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Palaeoliquefaction evidence of prehistoric large/great earthquakes in North Bihar, India

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The Himalayan arc, 40% of which ruptured in the last two centuries, has witnessed half a dozen large to great earthquakes including the 1833 and 1934 Bihar–Nepal earthquakes. This paper, based on palaeoliquefaction studies in the meizoseismal area of the 1934 earthquake, provides evidence for two prehistoric seismic events dated to have occurred: (i) during 1700 to 5300 years BP and (ii) earlier than 25,000 years BP, besides the well documented 1934 and 1833 seismic events. Thus the findings suggest that the study area has been continuously seismically active. However, the limited data presently precludes estimation of recurrence period of devastating earthquakes in this area.

DURING the past two centuries, nearly half of the Himalayan arc has ruptured in half a dozen large to great earthquakes. These events have only partially released the strain out of the total slip potential of the Himalayan arc due to collision of the Indian and the Eurasian plates[1]. Based on the estimated slip potential given by Bilham *et al.*[1], one or more large/great earthquakes may be overdue in a large part of the Himalaya. Therefore, it is of utmost importance to obtain geological evidence of earthquake recurrence at different source regions in the Himalaya. Due to lack of surface exposure of the causative faults, direct dating of these earthquakes is not possible. Paleoseismological studies[2,3] involving the dating constraints on the resultant secondary coseismic off fault effects like liquefaction[4,5] and soft sediment deformation features have been of help in providing evidence of large/great palaeo-earthquakes as well as establishing their recurrence period[6,7]. In the Shillong Plateau, located south of the eastern Himalayan segment in India, Sukhija *et al.*[8,9] have estimated a recurrence period of 400–600 years for major/great earthquakes based on the palaeoliquefaction evidences and radiocarbon dating. The objective of the present paper is to provide geological evidence of large/great earthquakes in the epicentral area of the great 1934 earthquake based on the dating of the seismically-induced liquefaction and soft sedimentary deformation features.

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The area under the present study experienced major earthquakes during 1833 (ref. 10) ($M = 7.7 \pm 0.2$) and 1934 ($M = 8.3$). The 1833 event had shaken almost entire Northern India/Nepal (~ 1 million sq km area) with intensity (Mercalli scale) reaching up to X near Kathmandu (Nepal), Monghyr (Bihar) and some parts of southern Tibet[10]. Though there are differing views about the epicentres of 1833 and 1934 earthquakes, the general perception is that these are located in the Himalaya about 180 km east[11] and ~ 80 km north[10] of Kathmandu (Nepal) for the 1934 and 1833 seismic events respectively. During the 1934 great earthquake, extensive slumping had taken place and the slump belt was well defined covering an area of 12,200 km^2 (ref. 12) (Figure 1).

Almost entire North Bihar plains are covered by the Gangetic alluvium of the Quaternary age, comprising several hundred meters of unconsolidated sediments. Geophysical surveys and selective test drilling by the Oil and Natural Gas Commission (ONGC) indicate that in North Bihar the alluvium is around 300–400 m thick and is underlain by the Siwalik sediments[13]. Most of the stream courses in the area show: (i) sharp knee bends with linear alignment, (ii) shifting of their courses, and (iii) entirely abandoning their courses. The major rivers show directionality in shifting, e.g. Kosi and Bhagmati are shifting towards west. Thus, the above geomorphologic features possibly indicate basin floor upwarping and sinking in particular blocks[13,14]. Therefore, the local surficial deposits of unconsolidated alluvium may contain evidence for neotectonic activity and fossil seismicity in this region.

