Review Paper:

A review on the tectonic setting and seismic activity of the Shillong plateau in the light of past studies

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Abstract

The Shillong Plateau originated due to the movement in the faults surrounding it; however which fault caused the uplift of the plateau is debatable. Several earthquakes have occurred in the plateau due to these surrounding faults. One such earthquake is the Assam earthquake of 1897 (Mw=8.1). Also, there are evidences that similar earthquakes had occurred prior to 1897. In the light of the partial evidences, the return period of such great earthquakes remains uncertain. Further, several research studies had also highlighted the damages evidenced in the Shillong Plateau during many of the past earthquakes. The location and mechanism of such earthquakes however were observed in a variety of ways by different researchers.

This paper presents a detailed review on the different opinions about the origin of the Shillong Plateau as well as the location and orientation of the faults surrounding it. Further, a detailed discussion on the devastations caused by past earthquakes in terms of geological changes, structural damages and loss of life during each of the past earthquakes is done. This study highlights the need for detailed regional studies to be conducted in the Shillong Plateau filtering out the different opinions by various researchers such that ongoing seismicity can be considered for future studies.

Keywords: Shillong Plateau, seismicity, past earthquakes, damages, active faults.

Introduction

The Indian plate is subducting under the Eurasian plate in the north. Towards the east the Indian plate is colliding and subducting under the Burmese plate. The northern subduction zone brought the Himalayan mountain ranges into picture while the eastern collision-subduction zone caused the existence of the Indo-Burma ranges as mentioned in figure 1. The north-eastern region of the Indian plate is thus located in the converging zone of these two mountain ranges. As a result of which the region has a complex tectonic setting with a history of past large to great earthquakes.[2,17] Some of the well-known earthquakes (EQs) that had occurred in the region include 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(Mw 6.9)[6].

Based on the distribution of epicenters of past reported earthquakes and taking into account the regional seismic activity, the north-eastern region was divided into five seismotectonic zones namely; (1) Northeastern Himalaya, (2) Indo Burma ranges, (3) Eastern Himalayan Syntaxis, (4) Shillong Plateau-Mikir hills-Assam valley and (5) Bengal Basin and Tripura fold belt[17]. Each of these regions extends across large areas with wide variety of topography and geological characteristics. For the present work, detailed consideration is made for the Shillong Plateau tectonics.

The Shillong Plateau-Mikir hills-Assam valley region extends from the Himalayas in the north to Bangladesh in the south. Both the Shillong Plateau and the Mikir hills show high seismic activity as a result of which many damaging earthquakes have occurred in the past. The 1869 Cachar EQ (M_w=7.5) and the 1943 Assam EQ occurred on the N-S trending Kopili fault. This fault lies in between the Shillong Plateau and the Mikir hills as shown in figure 1. To the south of the Shillong Plateau is the E-W trending Dauki fault (Figure 1) which is responsible for the 1923 Meghalaya EQ (M_s=7.1). Towards west of the Shillong Plateau is the N-S trending Dhubri fault (Figure 1) which caused the 1930 Dhubri EQ(M_s=7.1)[17]. The location and year of occurrence of these past earthquakes are shown in figure 1 along with the faults surrounding the Shillong Plateau. According to Bilham and England[4], the great earthquake of 1897 known as “Assam earthquake” was caused by two faults bordering the Shillong Plateau. First was the Dauki fault in the south and second fault was in the north of the plateau which was called as the “Oldham Fault” by Bilham and England[4]. The Oldham fault as per Bilham and England[4] is a 110km long fault dipping 57° to the south beneath the northern edge of the Shillong Plateau.

The seismic activity in the neighboring Assam valley is relatively less compared to the seismicity of the Shillong Plateau and the Mikir hills. However a high level of seismic activity was seen towards east in the collision-subduction zone of the Himalayas and the Indo-Burma ranges. This zone is known as the Assam syntaxis. It was the source zone for the 15th August, 1950 Assam EQ (Ms=8.7) which is considered to be one of the most damaging earthquakes in India. The Assam valley area between the Assam syntaxis and the Shillong Plateau is known as the Assam Gap[19]. The seismically inactive Assam Gap is expected to be the zone of anawaiting future earthquake of larger magnitude (M>7.0)[17].

In the present work, a review is presented about the different opinions made by various researchers about the origin of the Shillong Plateau in the light of available records of past earthquakes in and around the plateau. Further, the seismicity of the plateau is highlighted with a detailed discussion on past earthquakes in terms of damages to various kinds of structures, the amount of casualties and the geological changes made in the region during each of the earthquakes. The contrasting views in relation to the faults bounding the Shillong Plateau and their association with the great 1897 Assam earthquake are also highlighted in this work.

Tectonic setting of the Shillong Plateau: The Shillong Plateau[32] is spread over approximately 47,614km^2.The coordinates of the Shillong Plateau are at latitude 25°34'60" N and longitude 92°0'0"E as shown in figure 1. The Shillong Plateau originated approximately 60 million years ago when the Eurasian and the Indian plates started colliding with each other in the N-S direction.[10] During the same time the Indian plate was also sub-ducting under the Burmese plate in the E-W direction[29]. As a result of the N-S collision and the E-W subduction, the area in between the two zones had developed complex tectonic setting. This led to the formation of the five different seismotectonic regions as discussed above. Considering the extent of past reported damages and the active faults available around the Shillong Plateau, understanding its seismic potential is very important.

A number of faults surround the Shillong Plateau while another set of faults exists within the plateau itself. The Shillong Plateau is separated from the Bengal Basin in the south by the Dauki Fault. The Dauki fault is an E-W trending, approximately 320km long north dipping reverse fault. It extends from latitude 25°14'30"N and longitude 91°13'00"E in the west to latitude 25°10'00"N and longitude 93°02'00"E in the east as shown infigure 1. As per Murthyet al[23], the Dauki fault is a system of four faults, dipping towards north on surface level and then continuing further below the surface. Further, Srinivasan[35] performed remote sensing studies of the Dauki Fault with the help of aerial photographs and field surveys. As per Srinivasan[35], it was found that the eastern segment of the Dauki Fault from Borghat in Meghalaya to Leike in Assam is a single fault and not a system of faults as proposed by Murthy et al[23]. Also, the fault was found to dip towards south as a normal fault contrary to the findings of Evans[8].

The investigation performed by Srinivasan[35]further highlighted that the sediments of the Surma valley south of the Dauki Fault had folded and pushed towards the west, thus implying a right strike slip movement of the Dauki fault. A northwest extension of the Dauki fault is the Dapsi thrust which exists within the plateau along NW-SE direction and is 90~100km long. It is a reverse fault with a strike slip component. Dapsi thrust separates the sediments of the Bengal basin to the southwest of the Shillong Plateau from the rocks of the plateau itself in the northeast.[13,17]

Towards the northeast of the Shillong Plateau lie the Mikir hills, the NW-SE trending Kopili fault separating the Shillong Plateau from the Mikir hills. The Kopili fault is 300-400km long and 50km wide fault and it extends in the north to the Main Central Thrust (MCT) in the Himalaya as shown in figure 1.Kayal et al[15] had analyzed the data for a period of 2001 to 2003 from a 20 permanent station digital seismic network to understand the seismicity of the Shillong Plateau. The results of the analyses by Kayal et al[15] showed a cluster of earthquake epicenters to be concentrated on the Kopili fault. Further, two cross sections of the events found on the Kopili fault zone were examined by Kayal et al[15].The first section was developed in the NW-SE direction, along the direction of the fault. The second section was createdin the NE-SW direction across the fault. The sections revealed that the intense seismic activity was located at an approximate depth of 50km below the Kopili fault.[15,16] The Kopili fault was also found to have a normal and strike slip faulting with a dip in the N-E direction. The recent seismicity discovered along the fault has led to speculations that the Kopili fault is one of the most seismically active faults of the region and a major earthquake could be expected in the future.[15,16]

