



Soft sediment deformation features in Dauki Fault region: evidence of paleoearthquakes, Shillong Plateau, NE India

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Abstract

The northeastern region (NER) of India has several complex regional geological structures, out of which the Dauki fault (DF) is a prominent one. The E–W trending reverse DF, which is inferred to go through the southern margin of Shillong Plateau (SP), has played major role in the regional deformation of the adjoining areas and was believed to be active during the Late Quaternary time. Previous paleoseismological studies conducted on the eastern and western part of the DF, Bangladesh, revealed that the fault ruptured in AD 849–920 and AD 1548, respectively. However, there were no studies on the DF from southern side of the SP, India. For the first time, from Indian side, soft sediment deformation structures (SSDS) are reported from five trenches in and around the DF zone, SP. Close to the Dauki village, five trenches in the eastern part of the DF, SP, show micro faulting, sand dykes, disturbed strata, and water escape structures. The detailed investigation of SSDS indicates that the origin of deformation is seismic trigger. The ¹⁴C AMS dating of deformation structures generated by earthquakes suggests three seismic events occurred between 130 and 920 year BP, 5415 to 9140 year BP, and at about 4285 year BP. This study confirms that DF is indeed active, at least, since the mid-Holocene. More trenching and dating of seismically induced deformation features are needed to accurately calculate the recurrence interval of significant earthquakes that can strike the fast-expanding urban areas in India and Bangladesh.

Keywords Earthquake · Dauki fault · Soft sediment deformation · Micro faulting · ¹⁴C AMS dating · Mid-Holocene

Introduction

Paleoseismology came into existence in the late nineteenth century, but modern paleoseismology formed in the 1970s. The goal of paleoseismological studies is to characterise the location, size, and frequency of strong earthquakes that have occurred in the recent geological past as a way to understand both short-term and long-term seismic hazards (Jayangondaperumal 2021). This geological information also complements historical records of significant seismic events, and offers a more complete picture of seismic hazards and fault behaviour. Studies on geologic evidence of prehistoric earthquakes include primary and secondary or off-fault. Throughout the world, paleoseismological studies contributed much to understanding the long term activity of the active faults (McCalpin 1996; Cox et al. 2000;

Rockwell et al. 2002; Philip et al. 2011; Sapkota et al. 2013; Morino et al. 2014; Malik et al. 2015; Rajendran et al. 2015; Mishra et al. 2016; Malik et al. 2017; Priyanka et al. 2017; McCalpin and Reicherter 2018; Masana et al. 2018; Manighetti et al. 2020; Pandey et al. 2021; Singh et al. 2021 and references therein) and liquefaction and soft-sediment deformation (Youd 1991; Obermeier 1998; Sukhija et al. 1999; Jayangondaperumal et al. 2008; Reddy et al. 2009; Tuttle et al. 2010, 2019; Mugnier et al. 2011; Cox et al. 2012; 2014; Kumar et al. 2016). The information about past seismic activity can be inferred from the soft-sediment deformational structures (SSDS) in the late quaternary geologic record (Allen, 1975). SSDS is generally used to denote structures that reflect deformational processes in unlithified sediments (Maltman 1984). Seilacher (1969) proposed the term ‘seismites’ that describe a variety of post-depositional structures in unconsolidated sediments produced by seismic shocks. In seismically active regions, seismites formed during or shortly after deposition are essential indicators of paleoseismic activity (Lowe 1975, 1976; Sims 1975; Hempton and Dewey 1983; Owen 1987, 1996, 2003; Obermeier

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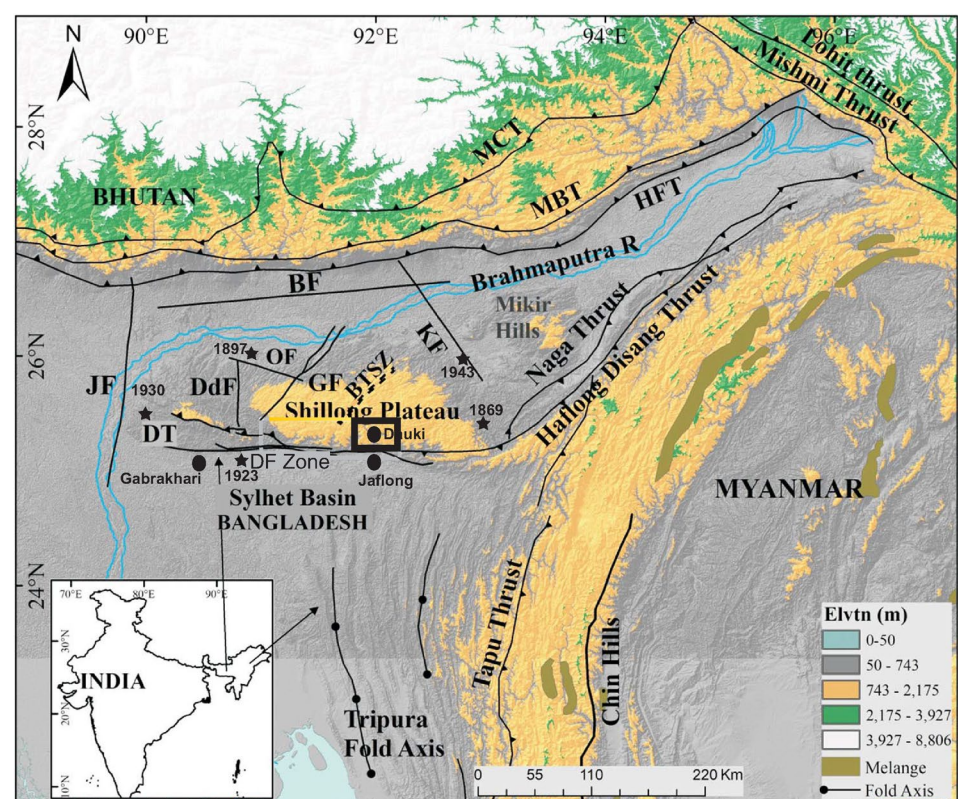
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1996a; Calvo et al. 1998; Rossetti 1999; Vanneste et al. 1999; Jones and Omoto 2000; Moretti 2000; Bowman et al. 2004; Mohindra and Bagati 1996; Mohindra and Thakur 1998; Upadhyay 2003; Juyal et al. 2004; Kotalia and Rawat 2004; Singh and Jain 2007; Jayangondaperumal et al. 2008; Binita and Sharma 2009; Reddy et al. 2009; Rana et al. 2013; Singh et al. 2020). There is no standard terminology to describe these seismites (Lowe 1975). But, different individual studies can be used to infer a formal geometric classification to describe the observed structures. They have been reported in continental environments (Hempton and Dewey 1983; Scott and Price 1988; Karlin and Abella 1992; Alfaro et al. 1997; Sukhija et al. 1999; Jayangondaperumal et al. 2008; Reddy et al. 2009; Jones and Omoto 2000; Rodríguez-Pascua et al. 2000; Neuwerth et al. 2006; Koç-Taşgin and Altun 2019), transitional settings (Gibert et al. 2005; Owen and Moretti 2008) and marine successions (Moretti et al. 2001; Rossetti and Santus 2003; Kangi et al. 2010; Mastrogiacomo et al. 2012; Chen and Lee 2013; Yamamoto 2014; Alves 2015; Ortnier and Kilian 2016). SSDS has been reported from both recent to ancient depositional environments (e.g. by Sims 1973; Allen 1982, 1985; Mazumder et al. 2006; Owen et al. 2011). The SSDS that form from the escape of pore fluids, usually water, occur commonly in fine to medium grained sand. These structures directly respond to fluid escape processes during liquefaction and fluidization (Lowe 1975). The SSDS attributed to seismic

activity are (1) ball and pillow structures (Potter and Pettijohn 1963), pseudonodules or cycloids (Hempton and Dewey 1983), pinch and swell bedding and lenticular boudins, pocket and pillar structures (Postma 1983) and flame-like structures (Visser and Cunningham 1981). Deformation structures linked to seismic shock can play an important role in analyzing the distribution and intensity of ancient tectonic activity (Sims 1973, 1975). A direct relationship between earthquake occurrence and the resulting deformation of the sediments has been invoked by various workers (Sims 1973, 1975; Sieh 1978; Hempton and Dewey 1983; Talwani and Schewer 2001; Jayangondaperumal et al. 2008).