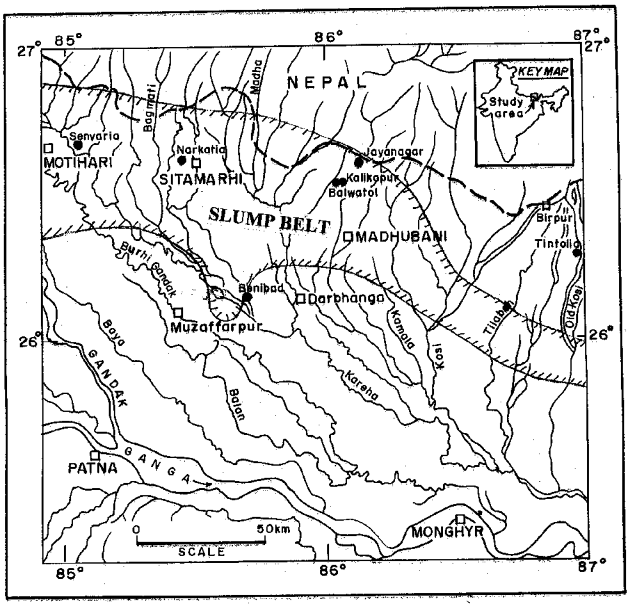

Figure 1. The area under palaeoseismological investigations in a part of meizoseismal area of 1934 Bihar–Nepal earthquake is characterized by intensive drainage system. Hatched portion shows slump belt[12] covering an area of 12,200 km^2. Westward shifting of Kosi river course is evident from the positions of old Kosi in the east and present Kosi in the west. The study sites for palaeoseismic evidences are shown by dark circles (•) and district headquarters are denoted by squares (□).

We dug trenches in the Holocene sedimentary strata to locate liquefaction/deformation features. The features identified in the trenches were logged, and the organic material present in the host strata and in the strata subsequently deposited just above the features was collected for dating. Radiocarbon dates from the host strata provide lower bound (maximum age) and the dates of samples collected from the strata just above the feature provide upper bound (minimum age) of that feature. The detailed procedure constraining the timing of the causative seismic events is described in ref. 8.

We made extensive field surveys along all the major rivers/streams and uplands covering over the floodplains of the Gandak, Burhi (Great) Gandak, Kamla, Bagmati, Bhuti Balan, and Kosi rivers of North Bihar, and along the river Ganga between Patna and Monghyr (Figure 1). Though the historical earthquakes of 1934 and 1988 in this area are reported to have produced extensive liquefaction features[12,15], we could locate only a few of them during our investigations. This is understandable in view of the frequent floods in the region, which might have washed away the liquefaction/deformation features formed during earthquakes. Hence in our subsequent field campaigns we concentrated on the elevated mainland parts, possibly unaffected by floods, and could locate liquefaction features in the form of sand dykes at sites: Kalikapur (Madhubani), Balwatol (Madhubani), Benibad (Muzaffarpur), Senwaria (East Champaran), Narkatia (Sitamarhi) and Tintolia (Supaul) districts of North Bihar (Figure 1). Investigations of these geological signatures at different sites are described here.

In a 10 m long trench (Figure 2, restricted only to 2 m) along the road at village Narkatia, ~ 12 km west of Sitamarhi town, we found sand dykes at a depth of 0.5–1 m from the ground surface. The fine white sand has intruded into the overlying sandy silt layer in the form of dykes, which are about 30 cm in height. These sand dykes which have intruded into silt are connected to the source sand which was liquefied due to increase in pore pressure as a result of seismic shaking. The abrupt truncation of sand dykes indicates the erosional unconformity between these layers. The charcoal sample (BH-2) collected from the top silt layer indicates upper bound and that (BH-3) from white sand reservoir represents lower bound for the liquefied horizon.

Based on the information provided by the locals, we made a trench ~ 500 m north of the above site. This site is locally known as 'Balukhet' (meaning field of sand), where during the 1934 event, a lot of sand and water was discharged covering a large surface area. In the 0.75 m deep pit, we observed a 5–10 cm thick sand dyke with N–S orientation and spread laterally at a depth of 15–20 cm from the present ground surface.