Further to the north of the Shillong Plateau is the Brahmaputra River which separates this plateau from the Himalayas as shown in figure 1. The N-S trending Dhubri fault lies to the west of the plateau separating the plateau from the Indian subcontinent (Figure 1). Other faults in and around the plateau include the Chedrang fault, the Samin fault, the Dudhnoi fault and the Barapani shear zone[2,15]as shown in figure 1. The presence of number of seismic sources around the Shillong Plateau had resulted incomplex tectonic setting of the plateau resulting in several earthquakes; the oldest great earthquake known to man in the Shillong Plateau is reported to be before 600 AD[38]. From 1762 a total of 156 earthquakes were reported to occur in the Shillong Plateau. The greatest earthquake reported in the Shillong Plateau is the 1897 earthquake of Mw 8.1[33].

Uplift of the Shillong Plateau: Past studies had suggested that the earthquakes occurring in the Shillong Plateau are the result of the uplift of the plateau itself. There exist many views on the reason for the uplift of the Shillong Plateau. As per Khattri et al[20] and Kayal and De[14], the plateau was a Horst which rose due to thermal disturbance in the upper mantle. Similarly as per Kailasam[11], Shillong Plateau rose as a result of isostatic adjustment. However the most popular theory for the uplift of the Shillong Plateau is the popping up of the plateau due to tectonic movement.[4,13,18,28,29,34] According to Kayal[18], Kayal and

De[13], Rao and Kumar[29], Bilham and England[4], Rajendran et al[28] and Srinivasan[34], the Shillong Plateau rose as a result of movement along the faults bounding the plateau and popped up to the present position. Further there exist various opinions about which faults are responsible for the "pop up" mechanism of the plateau.

Kayal[18] and Kayal et al[15] performed microearthquake studies in the Shillong Plateau and the Assam valley during the periods 1982-1984 and 2001- 2003 respectively to study the complex tectonic model of the Shillong Plateau. As per the above studies the seismicity was found to be highest in the western part of the Shillong Plateau. Kayal et al[15] concluded that the pop up of the Shillong Plateau was due to the Dapsi thrust in the west and the Brahmaputra Fault. As per Rajendran et al[28], the Brahmaputra fault is a south dipping fault located below the Brahmaputra River in the Assam valley to the north of the Shillong Plateau. The fault plane solutions obtained by Kayal et al[15] inferred that the Dapsi thrust and the Brahmaputra faults were the two boundary faults of the plateau. The sections taken along the depth of the Shillong Plateau and the fault plane solutions for the earthquakes recorded during 1982-1984 and 2001-2003 as per Kayal[18] and Kayal et al[15] revealed that the N-E dipping Dapsi thrust in the western part of the plateau is seismically active. Also the maximum intensity isoseism of VIII for the 1897 earthquake lies over the Dapsi thrust.

Another study performed by Rao and Kumar[29] proposed that the complex tectonic setting of the Shillong Plateau had lead to compressive forces which resulted in "pop up" mechanism of the plateau. Further Rao and Kumar[29] suggested that the "pop up" structure was facilitated by the Dauki fault in the south, the Brahmaputra fault in the north, the Dhubri fault in the west and the Disang thrust in the east of the Shillong Plateau.

The Bengal Fan defines the entire surface area of the Bay of Bengal. According to Bilham and England,[4] the Himalayas in the north and the thick sediments of the Bengal Fan to the south and east of the Shillong Plateau have added weight to the region around the plateau. Along with this the west ward movement of the Indo-Burma range towards the Bengal Fan added more weight to the Indian plate[4] as a result of which the Indian Plate below Shillong Plateau underwent flexure. In order to relieve these bending stresses, the Indian plate popped up between two bounding faults to its north and south. The fault in the south is the north dipping Dauki Fault and towards north is the Oldham Fault. Bilham and England[4] proposed that the Oldham fault is a 110km long, 57° south dipping reverse fault beneath the northern edge of the Shillong Plateau.

With the help of geodetic and GPS data, Bilham and England[4] found that the 1897 earthquake occurred as a result of slip of 16m along the Oldham fault. Further, Bilham and England[4] suggested that the earthquake was a blind earthquake with the slip on the plane extending to a depth range of 9 to 45km below the surface. Bilham and England[4] also concluded that during the 1897 Assam earthquake the northern edge of the Shillong Plateau rose by 11m and the return period of earthquakes similar to 1897 in the plateau is 3000 years.

Later,Nayak et al[24] developed a gravity model to inspect the presence of the Oldham fault in the north of the Shillong Plateau. As per Nayak et al[24], the gravity model showed a change in the gravity values from -30mGal to 0mGal over a distance of 25km which weakly supported the existence of the Oldham fault on the gravity map. Further Nayaket al[24] compared the gravitational potential energy required to uplift the plateau by 11m as given by Bilham and England[4] with the energy released during the 1897 earthquake using an empirical correlation between surface magnitude and energy.[12,27]

Based on the work by Nayak et al[24], it was found that the energy required to uplift the plateau to a height of 11m is $4.5x10^{19}$J and the energy released during 1897 was $4.8x10^{19}$J. Similarly the seismic moment generated by the 110km long Oldham fault was compared to the seismic moment obtained by keeping the moment magnitude Mw as 8.1and using empirical relations. The study revealed that the seismic moment generated by the Oldham fault during the 1897 Assam earthquake was $2.18x10^{21}$ N-m and the seismic moment obtained from the empirical correlation was $1.86x10^{21}$N-m[24]. Hence, the gravity model of Nayak et al[24] clearly supported the presence of the Oldham fault of Bilham and England[4].The gravity model also revealed that there was no fault further to the north of the Oldham fault and thus this fault demarcates the northern boundary of the plateau.

Further studies on the existence the Oldham fault of Bilham and England[4] include geophysical field investigation with the help of Magnetotelluric (MT), Deep Electrical Resistivity Sounding (DES) and the analysis of seismological data previously recorded by permanent or temporary networks by Saha et al.[31] The integrated DES and MT surveys were performed along three different traverses across the Shillong Plateau and the Assam valley. Based on the tests it was found that the earth's crust dipped towards north from the Shillong Plateau to the Assam valley. The MT stations located north of the proposed Oldham fault of Bilham and England[4] also showed conductive zones at a depth of 8km. These conductive zones were interpreted as faults or shear zones.

