

Investigation of past earthquakes in the Kopili Fault zone, NE India: New evidence of paleoliquefaction

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Abstract

The Kopili Fault (KF) zone, one of the active faults in Northeastern region (NER), has experienced large earthquakes in 1869 (M_w 7.5) and 1943 (M_w 7.2). In order to mitigate future occurrences of earthquakes in the KF zone it is essential to understand its long term seismic history and seismic hazard implications. Seismogenic liquefaction features were identified at three trench sites in the floodplain deposits of Kolang River, near KF zone. The liquefaction features include multiple sand dykes, sand blows and flame like intrusion. These structures are direct response to a fluid escape during liquefaction mechanism and past seismic activity. The earthquake induced liquefaction features were dated at AD 1848-1915, AD 1782-1826, AD 1640-1770, AD 1540-1626, and AD 1057-1211. The liquefaction event dated at AD 1640-1770 may correlate with the 250 ± 50 yr BP earthquake, recognized in an earlier study in the KF Zone, Assam. The late medieval liquefaction episodes were also identified in the study sites. The study sections also revealed sand dykes and sand blows that can be ascribed to the 1869 earthquake. The data generated in the present study deciphers five temporally close intervals of earthquakes of large types in the KF Zone during the last ~ 1000 years with a return period of ~ 200 years. Additional excavations and dating of earthquake induced liquefaction features is required to precisely evaluate the frequency of major earthquakes in the KF zone.

1. Introduction

One of the most useful secondary evidence in the category of seismically generated structures in the field of Paleoseismology is liquefaction. Liquefaction of saturated cohesionless sediments is caused by increase of the pore-water pressure due to the propagation of the cyclic shear waves during seismic shaking (Youd 1973; Sims 1973; Youd 1977; Seed 1979; Obermeier 2009). Liquefaction is defined as transformation of a granular material from a solid to liquefied state due to increased pore-pressure. One of the main mechanisms, which produce liquefaction, is the cyclic shear stress/strain induced by earthquakes. Liquefaction occurs mostly in soft sedimentary sequences like fine and coarse sand/silt but has minor effect on sandy-gravels (Obermeier 1996; Owen and Moretti 2011). The liquefaction structures include sand dykes, sand blows, sand viens, pseudonodules, convolute bedding, load structure, diapirs, etc. The minimum earthquake magnitude able to cause liquefaction is M 5–6 (Allen, 1986; Obermeier and Pond 1999) and the factors that control the liquefaction are lithology, depth to the water table, epicentral distance, magnitude, earthquake duration, ground acceleration and amplitude of cycles (Seed, 1979; Obermeier 1996; Moretti et al., 1999). Several studies have used liquefaction features as proxies in various geological and tectonic settings to investigate the seismic history (e.g. Russ 1982; Obermeier 1998; Talwani and Cox 1985; Sims and Garvin 1995; Sukhija et al. 1999; Rajendran et al. 2004; Tuttle et al. 2006; Obermeier 2009; Tuttle et al. 2019).

The north-east region (NER) of India has experienced high-magnitude earthquakes due to the ongoing collision of the Indian Plate with the Eurasian plate to the North; and Burmese plate to the East (Ambraseys and Douglas 2004; Bilham 2004) and the continual tectonics can potentially lead to more seismic activity. Hence, comprehending the frequency of major earthquakes becomes a prerequisite by focusing at evidence of the paleoearthquakes in the tectonically active regions. In the Himalaya, Paleoseismic investigations have been carried by trenching across primary fault scarp (e.g. Anand and Jain 1987; Jayangondaperumal

and Thakur 2008; Kumar et al. 2010; Philip et al. 2011; Malik et al. 2015; Rajendran et al. 2015; Mishra et al. 2016; Jayangondaperumal et al. 2017; Malik et al. 2017; Priyanka et al. 2017; Pandey et al. 2021; Singh et al. 2021). Paleoseismic studies using liquefaction features (Sukhija et al. 1999; Singh and Jain 2007; Jayangondaperumal et al. 2008; Binita and Sharma 2009; Reddy et al. 2009; Morino et al. 2011; Singh et al. 2020; Jayangondaperumal 2021; Rajendran 2021; Lakshmi and Gawali 2022), and the historical earthquake catalogues (Bapat et al. 1983; Iyengar et al. 1999; Baro and Kumar 2017) suggested multiple seismic events to have occurred during the last millennium.