Balwatol is located at the Kosi Canal (under construction for irrigation purpose) excavations, ~ 2 km west of village Bardapur, and 14 km south of Jayanagar on the Jayanagar–Darbhanga road (Figure 1). In a 2.5 m deep section (Figure 3), top 1 m is silty clay, which is underlain by 40 cm thick black clay. Below the black clay, the sequence consists of about 30–40 cm silt, followed by 50 cm white sand further underlain by clayey silt. Two sand dykes were observed to be intruding into the overlying silt and are truncated below the black clay (Figure 3) which have resulted from liquefaction due to seismic shaking. Truncation of sand dykes is indicative of the unconformity. At this site, we also observed a sand dyke in the clayey silt below the white sand bed, though the source of this could not be traced. These dykes are oriented approximately in north–south direction and may have been generated by earthquakes.

Two charcoal samples few meters apart were collected from the black clay for radiocarbon dating to obtain the upper bound while no representative sample was found for the lower bound. The shells sample (BH-4) collected from the top silty clay bed also represent the upper bound for this feature.

Kalikapur is located about 5 km east of Balwatol along the Kosi canal. Under Kosi canal excavations at a depth of 1.5–2 m from the surface, we observed fluidization features. The depositional sequence here is constituted by top 50 cm thick clay underlain by undisturbed silt and silty sand up to a depth of 1.5 m. At 2 m depth, a thin white sand layer about 10–15 cm thick has intruded into the overlying silty sand bed in the form of sand dyke and sill structures which are 0.3–0.5 m high (Figure 4). The soft sediment deformation in the form of convolute structures observed in the top clay bed may be attributed to seismic shaking when the clay was soft. Hence, these two seismic features comprising the soft sedimentary deformation feature at the top; and fluidization at a depth of 2 m with undisturbed intervening beds appear to have been generated by two seismic events. At the same site, a few meters away, another trench was made and in the south wall of the trench, we also identified liquefaction of sand in the form of dykes and sills intruding into the overlying silty sand layer. However, no organic sample was available at this site.

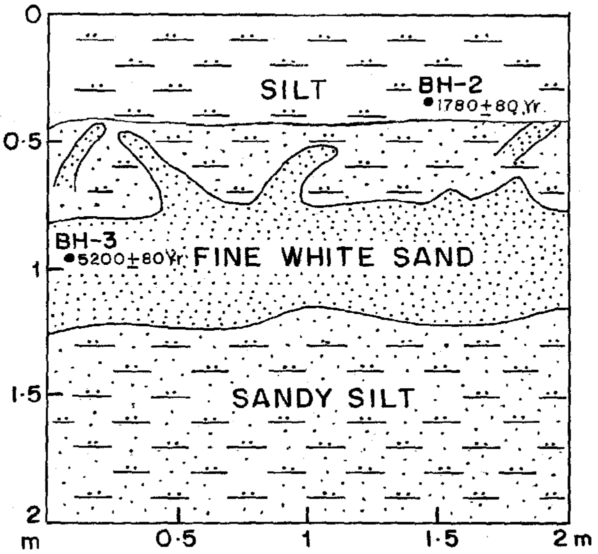

Figure 2. A geological section along the road at Narkatia village (west of Sitamarhi) showing the fine white sand intruded into overlying sandy silt in the form of sand dykes. These sand dykes are also truncated because of erosion. Subsequently silt is deposited over the feature. The sample BH-2 collected from the top silt bed and the sample BH-3 collected from sand reservoir of the flame structures provide upper bound and lower bound respectively for the causative event that occurred during 1700–5300 years BP.