The northeastern region (NER) of India is tectonically active due to the ongoing collision of the Indian Plate with the Eurasian Plate to the North; and Burmese Plate to the East (Singh et al. 2021). The northern subduction zone brought the Himalayan mountain ranges into picture while the eastern collision-subduction zone caused the Indo-Burma ranges, as mentioned in Fig. 1. The NER of the Indian plate lies in the converging zone of these two mountain ranges. As a result, the region has a complex tectonic setting with a history of past large to great earthquakes (Ambraseys and Douglas 2004; Oldham 1899; Poddar 1950; Bilham 2004; Kayal 2008; Angelier and Baruah 2009; Priyanka et al. 2017; Pandey et al. 2021). The NE states of India are seeing a steady rise in population in recent years that has led to indiscriminate construction of multi storied

Fig. 1 Regional tectonic settings of Northeast and Shillong Plateau. MCT main central thrust, MBT Main Boundary Thrust, HFT Himalaya Frontal Thrust, BF Brahmaputra Fault, JF: Jamuna Fault, KF Kopili Fault, OF Oldham Fault, DdF Dhudnoi Fault, DT Dapsi Thrust, GF Guwahati Fault, BTSZ Badapani Tyrsad Shear Zone, DF Dauki Fault. Map sources (Biswas and Greasemann 2005; Islam et al. 2011; An et al. 2010)



buildings for mass habitation. The new constructions may not adhere to seismicity-resistant guidelines while constructing these buildings. In the event of a great earthquake, the loss of life and property will be pretty high. The effects of the past sequences were theatrical, but can pale in significance if a major event were to occur now in this region. The concentration of population has increased manifold in this region. The loss to life and property will be immense. Hence, understanding the recurrence interval of major seismic events becomes necessary to be comprehended by looking at signatures of the past earthquakes along the seismically active terrain.

Paleoseismic studies in the Himalayan region, based on trenching across primary fault scarp (Kumar et al. 2010; Jayangondaperumal et al. 2011, 2017, 2018; Philip et al. 2011; Malik et al. 2015, 2017; Rajendran et al. 2015) SSDS due to liquefaction (Mohindra and Bagati 1996; Mohindra and Thakur 1998; Upadhyay 2003; Juyal et al. 2004; Kotalia and Rawat 2004; Singh and Jain 2007; Jayangondaperumal et al. 2008; Binita and Sharma 2009; Reddy et al. 2009; Rana et al. 2013; Morino et al. 2011; Singh et al. 2020), and the historical earthquake catalogues (Bapat et al. 1983; Iyengar et al. 1999; Baro and Kumar 2017) suggest multiple seismic events to have occurred during the last millennium.

Paleoseismological investigations based on liquefied deformed structures along the Shillong plateau (SP) have provided major earthquake recurrence interval to be 500 years (Sukhija et al. 1999) and 1200 years (Rajendran et al. 2004), which is in stark contrast to the speculative interval of 3000 year of Bilham and England (2001). The SP, according to Sukhija et al. (1999), experienced three major earthquakes with a return period of 400–600 years. Morino et al. (2011, 2014) have reported deformation features in the trenches from Gabhrakhari village, Bangladesh (south of Dauki fault), whose ages correspond to AD 840–920, AD 1500–1630 and 1897 seismic events, with a recurrence interval of 350–700 years, which they attribute to the movement along Dauki fault (DF). The DF is a major geotectonic structure along the southern boundary of the SP, which could trigger future destructive seismic hazards, adversely impacting the NER of India and the adjoining areas of Bangladesh (Fig. 1). Constraints on timing and location of the palaeoearthquakes in the SP have also been attempted by studying earthquake induced liquefaction features (Sukhija et al. 1999; Thomas et al. 2007; Reddy et al. 2009; Kumar et al. 2016). In short, the SP and its adjoining areas is prone to seismic activity and the ensuing damages, which in the era of urbanization, can be ruinous.

The instrumented observations of seismic activity, quite obviously, do not go back in time beyond 100–150 years. The general earthquake recurrence times, at least of medium and large size earthquakes, far exceed this short time interval by an order of magnitude or two, even in seismically active

regions of the world. Therefore, effectively precludes the analysis and understanding of the entire earthquake cycle with the help of instrumental records. The tectonics of a region is a complex phenomenon depending on a large array of variables that include the geology, geomorphology and the stress and strain conditions. Despite many geotectonic unknowns it is now widely accepted that 80% of the seismic activity is directly associated with the active fault (Jayangondaperumal et al. 2018).

The article presents the first-ever recording of the presence of SSDS and their utility in assessing the paleoseismicity of the region around DF, lying to the south of SP, India. The study aims to locate, characterize and date SSDS and assess their significance as indicators of palaeoseismicity.

Seismotectonics and geomorphology of the study area

The SP has a complex origin and is bounded by an array of faults like Dauki, Kopili, Oldham (Brahmaputra) and Dhubri (Fig. 1), which are seismogenic (Kayal et al. 2006). According to Panthi and Jyoti (2013), the SP, between 1962 and 2012, experienced 317 seismic events of $M_s \leq 4.4$; 187 $M_s \geq 4.5$; 58 $M_s \geq 5.0$; and only 1 $M_s \geq 6.0$ event. Some of the well-known earthquakes (EQs) in the NER include the 1548 EQ (Bilham and Hough 2006), the 1869 Cachar EQ ($M_w = 7.5$), 1897 Assam EQ ($M_w = 8.1$), 1923 Meghalaya EQ ($M_s = 7.1$), 1930 Dhubri EQ ($M_s = 7.1$), 1943 Assam EQ ($M_s = 7.2$), 1947 Arunachal Pradesh EQ ($M_s = 7.7$), 1950 Assam EQ ($M_w = 8.7$), 1988 Manipur EQ ($M_s = 7.3$), 2009 Assam EQ ($M_w = 5.1$) and the very recent 2011 Sikkim EQ ($M_w = 6.9$). The 1869 Cachar EQ ($M_w = 7.5$) and the 1943 Assam EQ ($M_w = 7.24$, Nandy and Dasgupta 1991; Dasgupta et al. 2000; Nandy 2001; Ambroseys and Douglas 2004) occurred on the N–S trending Kopili fault (KF). This fault lies between the SP and the Mikir hills (Kayal et al. 2006; Kayal 2001). To the south of the SP is the E–W trending DF (Fig. 1) which is responsible for the 1923 Meghalaya EQ ($M_s = 7.1$). Towards west of the SP is the N–S trending Dhubri fault (DHT, Fig. 1) which caused the 1930 Dhubri EQ ($M_s = 7.1$). Among these historic earthquakes, the 1548 EQ, the 1897 EQ and the 1923 EQ could be the manifestation of the DF. However, Duarah and Phukan (2011) are of the opinion that the present area under study is free from seismic activity.