Further Saha et al[31] confirmed that the conductive zones detected by the MT stations were oriented in the NW-SE direction, similar to the direction of the Oldham fault but there were no visible signs of any deeper conductive zones to the south of these stations. According to Saha et al[31], a steep dipping, 110 km long fault like the Oldham fault would have been detected by the MT instruments further towards south if it really existed. Hence Saha et al[31]concluded that the MT survey results did not reveal the Oldham fault. However the analysis of previously recorded microearthquake seismological data by Saha et al[31] revealed two reverse faults, the Dapsi thrust to the south of the Shillong Plateau and possibly the Oldham fault in the northern boundary of the plateau. The observed seismic activity in the plateau region bounded by these two faults was found as an attribute of the “pop up” mechanism of the plateau by Saha et al.[31]

Study performed by Rajendran et al[28] suggested that the pop up structure of the Shillong Plateau was due to the presence of the Brahmaputra fault and the Dauki fault. Further, Rajendran et al[28] raised doubts about the existence of the Oldham fault to the north of the Shillong Plateau and concluded that the Brahmaputra fault is the actual northern boundary of the Shillong Plateau and not the Oldham fault as suggested by Bilham and England[4], Nayaket al[24] and Saha et al.[31] Work performed by Rajendran et al[28] also suggested that the great earthquake of 1897 had occurred on the Brahmaputra fault itself. The gravity method conducted by Rajendran et al[28] showed a gravity anomaly ranging from -80 to -200 mGal in the Assam Valley. This variation in the gravity values was concluded to be due to a fault below the valley by Rajendran et al.[28]

Paleo-liquefaction studies for the 1897 earthquake were also conducted by Rajendran et al[28] near Dilma and Jira of the Assam valley near the Chedrang fault north of the Shillong Plateau. The paleo-liquefaction study showed that the area had undergone multiple liquefactions during previous earthquakes indicating the presence of a fault (the Brahmaputra fault) within the river basin. Rajendran et al[28] also found ruins of ancient temples spread all over the Assam valley dating back to the 9th or 10th century AD. Similarly, several other historical records indicating the reconstruction of the damaged temples throughout Assam during the same time were also found by Rajendran et al.[28] Such historical evidences inferred that damage at such a large scale could only be caused during major to great earthquakes.

Hence, Rajendran et al[28] suggested that earthquakes of sizes similar to 1897 must have occurred in Assam due to a fault lying below the valley and the return period of such earthquakes is approximately 1200 years, contradicting the speculative time of 3000 years as per Bilham and England[4]. Severe topographic changes in the river valley were also seen after the 1897 earthquake. These include, the south flowing rivers of Pagladia and Puthimari changing their course towards east and joining the Brahmaputra River[25]. Also, there were reports of extensive growth of swampy areas in the Assam valley along with the raised alluvium and occurrences of sand vents at various locations.

Morino et al[21] however did not agree with the findings of Rajendran et al[28] and pointed out that the variation in the gravity anomaly found below the Assam valley by Rajendran et al[28] was too weak and did not support the presence of the Brahmaputra fault. Morinoet al[22] also concluded that the paleo-liquefaction associated with the 1897 earthquake had occurred on both north and south sides of the Shillong Plateau. Hence, the claim of Rajendran et al[28] that the Brahmaputra fault was the cause of the maximum intensity in the Assam valley was found questionable by Morino et al.[22] Later, Sukhija et al[38]had also raised doubts about the presence of Brahmaputra fault as suggested by Rajendran et al.[28] Sukhija et al[38] also claimed that the existence of the Brahmaputra fault was deduced without taking into account the triangulation report of Geological Survey of India which clearly stated no evidence of slip along the proposed Brahmaputra Fault.

Further, as per Sukhija et al[38] there exists no remote sensing evidence of the Brahmaputra fault to support the work by Rajendran et al.[28] Observations made by Rajendran et al[28] on the basis of historical and paleo-liquefaction evidences had pointed out that the recurrence interval of great earthquakes in the Shillong Plateau is 1200 years. Again, Sukhija et al[38] claimed that the Shillong Plateau had experienced three major earthquakes and one great earthquake till date. The first major earthquake dates before 600A.D, the second earthquake during 700-1050 A.D and the third earthquake during 1450-1650 A.D. As per Sukhija et al[38] the return period of such major earthquakes is 400-600 years. Further, the recurrence interval of great earthquakes like the 1897 earthquake in the plateau is 500 yearsand not 1200 years as per Rajendran et al.[28]

Other works include conducting remote sensing studies by Srinivasan[34] which put forward another theory for the uplift of the Shillong Plateau. The digital images obtained from remote sensing surveys by Srinivasan[34] showed that for the eastern part of the Shillong Plateau, the topographic height varies from 1200m to 1900m while the western part of the Shillong Plateau attains a topographic height of 1200m to 1400m. In these areas the present course of the Brahmaputra River is also constricted. In the central part however, the height of the Shillong Plateau drops to approximately 300m and the width of the Brahmaputra River broadens as per Srinivasan[34]. The digital images showed NNE trending fractures in the Shillong Plateau having a higher density of such fractures in the central portion of the Shillong Plateau in comparison to the eastern and western parts.

Srinivasan[34] interpreted these images as indication of movement of the eastern and western portions relative to the central portion of the Shillong Plateau. Thus pressure was exerted in the central part and hence the high density of the fractures was evidence as per the digital images. The differential uplift of the plateau, as mentioned above, was assumed to be caused by the vertical movement of deep seated faults trending perpendicular to the Oldham fault of Bilham and England[4] as per Srinivasan[34]. The remote sensing studies conducted by Srinivasan[34] did not support the existence of any major faults in the northern boundary of the Shillong Plateau. Hence, the uplift of the plateau was solely inferred to be due to the differential uplift of the eastern and western parts of the plateau with respect to the central part by Srinivasan.[34]

Damages in the Shillong Plateau due to historic as well as recent earthquakes

The above mentioned complex tectonic setting of the Shillong Plateau indicates that the plateau is prone to seismic activity. A large number of earthquakes have already occurred in the faults surrounding the Shillong Plateau in the past. Information about the extent of damage caused in the Shillong Plateau by the past earthquakes since the 1869 Cachar earthquake is available. However there is very little to no information available about the strength of shaking of the earthquakes that had occurred prior to the Cachar earthquake. Only historical and archaeological records shed some light upon the occurrence of earthquakes in and around the Shillong Plateau in terms of the damages to the structures of those times.

To evaluate the hazard scenario of the Shillong Plateau and the return period of major earthquakes in the plateau, Sukhija et al[36] and Sukhija et al[37] conducted paleo-liquefaction studies for the 1897 great Assam earthquake. The paleo-liquefaction studies were conducted at various sites in the alluvium river valley of the Krishnai and the Dudhnai rivers close to the Chedrang fault. The first site was at Jira, south of the Krishnai River in Assam. At a depth of 8m, Sukhija et al[36] and Sukhija et al[37] found 30cm thick sand dykes breaking into the overlying clay layer of 1m height. From the samples collected at this clay layer, a major earthquake was found to have occurred ≤50 years ago. Similar results were obtained from the Rongkhaminchi site in Meghalaya. This corresponding earthquake for these alterations was deduced to be the 1897 Assam earthquake by Sukhija et al[36] and Sukhija et al.[37]

At another site at Bedabari, near the Krishnai River, clear signs of shaking and faulting of the alternating clay and sand subsurface layers were found. Also at the Kharidhara site, sand dykes that had rose to a height of 2m intruding the silt layer above the sand reservoir were found. Again at Nayapara similar sand dykes were found and at the Dainadubi site, along the Dudhnai River, organic samples were found at sedimentary beds which had deformed due to seismic shaking. Testing all the samples from these sites Sukhija et al[36] and Sukhija et al[37] concluded that a major earthquake had occurred during 1450-1650 AD. From the samples collected from the paleo-liquefaction study site at Beltaghat near the Krishnai River Sukhija et al[36] and Sukhija et al[37] found the evidence of a major earthquake dating back to 700-1050 AD.

