagmati

Shifting attention to about 25 km east of Bagmati, there exist two prior paleoearthquake studies, one reported by Lave et al. (2005) at Marha Khola and another reported in the papers of Sapkota et al. (2013) and Bollinger et al. (2014) at Sir Khola (Fig. 1). Marha Khola is just 7 km west of Sir Khola. At Sir Khola, surface rupture was recognized for the great 1934 M ∼ 8.4 Bihar earthquake and along with limited geomorphic observations led to interpretation that it ruptured at least the 150 km section of the HFT indicated in red on Fig. 1. No support for surface rupture in 1934 is provided by our analysis of the HFT scarp at Bagmati, which may be interpreted to place a firm bound on the western extent of surface rupture during 1934. The Sir Khola site was also interpreted by Sapkota et al. (2013) to preserve evidence of prior surface rupture of an historically reported earthquake in 1255 AD. The 1255 AD age at Sir Khola falls within the 41-year (1221 AD to 1262 AD) window suggested by radiocarbon for the offset we observe at the Tribeni site. Coupled with the large displacement event bracketed more loosely between 1031 AD and 1321 at the Bagmati site, the observations would then appear to allow a single rupture to have extended a total of 225 km between Sir Khola and the Tribeni site. The interpretation though is complicated by the observations of Lave et al. (2005) at Marha Khola (∼7 km west of Sir Khola and closer to Bagmati and Tribeni, Fig. 1).

Lave et al. (2005) interpreted the occurrence of a single earthquake displacement at Marha Khola on the order of 17 m to have occurred at about 1100 AD, well before the 1255 AD age interpreted for the penultimate surface rupture at Sir Khola by Sapkota et al. (2013). Our reanalysis of the radiocarbon data reported in Supplementary Table S1 of Lave et al. (2005) with Oxcal v4.2.4 is shown in Fig. 5c and places a formal 95% bound on the event horizon observed at Marha Khola at between 1022 and 1102 AD. Additionally, Lave et al. (2005) interpret the stratigraphy to indicate that the 1934 Bihar earthquake did not produce surface rupture a Marha Kohla. Sapkota et al. (2013) discount these interpretations of Lave et al. (2005). The reasons for disregarding Lave et al.'s (2005) analysis are worth considering.

Sapkota et al. (2013) discount the ∼1100 AD event interpreted by Lave et al. (2005) because of historical accounts of a large earthquake that produced significant damage and several thousand deaths in Kathmandu in 1255 AD (Pant, 2002). The knowledge of the 1255 AD earthquake was emplaced as an *a priori* input by Sapkota et al. (2013) in their analysis of radiocarbon ages to assess the timing of the paleoearthquake observed in their trench. The stratigraphy in their studied exposure at Sir Khola though provided radiocarbon samples only in sediments deposited subsequent to the displacement attributed to the 1255 AD earthquake, and not before. An examination of their reported ages using Oxcal 4.2.4 in absence of any Bayesian bias shows the data they report in their Fig. S3C to very loosely limit the timing of the event horizon attributed to 1255 AD at between 644 and 1210 AD, a span that does not include 1255 AD (Fig. 5d). The radiocarbon stratigraphy at Lave et al.'s (2005) Marha Khola site is in contrast quite robust, with several samples reported both immediately above and below the event horizon attributed to the ∼1100 AD event (Fig. 5c). In the context of these preceding observations, the data at Marha Khola and Sir Khola are compatible with each experiencing simultaneous rupture between 1022 and 1102 AD, and Lave et al.'s (2005) earlier speculation that the ∼1100 AD paleoearthquake might correspond to a paleoearthquake surface rupture reported ∼250 km to the east near the Nepal border may remain valid (Nakata et al., 1998; Upreti et al., 2000). To this discussion, we add the suggestion that our result at Tribeni that defines a surface rupture event between 1221 AD and 1262 AD is perhaps a better, less ambiguous, candidate for the 1255 AD historical earthquake than is the Sir Khola site. Radiocarbon dating thus allows that this proposed 1221–1262 AD event at Tribeni ruptured 200 km eastward through Bagmati, but whether or not the rupture extended another 25 km to the east to Sir Khola is debatable.