Where seismogenic faults are difficult to recognize, earthquake-induced liquefaction features have been the focus of a number of Paleoseismological studies (e.g. Amick et al. 1990; Obermeier 1998; Saucier 1989; Tuttle and Seeber 1991; Tuttle and Atkinson 2010). Several recent earthquakes, including the 1897 Shillong and the 1950 Assam, induced liquefaction but were not associated with surface rupture. These earthquakes raised the awareness that certain types of prehistoric earthquakes could not be identified by studying surface faults. Therefore liquefaction features are used increasingly in Paleoseismological investigations around the world, wherever sediments susceptible to liquefaction are present. Criteria for recognizing earthquake induced liquefaction features from other types of soft sediment deformation structures already have been described in several papers (e.g. Sims and Garvin 1995; Obermeier 1996; Tuttle et al. 2006 and reference therein). Paleoseismic investigations in the meizoseismal area of 1897 Shillong earthquake, 1950 Assam earthquake, along Kopili Fault (KF) and Dauki Fault (DF), revealed well-preserved liquefaction and deformed syndepositional features at selected sites in the alluvial deposits along the tributaries of the Brahmaputra River, Shillong plateau (SP), NER, India (Sukhija et al. 1999; Rajendran et al. 2004; Reddy et al. 2009; Kumar et al. 2016; Morino et al. 2011, 2014, Lakshmi and Gawali 2022).

Kumar et al. (2016) carried out paleoseismological studies using seismogenic liquefaction in the floodplain deposits of Kopili and Kolong Rivers. They excavated trenches at two locations and observed several sand dykes. In addition, they suggest three intervals of liquefaction formations using radiocarbon and OSL dating techniques. The paleoseismological record, however, provides only part of the data necessary to fully understand seismic hazard in the region. Observations of liquefaction features in the NER (Sukhija et al. 1999; Rajendran et al. 2004; Reddy et al. 2009) and accounts of liquefaction during historical earthquakes suggest that a history of paleoliquefaction events can be gleaned from the geologic record that would shed light on the long-term behaviour of the KF.

Here we present new evidence of sand blows and sand dykes resulted from the paleoearthquakes centered at KF region. In this paper, we communicate the outcome of study carried out mainly in River/channel cut-offs of Kolong River, Assam to investigate the liquefaction fields by excavating abandoned flood plain of Brahmaputra River and age constrains on liquefaction features using OSL dating.

2. Seismotectonics

The contiguous distribution and frequency of large intraplate earthquakes in India are poorly understood. The subduction of Indian plate under the Eurasian plate in the north brought Himalayan mountain ranges into picture while the eastern collision-subduction zone caused the existence of the Indo-Burma ranges

(Fig. 1). As a result, the NER has a complex tectonic setting with a history of past large to great earthquakes (Ambraseys and Douglas 2004; Oldham 1899; Bilham 2004; Kayal 2008; Angelier and Baruah 2009). Four great earthquakes of magnitude (M) > 8.0 in the last ca. hundred years: the 1897-Assam earthquake; 1905 Kangra earthquake; 1934 Bihar-Nepal earthquake, and 1950 upper Assam earthquake occurred in NER (Fig. 1). The 300 km long and 50 km wide KF is seismically very active due to its transverse tectonics which makes the region at risk for impending large earthquakes (Kayal et al. 2012). The KF which separates Shillong Plateau from the Mikir hills, is one of the most important tectonic features of the NER. The KF zone is bounded by the Himalayan collision in north, the Indo-Burmese subduction zone to the south, the syntaxis zone in the east, and the SP in the west (Fig. 1). Many devastating earthquakes occurred in the past around the KF zone viz., 1869 Cachar earthquake of M_w -7.38 (Oldham 1883), 1943 Hajo earthquake of M_w -7.24 (Nandy and Dasgupta 1991; Nandy 2001; Ambraseys and Douglas 2004); 1941 Tezpur earthquake of M -6.5 and 2009 Bhutan earthquake of M -6.9 (Kayal et al. 2012) (Figs. 1 and 2).

3. Methods And Research Approach

Sites that liquefied during large modern earthquakes and historic earthquakes furnish good target for paleoliquefaction studies because liquefaction often reoccur where susceptible sediments are present. Therefore we have carried out investigation for liquefaction features along Kolong River near Namgaon, Satargaon and Nampani near KF Zone in the eastern part of SP where ground failure and sand vents were reported during 1869 Cachhar and 1943 Hajo earthquakes. Overbanks of the Kolong River were examined, during November and December 2016, for the liquefaction and other soft-sediment deformation structures, to assess spatiotemporal extent of strong shaking in KF zone (Figs. 3, 4, and 5). We found, and have studied, many earthquake-induced liquefaction features along Kolong River. The information from sites is gathered from local knowledge by oral communication. The methods employed for identifying earthquake induced liquefaction include reconnaissance of open ground and River/stream cut-offs, investigation of sand-blow/sand dyke features by making trenches, documentation of liquefaction features by logging and river exposures.