DF is a 300 km-long E–W trending prominent structural feature defined by steep scarps, especially at some places in Bangladesh (Das et al. 1995). Hiller and Elahi (1984) suggested Dauki is a south directed normal fault, whereas Johnson and Alam (1991) consider it to be north-directed low angle ($5\text{--}10^\circ$) thrust fault. According to Lohmann (1995), this is high-angle reverse-fault at depth and right-lateral

strike-slip fault near the surface. However, Alam et al. (2003) consider it to be an upthrust fault. The DF is opined to have undergone horizontal displacement of approximately 250 km, along which tectonic activity of great significance took place in the Pliocene (Evans 1964). According to Chen and Molnar (1990) DF separates the ancient continental crust of the Indian Shield from the Cretaceous Ocean floor. The drainage pattern within the SP and its adjoining area is greatly influenced by the tectonics and the physiography of the region, where the lineaments and faults are seen to control the direction of flow.

Dauki River basin occupies parts of Jaintia Hills and East Khasi Hills districts with a catchment area of 872 km². Dauki is a 6th order river and runs for about 102 km to enter the Bangladesh plains. Valley profiles and basin asymmetric factor of Dauki River Basins reveals obvious tilting towards the east. Correspondingly, numerous small channels (3rd and 4th order streams) around the central section on the southern periphery of the plateau show right lateral component (deflecting towards the east) in the channels (Watinaro et al. 2016), and this supports the sense of movement suggested by Evans (1964) for the DF. Watinaro et al. (2016) have suggested that entire SP is undergoing tectonic instability while the central segment of the plateau is witnessing accelerated deformation/uplift. Further, their study indicates that the observed deformation in the river basins is associated with the episodic activity along the Dapsi Thrust (DT) and the DF. Structural patterns deciphered from satellite imagery of southern parts of SP reveal N–S trending Um Ngot lineament, a major 45–50 km-long transverse lineament that runs parallel to the Um Ngot (Dauki) River (Srinivasan 2003; Das 2004; Duarah and Phukan 2011). The trench locations, discussed in the present study, are along the Dauki River (Um Ngot) near Dauki village (sites 1 and 2, in Fig. 2). Sites 3, 4 and 5 are located near Pyrdiwah village (Fig. 2).

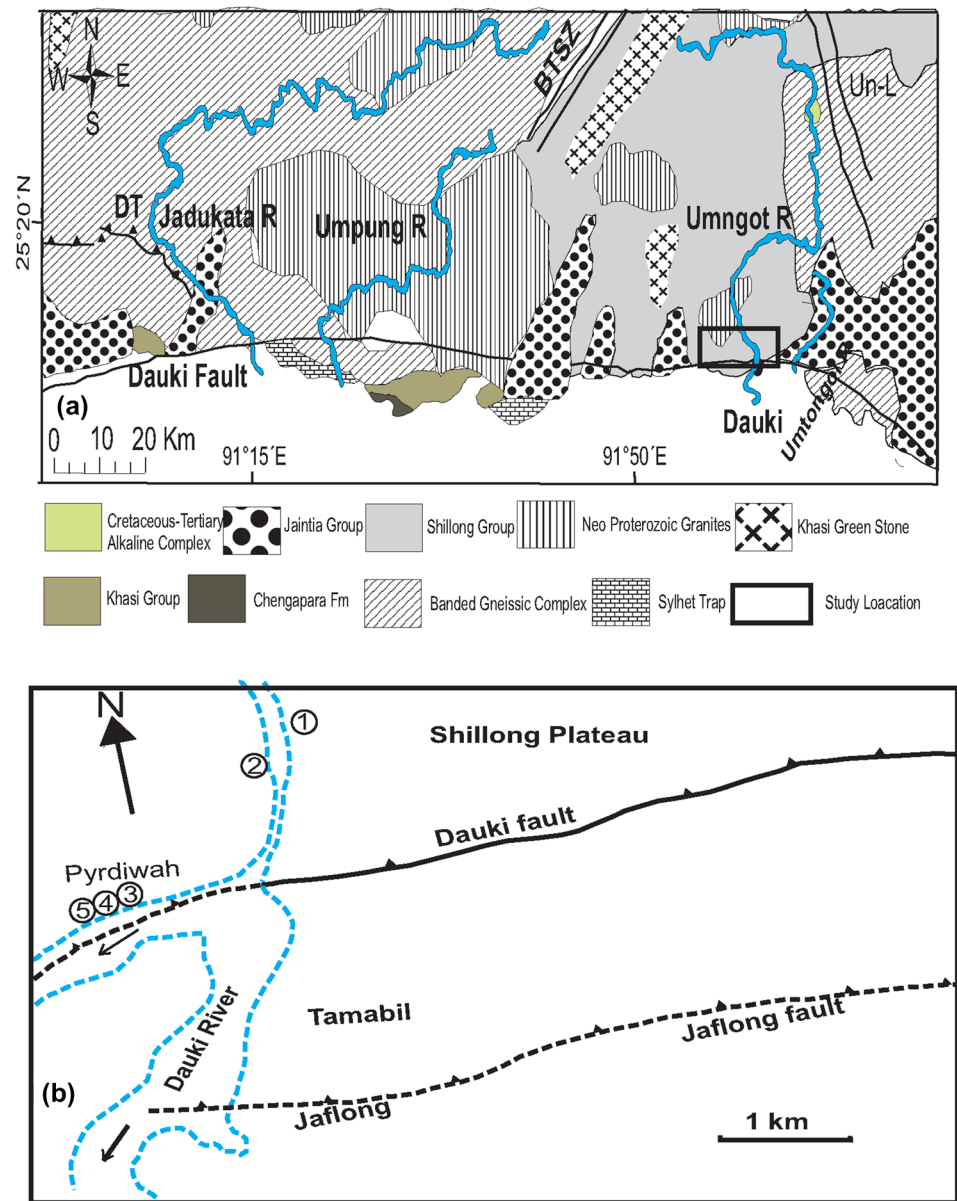
According to Obermeier (1996a) the best sites for trenching for seismites can be found within the meizoseismal areas of large earthquakes. Accordingly, trenching was carried out along the Um Ngot river banks, near the DF, that influenced the 1548, 1897 and 1923 large earthquakes in the area (Fig. 1). Care was taken to break the earth where clay, silt and sand banding was expected. The local geology and geomorphology was closely scrutinized to look for most probable sites for seismite formations. The rivers in spate spill out through their channels and dump the detrital material along their banks. Formation of levees and low-lying pond sediments are also the most likely candidates to scour for seismites. These virgin deposits are the most likely candidates for developing imprints of the large earthquakes that they experience during their infancy. Such suitable places were identified to dig out the trenches. The geomorphic indicators like linearity of the river flow was also taken into consideration

while identifying a suitable location. The location selected for trenching has the meandering Um Ngot River flowing almost in a straight line near the Dauki village indicating an abrupt change in its course due to a physiographic change over the terrain it is travelling. Also, some of the trenches showed cyclic repetition of structures indicating the seismic origin of the deformations. The field evidence also revealed absence of unequal loading that could have led to some deformational features within the sediments.

The study area has copious stretches of partly consolidated, and mostly unconsolidated, floodplain deposits that are saturated with water for most of its thickness. There also exists grain size contrast as well as density variation within the deposit for the grains to rearrange in the wake of sudden and momentary force applied leading to vertically directed hydraulic force generating seismites. Rapid sedimentation can be a possible process that can lead to deformation of the sediments. The study area lies within the Brahmaputra basin which is prone to flooding during the monsoon months. The rate of sedimentation during such episodes could be quite high. However, the soft sediment deformation structures identified in the excavated trenches are found to be at shallow depths precluding overloading of the sediments. In any case, the study area is away from the intense and flash floods so common in the plains of Assam.