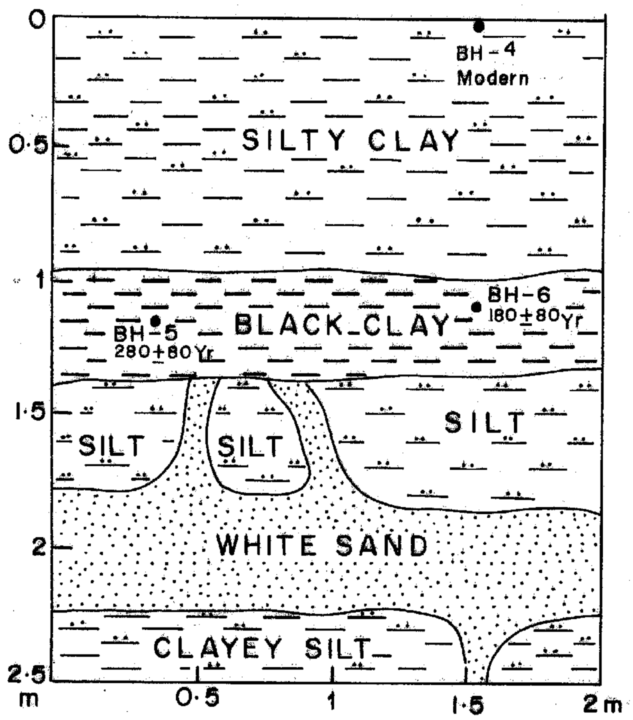

Figure 3. A geological section along the Kosi canal at Balwatol village (near Jayanagar) shows white sand intruded into the overlying silt in the form of sand dykes. The surface of the sand dykes is eroded and subsequently black clay and silty clay beds are built up over it. The samples BH-4, BH-5 and BH-6 provide upper bound for the seismic event leading to the formation of sand dykes. The BH-5 sample (280 ± 80 years BP) predates the older of two upper bounds of the liquefaction feature, thus it may represent the 1833 or earlier seismic event.

Tintolia is located in the old Kosi river section near Pratapganj in Supaul district. Here we observed disturbed and disrupted beds in 10 m long (restricted to 3 m in Figure 5) and 1.5 m deep section. In the silty sand and sand successions, the silty sand layer at ~ 70 cm depth below the surface, is flexured and disrupted as well as truncated (Figure 5) whereas the top layer is undisturbed. The deformation mentioned above in the lower layer is attributed to seismic shaking. In order to establish the time of disturbance, though we collected two organic samples (BH-11 and BH-12) representing the lower and upper bound, we could date only BH-12, because of lesser quantity of organic sample for BH-11.

On Muzaffarpur–Darbhanga highway about 40 km from Muzaffarpur at Benibad village, we observed, 4–5 cm thick sand dyke oriented in N15°E direction. In a 3.5 m deep trench (Figure 6), top 1.7 m is occupied by alternate layers of sand and silt underlain by two types of sedimentary deposits, possibly older and younger, side by side giving an impression of abrupt truncation. Western side of the trench comprises older alluvium with silica nodules while the eastern part is less cohesive younger alluvium. Though the sand dyke follows the boundary of