The strata here are susceptible to liquefaction, because the riverine sand beds with confining clay layers are better situated for increased pore pressure, under shallow water table conditions. Identification of liquefaction features in the field in Brahmaputra flood plain is not always suitable due to experience of monsoonal flooding and erosion by River during high flows. Consequently, during progressive excavation we observed liquefaction features viz., several sand dykes (Figs. 3–5) as well as multiple dykes rising from the sand reservoir, mainly along and adjoining areas of the Kolong River, a tributary of Brahmaputra and in distal parts of the alluvial fans. Samples for optically stimulated luminescence (OSL) age determinations were collected from different stratigraphic level to obtain maximum and minimum or contemporaneous ages of the liquefaction feature. As it is found that both sites have fluvial dominated deposits which hindered to trace the presence of organic samples. The samples were collected in PVC tubes of 20 cm long and 2.5 cm diameter and OSL dating was carried out by Wadia Institute of Himalayan Geology (WIHG), Dehradun (Table 1). Several studies have shown that in a given site recurring liquefaction corresponds to multiple earthquakes occurring at different time intervals (Youd 1977; Saucier 1989; Tuttle and Seeber 1991;

Obermeier 1998; Sims and Garvin 1995). The method to differentiate subsequent events of liquefaction is based on the stratigraphic criteria and cross-cutting relationships.

Table 1

Optically stimulated luminescence (OSL) ages of sediment samples(See Figs. 4, 5&6 for sample location)

Lab No	Sample No/site no.	Protocol	Depth cm	K (%)	U (ppm)	Th (ppm)	Mean Equivalent Dose (De) Gy	Dose Rate (Gy/ka)	Age Age (yrs) (AD)
LD3120	1/NG/SB	DSAR	130	1.8	2.71	17.8	0.88 ± 0.1 (n = 5)	3.1 ± 0.3	286 ± 39 AD 1692–1770
LD3124	2/NG	SAR	100	1.7	3.13	14.2	0.65 ± 0.05 (n = 17)	3.0 ± 0.3	213 ± 22 AD 1782–1826
LD3122	3/NG	DSAR	80	2.3	1.38	23.7	0.54 ± 0.05 (n = 6)	3.6 ± 0.3	151 ± 18 AD 1848–1885
LD3123	4/NP/SB1	SAR	30	1.9	2.19	22.3	0.38 ± 0.03 (n = 17)	3.3 ± 0.3	115 ± 13 AD 1889–1915
LD3125	5/NP/SB2	DSAR	82	1.7	2.78	17.3	1.07 ± 0.09 (n = 17)	3.2 ± 0.3	339 ± 38 AD 1640–1716
LD3126	6/NP/SB3	DSAR	70	1.9	1.77	14.4	1.28 ± 0.08 (n = 20)	2.9 ± 0.3	434 ± 43 AD 1540–1626
LD3121	7/SG/SB1	SAR	57	2.5	3.52	28.0	3.9 ± 0.13 (n = 26)	4.4 ± 0.4	883 ± 77 AD 1057–1211

Optically stimulated luminescence (OSL) measurement were carried out in an automated Riso TL/DA15 reader equipped with filtered green light from a halogen lamp, which is located at the Wadia Institute of Himalayan Geology, Dehra Dun, India. For the annual dose rate estimation, concentration of uranium, thorium, and potassium in the sediments were measured by XRF. The single aliquot regeneration protocol (Murray and Wintle 2000) was used for equivalent dose determination. Water content assumed: 15 ± 5% by weight. 35 aliquots were used per samples. However, for LD3120 and 3122, 70 disc each were analyzed. For De calculation aliquots with recycling ratio within 10% were considered, n represents the number of aliquots qualified the criteria and considered in ED estimation. Overdispersion for all the samples was less than 20 hence mean age model was used for paleodose estimation

4. Results Of Investigations

Results of the search for and dating of liquefaction features along Kolong River, near KF region are summarized in Table 1 and illustrated on Figs. 3, 4 and 5. Along Kolong River, we found twelve liquefaction features in three trenches at three sites Namgaon (NG; Trench 1) Nampani (NP; Trench 2) and Satargaon (SG; Trench 3) (Fig. 2). Liquefaction features include sand dykes up to 23 cm wide and six sand blow deposits. The documented liquefaction features and their age constraints are discussed below.

