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# Slip deficit in central Nepal: omen for a repeat of the 1344 AD earthquake?

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## Abstract

In 1255, 1344, and 1408 AD, then again in 1833, 1934, and 2015, large earthquakes, devastated Kathmandu. The 1255 and 1934 surface ruptures have been identified east of the city, along comparable segments of the Main Frontal Thrust (MFT). Whether the other two pairs of events were similar is unclear. Taking into account charcoal's age inheritance, we revisit the timing of terrace offsets at key sites to compare them with the seismic record since 1200 AD. The location, extent, and moment of the 1833 and 2015 events imply that they released only a small part of the regional slip deficit on a deep thrust segment that stopped north of the Siwaliks. By contrast, the 1344 or 1408 AD earthquake may have ruptured the MFT up to the surface in central Nepal between Kathmandu and Pokhara, east of the surface trace of the great 1505 AD earthquake which affected western Nepal. If so, the whole megathrust system in Nepal broke in a sequence of earthquakes that lasted less than three centuries, with ruptures that propagated up to the surface from east to west. Today's situation in the Himalayan seismic sequence might be close to that of the fourteenth century.

**Keywords:** Himalayan earthquakes, Seismic cycle, Paleoseismology, Inbuilt age

## Introduction

The deadly Mw 7.8 Gorkha earthquake of April 25, 2015, is the latest of a long series of earthquakes which has affected Kathmandu valley, partially releasing the strain accumulated along the Main Himalayan Thrust fault (e.g., Ader et al., 2012; Stevens and Avouac, 2015; Grandin et al., 2015; Kobayashi et al., 2015). Determining whether the interseismic geodetic strain accumulation, measured during the last decades and extrapolated to centuries, is balanced by the strain released during the seismic events since medieval times is essential to re-assess the seismic hazard in central Nepal following the 2015 earthquake.

Indeed, along the Himalayan range, the apparent absence of regularly recurring events has led some to infer that great earthquakes could occur anytime anywhere along the Main Frontal Thrust (MFT) (Mugnier et al., 2013; Rajendran et al., 2015). Conversely, recent paleoseismological work in eastern Nepal (Sapkota et al., 2013; Bollinger et al., 2014) suggests that both recurrence periods and coseismic displacements are more regular than previously thought. Along the MFT, in the Bardibas area for instance (Fig. 1), in the past 4500 years, 6 to 7 events, 870 ± 350 years apart, each accommodating 12 to 17.5 m of slip up to the surface (Bollinger et al., 2014), released most of the 18-mm/year interseismic convergence estimated from GPS/InSAR measurements (Ader et al., 2012; Grandin et al., 2012).

To clarify this critical issue, we revisit the distribution of large events along the Nepalese Himalayas by comparing historical catalogues to available geomorphological/paleoseismological data. We then estimate the seismic moment deficits accumulated and released in eastern/central Nepal from ≈1200 AD to 2015. The results show that both Kathmandu and Pokhara, the two largest cities of Nepal, may now be exposed to earthquakes rupturing the MFT, as it likely last did in medieval times.

### Historical chronicles of large earthquakes

Assessing the seismic moment distribution on the MFT requires access to the most complete historical earthquake catalogues and to reliable estimates of slip rates and seismic coupling. The Himalayan history is rich with a remarkable succession of destructive shocks

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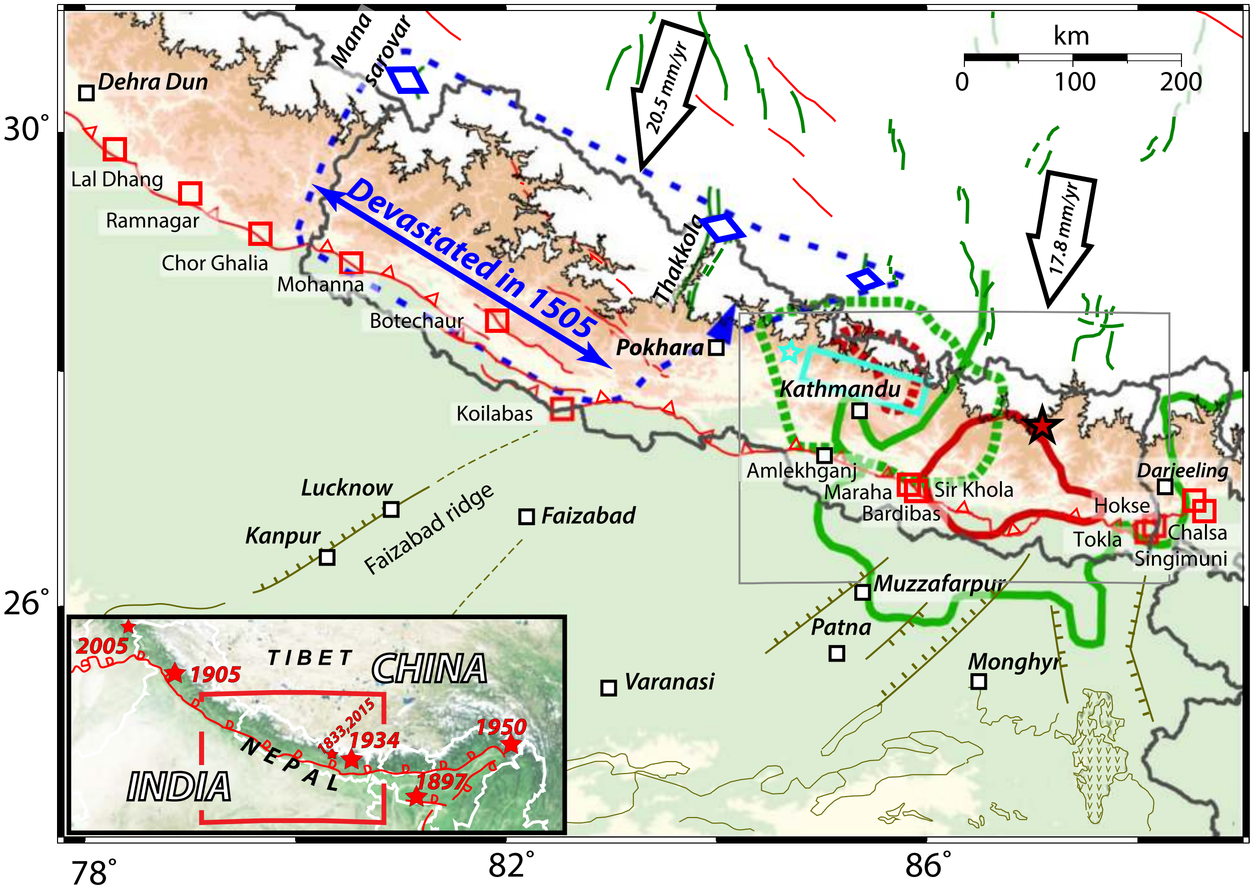