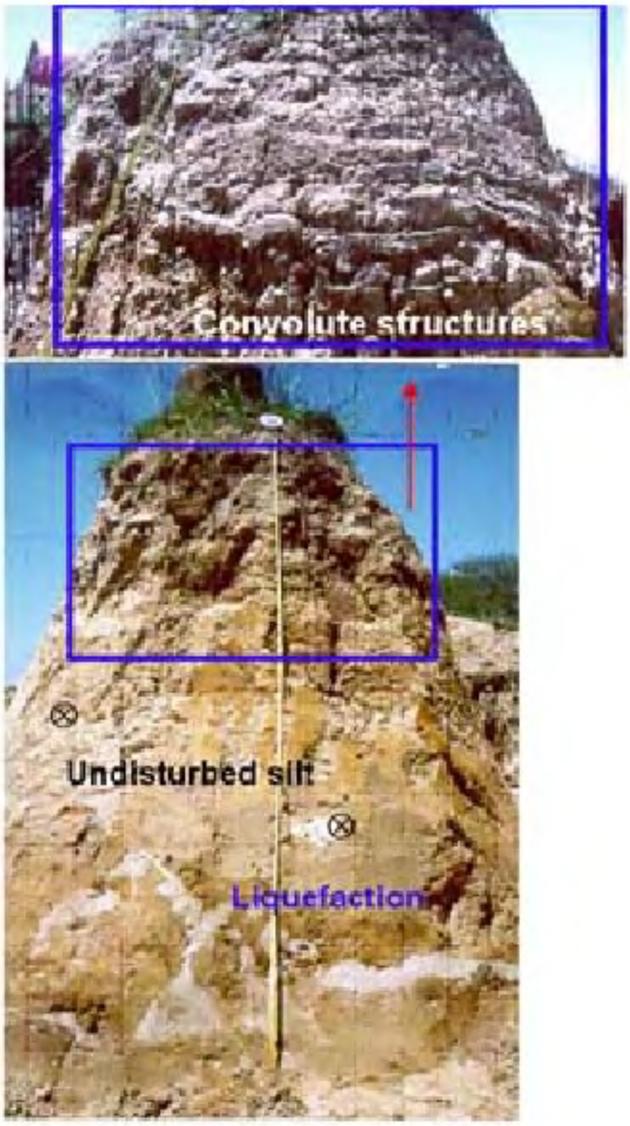

Figure 4. Photographs of convolute structures and liquefaction features observed at Kalikapur near Jayanagar (Madhubani district). The liquefaction features in the form of sand dykes and sills intruded in the overlying silt are at a depth of ~ 2 m from the top of the earthen column as depicted by the lower photograph. The top 50 cm clay layer, blown up and depicted in the top photograph, has convolute structures formed due to high energy shaking possibly by the 1934 seismic event. Silt strata between these two features seems to be undisturbed, the two features may represent two seismic events. It may be noted that white patches indicated by ⊗ are due to cluster of fallen sand particles which should not be confused with intruded sand.

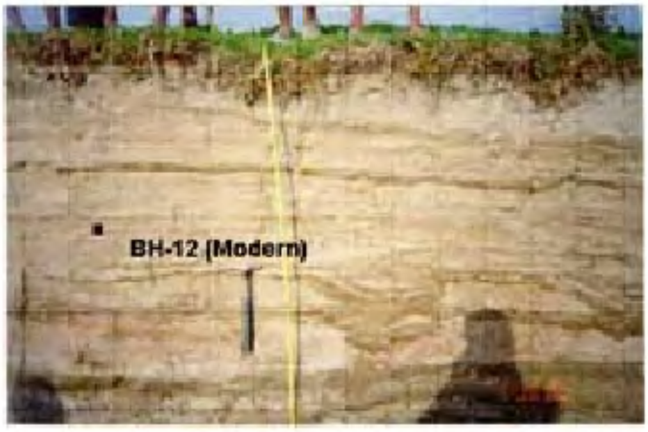

Figure 5. Photograph showing the flexured and disrupted silty sand strata at a depth of 0.7 m subsequent deposition over the disturbed beds had a similar alternating depositional succession as below it. Flexured and disrupted strata is an indication of seismic shaking. The sample BH-12 (^{14}C date 'Modern') represents the upper bound for the seismic event (possibly 1934), however the lower bound for this event is lacking.

Figure 6. A 4.5 m deep cross-section at Benibad village about 40 km from Muzaffarpur on Muzaffarpur–Darbhanga highway, depicts a 2.8 m high and 4–5 cm wide sand dyke oriented in N15°E direction. Top 1.7 m of the section is occupied by alternate layers of sand and silt underlain by older and younger alluvium side by side. The sand dyke has a lower bound of 6130 ± 280 years BP as dated using shell samples.

older and younger alluvium up to certain depth, it cross-cuts the individual formations of older and younger alluvium at different places within the section. From the exposed section, we could measure about 2 m high and 4–5 cm thick sand dyke constituting fine to medium grained sand. It was also observed that two parallel dykes might have originated together at a depth of 3.5 m but later joined to appear as a single dyke. Detailed observations show that lateral variation in geological strata represents an older riverbank filled up by silt during change in river course. However, no organic material from the trench was available to establish the age of the sand dyke but the shell samples (BH-13) collected from the boundary of older and younger alluvium represent lower bound for the event to be 6130 ± 280 years BP.