4.1 Namgaon Site

The liquefaction features were developed in alluvial sediments and best observed at excavation area (Fig. 2). In ~ 1.8 long and ~ 2 m deep trench 1 along Kolong River at Namgaon (N 26°12'50.5"; E 92°26'41.7"), five dykes (D1, D2, D3, D4 and D5) in a radial pattern and a small sand blow (SB) are observed (Fig. 3A). These dykes range from 25 to 55 cm height and 5 to 20 cm wide. Two generation of main dykes D1 and D2 indicate that they may be originating from the same source and two dyke outlets (D3 & D4) are originating from the D1 dyke (Fig. 3B). They are composed predominately of fine to medium sand. In addition, there is a second generation of sand dyke D2 composed of fine sand that crosscuts the older D3 dyke. The stratigraphic position and crosscutting relation of D3 dyke shows that it is older than D2 dyke and clearly indicates their formation in two distinct events which might have occurred within a short period of time. The D1 dyke intruding into host silt/clay layer is seen to terminate in to the related sand blow (Fig. 3B). This sand dyke (D1) appears to be a compound feature that was utilized during repeated episodes of liquefaction. The oldest sand blow occurring in the bottom of the section (1.3 m below the surface) is about 10 cm thick, composed of very fine sand and fed by D1 dyke. Older dykes D3 and D4 terminate in the host deposit at 110 cm and 95 cm from the ground surface and younger D2 dyke at 80 cm respectively. Given its stratigraphic position within the section, the D2 dyke probably resulted from the youngest earthquake. Older Dyke D5 indicate that this may be originating from different source sand and terminates at ~ 98 cm in the host deposit. D3, D4 and D5 are laid approximately at the same depth. The timing of the earthquake(s) which caused the formation of these features can be found (a) by direct dating of blown out sand (from sandblow) and (b) bracketed between the age of the intruded sand and age of the capping layer. Age constraints were developed on the basis of three OSL dates: AD 1848–1885 (151 ± 18), AD 1782–1826 (213 ± 22 years) and AD 1692–1770 (286 ± 39 years). Among these the OSL date of AD 1692–1770 denotes the contemporaneous age for the older event (Sand blow, Fig. 3B), AD 1782–1826 provides maximum age for D2, D3 and D4 dykes and AD 1848–1885 provides maximum age for D2 dyke (Fig. 3B).

4.2 Nampani site

Trench 2 near Nampani village (N 26°21'58"; E 92°46'38.7"), revealed a 3 m long and 2 m deep sedimentary section consisting of white sand layers, brown sand, and clay (Fig. 4A). Here we observed three generations of sand blows and related sand dykes. The oldest sand blow 3 (Unit 6) occurs low in the section and is up to ~ 5–15 cm thick, composed of fine brown sand, and fed by two sand dykes, ranging from 8 to 10 cm in width (Fig. 4D). The sand blow immediately overlies a soil developed in clay. Dyke 2 is intruding on to the

surface and light yellow in color and attains an height of 60 cm and 5 cm width (Fig. 4D). A younger sand blow 2 (Unit 4), occurring in the middle of the section is about 10–30 cm thick, composed of very fine sand containing a few small clasts, and of limited lateral extent and is fed by at least one sand dyke (Dyke 1) (Fig. 4C). The youngest sand blow 1 (Unit 2), occurring high in the section is only 50 cm thick and consists of white fine sand (Fig. 4B).

Age constraints were developed on the basis of three OSL dates within SB1, SB2 and SB3 yielded ages of AD 1889–1915 (115 ± 13), AD 1640–1716 (339 ± 38) and AD 1540–1626 (434 ± 43) respectively (Fig. 4, Table 1). These dates (AD 1889–1915, AD 1540–1626 and AD 1640–1716) provides contemporaneous ages for the sand blows 1, 2 and 3 respectively.

4.3 Satargaon site

At Satargaon site (N 26°23'12.5"; E 92°47'43.1), we observed two sand blows (Sand blow 1 (SB1) and sand blow (SB2)) and a dyke 2 m long and 1.2 m deep trench (Fig. 5A). The section consists of alternate layers of clay, silt and sand. The SB2 (Unit 5) is ~ 10 cm thick and SB1 is 25 cm thick and composed of fine silt and brown sand (Fig. 5B). One main sand dyke, 5 cm wide, fed the SB1. The dyke composed of fine light yellow color sand, crosscutting unit 6 and is terminated in Unit 5 (SB2). Flame like intrusion of clay deposit is also observed (Unit 4) and clasts of clay are also seen in the sand blow. Sample collected from within the sand blow 1 yielded OSL date of AD 1057–1211 (883 ± 77) (Table 1). It provides contemporaneous age constraint for the event.

5. Discussions

5.1 Timing, Sources and Magnitude of Paleoearthquakes

The stratigraphic criteria, geometry and cross-cutting relations of deformational features provide evidence for repeated liquefaction events to seismic activity. The deformational features found in the present study, such as sandblows, sand dikes and flame structures, are correlated to earthquake induced mechanism because their morphology indicates sudden application of a large upward-directed hydraulic force of short duration (Obermeier 1996) and presence of clasts. Similar features were observed in different geological and tectonic regimes during strong historical earthquakes (Obermeier 1996; Tuttle and Atkinson 2010; Mugnier et al. 2011; Cox et al. 2012, 2014) and have been reported earlier from different depositional environments in India including the Brahmaputra plains of NE India (Sukhija et al. 1999; Sukhija et al. 2002; Rajendran et al. 2004; Thomas et al. 2007; Jayangondaperumal and Thakur 2008; Reddy et al. 2009; Jayangondaperumal et al. 2011; Mugneir et. al. 2011; Kumar et al., 2016; Lakshmi and Gawali 2022).