In the field, several trial pits were made in the overbank of Dauki River to search for possible seismites, and subsequently trench was made, for detailed study. The detailed lithology (Figs. 3c, 4d, 5d and 6c) of the trenches was prepared in the field and the actual positioning of the deformation features with respect to different layers was understood and fixed. However, the shallow water table, peculiar climatic conditions in the area and the perennial rivers in this NE Himalayan ranges, in some cases, made it difficult to go to the root of the source. Organic material present in the host strata and in the strata subsequently deposited just above the features was collected for dating. The methodology assumes that ¹⁴C date on associated organic material is coeval with the deposition of sediments. However, the organic material is generally older (ten to hundred years) than the sediment in which it is incorporated, depending upon the source of material (plant/tree/herb, outer rings or inner core of tree (Nelson et al. 1995). 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. Six samples were collected for ¹⁴C dating to ascertain the ages of different events and analysed from trenches. The results of radiocarbon dating are presented in Table 1. All samples were analysed by Accelerator Mass Spectrometry (AMS) method (Poznan ¹⁴C Laboratory, Poland). Calendar years were calibrated by the

Fig. 2 **a** Regional geology of the study area **b** Location map of trench sites in and around Dauki River, sites 1 and 2 are at Dauki village; 3, 4 and 5 are at Pyrdiwah village



calibration curve with data set of IntCal04 (Reimer et al. 2004). The error range of calendar years is 2σ .

Soft sediment deformation structures (SSDS)

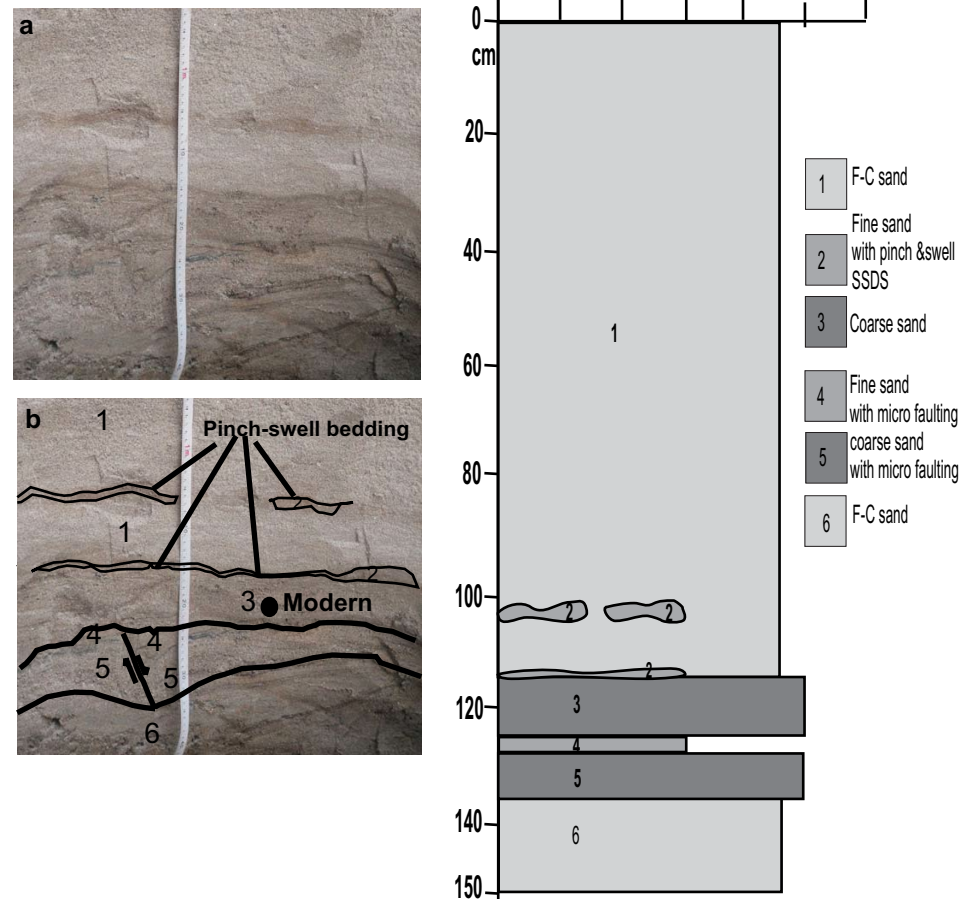
Evidence of past earthquakes in the form of seismites is an alternative way to understand the seismicity of a region in a very comprehensive manner that complements the traditional approaches. It can also aid in giving the recurrence interval of large earthquakes in each area. The area from where the samples have been collected is a watershed area of Um Ngot or the Dauki River that has been draining the hinterland and undergoing avulsion from time to time.

Sites were selected along the banks of this river such that the sediment section was clearly visible and away from any anthropogenic influence.

Sites 1 and 2

These two sites were located, close to each other, on the west bank of the Dauki River near the Dauki village (Fig. 2) where trenches were excavated. At site 1, a section 1.5 m deep and 1 m wide was exposed. In this section six visually distinguishable coarse to fine sand beds of varying thickness can be identified and have been designated as Units 1, 2, 3, 4, 5 and 6 from top to bottom (Fig. 3b, c). Unit 1 consists

Fig. 3 Site 1. **a** Uninterpreted photograph and **b** interpreted photograph of 1.5 m deep trench at site 1 showing pinch-swell structures and micro fault in Units 2, 4 and 5 interpreted to be caused by liquefaction and ground shaking. Unit 1: fine to coarse sand; Unit 2: fine sand with pinch-swell structures; Unit 3: coarse sand; Unit 4: fine sand with faulting; Unit 5: coarse sand with faulting; Unit 6: fine to coarse sand. Solid circle in Unit 3 represents the organic sample collected for radiocarbon dating. The sample (^{14}C date “Modern”) represents the upper bound for the seismic event (possibly 1897). **c** The stratigraphy in the trench is divided into units 1 to 6



of coarse to fine sand with pinch and swell deformation features (of Unit 2), which are seen to be separated by some distance as well as height. Unit 3 consists of bedded coarse sand which is devoid of any deformational features, and the underlying unit 4 consists of fine sand with a black layer of heavy mineral lensoids. The heavy mineral lensoids are clearly seen to be disturbed. The heavy mineral lenses are randomly oriented wherein some are seen to be disturbed from horizontal and some are vertical. Underlying Unit 5 consists of coarse sand and units 4 and 5 are disturbed and displaced by a micro fault with a displacement of 7 cm. Unit 6 consists of coarse to fine sand. At the nearby site 2, just a few metres away from site 1, in the 1 m-wide and 1 m-deep pit, flexuring and intrusion of sand dyke of 3–5 cm in dimension with E–W orientation was observed. The depositional sequence here is constituted by top 50 cm-thick silty sand underlain by fine sand up to a depth of 1 m.