On Motihari–Dhaka road, about 14 km east of Motihari at Senwaria village (East Champaran dist.) at a brick industry site we encountered many sand dykes (Figure 7) in the shallow trenches made for taking soil for brick making. In general, about 15–20 cm thick silt covers the dykes. Many sand dykes were clearly seen in 1 m deep trenches in space for many meters long with varying thickness from 3 cm to larger than 30 cm. The dykes have overall orientation of about N 60–70°. Branching and joining of sand dykes is also common at this site, however no organic sample was available.

On the left bank of Kamala river, near Jayanagar, we exposed a section of 2 m deep and about 3 m wide (Figure 8). Bottom one-meter portion consists of alternate layers of silt and sand layers, which are highly disturbed. Deformed clasts of silt are embedded within the white sand layer. The topmost white sand bed with clasts of silt is truncated and subsequently 1 m thick silty clay is deposited (Figure 8). Truncation of disturbed sand bed at a depth of 1 m represents the erosional surface/unconformity after the disturbance. A charcoal sample was collected from the lower portion of undisturbed bed, overlying the disturbed bed, representing the upper bound of the event. However, no sample was available to constrain the lower bound.

Notwithstanding the unfavourable conditions for preservation of the seismically-induced liquefaction features in the area, we could observe about half a dozen of them and collect some samples for their age constraints. The results are significant for reconstructing the palaeoseismic history of the area as no other work of this nature has been reported so far from this region. The findings and their implications for the palaeoseismicity of the area are discussed here.

It is clear from the Figure 1 that the observed liquefaction features are located within and around the slump belt of the 1934 great earthquake. Interestingly, the only deformation feature observed at Tintolia is located away from the slump belt but right above the Monghyr–Saharsa Ridge Fault[16]. The observed liquefaction features along with their location and ^{14}C dates (obtained using

Figure 7. A brick-making field at Senwaria (East Champaran District) 14 km east of Motihari, on Motihari–Dhaka road, depicts a few meter long sand dyke (15–20 cm thick) at shallow depths (~ 1 m deep) generated due to the 1934 Bihar–Nepal earthquake. Local residents testify this event.

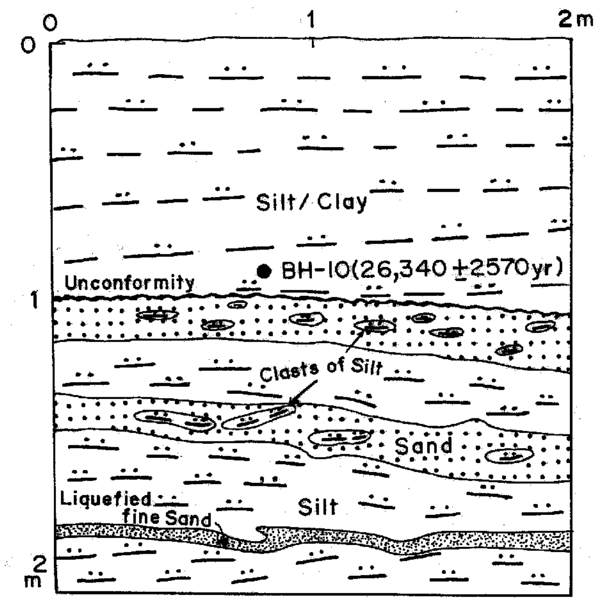

Figure 8. A geologic section along the Kamla river near Jayanagar. Top 1 m undisturbed silty clay is underlain by alternate layers of silt and sand. Bottom silt and sand layers are highly disturbed and particularly the sand beds contain clasts of silt. Topmost sand bed with clasts of silt also indicate the erosional surface, liquefied sand can also be seen. A charcoal sample (BH-10) collected from top undisturbed silty clay represents the upper bound for the event which was dated to be 25,000 years BP.