In the present study along Kolong River basin, from the structural, stratigraphic, and age relations at sites suggest that the paleoliquefaction features probably formed as the result of five earthquake events (Table 1) in a closely timed earthquake sequence including the 1869 Cachar earthquake. Previous studies demonstrates that using OSL, 'direct dating' of prehistoric earthquakes may be possible, if sand blows from liquefied dykes are preserved (Thomas et al. 2007; Porat et al. 2007). The ages obtained from present study is grouped in to five seismic events (Fig. 6). Evidence for Event I is recorded in Trenches 1 and 2 (Figs. 3 and

4). According to the OSL ages measured at this site (Table 1), the Event I is constrained by both maximum and contemporaneous ages (Fig. 6). The maximum age (AD 1848–1885) of Event I is provided by youngest liquefaction features in Trench 1 (Fig. 3) at Namgaon site. This event is also inferred from contemporaneous age (AD 1889–1915) in trench 2 and is recorded in youngest sandblow. Evidence for Event II liquefaction which took place sometime during the period AD 1782–1826 has been recorded in Trench 1 (Fig. 6). Event III has been inferred from the age constraints of sand blow in Trench 1 (Figs. 3 & 6) at Namgaon site and Sand blow 2 in Trench 2 (Figs. 4 & 6) at Nampani site. Two contemporaneous OSL ages AD 1692–1770 and AD 1640–1716 points to an earthquake in 17th and 18th century. Present study also provide Event IV in Trench 2 and the contemporaneous OSL age 1540–1626 points to an earthquake in the 16th and 17th century (Fig. 6). Event V occurring at AD 1057–1211 is also identified from Trench 3 at Satargaon site (Fig. 6).

Instrumental records over the last five decade suggest that Cachar earthquake of 1869 (Mw-7.4) and Hajoi earthquake of 1943 (Mw 7.2) occurred in the study area which was associated with the NW-SE trending KF (Figs. 1 & 2) (Kayal et al. 2012). These data allow us to correlate the Events I and II to one of the two large earthquake occurred in this time interval in this area: 1869 or 1943 events. As far as the age of the events is concerned, given the limited results of the dating available (Table 1) we can conclude that Events I and II may be associated to the 1869 Cachar, which is the nearest and strongest event for which historical sources report liquefaction in the area. The 1869 event occurred in the southeastern end of the KF and has been well described by Oldham (1883). It is equally possible that the AD 1943 Hajoi earthquake, on the basis of historical accounts, may have produced liquefaction if it was similar to the mechanism of 1869 earthquake. However, a little information is available for the 1943 event except newspaper report (Dasgupta 2011) which occurred farther north of 1869 event. However, there is no large event in the KF zone since the 1943 M 7.3 Hajoi earthquake. Although it is tempting to compare Event III (AD 1692–1770 and AD 1640–1716) with the earthquake of AD 1697 Sadiya, this event is unlikely to have generated liquefaction in the region, where our study sites are located due to the distance to the assumed source, However, this data support to tally the liquefaction episodes to 250 ± 25 year BP in the same geological conditions along KF Zone (Kumar et al., 2016). Although AD 1548 earthquake (Iyengar and Sharma 1998) is the closest historical event for Event IV (AD 1540–1626) from the present study, it is hazy to correlate the two, based on one exposure of a liquefaction layer. Kumar et al. (2016) dated the liquefaction feature that occurred about 900 year BP at the Kakotigaon along Kolong River which is near by present study sites. This data suggest that the liquefaction Event V (AD 1057–1211) at Satargaon site in the present study may correspond to 900 year BP, but only one age precludes this conclusion (Fig. 6). Dating of more paleoliquefaction features at additional sites in the KF would greatly improve our determination of the timing and the likely seismic source.

The contiguous spreading of liquefaction fields (~ 41 km) along the Kolong River indicate local earthquakes of approximately $M \geq 6.0$ using empirical relation of Ambraseys (1988) for moment magnitude to distance of farthest liquefaction to epicentre. If all the liquefaction events resulted from the KF, then according to Ambraseys (1988) the earthquakes were approximately $M \sim 6.5$. The present study

liquefaction fields recorded at least five local earthquakes in 1000 years, with a conjectural average recurrence interval of approximately 200 years for M 5.5 to 6.5 events.