**Fig. 1** Macroseismic effects of large Nepalese earthquakes. *Green* and *red*, *solid* and *dashed lines* are VII and VIII isoseists of the 1934 and 1833 AD events, respectively (Sapkota, 2011). *Dark blue dashed line* delineates reported strong effects of the great 1505 event; *largest blue diamonds* and *arrow* reflect the areas of devastation (Jackson, 2002). *Dark blue triangle* represents coeval debris flows in Pokhara basin (Fort, 1987). *Light blue star* and *rectangle* are, respectively, the epicenter and the main segment ruptured during the April 25, 2015, event. *Red squares* are paleoseismological trenches and morphotectonic sites with dated ruptures (see text for references). *Open arrows* reflect shortening rates across the Himalayan range (Ader et al., 2012). *White limit* is the 3500-m elevation contour

contributing to most of the seismic moment release. It includes four large instrumental events (Shillong, 1897; Kangra, 1905; Bihar–Nepal, 1934; Assam, 1950). Older historical earthquakes, chronicled at the time, were later compiled from different sources and with different approaches (Oldham, 1883; Iyengar et al., 1999; Pant, 2002; Martin and Szeliga, 2010). Studies of the corresponding macroseismic fields have yielded first-order information on their locations, sizes, and magnitudes (Ambraseys and Douglas, 2004; Szeliga et al., 2010), but nearly all of that information concerns events in the last two centuries, a short length of time compared to the return periods of the largest earthquakes (Bollinger et al., 2014).

Reports of early events are rare, with very few studies digging into the old manuscripts to challenge such lack of information. Among those rare studies, Iyengar et al. (1999) returned to more than 200 ancient primary sources, including holy texts and a large body of early chronicles. Some mention earthquakes, although without enough information on location.

Challenging this lack of information, Pant (2002) exploited local Nepalese chronicles, complementing an earlier study (Rana, 1936). He paid special attention to a genealogical record of Nepalese monarchs (Gopalraj Vamshavali) composed of two chronicles in Sanskrit and Newari (Kathmandu vernacular), compiled in the Sthiti Malla period (latest fourteenth century). That record covers the interval 1057–1389 AD and is deemed reliable by historians, particularly in the thirteenth and fourteenth centuries (Regmi, 1969), when the Malla Kings ruled from Kathmandu, already the political center of Nepal. Three large earthquakes are mentioned in 1223, 1255, and 1344 AD (Pant, 2002). The 1223 event, earliest known from a primary source, occurred on December 24, but its description remains indecipherable due to defaced letters and words.

By contrast, the chronicle of the next largest event, on June 7, 1255, specifies that temples and houses collapsed, killing one third of the inhabitants, including the king Abhaya Malladeva. The survivors left the country "within a fortnight and a month" (Pant, 2002). The Sanskrit text adds that aftershocks were felt during 4 months, strengthening the inference that this event was a great earthquake. Another violent earthquake occurred on midday, September 14, 1344, according to the Newari chronicle (Pant, 2002). This earthquake fatally wounded King Ari Malla who died the next day. Although the 1255 and 1344 earthquakes were very destructive, they are documented only in the Kathmandu valley. No records of shaking or destruction in regions around Nepal or in the far field have been found so far. Hence, even though the sources of these two events cannot be far from Kathmandu, the determination of a rupture extent requires paleoseismological evidence. Another earthquake is reported a few decades later in 1408 AD, during the reign of Syamasimha (Rana, 1936; which does not mention his sources, most probably Wright Vamshavalis cited in Regmi, 1969). However, unlike the previous events, no historical sources dated from that period were discovered. Indeed, the earliest source to our knowledge for that earthquake is secondary, dating from the nineteenth century, and looks questionable to historians (Lévi, 1905, Petech, 1958). First, the date reported for that earthquake (twelfth of Bhadra sudi) curiously corresponds to the date of the 1833 earthquake. Second, the chronology of the kings in the Vamshavali consulted is not concordant with the Ming Annals (Petech, 1958; Regmi, 1969). Further note that there were diplomatic relations between China and Nepal, reported in the annals of the Ming between 1387 and 1418. In 1409, a Nepalese embassy went to China with a tribute, but nothing was said on the earthquake according to Petech (1958). Whether the sources reported a true earthquake at a wrong date due to calendric problems must still be clarified by historians.

The next great earthquake known from historical sources, the June 6, 1505, event, is significantly better documented (Jackson, 2002; Ambraseys and Jackson, 2003). Although there is no mention of that large event in Kathmandu, as documents for that period are scanty, eyewitness reports in southwestern Tibet imply that it affected a ~600-km-long stretch of the high Himalayan range. The autobiography of Btsun-Pa-Chos-legs reports the earthquake effects in Mangyul Gungthang (Jackson, 2002), a Tibetan kingdom north of Kathmandu (Fig. 1). That region, however, was less severely hit than areas between Glo-bo (Thakkola-Mustang) and Guge-Purang (Manasarovar) to the west (Fig. 1). Moreover, far western Nepalese territories south of that region were devastated. That this event was a great earthquake is corroborated by primary testimonies from Mustang and India (Bilham et al., 1995; Iyengar et al., 1999; Jackson, 2002; Ambraseys and Jackson, 2003).

Another earthquake is reported as destructive of "many buildings" (Rana, 1936) during the reign of Sri Niwas Malla, but no primary sources are cited. The event is said to have occurred about 5 months after the observation of the Great Comet of 1680 in Nepal, on Jestha Sukla Saptami (May 15?). The magnitudes of this event and of seismic events that necessarily happened between the late sixteenth and the eighteenth centuries are likely smaller than 7.5 because they occurred during the chronicle-rich Mughal period in northern India and would have been reported if felt over significantly large areas.

The nineteenth century events are better known. They include the September 1, 1803, Kumaon earthquake west of the termination of the great 1505 event (Bilham et al., 1995; Rajendran et al., 2013). A lesser shock, on midday June 4, 1808, was felt in Faizabad and Dinagepore-Bhagalpur and affected Kathmandu (Oldham, 1883; Pant, 2002; Martin and Szeliga, 2010). Although some inhabitants perished due to house collapse, the effects were much less than these during the following large earthquake in 1833. For example, unlike in 1833, the several stories high Taleju and Pashupati pagodas resisted damage.