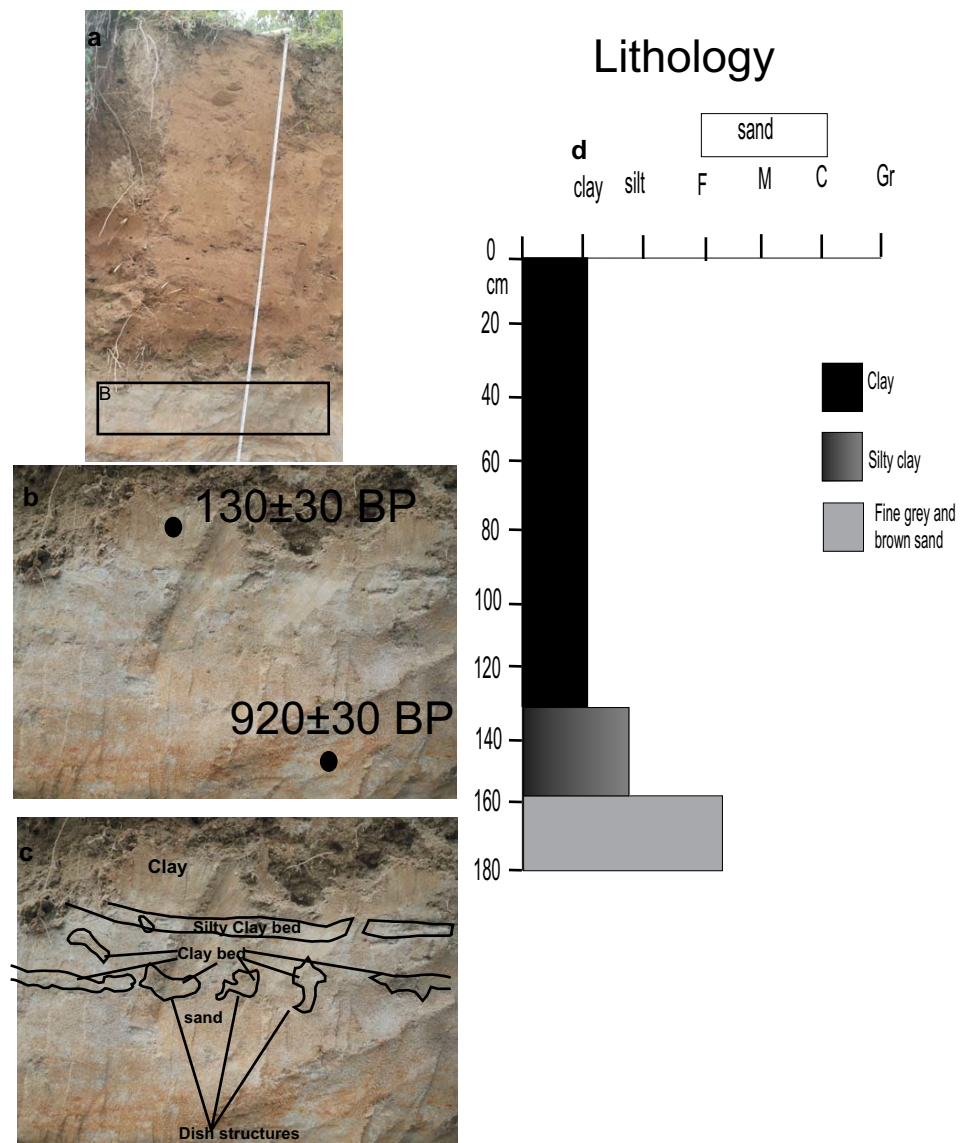
From site 1, plant material was extracted from unit 3, which yielded a “Modern” age. It provides minimum age

constraint for the faulting and maximum for the above deformation features. However, no dates are available for site 2.

Site 3

A 1.8 m-deep and 1.5m-wide trench was excavated at this site near the village of Pyrdiwah, which consists of silty clay, clay and fine grey and brown sand (Fig. 4a). The top 1.0 m sedimentary succession consists of undisturbed clay, wherein at the bottom 0.7 m some deformation features are seen to be present (Fig. 4d). A discontinuity in silty clay layer can be observed at the depth of 1.55 m, where the presence of clasts and individual clay bed deformed by fluid escape dish structures suggests strong, sudden water escape (Fig. 4c). These features are deciphered to have resulted from seismically induced liquefaction. Radiocarbon ages for the two organic sediments collected above and below the deformation features are 130 ± 30 BP (AD 1675–1940) and

Fig. 4 Site 3. Location of (4b) is shown on (4a). **a** The 1.8 m-thick sedimentary succession along the Pyrdiwah village containing deformation features embedded in clay and silty clay beds. Top 1.3 m of the section occupied by clay and followed by silty clay and fine grey to brown sand **b** Uninterpreted photograph and **c** interpreted photograph showing disturbed strata and dish structures. Solid circle represents the organic samples collected for ^{14}C dating. The samples collected from the top clay bed and fine brown sand provide upper bound and lower bound, respectively, for the causative event that occurred during 130–920 years BP. **d** Lithology of the studied trench consists of top clay followed by silty clay and fine grey to silty clay beds



920 ± 30 BP (AD 1030–1180) which, respectively, provides maximum and minimum age for the event (Fig. 4b).

Site 4

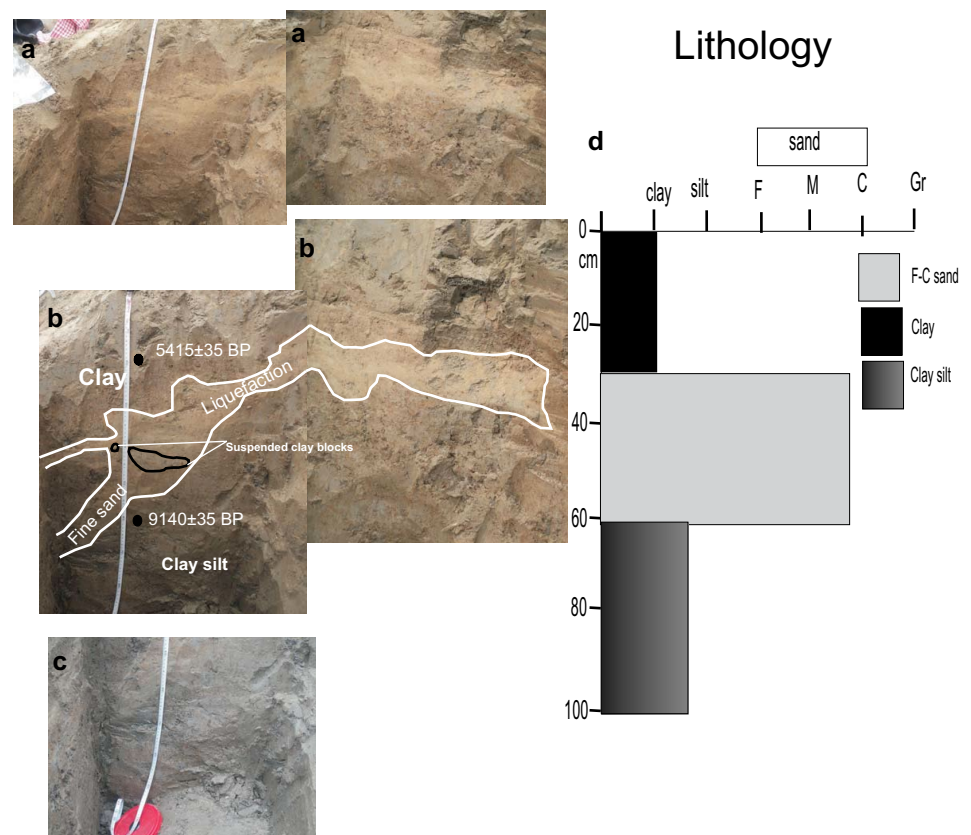
A 1 m-deep and ~1 m-wide trench, at site 4 was excavated few meters away from site 3. The 1-m trench section consists of fine to coarse white and brown sand, with clay overlying it, and clay silt underlying (Fig. 5d). The top 30 cm consists of clay, underlain by fine sand of 50 cm. In this section one can observe red color stains indicative of oxidation. One of the most conspicuous features observed here is intrusion of fine sand into the host sediment, like tubular feeder dyke, that gets wider towards the upper level (Fig. 5b). The sandy layer consists of clasts of host clay sediment. The sand dykes' lateral spread is covered by 10–30 cm-thick fine sand and silt, which must have been deposited after the

dyke intrusion. Incorporation of clasts derived from the host sediment indicates that these features are consistent with an explosive upwelling from a vent (Obermeier 1996b). The AMS ^{14}C dates of 5415 ± 35 BP (BC 4340–4180) and 9140 ± 50 BP (BC 8530–8270) obtained from the top and bottom of the liquefaction features are the maximum and minimum age for the seismic event.