In the past, the KF has experienced several earthquakes of magnitude 4.5 to 6.2, three of magnitude 6 to 7 and two earthquakes of magnitude greater than 7 viz., 1869 Cachhar and 1943 Hajoi earthquakes. This region has been identified as a probable region for future generating large magnitude earthquakes (Kayal et al. 2006, 2010, 2012). Recently, it is argued that KF cuts across the Himalayas and caused displacement and curvilinear structure at the Main Boundary Fault and Main Central Thrust zones (Kayal et al. 2010, 2012). Paleoseismic investigation in the KF zone by Kumar et al. (2016) revealed seismogenic liquefaction features near Kopili and Kolong Rivers which correspond to the occurrence of three (250 ± 25 year BP, between 400 and 700 year BP and 900 ± 50 year BP) causative seismic events. However, both the studies, Kumar et al. (2016) and present study, indicates that an earthquake of comparable magnitude occurred in the Assam, which has generated liquefaction features of similar dimensions in the source zone nearby KF zone. But there is also a possibility that even a distant great earthquake could generate liquefaction in the KF zone. The limited dating constrains based on only limited liquefaction features are presented here and are less than sufficient to develop a timeline of earthquakes that impacted the KF.

6. Conclusions

A wealth of information regarding paleoearthquakes is accessible in the form of seismically induced liquefaction features conserved in the alluvial deposits along Kolong River near KF region. During our paleoseismic investigation, we found eleven liquefaction features and included small to big five sand blows, eight sand dikes at sites Namgaon (NG), Nampani (NP) and Satargaon (SG). On the basis of OSL dating, we interpret that the episodic liquefaction features at the three sites formed about AD 1848–1915, AD 1781–1825, AD 1646–1769, AD 1539–1625, and AD 1056–1210. Several fault zones in the SP, including the DF, Oldham Fault, Dapsi Thrust and KF are thought to be active on the basis of their apparent influence on local topography and hydrography. The geological evidence for the five seismic events from the present study and previous studies indicates that the KF appears to be active since mid-Holocene. Additional investigations of identification of liquefaction features are required to authenticate our findings. More studies on liquefaction features would provide better constrains on timing, magnitude and sources of paleoearthquakes in the KF zone. These details in turn help in interpretation of long-term rupture history of faults and intraplate seismicity. Eventually, present study demonstrates that the paleoseismic investigations can provide useful information on past earthquakes through recognition of liquefaction features in the absence of surface rupture. Paleoseismic approach also contribute data on unknown seismic events in seismically active region like SP.

Declarations

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Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Figures