Carbon dating of two dead tree trunks found buried underground at the bank of the Mora-Krishnai River and another from the Mendipathar area further supported the occurrence of this event. At a site located 200m downstream of Beltaghat, Sukhija et al[36] and Sukhija et al[37] found a peat sample which upon examination indicated of another major earthquake that had occurred before 600AD. Hence Sukhija et al[36] and Sukhija et al[37] concluded from the paleo-liquefaction studies that the return period of major earthquakes in the Shillong Plateau is 400-600 years and for great earthquakes the return period is 500 years. Sukhija et al[36] and Sukhija et al[37] highlighted the fact that liquefaction can occur even for earthquakes of magnitude 5 if the site conditions are favourable.

However, for the Shillong Plateau the phenomenon of liquefaction was not triggered even by earthquakes of magnitude 6.0-6.5 as per Sukhija et al[36] and Sukhija et al.[37] Hence Sukhija et al[36] and Sukhija et al[37] concluded that the paleo-liquefaction evidences found in the plateau were developed by past major to great earthquakes. Further the sand dykes formed due to the earthquakes prior to 1897 and those formed by the 1897 earthquake itself were found having similar characteristics. Almost all of the observed sand dykes in the region were oriented in the east west direction and had similar thickness of approximately 30cm as per Sukhija et al[36] and Sukhija et al.[37]

Similar to the above studies, in another attempt, paleo-liquefaction studies were conducted by Rastogi et al[30] again along the Chedrang fault. Four trenches 5-10m long, 4-5m wide and 5m deep were dug. The first trench was located 0.5km south of Jira where Rastogi et al[30] found a sand dyke from a dried riverbed. The sand dyke was found to intrude the upper alternate layers of sand and clay. This observation was confirmed by the second trench dug by Rastogi et al[30] near the first trench. The third trench was dug further south of the first two trenches. In this trench inclined sand dykes which had cut through alternating sand and clay layers were found. As a result of which slumping of clay layers was observed by Rastogi et al.[30] The fourth trench was dug near Mendipathar, Meghalaya where a dead tree trunk at a depth of 4m below the ground surface was found.

Based on carbon dating of the tree trunk, it was found that the tree had died 1200 to 1300 years ago. Further at the base of the trench a dried river bed consisting of alternating clay and sand layers was found. The study of the sand dykes and the slumping of the clay layers by Rastogi et al[30] indicated the occurrence of liquefaction phenomenon in the area due to major to great earthquakes in the past. From the field investigations Rastogi et al[30] concluded that the presence of the sand dykes in all the four trenches and the finding of a 1200 year old dead tree was a clear indication of occurrence of a major to great earthquake approximately 1200±100 years ago in the Shillong Plateau region.

Above discussions are related to various investigations in general performed by different researchers highlighting the occurrence of earthquakes in prehistoric times (1000 AD or before). Detailed discussion about the observed damage scenario during many of past devastating earthquakes in the Shillong Plateau in last few centuries is presented below.

1869 Cachar Earthquake

Almost entire northeastern region was shaken on the afternoon of 10th Jan 1869 by an earthquake of magnitude 7.5. The earthquake had originated 9.4 km north of Kumbhirgram, Assam having epicenter at latitude 25°50'00"N and longitude 93°00'00"E[6]. The rupture area of the earthquake is located within the Kopili fault[7]. This earthquake caused a wide spread damage extending from Dibrugarh in the north, to Manipur in the east, Patna in the west and Kolkata in the south. Damages due to this earthquake were reported by Captain Godwin-Austen, surveyor of Topographical Survey of India (TSI) and by Thomas Oldham, the Superintendent of the Geological Survey of India (GSI) under the British rule.[3,26] In the city of Guwahati, the primary shock was felt at about 5:15pm which lasted for 45sec and was followed by a number of minor shocks.

As per Oldham[26], the walls of the jail in Guwahati had suffered horizontal cracks and slight cracks in the arches as well. Also, the brick buildings in Guwahati had undergone damage. However, no loss of life had occurred due to this earthquake in Guwahati. Oldham[26] had reported severe shocks in Goalpara that continued till the night of 10th Jan 1869 and were again felt on the 14th of Jan 1869. In the Khasi Hills to the west of Shillong city, public buildings had undergone moderate to severe damages. The arches and the walls of the Overseer's bungalow and Deputy Commissioner's courthouse were cracked. Oldham[26] also reported of severe shocks in Nongpoh which is located 48km south of Guwahati city in the Shillong Plateau.

Damage reports collected by Oldham[26]from Manipur highlighted the complete damage of the Manipuri King's two-storied brick house. Ground fissures and sand vents were also reported by Oldham[26] in Manipur, along the banks of the Jiri River in Assam and the Surma River in Bangladesh as shown in figure 2. In North Cachar, Austen[3] reported that the native houses of bamboo and wood had survived this earthquake. The river Barak had flowed backwards for almost an hour and the depth of the river bed became shallower due to the earthquake. Also, a number of ground fissures and sand vents had occurred in the area.[3] Figure 3 present a typical case of ground fissures shown during 1869 Cachar EQ modified after Oldham[26]. The aftershocks for this earthquake had lasted till 1st Feb 1869 as per Austen[3].

1897 Assam earthquake

On 12th June 1897 the Shillong Plateau and its neighboring areas were hit by an intraplate earthquake. Estimated magnitude of this earthquake as per Bilham and England[4] was Mw 8.1.This earthquake was powerful enough to cause damage to the buildings even in Kolkata and could trigger seiches in Myanmar. The shaking due to this earthquake was felt at several places across the Indian subcontinent[6]. Large fissures of 18 to 30m ran parallel to the banks of the Brahmaputra River and its various tributaries. The Dhubri bazaar in Dhubri, Assam was severely affected by fissuring and further east of Dhubri at Rowmari, Assam, sand vents were formed which ejected sand and mud upto a height of 1m above the ground level[25]. A typical case of sand vents reported at Rowmari during this earthquake is shown in figure 4.

The earthquake had occurred at the peak of the monsoon season which had increased the number of sand vents and liquefied sites and also caused flooding and landslides at several places throughout the Assam valley. The abutments of the bridge on Grand trunk road west of Guwahati were moved forward while one of the piers was tilted over due to liquefaction. The rivers were flooded due to the monsoons. Shaking from the earthquake gave rise to standing waves that rose up to a height of 3m above the existing water level in the Brahmaputra River. As a result, the bazaars and the houses along the banks of the rivers were flooded[25]. The water level in the Brahmaputra River had risen to a height of 7.6m along with a reversal in the flow direction during this earthquake. Numerous landslides were reported at Nongpoh and the hilly town of Tura in the West Garo hills[5]. At Tura most of the masonry houses were severely damaged due to the collapse of the masonry plinth. The ground had cracked and slid at places blocking water courses and forming lakes at various locations.

As per Bilham[5], fissures and landslides occurred along the Guwahati-Shillong road; also the houses and bridges in these areas had turned to rubble. According to Bilham[5] in Shillong city, the bazaar and the masonry houses of the people as well as the Government house, local church and the Telegraph Office were destroyed. The houses built of wood or masonry bound with lime mortar had however survived. The tombs and the gate pillars of the cemetery also twisted turned and were thrown over. As per Bilham[5], several aftershocks of 1897 earthquake were reported to last till 25th July 1897. The hills behind the hill to the west of the Mawphlang valley became visible after this earthquake. This was either due to the uplift of the distant hills or due to the subsidence of the intermediate hills[5].