The August 26, 1833, earthquake, only 25 years later, which severely damaged Kathmandu (Campbell, 1833; Oldham, 1883; Bilham, 1995), was felt as far as Calcutta and impacted the Ganges basin. Felt aftershocks were notable for 3 months, attesting to the large magnitude, possibly similar to the Mw 7.7 assigned by Ambraseys and Douglas (2004) and most probably greater than 7.3 ± 0.1 (Szeliga et al., 2010), given the similarities in terms of intensity distribution between the 1833 and 2015 AD earthquakes (Martin et al., 2015). It thus probably ruptured a segment of MHT similar to that which ruptured in 2015, though less to the west in the Gorkha region (Martin et al., 2015) with a macroseismic epicenter probably located farther east, north-northeast of Kathmandu (Oldham, 1883; Szeliga et al., 2010) (Fig. 1). On May 23, 1866, an event with a size intermediate between those in 1808 and 1833, given its effects in the Ganges basin, shook again the area northeast of Kathmandu (Szeliga et al., 2010).

The penultimate event to affect Kathmandu and much of eastern Nepal was the great January 15, 1934, "Bihar–Nepal" earthquake, extensively described (Rana, 1936; Roy, 1939; Pandey and Molnar, 1988; Sapkota et al., 2013; Bollinger et al., 2014). This event has been assigned a magnitude $Mw_{\text{macroseismic}} = 8.1$ (Ambraseys and Douglas, 2004) and $Mw_{\text{instrumental}}$ 8.4 (Molnar and Deng, 1984). Beyond macroseismic reports, recent fieldwork shows that the surface break of that event likely extended from at least Dharan in the east to the Mahara Khola area in the west (Sapkota et al., 2013) (Figs. 1, 2, and 3).

The April 25, 2015, Mw 7.8 earthquake followed by that of the May 12 Mw 7.3 event farther east, ruptured a segment of the Main Himalayan Thrust fault under the rim of the High Himalayas releasing decades of seismic slip accumulated at about 2 cm/year along the downdip end of the locked portion of the fault that extends southward from the front of the high range to the most frontal part of the Siwalik range (e.g., Ader et al., 2012; Grandin et al., 2012). Although the earthquake severely affected the valley, the corresponding rupture did not extended south of Kathmandu past the Mahabharat to the MFT, but stopped halfway instead (Avouac et al., 2015; Galetzka et al., 2015; Grandin et al., 2015; Kobayashi et al., 2015). Comparison of macroseismic data related to the Gorkha earthquake with data from previous events indicates that the rupture remained limited to an area roughly similar to the area shaken by the 1833 AD earthquake (Martin et al., 2015) and ended eastward in the area that was already broken during the 1934 AD earthquake (Adhikari et al., 2015).

Overall, despite the presence of a probable intermediate-sized earthquake in the seventeenth century, the timing structure of the reported earthquakes appears remarkably clustered in the thirteenth to fifteenth (1223–1255–1344–1408) and the nineteenth to twenty-first centuries (1833–1866–1934–2015). This clustering is