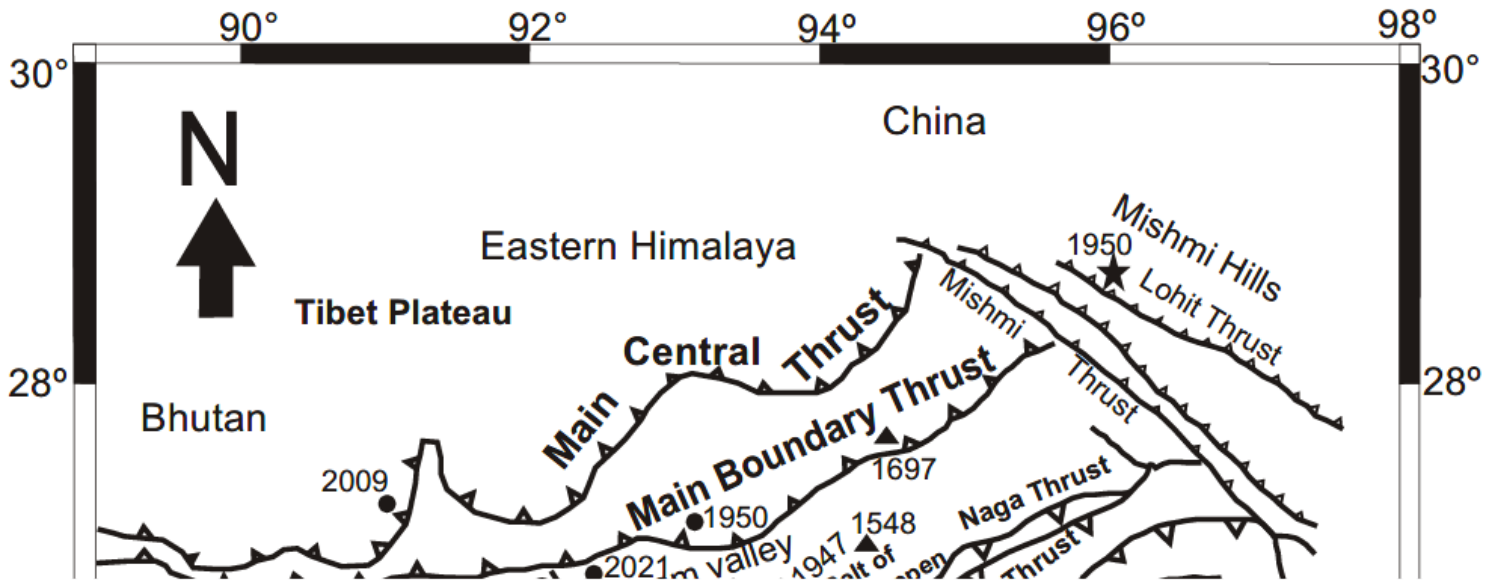


Figure 1

Regional tectonic settings of Northeast India and surrounding regions. CF: Chedrang Fault, OF: Oldham Fault, SF: Samin Fault, DdF: Dhudnoi Fault, DT: Dapsi Thrust, BS: Barapani Shear Zone, BL: Bomdila Fault (Map sources: Murthy et al. 1969; Nandy 2001; Angelier and Baruah 2009). Non-instrumental (Source: Iyengar et al., 1999) and instrumental earthquakes of magnitude ≥ 6 are plotted on the map (Sources: USGS and NCS, India). Black star depicts the two great earthquakes 1897 (Mw-8.1) and 1950 (Mw-8.3) that are occurred in the region

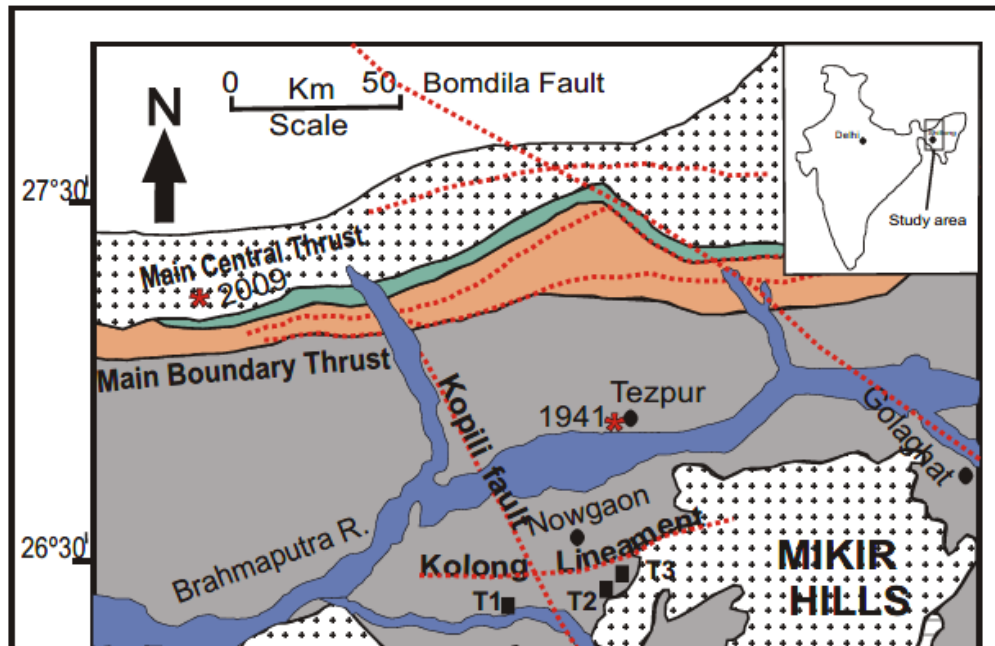


Figure 2

(a) Geological location map of the study trench sites along Kolong River, showing major structures (modified after Dasgupta, 1977 and Nandy, 2001). T1-Trench 1 at Namgaon site, T2-Trench 2 at Nampani site and T3- Trench 3 at Satargaon site. Epicentres of earthquakes that occurred in the Kopili fault region are plotted on the map



Figure 3

Namgaon site (Trench 1) (N 26°12'50.5"; E 92°26'41.7"). (A) Uninterpreted and (B) interpreted Photograph of multiple sand dykes (D1,D2,D3,D4 and D5) and related sand blow in a ~1.8 m long and ~2 m deep trench 1 section. (B) Two generation of main dykes D1 and D2 may be originating from the same source and D3 & D4 branched from D1 dyke. There is a second generation of sand dyke D2 crosscuts the older D3 dyke. The stratigraphic position and crosscutting relation of D3 dyke shows that it is older than D2 dyke and clearly indicates their formation in two distinct events which might have occurred within a short period of time. Another sand dyke D5 is terminated at 98 cm and no source sand layer observed. OSL date of AD 1692-1770 denotes the contemporaneous age for the older event, AD 1782-1826 provides maximum age for D2, D3 and D4 dykes and AD 1848-1885 provides maximum age for D2 dyke. From its stratigraphic position and OSL age data within the section, the D2 dyke probably resulted from the ~1869 earthquake. Lithology of trench section consists of Unit 1: massive clay, Unit 2: clay-silt of light grey-brownish color and Unit 3: Grey color silt/clay