gas proportional counting at NGRI and AMS measurements at Purdue Univ., USA) are presented in Table 1. Based on the available geological evidence and radiocarbon dates, we have tentatively characterized four palaeoseismic events dated as (i) 1934 event, (ii) 1833 or older than 1833 event, (iii) between 1700 and 5300 years BP event and (iv) older than 25,000 year BP event. These events are discussed below:

For the 1934 historic seismic event we have located well-marked liquefaction features at a number of sites, e.g. the well preserved and widespread sand dyke at Senwaria site (Figure 7) and also at Narkatia where extensive sand eruption in the field was named as Baluketh (field of sand). This liquefaction is attributed to the 1934 seismic event as the local senior citizens witnessed heavy sand and water pouring out in the area. Liquefaction features at both the sites are covered with 15–20 cm thick silt of post 1934 deposition. However, remarkable deformation feature observed at Tintolia (Figure 5) has only one radiocarbon age (BH-12, ^{14}C date: Modern) representing upper bound. Though using the 'Modern' radiocarbon age as upper bound, it is difficult to distinguish the 1988 and 1934 events, yet considering the compactness of strata above the deformed beds it is inferred to have been caused by the 1934 earthquake. Similarly, there are no dates available representing the timing of convolute structures at Kalikapur (Figure 4). Because of its relatively compacted nature and being closer to the surface, it is considered as of 1934 origin.

Out of these four sites, Senwaria and Narkatia sites are at the centre of 1934 earthquake slump belt for which liquefaction in the form of sand dykes was well documented[12]. However, two other sites at Kalikapur and Tintolia, are on the periphery of the slump belt, which have preserved convolute and deformation features respectively.

Palaeoliquefaction signatures observed around Sitamarhi and Jayanagar represent the older events. As we have limited number of samples to define upper and lower bounds, we have utilized other parameters as well to distinguish between different seismic events.

The liquefaction features located along the Kosi Canal excavations at Balwatol (Figure 3) may indicate the 1833 or earlier event. Two organic samples collected from the bed unconformably overlain by the sand dykes represent upper bound. These samples yielded radiocarbon ages of 280 ± 80 and 180 ± 80 years BP while the BH-4 sample collected from the top silty clay bed yielded 'Modern' ^{14}C age. The older upper bound (280 ± 80 years BP) is more applicable as this sample overlies immediately above the liquefaction feature whereas the younger sample is close to the present surface. Thus these liquefaction features are older than 200–360 years and may represent the event older than 1833 or the 1833 event itself. This event is also supported from the features at Kalikapur (Figure 4), ~ 5 km away from Balwatol. As mentioned earlier, the top convolute structure at Kalikapur shown in Figure 4 (inset) represent the 1934 seismic event, which however is separated by undisturbed silt bed overlying the liquefied sand dykes and silt structures. Incidentally, the liquefaction at Kalikapur is at the same depth (1.5 m) and having same orientation (N–S) and is in the close proximity, suggesting that liquefaction at Balwatol and Kalikapur would have been contemporary (1833 or older event), though this criterion cannot be used strictly for the purpose.

At the Narkatia site, the paleoliquefaction features are radiocarbon dated for the upper bound 1780 ± 80 years BP and the lower bound to be 5200 ± 80 years BP indicating wide time gap in between these two dates (Figure 2). This age gap can be easily explained geologically as the period of erosion/non-deposition.

Radiocarbon age (6130 ± 280 years BP) for the lone shell sample (BH-13) from the Benibad site (Figure 6) represents lower bound for the well-marked sand dyke

Table 1. ^{14}C dates of palaeoseismological samples from the meizoseismal area of 1934 Bihar–Nepal earthquake.