For convenience of presentation, the 1221 AD to 1262 AD displacement observed at Tribeni (Fig. 5a) and the 1022 to 1102 AD earthquake reported at Marha Khola (Fig. 5c) are herein referred to as the 1255 AD and 1100 AD earthquakes, respectively.

3.4. Contemporaneity of rupture at Bagmati and Tribeni?

If one follows the interpretation that the scarp at Bagmati is the result of a single earthquake, the broad and formal temporal bounds on the displacement horizon at Bagmati (1031–1321 AD) (Fig. 5b) also allow another scenario whereby displacement at Bagmati did not occur contemporaneously with Tribeni in 1255 AD but instead with the ∼1100 AD event at Marha Khola, and possibly Sir Khola too (Fig. 5c and d). If so, one encounters the question of why there is such a long hiatus in deposition at Bagmati subsequent to a hypothesized ∼1100 AD event (Fig. 5b). It is difficult to reconcile the hiatus with the expectation that deposition on the footwall (arising from scarp degradation and local scarp incision) would begin soon after creation of a scarp (e.g., Sapkota et al., 2013). It is more intuitive that the hiatus is the result of an earlier abandonment of the surface across which the Bagmati scarp cuts, either from a change in the course or an earlier incision of the Bagmati River. This latter idea finds some support in the observation that the footwall of the Bagmati scarp is now inhabited and sits ∼8 m and more above the present course of the Bagmati River. The incision, all or in part, or a significant change in stream course may have occurred well before the scarp forming event at Bagmati. Albeit one cannot disprove with the radiocarbon data available that Bagmati ruptured simultaneously with Marha Khola in ∼1100 AD, the geological context provides a reasonable basis to interpret that, if indeed Bagmati ruptured simultaneous with one of the adjacent sites, it more likely ruptured with the 1255 AD event at Tribeni rather than with the ∼1100 AD event at Marha Khola.

The observed hiatus in deposition at Bagmati subsequent to a hypothesized ∼1100 AD event (Fig. 5b) may though be apparent if the scarp at Bagmati is the result of multiple earthquakes. In this case, the observed hiatus in deposition may be considered to be the consequence of our inability to excavate deeper and possibly observe the presence of older deformed packages of growth stratigraphy (Fig. 4b). The conjecture leads to other possible scenarios whereby the ∼1100 AD rupture documented at Marha Khola and the 1255 AD event at Tribeni each extended and overlapped at Bagmati, or all displacement at Bagmati occurred simultaneously with the ∼1100 AD earthquake.

3.5. Limit on westward extent of Mw ∼8.4 1934 Bihar earthquake

Shifting attention back to the Mw ∼ 8.4 1934 Bihar earthquake, the lack of deformation in sediments post-dating and overlying the Bagmati surface rupture that occurred between 1031–1321 AD may be viewed to place a firm western limit on the extent of surface rupture during the 1934 event (Figs. 4b and 5b). Sapkota et al. (2013) also interpret that the lack of 1934 rupture at the Marha Khola site of Lave et al. (2005) is not inescapably demonstrated because two thrusts emerging near the base of a 4 m-high scarp studied along a river cut are not sealed by dated deposits. Yet, Lave et al. (2005) studied an additional two trench exposures within ∼100 m of the river cut and each of these displayed 1 to 2 m of unbroken sediments post-dating ∼1100 AD and predating 1934 over the active strands of the fault (Figs. 2 and 3 in Lave et al., 2005). In this regard, the possibility that Marha Khola actually marks the western limit of rupture during the 1934 Bihar earthquake should not be ruled out.

3.6. West of Tribeni

Moving focus to the west of Tribeni, there are few observations and studies to bear on the past history of large earthquakes in Nepal. Mugnier et al. (2005), about 150 km west of Tribeni (Fig. 1), report a radiocarbon sample of 775 ± 35 yr BP (1190–1285 AD) taken from a terrace that is displaced vertically 8 m by one or more events by the HFT. The limiting terrace age encompasses the timing of the 1221 AD to 1262 AD surface rupture event we observe at Tribeni, and they speculated the terrace offset may in part record the 1255 AD earthquake that produced damage in Kathmandu (Pant, 2002). This observation and the large displacement at Tribeni certainly allow one to consider that the earthquake that produced the scarp at Tribeni extended 150 km westward, and maybe significantly more.