Site 5

At site 5, few meters away from site 3, a 2.1 m-deep and 1 m-wide section was exposed consisting of clay and silty sand (Fig. 6). Liquefaction dykes have been observed with conical and tubular shape (Fig. 6b). Branching of liquefaction is also observed and formation of these sand dykes is attributed to the generation of cyclic shear stresses. The

Fig. 5 Site 4. **a** Mosaic photograph of ~1 m trench excavated reveals liquefaction features that can be attributed to violent shaking of the earth. **b** Interpreted Mosaic photograph showing sand dyke is intruding into the upper clay layer and form a sill in the right flank of the trench. The suspended clay blocks might be included in the sand during movement related to liquefaction. Solid circle represents the organic samples collected for ^{14}C dating. The samples collected from the top clay bed and below the sand dyke provide upper bound and lower bound, respectively, for the causative event that occurred between 5410 and 9140 years BP. **c** Bottom of the trench section showing clay silt and fine to coarse sand beds **d** Lithology of the studied trench consists of top 30 cm clay followed by fine-coarse sand and clay silt beds



organic sediment collected from within the liquefaction feature provides AMS ^{14}C age of 4285 ± 35 BP (BC 3010–2870) for the seismic event that led to liquefaction (Fig. 6b).

Discussion

Interpretation of soft sediment deformation structures (SSDS)

There are several possible mechanisms that may be involved in SSDS. Such mechanisms include rapid deposition of sand leading to over-pressure in underlying sediments (Lowe and LoPiccolo 1974), gravity driven density (Jones and Omoto 2000; Spalluto et al. 2007), and shock from earthquakes (Sims 1975). These SSDS can be the result of liquefaction and fluidization of sands, silts and clays and loss of coherence because of increased pore fluid pressures that exceed shear strength. Such overpressures may result from rapid deposition of sand over mud with a high-water content (Lowe 1975; Owen 1996; Jones and Omoto 2000), due to the passage of storm waves/currents, the arrival of gravity-driven density currents (Pope et al. 1997; Jones and Omoto 2000) or the passage of a seismic wave (Sims 1975). Seismically induced vibrations destabilize the granular framework causing the granular solid to behave like a fluid (Lowe 1975;

Pope et al. 1997). Seismic activity may result in the deformation of unconsolidated sediments leading to liquefaction and fluidization (Obermeier 1996a; Sukhija et al 1999; Gucione 2005). These seismically induced SSDS (Ricci Lucchi 1995) are important indicators of syn-sedimentation earthquake activity and can throw light on the tectonic setting of the depositional basin (Seth et al 1990).

The trenches revealed presence of deformation features such as micro fault, sand intrusion, water escape structures and disturbed beds, besides pinch and swell structures. The sedimentary layer hosting the fault is covered by undeformed sedimentary layers indicating syn-sedimentary origin of the faults. Seilacher (1969) first described such syn-sedimentary faults and questioned their genetic relation to earthquakes (Seilacher 1984). However, according to Vanneste et al (1999) and Singh and Jain (2007) such faults may develop by earthquake shocks. Faults are a semi-brittle type of soft-sediment deformation formed by an increase in pore pressure in the sediment due to the instantaneous action of stress (Vanneste et al 1999 and references therein). Syn-sedimentary faults and other SSDS are formed because of localized stresses induced by seismicity (Anand and Jain 1987; Miyata 1990). Hence faults in soft-sediment cannot be generated from downward slumping alone. The sedimentary faults are localised features. The surface do not have any slickensides on them or crushing adjacent to them. Load features are also

Fig. 6 Site 5. **a** Uninterpreted photograph and **b** interpreted photograph showing liquefied silty sand dyke into the formless host clay. Solid circle represents the organic samples collected for ^{14}C dating. The samples collected from sand dyke provide lower bound placing maximum age of 4290 years BP for the causative event. **c** Lithology of the studied trench consists of top 60 cm silty clay followed by 100 cm of clay and 40 cm of silty sand

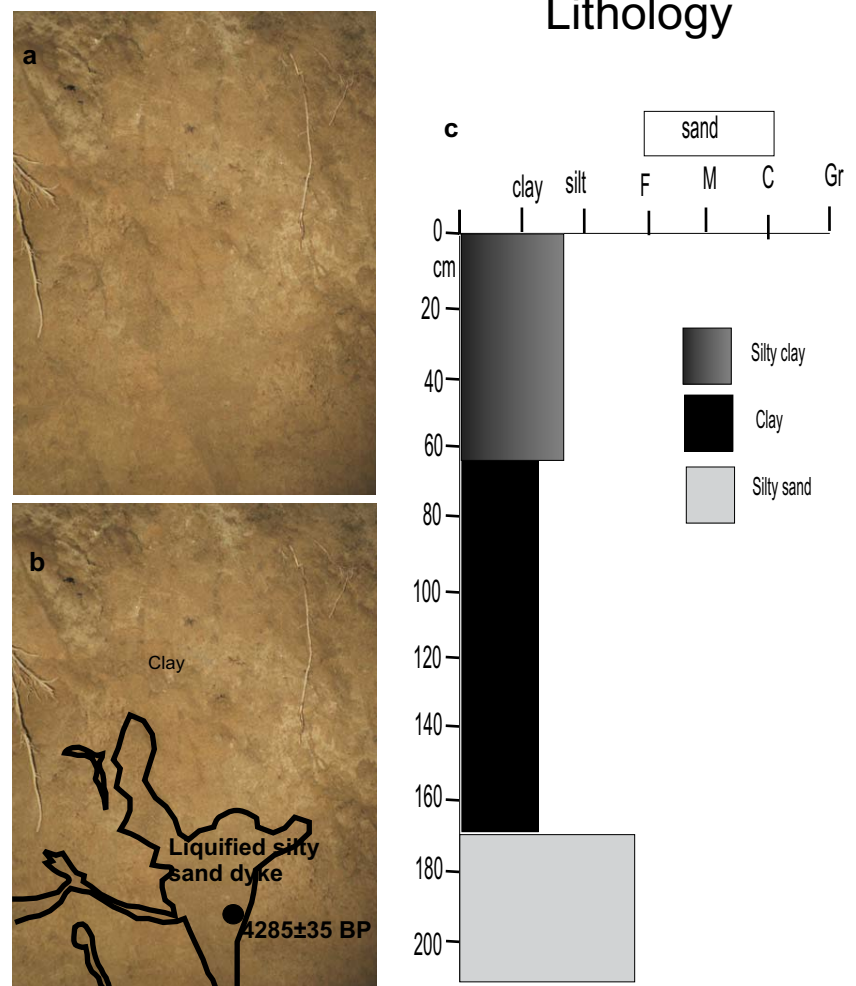


Table 1 AMS Radiocarbon Dates of the organic matter from the studied Trench sites

Sample ID	^{14}C age (year BP)	Calibrated ages (years AD, 2σ)
DK-1POZ-82946	102.58 ± 0.32	Modern
DK-2 POZ-82942	130 ± 30	(cal A.D.1675: cal A.D.1777) (cal A.D.1799: cal A.D.1894) (cal A.D. 1905: cal A.D.1941) Range: A.D.1675–1940
DK-3 POZ-82941	920 ± 30	(cal A.D.1029: cal A.D.1170) (cal A.D.1172: cal A.D.1183) Range A.D.1030–1180
DK-4 POZ-82943	5415 ± 35	(cal B.C.4344: cal B.C. 4230) (cal B.C.4194: cal B.C. 4176) Range B.C.4340–4180
DK-5 POZ-82944	9140 ± 50	(cal B.C.8533: cal B.C. 8515) (cal B.C.8481: cal B.C. 8270) Range: B.C.8530–8270
DK-6 POZ-82945	4285 ± 35	(cal B.C.3011: cal B.C. 2948) (cal B.C.2944: cal B.C. 2873) Range: B.C.3010–2870

AMS dating of organic samples were conducted at Poznan Radiocarbon Laboratory (Poland)