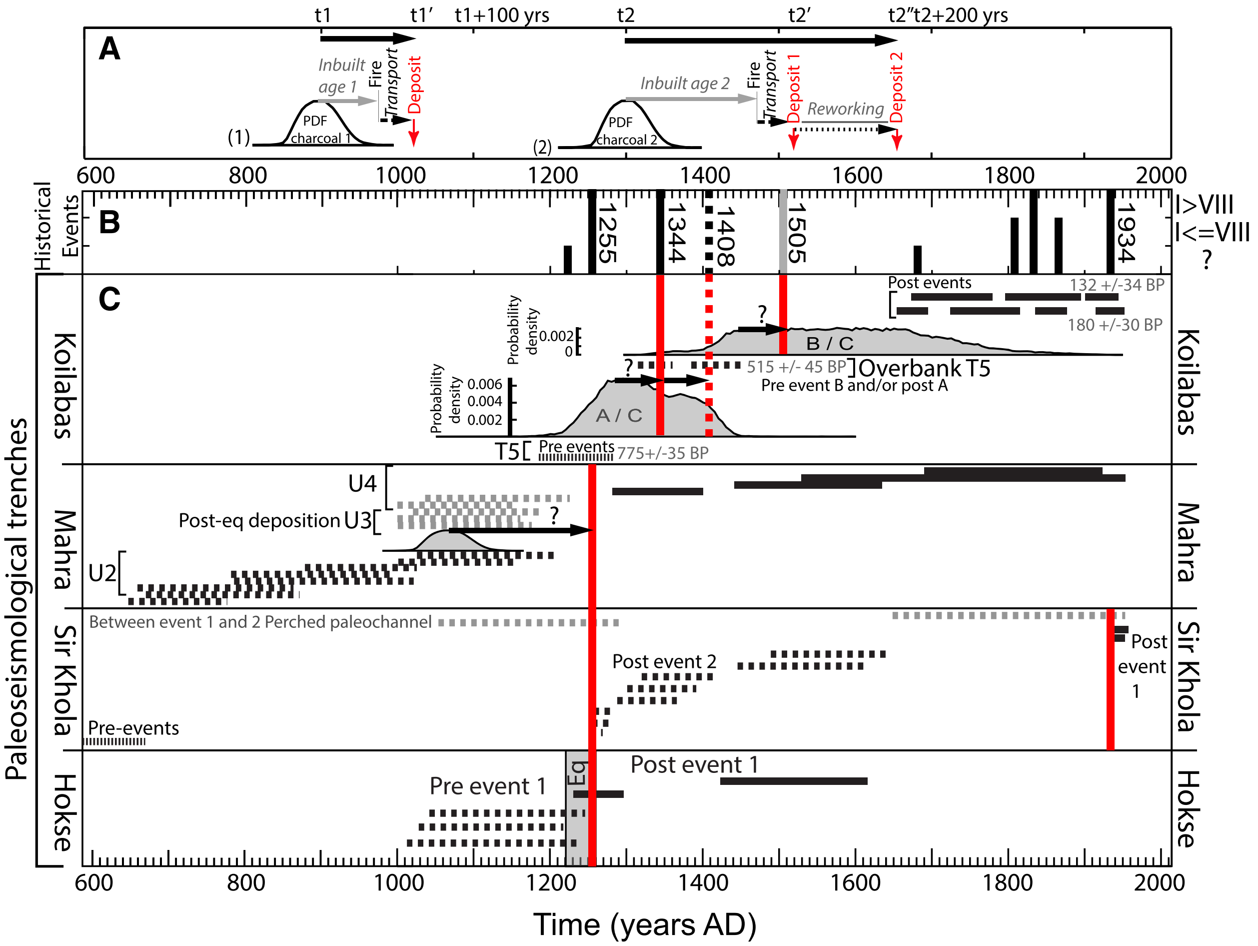

**Fig. 2** Detrital charcoal radiocarbon ages and great earthquakes. **a** Relationships between detrital charcoal AMS $^{14}$C dates and actual deposition ages. (*1*) Short time-lag (decades), as in Sir Khola charcoals. (*2*) Longer lag, due to long-lived wood species, long residence time, and reworking. *Horizontal black arrows* show plausible total time-lags, including inbuilt ages, transport, and eventual reworking. **b** Historical earthquake macroseismic intensities in Kathmandu (*black bars*) and western Nepal (*gray bar*). **c** $^{14}$C ages of the last surface ruptures at Koilabas, Mahara Khola, Sir Khola, and Hokse (Mugnier et al., 2011; Lavé et al., 2005; Sapkota et al., 2013; Bollinger et al., 2014; Upreti et al., 2000). *Continuous*, *dashed*, and *short dashed lines* refer to detrital charcoal deposited post-last, pre-last, and pre-penultimate identified events, respectively. *Ages in gray* are uncalibrated ages mentioned in the text. Calculated probability density spectra for earthquakes (*gray*) assume no inbuilt age and transport. *Horizontal black arrows* show plausible time-lag taken into account as detailed in **a**

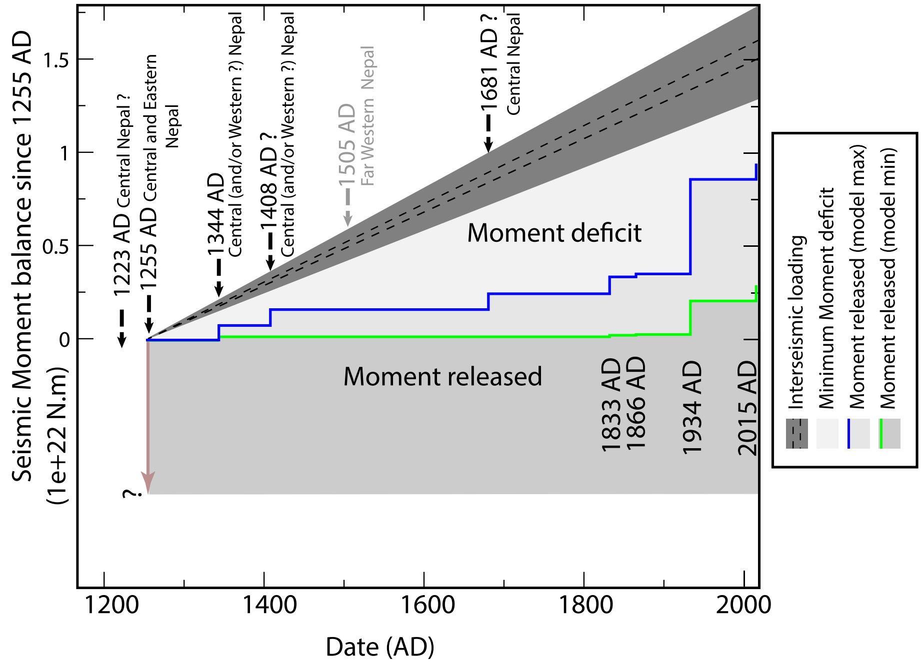

**Fig. 3** Accumulated moment deficit and co-seismic moment released due to major earthquakes from 1255 to 2015 along the 400-km-long eastern stretch of the Main Frontal Thrust, between Kathmandu klippe and eastern India/Nepal border (Fig. 4). Accumulated moment deficit rates and uncertainties (*dark gray*) are predicted from local seismic coupling distribution (Ader et al., 2012). *Upper* and *lower dashed lines* correspond to the seismic moment accumulated on a MHT fully locked downdip over 80 km, accommodating 18.5 and 17.5 mm/year shortening, respectively. Moments released in 1833, 1866, 1934, and 2015 earthquakes are derived from published minimum (*green*) and maximum (*blue*) moment magnitude estimates for these events. Periods 1344 and 1408 AD were assigned a moment release that is identical to the 1833 AD (*green*) and 2015 AD (*blue*) earthquakes, which is probably a lower estimate considering their macroseismic effect in Kathmandu valley and the possible surface rupture. No post-seismic strain releases were taken into account (see the text for details)

probably not a bias of the variable completeness of the historical catalogues. Indeed, a Mw > 8 event, potentially rupturing the MFT, occurring during or after the chronicle-rich Mughal period, would have been reported in northern India.

The conflict between the historical catalogue and earthquake surface ruptures is an opportunity to refine the date of occurrence of these geological events. This association is necessary to test whether the clustering in time is also associated with a particular earthquake sequence.

## Links with paleoseismology and morpho-tectonics

Historical chronicles are now complemented by growing paleoseismic and geomorphic evidence of ancient earthquakes along the main active fault segments along strike the Himalayas (Nakata, 1989; Nakata et al., 1998; Upreti et al., 2000; Lavé et al., 2005; Mugnier et al., 2005; 2011, 2013; Kumar et al., 2006; Yule et al., 2007; Sapkota et al., 2013; Kumahara and Jayangondaperumal, 2013; Bollinger et al., 2014; Berthet et al., 2014; Murphy et al., 2014; Rajendran et al., 2015; Malik et al., 2015) (Fig. 1). It is thus possible to test the compatibility between these two independent datasets at several key sites (Fig. 2). Because paleoseismic radiocarbon dates come mostly from detrital charcoal, one should expect them to be older than the actual charcoal deposition ages by the age of the wood at the time of burning (the charcoal's "inbuilt age") (Gavin, 2001) and a transport time (Fig. 2a). The $^{14}$C age of a collected charcoal represents the time since carbon was removed from the atmosphere, being then incorporated into the living plant (here wood) by photosynthesis. Commonly, the wood was already decades old or more when burned by fire. The charcoal was subsequently transported until it was deposited in the alluvial sediments from which it was later collected. While we know of no systematic study of "inbuilt ages" in the Himalayas, the very young charcoals Sapkota et al. found along the Siwalik front imply inbuilt ages as small as a few decades (e.g., 24–50 years at Sir Khola (Sapkota et al., 2013; Bollinger et al., 2014)). This, however, does not exclude larger values, from longer-lived tree species and/or due to longer residence times.

Across the Mohana Khola terraces (Fig. 1), where the westernmost paleoseismic trench was excavated in Nepal, the 7.5-m-high, fifteenth to sixteenth century thrust break found by Yule et al. (2007) is readily attributed to the great June 1505 event.