In Cherrapunji, similar damages to the houses, roads and tombstones had occurred and 500 to 600 people died mainly due to landslides[5]. Kumar[21] observed that one of the ancient traditions of the Khasi tribes of Meghalaya is to erect a set of upright and flat stone monoliths in the memory of their ancestors. Several of these Khasi monoliths at Maokhar, Maophlang and Maosmai had fallen after the 1897 earthquake. The vertical acceleration at the Shillong Plateau was reported to be greater than earth's gravitational force based on reported observations that at several places stones were hurled into the air. Due to the severe damages reported in the Shillong Plateau by the 1897 earthquake, Ambraseys and Bilham[1] attributed an intensity of X on the Rossi-Forel scale to the plateau.

1923 Meghalaya earthquake

Another earthquake occurred on the morning of 9th of September 1923. The magnitude (Ms) of this event was 7.1 and is known as 1923 Meghalaya earthquake. Later studies suggested that the epicenter of this earthquake was located towards the southern edge of the Shillong Plateau at latitude 25°25'00"N and longitude 91°00'00"E on the Dauki fault[6]. Very limited information about this earthquake is available. It shook the southern part of Meghalaya, also the north of Meghalaya at Sivasagar and Borjuli in Assam and Nagrakata in West Bengal. In the south the ground shaking was felt across Srimangal, Barisal, Chittagong, Midnapore and Narayanganj. Also heavy damages were reported in Mymensingh in Bangladesh, Cherrapunji and Guwahati in India by CNDM[6].

1930 Dhubri earthquake

On 2nd July 1930 an earthquake of magnitude (Ms 7.1) shook the northeast part of the country with its origin near Dhubri, Assam. The shock due to the earthquake had lasted for three to five minutes and a roaring sound was heard just before the earthquake. The epicenter of this earthquake was located 3.9km NNW of Dabigiri, Meghalaya at latitude 25°5'00"N and longitude 90°0'00"E. The area affected by this earthquake was spread over approximately 80,0000km^2 from Dibrugarh and Manipur in the east, Kolkata in the south, Patna in the west and Nepal, Bhutan and Sikkim in the north[17].

As per Kayal,[17] the Dhubri fault on the western boundary of the Shillong Plateau is the source of this earthquake. Further Gee[9] reported that the Dhubri town lying in close proximity to the Dhubri fault was the worst affected region with an intensity of IX on the Rossi Forel scale. Tura in Meghalaya, south of Dhubri in the Shillong Plateau, was shaken with an intensity of VIII.

An outcrop of the Dhubri fault was visible at Tura during this earthquake. Most of the government buildings were affected; some suffered minor damages like cracked walls as shown in figure 5 and peeling of plasters off the walls while others underwent severe damages. To the west of the Garo hills near the N-S trend of the Brahmaputra River, fissures and sand vents were reported by Gee[9] as shown in figure 6. As per Gee,[9] Goalpara and Guwahati in Assam were shaken by an intensity of VII and Cherrapunji and Shillong in the Shillong Plateau were shaken by an intensity of VI on the Rossi Forel scale. In spite of the high intensity, Gee[9] reported that in the city of Shillong the building damages were comparatively less since after the 1897 earthquake most of the houses were built of bamboo and other locally available light materials. In Cherrapunji however the houses faced damages due to poor construction practices. A number of aftershocks were also reported by Gee[9] till 5th July 1930.

1943 Assam earthquake

Continuing the seismic experience of the past, the area in close proximity to the Shillong Plateau was again hit by an earthquake (Ms=7.2) on 23rd of October 1943. The epicenter of this earthquake was located at latitude 26°0'00"N and 93°0'00"E which is 13.6km east of Hojai in Assam. The source fault of this earthquake is the Kopili fault which had previously caused the 1869 Cachar earthquake[6] and was highlighted to be seismically active in the present times as well by Kayal et al[15] and Kayal et al.[16] Very little information is available about the 1943 Assam earthquake. The only information is of the intense shaking brought by the earthquake that woke up people in the night and the report of a rumbling noise. Fissures and unevenness of the ground, falling of trees and damaged buildings due to the earthquake were also reported.[6]

2009 Assam earthquake

In recent times, on 19th August 2009, an earthquake of magnitude Mw 5.1 was recorded on the Kopili fault. The epicenter for this earthquake was located at latitude 26°56'00"N and longitude 92°48'00"E and the focal depth was approximately 10km. The fault had undergone a right lateral strike slip movement as per Kayal et al.[16] On 21st September 2009 another earthquake of magnitude Mw 6.3 located approximately 100km north of the 19th August 2009 earthquake was felt in Bhutan and along the same Kopili fault. This earthquake had similar focal depth and focal mechanism as that of 19th August 2009 earthquake. Kayalet al[16] suggested that the 19th August earthquake in the Assam valley must have been the foreshock of the Bhutan earthquake.

Based on the above discussion, an attempt has been made in this work to give an alarming picture concerning the ongoing seismicity across various active sources surrounding the Shillong Plateau. The limitation of present IS codes in understanding the true seismicity of a region has been highlighted by many researchers. Keeping this in mind, a number of regional seismic hazard studies were attempted for different parts of the Indian subcontinent in general and for selected urban centers in the northeast in particular. Some of these studies were performed either by using the past reported earthquakes and selecting suitable ground motion prediction equations while others generated synthetic ground motions for scenario earthquakes such as 1897 earthquake and 1950 Assam earthquake considering the source details and target magnitude.

For such studies however, there are ambiguities as discussed earlier related to the location of these earthquakes and the sources responsible for each of these events. Detailed studies which can target about collecting more information about the damage signature during such earthquakes are required. Similarly identification of the possible locations of strain accumulation and the in-situ slip mapping along potential sources can provide a more clear and updated knowledge about the present seismic status of the Shillong Plateau. Keeping the development plans of the Government of India for the north-eastern region of the country and the high population density in addition to the poor construction practice, detailed studies in the Shillong Plateau will be very helpful to provide data for risk assessment and for identification of potential sources which may undergo future rupture.