Calendar years were calibrated using the intcal 104 data set (Reimer et al. 2004). The error range of calendar years is 2σ . Ages are rounded off to the nearest decade. Age ranges are rounded off

absent above the deformed horizon. So, this faulting is not due to slope-gravity controlled slumping of the undeformed sediment. Hence a seismic shaking can be envisaged for the development of such soft sediment deformation features (cf. Singh and Jain, 2001). The water escape structures can be directly related to gravitational readjustment (upward-directed movement of underlying light sands), and/or it can be the result of beds with different selective fluidization processes arising from the restoration of grain supported packing after complete liquefaction (Allen 1982; Owen 1987). Sediments can be liquefied by external shocks and then moving up through cracks which may form water escape structures (Collinson and Thompson 1982). Shear stress may be generated during water escape leading to disruption of overlying lamination; additionally, voids may form during dewatering within the sediment, which influence fluid drag that may balance gravitational forces (Tasgin and Turkmen 2009 and references therein). According to Lowe (1975), gravitational pull or overloading only play a subordinate role in the formation of water escape structures; consequently, seismic shocks are thought to be responsible for their formation (Moretti et al 1999). Hence the water escape structures breaching the sand–clay laminae in the present study can reasonably be interpreted as reflecting seismic shocks. The occurrence of pinch-and-swell structures and dykes suggest that the deformation mechanism reduced the sediment strength and some driving force-induced deformation from the sediment column. The underlying and overlying undeformed beds were deposited before and after the development of SSD structures. This also shows that the deformation was of limited duration producing confined SSD structures. According to Ghosh et al. (2012) when the pore water pressure is greater than the load pressure and less than the confining pressure, antiformal cusps, small-scale folding as well as contorted beds are formed, but when the pore water pressure in the liquefied bed is significantly larger than the confining pressure, dykes are formed.

The observed SSDs are correlated with seismites and are validated in the present study on the basis of field evidence, previous studies, together with the important criteria given by Sim, (1975), which are as follows: absence of slump, slope failure or gravity pull; the SSDs are found between sand and clay layers and are invariably separated by the undeformed sub horizontal beds; these are small scale internal structures within deformed zones that suggest liquefaction; different types of structures are present together indicating synchronicity and instantaneity of deformation; the deformed horizon is underlain and overlain by undeformed strata; sedimentation occurs within an active tectonic setting, and similar structures have been described in published literature as seismites (Seilacher 1969; Sims 1975; Jones and Omoto 2000; Bose et al 2001; Wheeler 2002; Rodriguez-Lopez et al. 2007; Sarkar et al. 2014; Singh

et al. 2020). SSDs and the formation of clastic dikes in the Himalaya have recently been related to in situ deformation during earthquake shaking (Jayangondaperumal et al 2008; Mugneir et al. 2011; Rajendran and Rajendran 2011) and are referred as to be seismites.

Age analysis of soft sediment deformation structures

The geological evidence and AMS radiocarbon dates have revealed four palaeoseismic events that occurred between 130–920 BP; between 5420 and 9140 BP; at 4290 BP and Modern. Almost all the deformational features observed in the trenches are confined to specific layers and have undeformed sediments over and below these features. At site 1 (Fig. 3) micro fault, displacement of two layers, unit 4 and 5, by almost 7 cm and pinch swell bedding at the top of the trench is clearly visible. Their formation at different levels suggests these features belong to two distinct seismic events. Unfortunately, the lack of suitable material rendered just one maximum age “Modern” for unit 3. The modern age for Site 1 is a curious finding/feature as it has captured the historical earthquake within the confines of the sediments. It is quite tempting to attribute the deformation features that are present above layer 3 to the 1897 event. The younger formations have developed pinch and swell structures due to intense shaking of the detrital material. However, the faulting observed at the site is inferred to have been caused by an older seismic event. Units 4 and 5 are highly deformed and even faulting is seen to have occurred between the two. Assuming the rate of deposition of sediments from the thickness of modern sediments is quite brisk, the Unit 4 and 5 sediments could be not more than 200–300 years old than the ‘Modern’ sediments. If this be the case, then the observed faulting could be speculated due to ~1548 AD event as the upper deformation features are caused by 1897 earthquake. However, such a proposition could be pure speculation since the rate of deposition of sediments is not quite uniform in any fluvial system. It depends largely upon climate and lithology as well as the gradient of the river. There are ‘episodes’ of deposition and erosion which do not seem to be proportional to each other. The episodes of erosion could be far greater in scale than deposition and vice versa. Hence, assigning an age for such sediments could be specious. Be that as it may, the fact that the older sediments contain signatures of multiple earthquakes is an important factor in determining the palaeoseismicity for a region. Based on historical observations and field evidence, evidently, liquefaction is seen to have a strong tendency to recur at the same site (Obermeier 1996b).

The seismic activity captured at trench site 3 (Fig. 4) has provided the lower and upper bound AMS radiocarbon ages within a timeframe spanning between 130 and 920 years BP.

The window of possible earthquake (Fig. 5) is quite large at trench site 4, of almost 4000 years (AMS radiocarbon dated for the upper bound 5415 ± 35 years BP and the lower bound to be 9140 ± 35 years BP), indicating a period of long hiatus in deposition. AMS Radiocarbon age for the lone organic sediment sample from the trench site 5 (Fig. 6), within the dyke, is found to be 4284 ± 35 year BP. This is taken to be the contemporaneous age of the event that caused the deformation. Interestingly, the contemporary age of deformation at trench site 5 can be applied to the deformation event unraveled at site 4. The long gap revealed by the upper and lower bound ages for site 4, can be filled in by the coeval age obtained at site 5. This scenario, though speculative, seems plausible. The generation and compilation of radiometric ages, when seen in consonance with the geological formations, suggests the liquefaction features observed at these trench sites are a result of distinctly different events. The well documented event(s) at sites 4 and 5 belong to mid-Holocene.

Source Characteristics

It must be noted that spatially restricted investigation, based on limited sites along Dauki River as shown in this study, are insufficient to classify the source characteristics of liquefaction features observed in the trenches. However, paleo-liquefaction studies conducted by Sukhija et al. (1999), Rajendran et al. (2004) and Morino et al. (2011, 2014) in the Indian side of SP offer some benchmark dates to compare our obtained results in the DF region from the present study (Fig. 7). Sukhija et al. (1999) carried out paleo-liquefaction studies along the Krishnai River, on the northern margin of the SP, and suggested that except the 1897 Ms. 8.0 Great Assam earthquake, two other seismic events caused paleo-liquefaction, i.e., the events in 500 ± 150 years BP and 1100 ± 150 years BP. Rajendran et al. (2004) re-examined the data and modified the radiocarbon ages obtained by Sukhija et al. (1999) to calendar years. This yielded A.D. 1450–1650 and A.D. 700–1050 as the periods of occurrence of these two events. Morino et al. (2011, 2014) conducted paleoseismic studies in Gabrakhari and Jafalong, along DF, Bangladesh and the seismic events identified correspond to A.D. 840–920, A.D. 1548 and 1897 (Fig. 6). The radiocarbon ages at sites 4 and 5 from the present study are older than these events in this region.