Ambraseys and Jackson (2003) followed Jackson (2002) in interpreting historical reports to suggest the occurrence of an M > 8 earthquake in western Nepal in 1505. It has since often been speculated that the earthquake was the result of displacement on the HFT (Avouac et al., 2015; Bilham, 2004; Bollinger et al., 2016), though observational support arises primarily from felt reports quite distant to the north of the Himalaya in Tibet between Guge and Gungthang and the collapse of some tall buildings in Agra (Fig. 1). As such, it may be considered that the release of stress in 1505 could be a factor in limiting the westward extent of the next large surface rupture earthquake south of Kathmandu. If indeed the Mugnier et al. (2005) site records multiple events, it might even also be speculated that one of the events correlates to the 1505 AD earthquake.

About 100 km further west of the Mugnier et al. (2005) site and on a section of the Main Boundary Thrust, which is generally considered to sole into the same decollement as the HFT (Fig. 1), Hossler et al. (2016) interpret 8 m offsets of river terraces to record surface ruptures subsequent to 1860 BP and 640 BP, respectively, and conjecture that the latter of these two could have been produced in the 1505 earthquake. Equally, the post 640 BP Hossler et al. (2016) event can be considered to have occurred simultaneously with a large paleoearthquake recognized by Murphy et al. (2014) yet farther north on a strike-slip fault in the high Himalaya between 1165 AD and 1400 AD, which serves to illustrate the large uncertainty in assigning the post 640 BP earthquake to a particular historical account. Age constraints are limited and correlation of these earthquakes to a particular historical earthquake or each other is problematic. Nonetheless, the Hossler et al. (2016) study indicates that large earthquakes on out of sequence thrusts can also accommodate convergence along the Himalayan front and, in this case, perhaps play a role in controlling the endpoints of future ruptures along this section of the HFT.

Continuing westward, a paleoseismic investigation along the HFT reported in the abstract of Yule et al. (2006) has been cited by many (e.g., Hossler et al., 2016) to confirm that rupture occurred near the west Nepal border in 1505, and a number of similar investigations at sites along the HFT yet farther west in India may be consistent with that idea (Kumar et al., 2006). If both the Yule et al. (2006) and Hossler et al. (2016) sites record the same earthquake (e.g. 1505 A.D.), the observations would imply that rupture jumped between or was divided between both the MBT and HFT. Because of the limited age control and distance of the two sites from historical accounts of shaking, the idea that displacements at each site occurred simultaneously or, moreover, both occurred during 1505 AD is quite speculative.

Bringing the discussion back to the possible extent of the large 1221–1262 AD displacement we see at Tribeni, it seems reasonable to consider that the earthquake that produced the Tribeni scarp may have extended 150 km westward in light of the observations recorded at the site of Mugnier et al.'s (2005) study (Fig. 1), where offset occurred after 1190–1285 AD. The post 640 BP age rupture reported on the MBT by Hossler et al. (2016) appears to preclude synchronicity with the 1221–1262 AD Tribeni event. Assuming that large ruptures generally abut rather than overlap and that convergence across the Himalayan front can be shared between the MBT and HFT, the Hossler et al. (2016) site (Fig. 1) provides a possible maximum bound on the westward extent of the 1221–1262 AD Tribeni rupture. Finally, it may be said on the basis of Yule et al.'s (2006) study reported in abstract that the HFT in westernmost Nepal does not share the same earthquake history as Tribeni.

3.7. Aspects of earthquake recurrence at Bagmati and Tribeni

Convergence between India and Tibet accumulates as elastic strain at the transition from steady state creep located about 100 km north of the HFT beneath the high Himalaya to the locked portion of the decollement to the south (Ader et al., 2012; Bilham et al., 1998), which is intermittently released in large and great earthquakes (Bilham et al., 1997; Kumar et al., 2008, 2010; Molnar and Pandey, 1989). The Gorkha earthquake did initiate near this transition but rupture reached no closer than about 50 km to the trace of the HFT to the south. In so doing, it has transferred stress and further loaded the unruptured ($\sim$140 $\times$ 50 km^2) section up-dip and to the south. Our studies at Tribeni and Bagmati lend some insight to the past and possible future behavior of this unruptured section of the HFT.