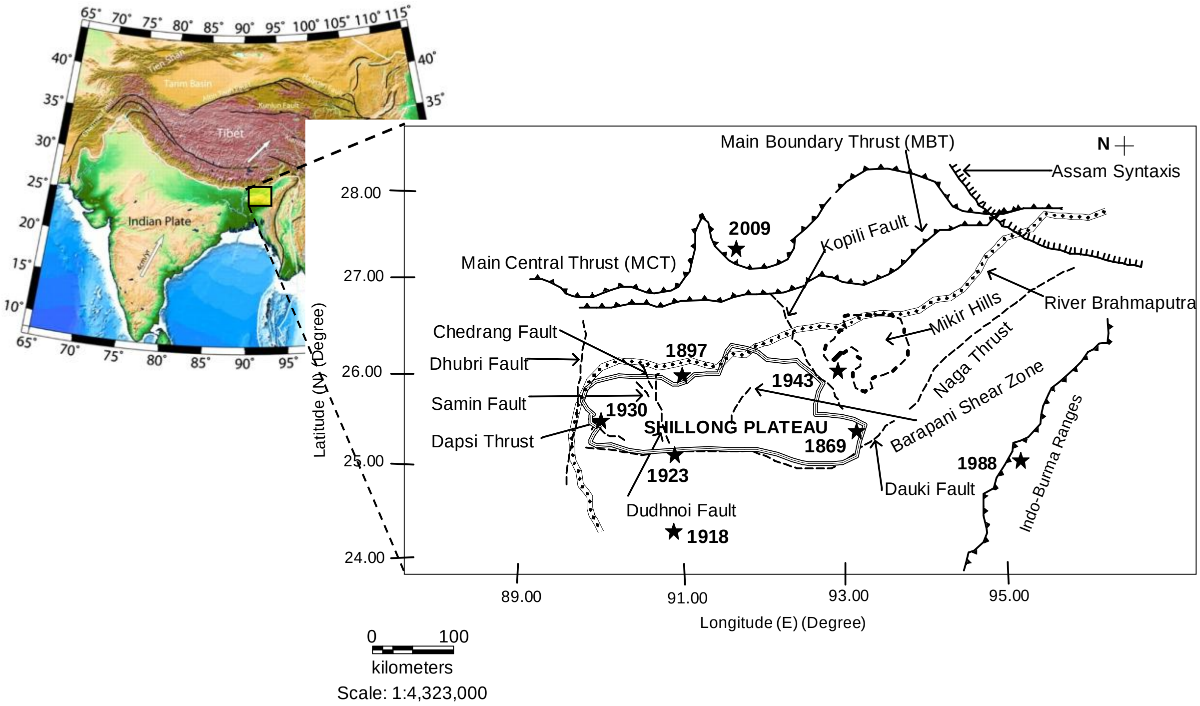

Figure 1: Active sources and past earthquake details of the Shillong Plateau

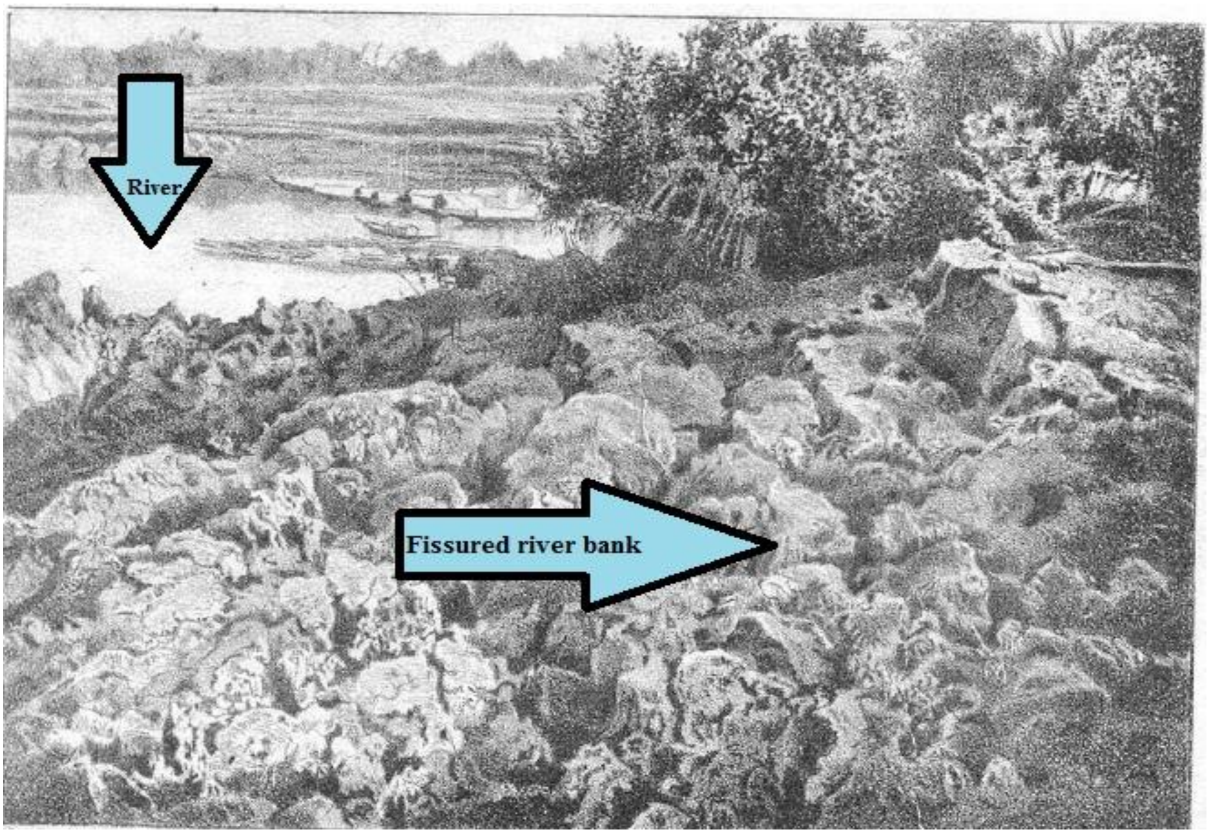

Figure 2: Fissured ground on the river bank after the 1869 Cachar earthquake[26]

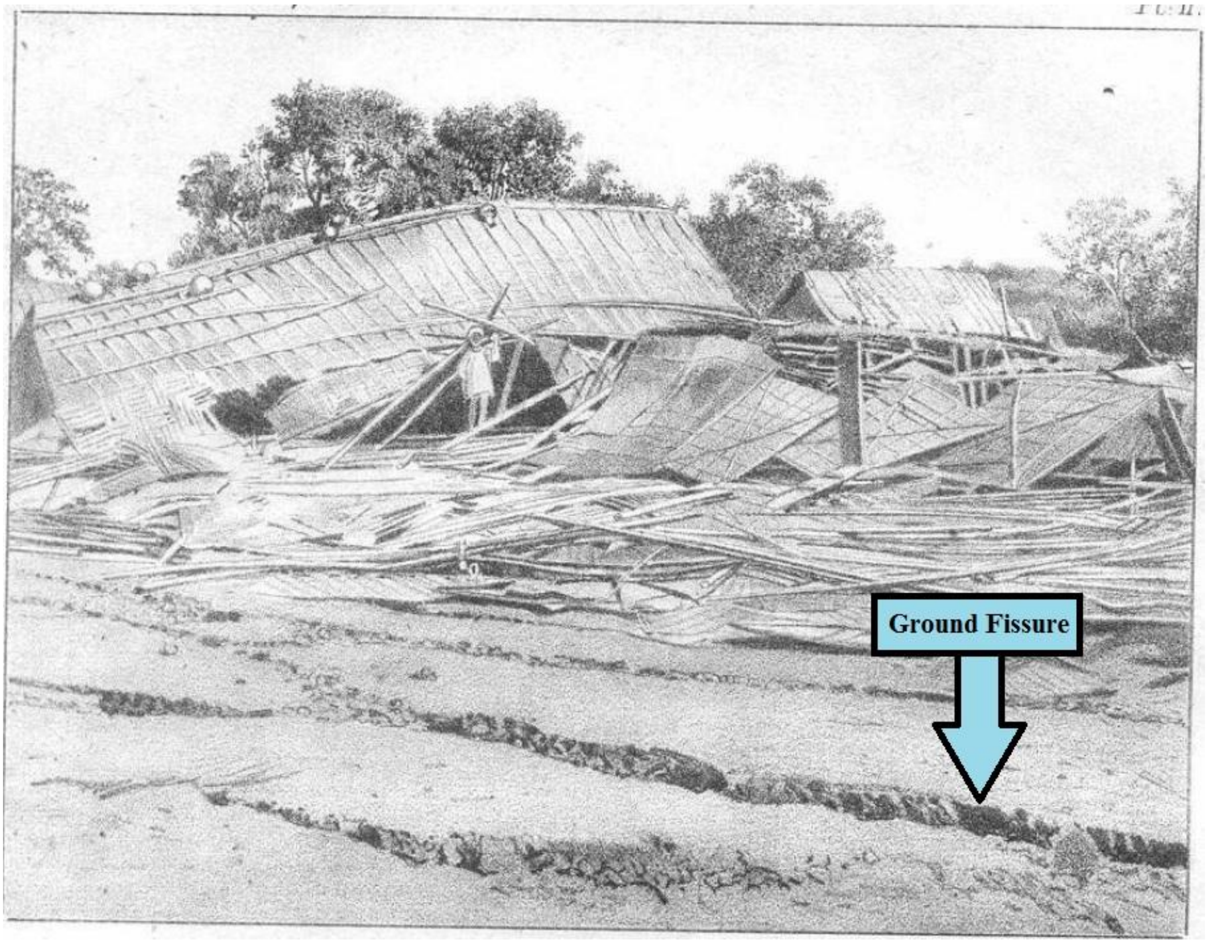

Figure 3: Fissures seen on the bazaar road in Cachar, Assam after the 1869 Cachar earthquake[26]