The 2σ calendar ages (Table 1) for liquefaction at site 3 are inferred to lie between A.D. 1030–1180 and A.D. 1675–1940. The seismic event has occurred after A.D. 1030. The 1548, 1897 and 1923 earthquakes are known as large historic earthquakes which have occurred after A.D. 1030. Though the ages obtained from the present effort do not seem consistent with the documented seismic events by Sukhija et al. (1999), Rajendran et al. (2004) and Morino

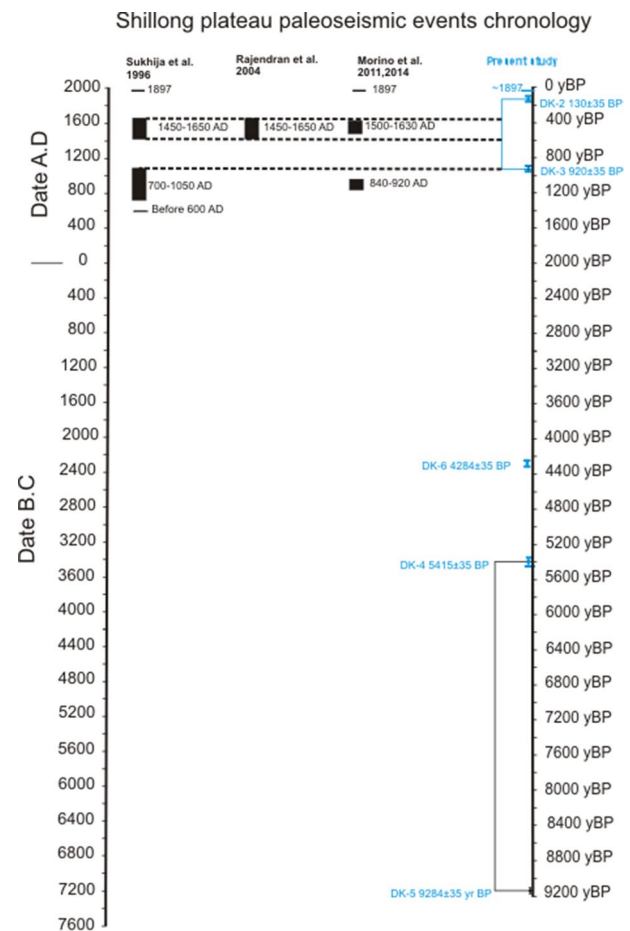


Fig. 7 The occurrence of earthquakes depicted in trench sediments unraveled by different workers is stacked up for possible correlation of events. Sukhija et al (1999), Rajendran et al (2004) and Morino (2011, 2014) dated events are compared with our findings. There is some consonance with the younger events. However, the older events are reported for the first time in this study

et al. (2011, 2014), they can still find some overlap with the ages of 500 ± 150 years BP Sukhija et al. (1999), Rajendran et al. (2004; 1450–1650 AD) and Morino et al. (2011; 1548 AD). According to Rajendran et al. (2004) the A.D. 1450–1650 paleo-liquefaction had a distant source influenced by DF. The present study reveals the north-dipping DF has caused paleo-liquefaction towards north and south of the SP. The 1897 liquefaction on the northern margin of the Shillong Plateau may have also been created by the activity of the DF. Since all the studied sites are very close to the DF and lie in the hinterland or hanging wall of the DF we tentatively assign paleoearthquakes related to this liquefaction to movement along the DF. SSDS can be formed both in the static stress (near the epicenter) and dynamic (away from the epicenter) stress-dominated regions (cf. Jayangondaperumal and Thakur, 2008). However, farther earthquake induced by

Himalayan structures or other transverse structures can also equally plausible.

However, the formation of these deformation structures (seismites) by earthquakes in far off Himalayan region are plausible, though they can be discounted on account of the evidence that has been listed in the previous sections. In the present case, the earthquake magnitude was large enough to produce a significantly enhanced pore pressure leading to soft sediment deformation. The magnitude of the seismic events can be roughly estimated by examination of trends of liquefaction versus the epicenter distances of modern earthquakes. Liquefaction over a wide area is likely to have been triggered by earthquakes of a magnitude of ≥ 5.5 or 6 and earthquakes of a higher magnitude (Allen 1985). The type, size, and extent of earthquake-induced SSDS are generally controlled by various factors. Some researchers have suggested that SSDS induced by seismic liquefaction are genetically related to seismic shocks of $M > 5$ (Ambraseys, 1988; McCalpin, 1996). The threshold magnitude for inducing initial liquefaction in sand deposits is about 5.0, whereas the magnitude for gravel deposits is about 7.0 (Obermeier, 1996b). Monecke et al. (2004) suggested that disturbed and convolute structures are generated by earthquakes when $M = > 5.5$. Marco and Agnon (1995) documented that seismically related surface faults could be generated at magnitudes equal to or greater than 5.5. Considering the quantitative analyses of the threshold of liquefaction in terms of the magnitude of palaeo-earthquakes, the SSDS in the study area, likely resulted from earthquakes with $M > 5.5$. Accordingly, liquefaction is not likely to occur more than 70 km from an earthquake epicenter with magnitude $M = 7.0$. For $M = 7.5$, the liquefaction distance may not exceed 100 km, however, Galli (2000) has showed a 7-magnitude event can lead to the formation of seismites even beyond 100 km. Applying Ambraseys (1988) regression of moment magnitude to distance of farthest liquefaction to epicenter, the long-axis radii of the Dauki liquefaction fields (12 km) suggests a local earthquake of ≥ 5.5 –6.

Rajendran et al. (2004) suggested that earthquakes of sizes like 1897 must have occurred in Assam due to a fault lying below the valley and the recurrence interval (RI) of such earthquakes is approximately 1200 years. Sukhija et al. (1999) concluded from the paleoliquefaction studies that the RI of major earthquake in the SP is 400–600 years and for great earthquakes the RI is 500 years. However, RI cannot be inferred based on liquefaction study provided actual epicenter or causative fault is known. Present study has unfolded at least four major earthquakes in a time span of 9000 years. Since all these earthquakes are local, an average recurrence interval for the Dauki region comes out to be about 2250 years for $M 5.5$ to 6.5 events. Though there are no enough age data to collate, cursory inspection of Fig. 7 indicates lack of seismic activity for a long period of time

from 4000 to 1000 years ago, suggesting temporal clustering of earthquakes and a 3000-year interval between clusters. Alternatively, this hiatus may be an artifact of limited sampling. We also speculate that this hiatus may be due to a low water table and thus reduced liquefaction susceptibility during a drier mid-Holocene climate. However, this could be a very premature inference since few studies are carried out on the mid-Holocene sediments. The limited data from the present study are not sufficient to estimate the recurrence interval of large to great earthquakes in this region. However, the agreement in the ages obtained for the recent sediments with those of other independent workers is a very positive indication for continuing trenching for seismites. Such an approach is most likely to work out the recurrence interval of the devastating earthquakes that visited the SE Shillong plateau. Our preliminary studies in the region have provided a robust time series of earthquakes, which further underlines the need to excavate more trenches in and around Dauki and the Shillong regions.

Conclusions

The following conclusions can be drawn from the present study.

(1) Trenching carried in meizoseismal areas of 1548, 1897 and 1923 large earthquakes occurred in areas contiguous to the DF unraveled seismites at five locations wherein the geological and geomorphological terrain is quite complex.

(2) The SSDS features identified in and around DF region contained micro fault, sand dykes, detached blocks suspended in sand, water escape structures and pinch-swell features formed through liquefaction of alluvial sediment during strong ground shaking.

(3) This area is inferred to have experienced four episodes of (Modern, 130 and 920 yr BP, 5415 to 9140 yr BP, and at about 4285 yr BP) seismic shocks imprinted in the sediments contain seismically deformed diagnostic features.

(4) The present study, in unambiguous terms, revealed the north-dipping DF caused paleo-liquefaction towards north and south of the SP. The present study provides for the first time the geological evidence of at least four distinct major events that occurred during the mid-Holocene and recent times indicating DF is active at least since mid-Holocene.

(5) A provisional recurrence interval of ~ 2250 years for $M 5.5$ to 6.5 events is inferred for the Dauki region. It experienced four major seismic events in a span of 9000 years. However, more trenching and dates are required for arriving at a more realistic recurrence interval.

(6) The Dauki region likely did not experience any seismic activity from 4000 to 1000 years. Clustering of earthquakes is inferred from the present study.

(7) The robust time series of earthquakes provided in the present study can be further refined, which further underlines the need to excavate more trenches in and around DF in particular, and the SP region as a whole.

(8) Close agreement is found in some related studies by other independent workers.

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Declarations

Conflict of interests The authors declare no competing interests.

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