Farther east, Nakata et al. (1984) identified an active strand of the Main Boundary Thrust. This fault segment offsets the alluvial terraces of the Bheri River near the village of Bhotechaur. Hossler et al. (2016) demonstrated that the last earthquake accommodated more than 8 m of thrusting after 640 ± 30 BP in that location. This date corresponds to the age of a detrital charcoal sampled in a pebble unit that is overthrusted by a thick pile of older warped-and-folded alluvial material within an 8-m-high fault scarp. The local thrust system branches on an interseismically locked segment of the Main Himalayan Thrust (Bollinger et al. 2014; Ader et al., 2012; Stevens and Avouac, 2015) in the hanging wall of the MFT, suggesting that this rupture happened during a large megathrust earthquake that ruptured the detachment and the outer wedge faults (MFT and MBT). The site being located in the area devastated in 1505 AD and the post-640 BP age of the earthquake are complementary arguments leading to associate that rupture to the June 1505 earthquake or one of its aftershocks.

Near Koilabas (Fig. 1), 230 km farther east, Mugnier et al. (2005) described the 6-m-high vertical offset of an upper terrace level across the MFT. A detrital charcoal age (775 ± 35 BP) in the thrust footwall implied that the last earthquake is post-dated 1225–1271 AD (calibrated age (Reimer et al., 2009)) (Fig. 2b). Overbank deposits dated at 515 ± 75 BP suggest that the high terrace was abandoned after 1332–1442 AD. A younger terrace unconformably overlies the MFT. Two charcoal ages (132 ± 34 and 180 ± 30 BP) sampled in this terrace, deposited 9 m below the former, indicate that the last surface rupture predated 1666–1953 AD (Fig. 2b). Mugnier et al. (2011) attributed much of the higher terrace offset to the great 1255 AD earthquake. However, other interpretations are equally or more plausible. The abandonment of the youngest terrace overlying the MFT, and of those deposited above since ≈1300 AD, might just result from lateral avulsion and/or climate change-driven incision. Alternative simple scenarios might have involved either one earthquake post- or pre-dating the top of the overbank deposits (models A and B, respectively, Fig. 2b) or two events pre- and post-dating these deposits (model C in Fig. 2b—Koilabas). We tested such scenarios by introducing the corresponding a priori stratigraphic information in Oxcal (Bronk Ramsey, 2008), a radiocarbon calibration program based on Bayesian statistics allowing for the incorporation of stratigraphic or historical constraints, among others, to reflect prior understanding by field geologists or historians. We first assumed negligible "inbuilt ages." The results show that the great 1505 AD earthquake is then a plausible candidate (scenario B/C, Fig. 2b, consistent with a time interval for the earthquake occurrence of 1383–1806 AD at the 95.4 % confidence level), while the 1344 AD earthquake is the most likely event to have produced a surface rupture predating the overbank deposit (A/C). The Oxcal tests thus imply that the 1255 earthquake is the least likely event at Koilabas, although, from the probability density functions alone (PDF, Fig. 2b), it is only slightly less probable. However, only a few decades of inbuilt age is enough to significantly lower such probability and exclude 1255 (Fig. 2a, b). If due to just one of the 1344 or 1505 events, the 6-m vertical offset of the uppermost terrace would imply seismic slip amounts of 18 to 8 m, assuming thrust dips of 20° to 45°, respectively.

On the west bank of the Mahara river, 320 km east of Koilabas, trenching across a young fault scarp identified by Delcailleau (1992), exposed evidence of a great (17 m of slip) medieval (≈1100 AD) earthquake (Lavé et al., 2005). That there is no report of that event in Indian or Nepalese chronicles, however, raises doubt about its age, even though this epoch corresponds to a "dark period" of time that remains obscure to historians. A later date is in fact likely. For a start, inbuilt charcoal ages of ≈150 years from common, fairly long-lived trees (e.g., Sal) would suffice to make the great well-recorded 1255 AD event a plausible candidate (Fig. 2). Inherited charcoal reworked in the scarp colluvial wedge could further bias the model ages. Moreover, as it breached and incised the scarp soon after the earthquake, the Mahara River likely deposited hanging wall sediments on the footwall. A date younger than 1100 AD is corroborated by the charcoal age distribution, which is similar in faulted unit U2 (see units in Fig. 2b—Mahara) and overlying unfaulted fluvial/colluvial unit U3 at the foot of the scarp. Hence, the event would postdate the U3 charcoal and predate the top U4 units, consistent with the 1255 AD event. Note also that the lack of a 1934 surface rupture here was not inescapably demonstrated: thin deposits capping the near emergent thrusts on the 4-m-high riverbank exposure were not dated.

Only 5 km east of Mahara Khola, the Sir Khola rivercut cliff exposed a post-1660 AD MFT rupture, demonstrated to be that of the great 1934 Bihar–Nepal earthquake (Sapkota et al., 2013) (Fig. 2). Furthermore, a trench excavated 30 m east of that rivercut unearthed the older rupture of the 1255 AD event (Fig. 2; see detrital charcoal ages and corresponding analysis in (Sapkota et al., 2013; Bollinger et al., 2014) for additional clues deduced from an abandoned coeval paleochannel).

Finally, near the eastern border between Nepal and India, ≈210 km farther eastwards, a 3-m-deep trench on the east bank of the Berin river, near Hokse, exhumed surface rupture remnants eroded and overlain by young floodplain deposits (Nakata et al., 1998) (Fig. 1). Basal gravels covered by overbank deposits containing eleventh to thirteenth century detrital charcoals (Fig. 2) were overthrust at a low angle by a wedge of folded sands/gravels. Reconstructing the initial horizontal geometry of the folded sediments implies a >4-m thrust slip during the last exposed event (Upreti et al., 2000). The unfaulted unit above yielded late thirteenth and fifteenth to sixteenth century detrital charcoal ages (Upreti et al., 2000) (Fig. 2), consistent with rupture by the great 1255 earthquake or, less likely because it would require larger inbuilt ages, by the 1344 event. Note that the 1223 event, though felt only far to the west in Kathmandu, cannot be excluded either.

## Seismic rupture scenarios and return time

The consistency between the geomorphic rupture length and the meizoseismal extent of the 1934 earthquake (Sapkota et al., 2013) (Fig. 1) warrants a broader historical comparison between paleo-rupture extents, macroseismic source sizes, coseismic slip estimates, and likely positions of rupture termini or asperities. The homogeneous interseismic coupling along strike the Nepalese MHT (Ader et al., 2012) implies that rupture termini are chiefly controlled by long-term structural features in the footwall and hanging wall. Notably, tectonic structures in the underthrust Indian basement (Fig. 1) clearly impact both the frontal fold geometry and Lesser Himalayan exhumation (Bollinger et al., 2004a; Gahalaut and Kundu, 2012; Godin and Harris, 2014). Also, in the hanging wall, the main South Tibetan grabens (Armijo et al., 1986) coincide with abrupt changes—by a few degrees—of both the convergence azimuth and strike of the MHT (Bollinger et al., 2004b) (Figs. 1 and 3).