Geodesy shows that horizontal convergence is occurring at about 20 mm/yr along the Gorkha section of the Himalayan front (Ader et al., 2012) (Fig. 1), commensurate to 14–20 m and 15–16 m of shortening since the offsets at Bagmati (1031–1321 AD) and Tribeni (1221–1262 AD), respectively. There is thus currently sufficient stress accumulated in the crust to produce a very large earthquake, perhaps approaching Mw 9 with rupture length on the order of 900 km (Blaser et al., 2010; Leonard, 2010, 2014; Strasser et al., 2010). If we are not recognizing younger offsets at Tribeni or Bagmati or on other out of sequence thrusts to the north, the calculated accumulated strain would be accordingly less. We are aware of no studies at longitudes between Tribeni and Bagmati bearing on this issue and the historical chronicle of earthquakes of Pant (2002) is insufficient to assess with confidence the size or location of any such events.

One may address whether or not accumulated strain is currently sufficient to produce displacements of the size registered at Bagmati and Tribeni in (1031–1321 AD) and (1221–1262 AD), respectively. The fault scarps at Tribeni and Bagmati strike about 160° (Fig. 2) and the direction of shortening defined by geodesy is about 190° (Fig. 1 and e.g., Ader et al., 2012). With this obliquity, only one half of the 20 mm/yr geodetic convergence might be expected to produce fault normal displacement and uplift. The vertical separation expected along each of the scarps were they to rupture in releasing accumulated strain can be estimated by multiplying the shortening rate (10 mm/yr) by the tangent of the fault dip at the scarp and the times since creation of the event horizons documented for the last earthquake at Bagmati (1031–1321 AD) and Tribeni (1221–1262 AD). Assuming a possible range of fault dips between 15°–45°, the exercise leads to values of 2 to 8 m at Tribeni and 1.9 to 9.9 m at Bagmati. If one assumes the fault dips at the base of the Tribeni ($\sim$25°) and Bagmati ($\sim$30°) trenches continue downward without change, the values calculated are 3.5–3.7 m and 4–5.7 m, respectively. The computed values at Tribeni encompass the 5–7 m vertical separation interpreted to have occurred in 1221–1262 AD, and less if the dip observed in the trench ($\sim$25°) extends beneath the scarp. The range of values at Bagmati is less than the 10 m vertical separation observed across the scarp there, though if the scarp has been produced by two events, it also possible that the calculated range of uplift values encompasses the vertical separation that occurred in 1031–1321 AD. It is thus difficult with the limited observations to establish exactly where the HFT sits within the strain accumulation cycle leading up to a possible repeat of offsets similar to those observed at Tribeni and Bagmati. Yet additional uncertainty exists because there are to our knowledge no existing geological studies ruling out that displacement has also occurred on an out of sequence thrust to the north of Tribeni and Bagmati (e.g. the MBT) since 1221–1262 AD, and historical data also appear insufficient to confirm or deny such a hypothesis. Nonetheless, the observations in hand do provide reason to suggest that sufficient slip is stored in the system to produce a very large earthquake along the section of HFT that includes Tribeni and Bagmati.

Another clue toward ultimately understanding earthquake recurrence along this section of the HFT is recorded in the 801–541 BC age of the stratigraphically lowest sample B-19 in the dip panel of the Bagmati exposure (Fig. 4b). From its location and age, it may be said that the sediments of unit 2 were deposited on a flat lying surface of transport and aggradation absent of earthquake deformation for the period extending from or before 801–541 BC to 1310–1413 AD, the age of sample B4 (Fig. 4b). This suggests that the recurrence time between the penultimate and 1031–1321 AD earthquake at Bagmati exceeded $\sim$1572 to 2122 yrs, significantly greater than the $\sim$695 to 985 yrs since 1031–1321 AD, the bounding ages on formation of the Bagmati scarp (Fig. 5b).