Sample code/site	Type of feature	Lower-bound/ upper-bound	Type of sample	^{14}C age (year BP with 1950 as base year)	Preferred occurrence time of seismic event
BH-12 Tintolia	Flexured and faulted strata	UB	Plant material	Modern	AD 1934
Balukhet (Narkatia)	Sand dyke	~ 15–20 cm recent deposit over dyke	–	–	
Senwaria	Sand dyke	~ 15–20 cm recent deposit over dyke	–	–	
BH-4 Balwatol		UB	Shells	Modern	AD 1833 or older
BH-5 Balwatol	Sand dykes and sills	UB	Charcoal	180 ± 80*	
BH-6 Balwatol		UB	Charcoal	280 ± 80*	
BH-2 Narkatia		UB	Charcoal	1780 ± 80*	1700–5300 years BP
BH-3 Narkatia	Sand dykes	LB	Charcoal	5200 ± 80*	
BH-13 Benibad	Sand dykes	LB	Shells	6130 ± 280	
BH-10 Jayanagar	Deformation	UB	Charcoal	26,340 ± 2570	Older than 25,000 years BP

*Dates obtained using AMS facility of PRIME Lab-Purdue Univ., Department of Physics, West Lafayette, IN 47907-1396, USA.
'Modern' (≤ 50 years).

for this event. The shells collected for radiocarbon dating represent the presence of palaeo-river bank at that site. Subsequently, the river course was filled up with silt because of change in the river course. The sand dyke which is intruded into compact clay as well as the silt indicates that the sand dyke is younger than the river fill. Thus putting together the geological evidence of relatively compact dyke with upper bound of 1700 years and lower bounds of 5300 and 6000 years suggests an old seismic event during this time slot.

The event older than 25,000 years BP is inferred from upper bound sample (Figure 8, BH-10) age from Jayanagar site which is 26340 ± 2570 years BP. Lack of lower bound sample and considering the possibility of reworking of charcoal, one can expect the uncertainty in the age. However, the liquefaction feature observed at the site indicates an older seismic event.

Estimating the magnitude of a palaeoearthquake based on secondary features is still in the process of development. However, it is possible to make a semi-quantitative estimate based on liquefaction generated by the historical earthquakes. Two important parameters generally considered in this direction are thickness of sand dykes and farthest distance of liquefaction from the epicenter[17]. Though epicenter of palaeoearthquake is a critical component, it is not an easy task to locate it. Assuming that the epicenters of the historical earthquakes in this area[10,11] are located in the Himalaya and our present observations show liquefaction features located at distances of 250–300 km away (Benibad, Muzaffarpur) from the assumed epicenters and utilizing the empirical relationship[17], the approximate magnitude of the palaeoearthquakes turns out to be equivalent to that of large/great earthquake's magnitude.

From the above discussion, it is inferred that besides 1934 and 1833 events, at least two large/great events: one between 1700 and 5300 years BP and the other older than 25,000 years BP may have occurred in the North-Bihar and Nepal area, for which geological evidences could be traced out during the present study. Though we have been successful to a certain extent in identifying and dating a few palaeoseismic events in this seismically active area drained by shifting rivers, we must have missed some of the other older events due to lack of preservation of their signatures in this kind of environment. Thus by using palaeoliquefaction study, it is difficult to build up a complete record and recurrence interval for seismic events in such seismically active areas controlled by the phenomenon of shifting rivers.

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Gravity modelling across Satpura and Godavari Proterozoic Belts: Geophysical signatures of Proterozoic collision zones

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The modelling of a gravity profile across the Satpura Fold Belt (SFB) constrained from seismic and other available information, suggests that the gravity high observed over the SFB is caused due to high-density upthrusted blocks of lower crustal rocks in the upper crust exposed in some sections, and the gravity low towards the south of the Central Indian Shear (CIS) is caused due to low-density rocks below the Moho. The small-wavelength gravity lows and highs south of the CIS coincide with the felsic and the basic volcanics of tholeiitic to calc alkaline-type magmatism. These sig-

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