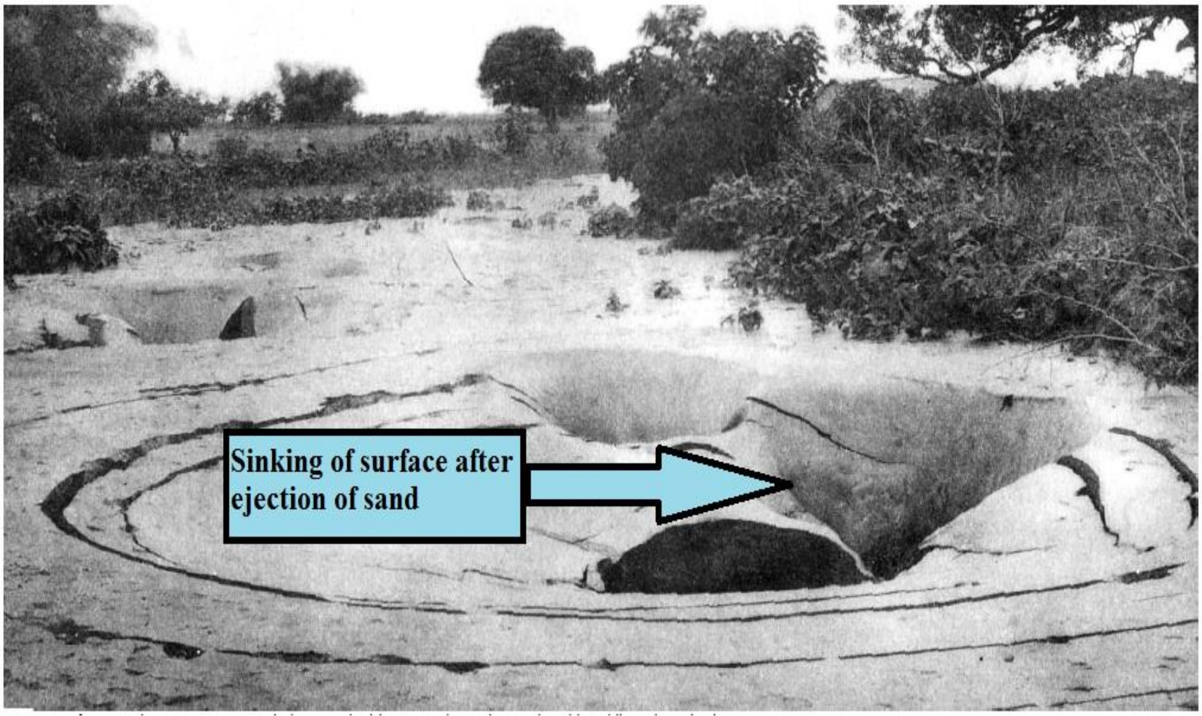

Figure 4: Sand vents created near Rowmari, Assam after the 1897 earthquake[25]

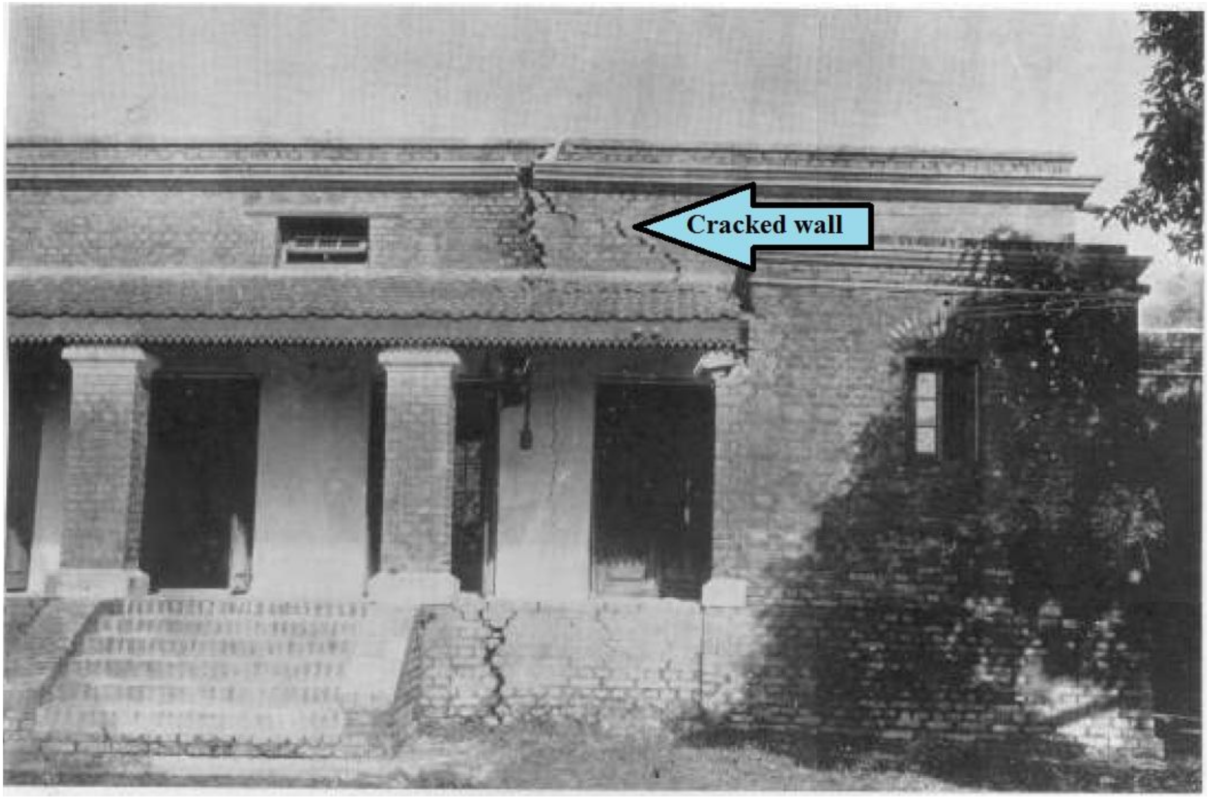

Figure 5: Walls of houses cracked after the 1930 Dhubri earthquake[9]