3.8. Synthesis of past and possible future ruptures

We venture in Fig. 6 to graphically portray a plausible sequence of past and possible future ruptures along the HFT in the vicinity of the Gorkha earthquake based on the observations presented. The history begins with a large surface rupture event in $\sim$1100 AD that extended eastward from Marha Khola for an unknown distance (Fig. 6a). Allowing that Tribeni and Bagmati ruptured simultaneously, the entire section of the HFT extending westward from Marha Khola, including Bagmati and Tribeni, is interpreted to have ruptured in 1221 AD–1262 AD (perhaps the 1255 AD earthquake) (Fig. 6b). The M $\sim$ 8.4 Bihar earthquake of 1934 subsequently re-ruptured all or part of the $\sim$1100 AD rupture (Fig. 6c). The most recent 2015 Gorkha earthquake ruptured a small down dip portion of the HFT that was perhaps previously broken in 1031 AD–1321 AD (1255 AD?) (Fig. 6d). Influenced by observation that shows us the Tribeni site may be approaching or in the later stages of strain accumulation before a large earthquake, the scenario hypothesizes that the next great earthquake may initiate to the west near Tribeni and propagate into the section of fault beneath Kathmandu that did not rupture during the 2015 Gorkha earthquake (Fig. 6e). The length of such a rupture would be $\sim$200 km or greater and capable of producing an M8 earthquake or greater.

The preceding scenario of Fig. 6 is not unique. One may consider scenarios whereby the Bagmati scarp is the product of two earthquakes in 1100 AD and 1255 AD, respectively (Fig. S7a), or a single event in $\sim$1100 AD (Fig. S7b). Regardless of the model, each need embody the observation that, up-dip of the Gorkha earthquake at Bagmati and to the west towards and perhaps past Tribeni, (1) sufficient time has passed along the HFT to accumulate significant slip since the last earthquake, (2) that the size of displacements at Bagmati and Tribeni are likely associated with ruptures of 200 km or more, and (3) it is plausible that Bagmati and Tribeni will rupture simultaneously in the future because they either ruptured simultaneously in the past at $\sim$1255 AD or close in time at $\sim$1100 AD and 1255 AD. Finally, there are other historically recorded earthquakes in the region, such as the M7.5–7.9 earthquake of 1833 (Fig. 1 and Bilham, 1995), that we do not include in the scenario of Fig. 6 because it is not certain that they occurred on the HFT.

4. Conclusion

The sum of observations suggests that the HFT extending $\sim$200 km from Tribeni to Bagmati may rupture simultaneously, that the next great earthquake near Kathmandu may rupture an area significantly greater than the section of HFT up dip from the Gorkha earthquake (Fig. 6), and that it is prudent to consider that the HFT near Kathmandu is well along in a strain accumulation cycle prior to a great thrust earthquake, much greater than occurred in 2015. In these regards, the 2015 Gorkha earthquake did not diminish the current level of seismic hazard in Kathmandu.