Too little is known about the 1223 event to safely locate its source. It is older than most charcoal in the Koilabas and Sir Khola trenches and less probable in Hokse than the 1255 event (Fig. 2). Since it was felt in Kathmandu, however, its source may not have been far from the city.

The lack of evidence, thus far, for a 1934 rupture in Hokse, and the 215 km separating Hokse from the Mahara Khola, suggests that the 1255 earthquake was the larger of the two events (Figs. 2 and 3). The 33 % 1255 fatality rate in Kathmandu, compared to only 1 % in 1934 (Sapkota, 2011), further suggests that the older event reached closer to the city and/or was larger, with a rupture extending well west of Sir Khola.

The 1344 and 1408 events are less probable than that in 1255 in both easternmost Nepal (Hokse) and at Sir Khola, where a post-event 1050–1290 AD paleochannel charcoal (Bollinger et al., 2014) (Fig. 2) would then require significantly larger inbuilt ages (by 89 or 153 years). Such negative evidence, and the absence of a reported 1505 damage in Kathmandu, suggests that at least one of these earthquakes struck a limited area between Pokhara and Kathmandu, west of the Kathmandu klippe, a region then historically quiet for the last 671 or 607 years (Figs. 1 and 3).

The extent of the region devastated in 1505 implies a longer rupture than that of the Mw 8.4, 1934 event. Eastwards, it likely stopped at the Thakkola graben and near Koilabas where the Faizabad basement ridge deflects the MFT and further exhumes the Lesser Himalayas (Figs. 1 and 3), forcing rupture termination over many cycles, as do persistent barriers at subduction zones (Meltzner et al., 2012). Westwards, it extended at least to the Mahakali–Manasarovar/Burang graben limit but may have reached farther, which, allowing for a multi-decadal inbuilt age and/or reworking, could account for the 1209–1430 AD charcoal ages in a unit overlying the MFT near Ramnagar (Kumar et al., 2006; Rajendran et al., 2015).

The 1808 and 1866 events were likely too small to breach the surface. But comparing the ruptures of the larger 1833/2015 and 1255/1934 events is warranted to assess the modern slip deficit in central Nepal.

Here, the long-term slip deficit or moment accumulation rate on the MFT (related to the fault slip rate at depth), which are well resolved within the dense Nepal GPS Geodetic Network (Ader et al., 2012), can be directly assessed, assuming they have remained constant overall with negligible dissipative processes other than earthquakes. We cannot demonstrate that significant aseismic deformation transients never occur at a given time within the seismic cycle. However, the working

**Table 1** Magnitude and afterslip needed in 1833 and 1934 to balance the seismic slip deficit accumulated since the great 1255 AD earthquake

| Earthquake rupture model[a] | Area ruptured in $km^2$ | Magnitude tested[b] | Magnitude needed[c] | Afterslip in %[d] |
|---|---|---|---|---|
| **1833_H1**<br>***Patch 1A*** | **85 × 40** | **7.3–7.7** | 8.0 | 2500–1200 |
| **1833_H2**<br>***Patch 1B*** | **120 × 40** | **7.3–7.7** | 8.1 | 1500–400 |
| **1934_H1**<br>***Patch 2A*** | **143 × 80** | **8.1–8.4** | 8.40 | 170–0 |
| **1934_H2**<br>***Patch 2A + B′*** | **12,500** | **8.1–8.4** | 8.42 | 195–5 |
| **1934_H3**<br>***All patches 2*** | **19,200** | **8.1–8.4** | 8.54 | 360–65 |

The input parameters are in bold

[a] The surfaces ruptured (fault patches 1A–1B for 1833 and 2A–2C′ for 1934) are illustrated on Fig. 4. Patches 1A and 1B correspond, respectively, to ruptures with a lateral extent of 85 km, corresponding to the MSK VIII isoseismal, and ruptures of 120 km

[b] Corresponds to the minimum and maximum magnitudes assigned to each event (see the text for discussion and references)

[c] Corresponds to the magnitude needed at the time of the earthquake to release all the slip deficit on the fault patch since 1255 AD, assuming a patch fully locked during interseismic and the slip deficit of 17.8 mm/year estimated by Ader et al. (2012)

[d] For the need of afterslip in % of the coseismic slip to fully release the slip deficit on the fault patch

hypothesis appears reasonable given that no transient slip event was detected along strike the Himalaya over the 15 years of GPS observations.

We then confront the moment deficit estimated by this approach with the moment released by the largest earthquakes. For each event, we test end-member scenarios, considering the minimum/maximum magnitudes assigned to the events in previous publications as well as rupture lengths, which are assumed to correspond approximately to the MSK VIII isoseismal and defined by additional field constraints when available (Table 1; Fig. 3).

The extent of the 1344 and 1408 AD earthquakes is unknown. We take the maximum 1255 rupture to have extended from Hokse to south of Kathmandu (Fig. 3). We first estimate the co-/post-seismic slip amounts in 1833 and 1934, assuming that both events released all the slip deficits corresponding to their minimum/maximum magnitudes (respectively 7.3/7.7 from Szeliga et al. (2010) and Ambraseys and Douglas (2004), and 8.1/8.4 from Ambraseys and Douglas (2004) and Molnar and Deng (1984). For the 1833 event, whose MMI VIII isoseist is consistent with an 85-km-long rupture (Fig. 4), we test first a model with this lateral rupture extent and an updip extent of 40 km (Rupture model 1833_H1 Table 1, rupturing segment 1B in Fig. 4), this last value being similar to the downdip rupture extent in 2015, a rupture probably controlled by the geometry of the MHT. We also test a longer rupture, 120-km long, centered on the MMI VIII isoseismal, and almost similar to the 2015 earthquake (Rupture model 1833_H2 Table 1, rupturing segment 1B in Fig. 4). However, even the largest magnitudes previously assigned to the 1833 earthquake (Mw = 7.7) would require implausible values of afterslip (Table 1), much greater than those previously reported on continental thrusts (considering 60 %+, after the 2005 Muzaffarabad, surface rupturing west of the Himalayan Thrust event (Jouanne et al., 2011) to be a high end-value).

The largest rupture scenarios for 1833 are thus beyond the uppermost credible limit to account for all the slip deficit accumulated since 1255 AD. However, 182 years after 1833 AD, the seismic slip deficit along its trace is in excess of 3.3 m, considering a seismic slip deficit rate around 18 mm/year (Ader et al., 2012). This corresponds within uncertainties to the slip accommodated in 2015.