Figure 4

Nampani site (Trench 2) (N 26°21'58"; E 92°46'38.7"). Locations of 5B, C and D are shown on 5A and 5C on 5B. (A) Photograph of ~3 m long and 2 m deep Trench 2 showing three generations of sand blows and related sand dykes. Age constraints were developed on the basis of OSL date within sand blow 1 yielded age of AD 1889-1915 (115±13). Lithology of trench section consists of Unit 1: clay, Unit 2: sand blow 1, Unit 3: brown silt, Unit 4: sand blow 2, Unit 5: sticky clay, Unit 6: sand blow 3 and Unit 7: sticky clay. (B) Mosaic photograph details showing a youngest sand blow 1 consists of white fine sand. (C) Photograph details showing sand blow 2 (Unit 4), sand blow 3 (Unit 6) and related sand dyke. Sand blow 2 is of limited lateral extent and fed by at least one sand dike (D1). OSL age of AD 1640-1716 (339±38) provides contemporaneous age on triggering paleoearthquake. (D) Photograph showing oldest sand blow 3 and related sand dykes 1 and 2. OSL age AD 1540-1626 (434±43) of sample from this unit 6 provides contemporaneous age for the paleoearthquake that caused the liquefaction feature

Figure 5

Satargaon site (Trench 3) (N 26°23'12.5"; E 92°47'43.1). (A) Uninterpreted and (B) interpreted photograph of 2 m long and 1.2 m deep trench section showing sand blow 1 (SB1), sand blow 2 (SB2), sand dyke and

flame like intrusion features. SB2 (Unit 5) is ~10 cm thick and SB1 is 25 cm thick and composed of fine silt and brown sand. One main sand dyke, 5 cm wide, fed the SB1. The dyke composed of fine light yellow sand, crosscutting unit 6 and terminated in Unit 5 (SB2). Flame like intrusion of clay deposit is also observed (Unit 4) and clasts of clay in the sand blow. Sample collected from within the sand blow 1 yielded OSL date of AD 1057-1211 (883 ± 77) provides contemporaneous age constraint for the event. Lithology of trench section consists of Unit 1: clay, Unit 2: silt, Unit 3: brown silt-sand, Unit 4: clay, Unit 5: fine sand and Unit 6: silt-clay

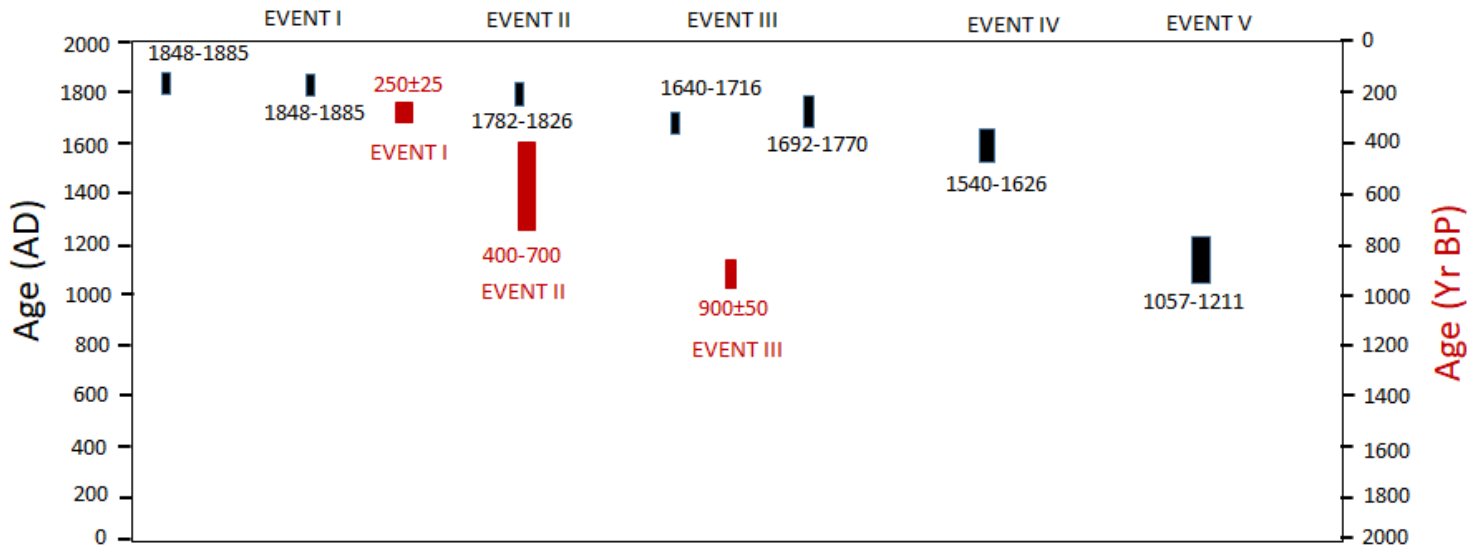


Figure 6

The occurrence of earthquakes depicted in trench sediments in Kopili region, is stacked up for possible correlation of events. Kumar et al. (2016) dated events are compared with our findings and there is some consonance with the events. Black and red thick bar ones are present and previous (Kumar et al. 2016) findings of paleoearthquakes in the Kopili fault region