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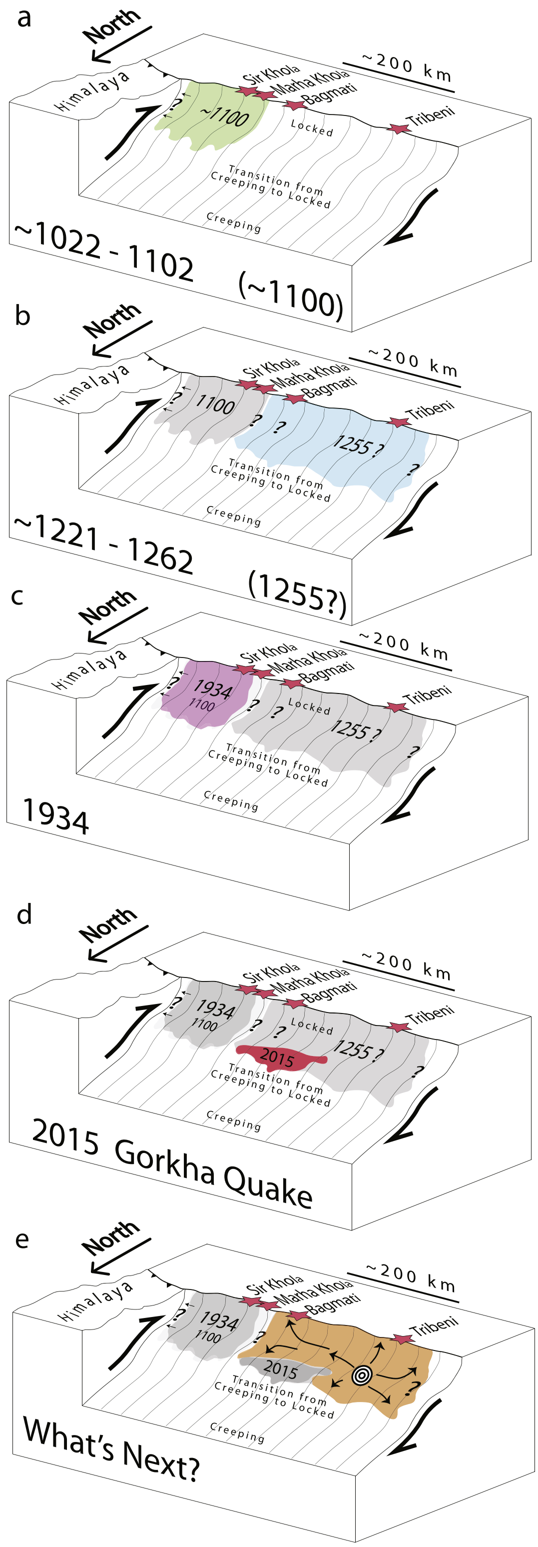

Fig. 6. Scenario of the extent and timing of ruptures along the HFT since ∼1100 AD is interpreted on data presented and reviewed in this paper and includes suggestion that section of fault west of the 1934 rupture is in advanced stages of strain accumulation cycle and may next produce a rupture >200 km in length that includes the section of fault up dip from the 2015 Gorkha earthquake extending westward to Tribeni and perhaps beyond. See text for discussion.

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Appendix A. Supplementary material

Tables of unit descriptions and original radiocarbon laboratory analyses, discussion and log of Trench B, photo logs of all Bagmati and Tribeni trenches, and additional fault rupture scenarios are provided in the Supplementary Information.

Supplementary material related to this article can be found online at http://dx.doi.org/10.1016/j.epsl.2016.10.006.

References

Ader, T., Avouac, J.P., Liu-Zeng, J., Lyon-Caen, H., Bollinger, L., Galetzka, J., Genrich, J., Thomas, M., Chanard, K., Sapkota, S.N., Rajaure, S., Shrestha, P., Ding, L., Flouzat, M., 2012. Convergence rate across the Nepal Himalaya and interseismic coupling on the Main Himalayan Thrust: implications for seismic hazard. J. Geophys. Res., Solid Earth 117.

Ambraseys, N., Jackson, D., 2003. A note on early earthquakes in northern India and southern Tibet. Curr. Sci. 84, 570–582.

Anderson, E.M., 1951. The Dynamics of Faulting. Oliver and Boyd, Edinburgh.

Angster, S., Fielding, E.J., Wesnousky, S., Pierce, I., Chamlagain, D., Gautam, D., Upreti, B.N., Kumahara, Y., Nakata, T., 2015. Field reconnaissance after the 25 April 2015 M 7.8 Gorkha earthquake. Seismol. Res. Lett. 86, 1506–1513.

Avouac, J.-P., Meng, L., Wei, S., Wang, T., Ampuero, J.-P., 2015. Lower edge of locked Main Himalayan Thrust unzipped by the 2015 Gorkha earthquake. Nat. Geosci. 8, 708.

Bilham, R., 1995. Location and magnitude of the 1833 Nepal earthquake and its relation to the rupture zones of contiguous great Himalayan earthquakes. Curr. Sci. 69, 155–187.

Bilham, R., 2004. Earthquakes in India and the Himalaya: tectonics, geodesy and history. Ann. Geophys. 47, 839–858.