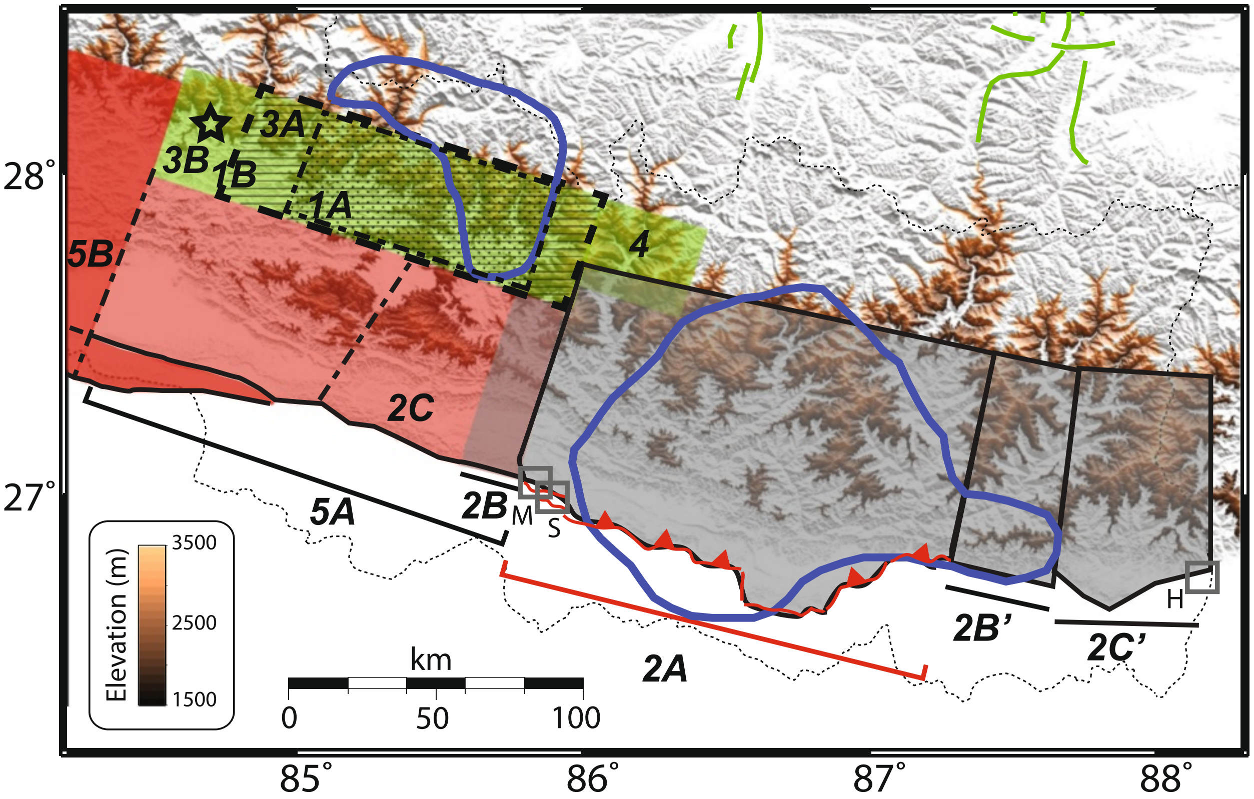

**Fig. 4** Rupture models described in the text and Table 1 for 1833 and 1934 earthquakes. *Green patches 1A–1B* correspond to alternative models of coseismic slip on MHT during the 1833 AD earthquake. *Gray patches* correspond to alternative rupture scenarios during the 1934 AD earthquake. Areas *3* and *4* correspond to the area ruptured, respectively, on April 25 and May 12, 2015. Areas *5A* and *5B* in *red* correspond to the region south and west of Kathmandu where the slip deficit is given to reach the highest values. *M*, *S*, and *H*, respectively, refer to Mahara Khola, Sir Khola, and Hokse paleoseismological sites

Therefore, a repeat of the 2015/1833 earthquakes every ≈200 years may account for the slip deficit along the MHT segment North of Kathmandu that ruptured in 2015. However, all the events known so far from historical sources will be required to balance the slip deficit in the area ruptured in 2015 north of Kathmandu leaving no event, except the great 1934 AD earthquake, potentially associated with events that propagate rupture to the south.

This 1934 event ruptured at least 143 km of the MFT (Sapkota et al., 2013). Using its lower bound magnitude, 172 % of afterslip would be required to fully release the seismic moment deficit since 1255 (Earthquake rupture model 1934_H1, minimum magnitude, Table 1). The upper bound magnitude, by contrast, fits well the seismic slip required (Earthquake rupture model 1934_H1, maximum magnitude, Table 1). However, it remains possible that the great 1934 earthquake broke more than the identified 143-km-long surface rupture, likely at least to the eastern limit of isoseismal VIII and up to the Kathmandu klippe to the west (patches 2B' and 2B respectively, Fig. 4). It might even have extended westwards to Amlekhganj (Fig. 1), complementing at shallow depth the blind 1833 rupture, and eastwards toward Hokse (patches 2C and 2C', respectively, Fig. 4), a place where the 1934 rupture was not seen (Fig. 2). This would increase the rupture length by up to ≈2/3, requiring up to 66 % of afterslip for a Mw = 8.4 event. A rupture propagating further west, under the whole southern extent of the Kathmandu klippe (patch 5A in Fig. 4), appears more unlikely, with a rupture (i) crossing a region less impacted by the 1934 rupture (between isoseists VI