Bilham, R., Blume, F., Bendick, R., Gaur, V.K., 1998. Geodetic constraints on the translation and deformation of India: implications for future great Himalayan earthquakes. Curr. Sci. 74, 213–229.

Bilham, R., Larson, K.M., Freymueller, J., 1997. GPS measurements of present day convergence across the Nepal Himalaya. Nature 386, 61–64.

Blaser, L., Krueger, F., Ohrnberger, M., Scherbaum, F., 2010. Scaling relations of earthquake source parameter estimates with special focus on subduction environment. Bull. Seismol. Soc. Am. 100, 2914–2926.

Bollinger, L., Sapkota, S.N., Tapponnier, P., Klinger, Y., Rizza, M., Van der Woerd, J., Tiwari, D.R., Pandey, R., Bitri, A., de Berc, S.B., 2014. Estimating the return times of great Himalayan earthquakes in eastern Nepal: evidence from the Patu and Bardibas strands of the Main Frontal Thrust. J. Geophys. Res., Solid Earth 119, 7123–7163.

Bollinger, L., Tapponnier, P., Sapkota, S.N., Klinger, Y., 2016. Slip deficit in central Nepal: omen for a repeat of the 1344 AD earthquake? Earth Planets Space 68.

Bronk, R., 2009. Bayesian analysis of radiocarbon dates. Radiocarbon 51, 337–360.

Elliott, J.R., Jolivet, R., Gonzalez, P.J., Avouac, J.P., Hollingsworth, J., Searle, M.P., Stevens, V.L., 2016. Himalayan megathrust geometry and relation to topography revealed by the Gorkha earthquake. Nat. Geosci. 9, 174.

Ellis, S., Schreurs, G., Panien, M., 2004. Comparisons between analogue and numerical models of thrust wedge development. J. Struct. Geol. 26, 1659–1675.

Hayes, G.P., Briggs, R.W., Barnhart, W.D., Yeck, W.L., McNamara, D.E., Wald, D.J., Nealy, J.L., Benz, H.M., Gold, R.D., Jaiswal, K.S., Marano, K., Earle, P.S., Hearne, M.G., Smoczyk, G.M., Wald, L.A., Samsonov, S.V., 2015. Rapid Characterization of the 2015 M-w 7.8 Gorkha, Nepal, earthquake sequence and its seismotectonic context. Seismol. Res. Lett. 86, 1557–1567.

Hossler, T., Bollinger, L., Sapkota, S.N., Lave, J., Gupta, H.K., Kandel, T.P., 2016. Surface ruptures of large Himalayan earthquakes in western Nepal: evidence along a reactivated strand of the Main Boundary Thrust. Earth Planet. Sci. Lett. 434, 187–196.

Hough, S.E., Bilham, R., 2008. Site response of the Ganges basin inferred from re-evaluated macroseismic, observations from the 1897 Shillong, 1905 Kangra, and 1934 Nepal earthquakes. J. Earth Syst. Sci. 117, 773–782.

Jackson, D., 2002. The great western-Himalayan earthquake of 1505: a rupture of the central Himalayan Gap? Tibet, past and present: Tibetan studies 1. In: Proceedings of the Ninth Seminar of the International Association for Tibetan Studies. Leiden, Netherlands, pp. 147–158.

Kumar, S., Wesnousky, S.G., Jayangondaperumal, R., Nakata, T., Kumahara, Y., Singh, V., 2008. Paleoseismological evidence of surface faulting along the northeastern Himalayan front, India. Himal. Geol. 29, 46.

Kumar, S., Wesnousky, S.G., Jayangondaperumal, R., Nakata, T., Kumahara, Y., Singh, V., 2010. Paleoseismological evidence of surface faulting along the northeastern Himalayan front, India: timing, size, and spatial extent of great earthquakes. J. Geophys. Res., Solid Earth 115.

Kumar, S., Wesnousky, S.G., Rockwell, T.K., Briggs, R.W., Thakur, V.C., Jayangondaperumal, R., 2006. Paleoseismic evidence of great surface rupture earthquakes along the Indian Himalaya. J. Geophys. Res., Solid Earth 111.

Lave, J., Avouac, J.P., 2001. Fluvial incision and tectonic uplift across the Himalayas of central Nepal. J. Geophys. Res., Solid Earth 106, 26561–26591.

Lave, J., Yule, D., Sapkota, S.N., Basant, K., Madden, C., Attal, M., Pandey, R., 2005. Evidence for a Great Medieval Earthquake (∼1100 A.D.) in the Central Himalayas, Nepal. Science 307, 1302–1305.

Leonard, M., 2010. Earthquake fault scaling: self-consistent relating of rupture length, width, average displacement, and moment release. Bull. Seismol. Soc. Am. 100, 1971–1988.

Leonard, M., 2014. Self-consistent earthquake fault-scaling relations: update and extension to stable continental strike-slip faults. Bull. Seismol. Soc. Am. 104, 2953–2965.

Molnar, P., Pandey, M.R., 1989. Rupture zones of great earthquakes in the Himalaya region. Earth Planet. Sci. 98, 61–70.

Mugnier, J.L., Huyghe, P., Gajurel, A.P., Becel, D., 2005. Frontal and piggy-back seismic ruptures in the external thrust belt of Western Nepal. J. Asian Earth Sci. 25, 707–717.

Murphy, M.A., Taylor, M.H., Gosse, J., Silver, C.R.P., Whipp, D.M., Beaumont, C., 2014. Limit of strain partitioning in the Himalaya marked by large earthquakes in western Nepal. Nat. Geosci. 7, 38–42.

Nakata, T., Upreti, B.N., Kumahara, Y., Yagi, H., Okumura, K., Rockwell, T.K., Virdi, N.S., 1998. First successful paleoseismic trench study on active faults in the Himalaya. Eos 79, F615.

NCEDC, 2014. ANSS composite catalog. Northern California Earthquake Data Center, UC Berkeley Seismological Laboratory Data set. http://dx.doi.org/10.7932/NCEDC.

Pandey, M.R., Molnar, P., 1988. The distribution of intensity of the Bihar–Nepal earthquake of 15 January 1934 and bounds on the extent of the rupture zone. J. Nepal Geol. Soc. 5, 22–44.

Pant, M.R., 2002. A step towards a historical seismicity of Nepal. Adarsa, 29–60.

Reimer, P.J., Bard, E., Bayliss, A., Beck, J.W., Blackwell, P.G., Ramsey, C.B., Buck, C.E., Cheng, H., Edwards, R.L., Friedrich, M., Grootes, P.M., Guilderson, T.P., Haflidason, H., Hajdas, I., Hatte, C., Heaton, T.J., Hoffmann, D.L., Hogg, A.G., Hughen, K.A., Kaiser, K.F., Kromer, B., Manning, S.W., Niu, M., Reimer, R.W., Richards, D.A., Scott, E.M., Southon, J.R., Staff, R.A., Turney, C.S.M., van der Plicht, J., 2013. INTCAL13 and marine13 radiocarbon age calibration curves 0–50,000 years cal BP. Radiocarbon 55, 1869–1887.

Sapkota, S.N., Bollinger, L., Klinger, Y., Tapponnier, P., Gaudemer, Y., Tiwari, D., 2013. Primary surface ruptures of the great Himalayan earthquakes in 1934 and 1255. Nat. Geosci. 6, 71–76.

Strasser, F.O., Arango, M.C., Bommer, J.J., 2010. Scaling of the source dimensions of interface and intraslab subduction-zone earthquakes with moment magnitude. Seismol. Res. Lett. 81, 941–950.

Upreti, B.N., Nakata, T., Kumahara, Y., Yagi, H., Okumura, K., Rockwell, T.K., Virdi, N.S., 2000. The latest active faulting in Southeast Nepal. In: Proceedings of the Hokudan International Symposium and School in Active Faulting. Awaji Island, Hyogo, Japan, pp. 533–536.

Yule, D., Dawson, S., Lave, J., Sapota, S.N., Tiwari, D.R., 2006. Possible evidence for surface rupture of the Main Frontal Thrust during the great 1505 Himalayan earthquake, far-western Nepal. Eos.