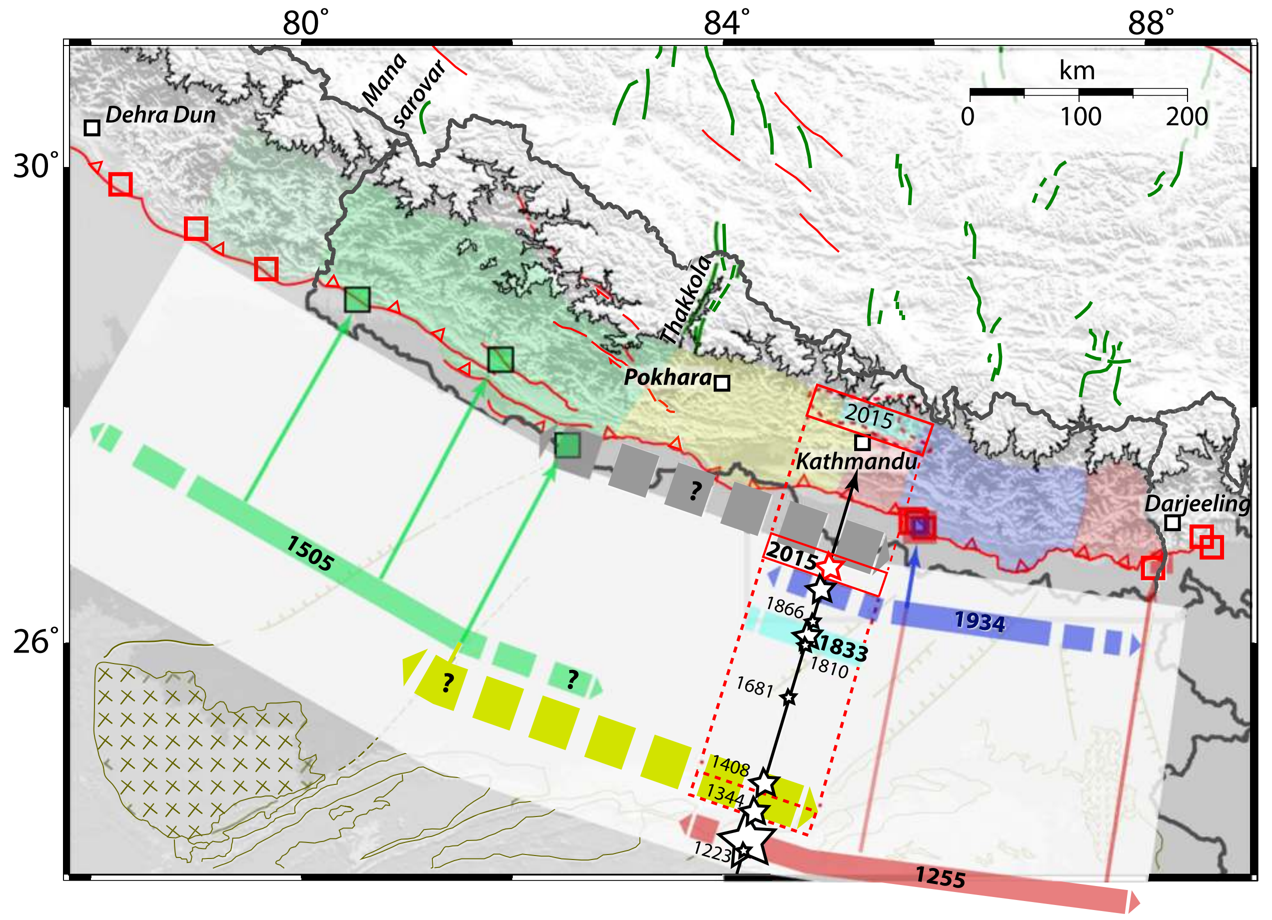

**Fig. 5** Rupture lengths and return times of great Himalayan earthquakes in Nepal since 1223 AD. Rupture extents are consistent with limited macroseismic historical evidence and growing paleoseismological/morphotectonic data, as summarized in the text. A *dashed yellow line* delineates the possible 1344 or 1408 AD rupture trace, assuming that one of these events was a great earthquake rupturing the front all the way to Koilabas (Fig. 2b scenario A/C), while the *thin red box* corresponds to the extent of blind Mw 7+ events similar to that in 2015. Note that rupture termini roughly coincide with the southernmost limits of major southern Tibetan grabens and/or Indian basement highs (Bollinger et al. 2004a, b; Gahalaut and Kundu, 2012; Godin and Harris, 2014). The position in time of the *gray dotted line* within the gap between Kathmandu and Pokhara is model dependent, plotted visually seven centuries after 1344 and 1408 AD, and is consistent with time clustering of earthquakes rather than the full variability of trench-derived return times (850 ± 370 years (Bollinger et al., 2014))

and VII, Fig. 1) and (ii) a scenario requiring even more afterslip.

Despite the hypothesis of a first scenario involving (i) a 1255 AD earthquake rupturing the MFT from west of the Kathmandu klippe to Hokse to the East, (ii) repeating 7.7–7.8 earthquakes in 1344–1408–1681—similar to the 1833/2015 events north of Kathmandu, and (iii) a high-end magnitude of 8.4 for the 1934 event, the values of afterslip required after 1934 to accommodate the slip deficit up to the surface appear larger than everything that have been previously measured on intercontinental megathrusts (Table 1, Fig. 4). This scenario further requires that no large earthquakes rupturing west of Kathmandu, between Pokhara and the Kathmandu klippe, were reported in the chronicles.

Another option is that one of the large medieval earthquakes reported, 1344 or 1408 AD, was significantly larger than 1833 or 2015, releasing more slip deficit at depth, eventually propagating the rupture to the surface. Both events appear consistent with a surface rupture in the region south and west of Kathmandu, given the paucity of the observations (only one trench published from Koilabas).

## Conclusion

The first conclusion to be drawn from this work is that the surface ruptures described along strike of the active frontal thrusts in Nepal can be tied to historical earthquakes, taking into account detrital charcoal age inheritance of a few decades. Another important conclusion is that one of the medieval earthquakes reported in the Kathmandu valley chronicles (1344 AD, or 1408 AD which is more questionable to historians) may have ruptured the Main Frontal Thrust in central-western Nepal within a sequence of three great earthquakes which ruptured the front from eastern to western Nepal between 1255 and 1505 AD. Finally, considering reasonable values of afterslip and negligible potential to episodic aseismic slip transient (two parameters that will probably be better constrained after monitoring the crustal deformation following the 2015 earthquake), whatever the scenario for the medieval earthquakes involved in partial or total rupture of the locked Main Himalayan Thrust in central-western Nepal, and in spite of the occurrence of three large earthquakes since the nineteenth century, another large earthquake is already due. Given the slip deficit accumulated west and south of Kathmandu since 1344 or 1408, and assuming that no significant event have been missed, historically and paleoseismologically, a future event might rupture the thrust segment between Amlekhganj and Koilabas, south of both Kathmandu and Pokhara, an area that probably has remained quiet for the past ≈600 years, a time span only slightly shorter than that between the 1255 and 1934 events, which ruptured eastern Nepal (Figs. 1 and 5). That the arguably still historically uncertain and geologically undefined 1344 and 1408 events occurred only a few decades after the great 1255 earthquake makes the present-day regional threat to central Nepal particularly ominous, considering the apparent longitudinal clustering of the past large earthquakes along the Himalayan front between the mid-thirteenth and early sixteenth centuries and the apparent repetition of broadly similar sequences of large earthquakes (super cycles) observed along plate-boundary faults elsewhere (Stein et al., 1997; Sieh et al., 2008). Studying in greater detail the surface expression of the frontal thrusts south and west of Kathmandu is therefore more urgent than ever.

### Competing interests

The authors declare no competing interests.

### Authors' contributions

LB performed the data analysis and models. All authors contributed to the interpretation. LB and PT wrote the article with assistance from SNS and YK. All authors read and approved the final manuscript.

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