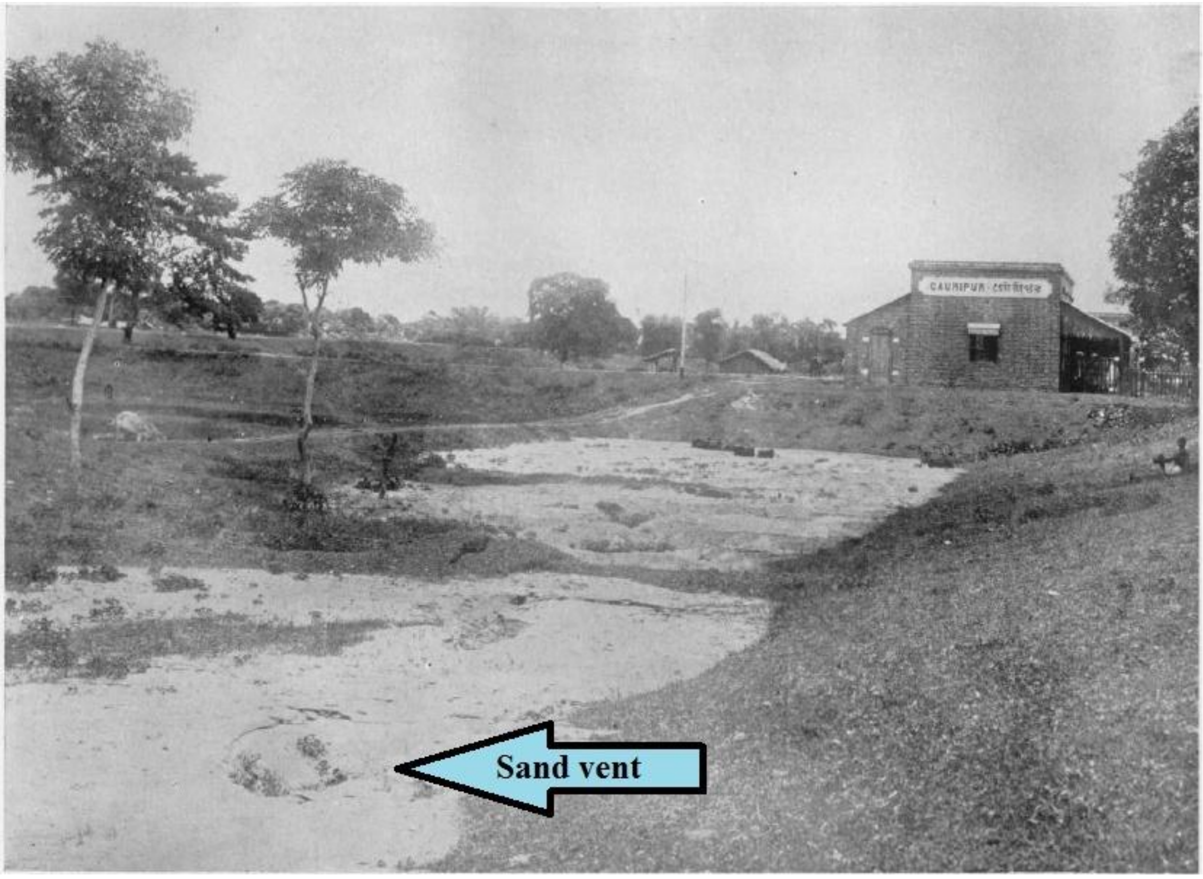

Figure 6: Sand vents seen in Gauripur near Dhubri, Assam after the 1930 Dhubri earthquake[9]

Conclusion

Previous published research works have attributed the uplift of the Shillong Plateau to thermal disturbance in the upper mantle, differential uplift, isostatic adjustments and "pop-up" mechanism. The most popular among various attributes is the pop-up mechanism of the plateau due to the faults surrounding the plateau. However there exists a conflict of ideas as to which faults are responsible for the uplift. Some studies have suggested the faults responsible for the uplift to be the Brahmaputra fault and the Dapsi thrust whereas according to others, the Dauki fault and the hidden Oldham fault caused the uplift of the plateau. None of these findings were however validated since the existence of some of these faults is controversial. Further the fault which caused 1897 Assam earthquake is also not confirmed. Some of the earthquakes originating in the faults surrounding the Shillong Plateau have caused severe damages to the plateau and its adjoining areas.

The Kopili fault is another region which has shown an active seismicity based on the evidences from the last century till present. Detailed studies focusing onground deformation and in-situ slip measurement for the Kopili fault in the future will be helpful in understanding the future seismic potential due to this fault. Similarly the northeast and northwestern parts of the Shillong plateau were analyzed in variety of ways. Detailed in-situ monitoring on ground deformation measurement on these faults will be helpful in understanding the present seismic status of each of these faults. Also ambiguities about the presence of causative fault in the northern extent of the Shillong Plateau can be filtered out and its role in future seismicity can be understood. Understanding the tectonic setting of the Shillong Plateau and the ongoing seismic activity of the Kopili fault will be helpful in providing more realistic scenario for the future earthquakes in the region.

References

1. Ambraseys N. and Bilham R., Re-evaluated intensities for the great Assam earthquake of 12 June 1897, Shillong, India, *Bull. Seismol. Soc. Am.*,**93**, 655-673 **(2003)**

2. Angelier J. and Baruah S., Seismotectonics in Northeast India: a stress analysis of focal mechanism solutions of earthquakes and its kinematic implications, *Geophys. J. Int.*, **178**, 303-326 **(2009)**

3. Austen G., Earthquake in the Cachar Hills, Extracts from Letters, Proceedings of the Royal Geographical Society, **13**,370-372 **(1869)**

4. Bilham R. and England P., Plateau Pop-up during the 1897 Assam earthquake,*Nature*, **410**, 806-809 **(2001)**

5. Bilham R., Tom La Touche and the Great Assam Earthquake of 12 June 1897, Letters from the epicenter, *Seismol. Res.Lett.*, **79(3)**, 426 – 437 **(2008)**

6. CNDM, Scenario of seismic hazard in Assam, A report by the Assam Administrative Staff College, Guwahati, Assam, India **(2002)**

7. Dasgupta S., Earthquake geology, geomorphology and hazard scenario in northeast India, an appraisal, in National Workshop on Earthquake Risk Mitigation Strategy in North East, Guwahati, Assam, 24-39 **(2011)**

8. Evans P., The Tectonic framework of Assam, *J. Geol. Soc. India*, **5**, 80-96 **(1964)**

9. Gee E.R., TheDhubri earthquake of the 3rd July 1930, *Memoir Geol.Surv. India*, **65(1)**, 1-106 **(1934)**

10. Johnson S.Y. and Alam A.M.N., Sedimentation and tectonics of the Sylhet trough, Bangladesh, *Geol. Soc. Am. Bull.*, **103**, 1513-1527 **(1991)**

11. Kailasam L.N., Plateau uplift in peninsular India, *Techtonophysics*, **61**, 243-269 **(1979)**

12. Kanamori H., The energy release in great earthquakes, *J.Geophys. Res.*, **82**, 2981-2987 **(1977)**

13. Kayal J.R. and De R., Microseismicity and tectonics in northeast India, *Bull.Seismol. Soc. Am.*, **81**, 131-138 **(1991)**

14. Kayal J.R. and De R., Pn velocity study using a temporary seismographic network in the Shillong Plateau, Northeast India, *Bull.Seismol. Soc. Am.*, **5**, 1718-1727 **(1987)**

15. Kayal J.R., Arefie S.S., Barua S., Hazarika D., Gogoi N., Kumar A., Chowdhury S.N. andKalita S., Shillong plateau earthquakes in northeast India region: complex tectonic model, *Curr. Sci.*, **91(1)**, 109-114 **(2006)**

16. Kayal J.R., Arefiev S.S., Baruah S., Tatevossian R., Gogoi N., Sanoujam M., Gautam J.L., Hazarika D. and Borah D., The 2009 Bhutan and Assam feltearthquakes (Mw 6.3 and 5.1) at the Kopili fault in the northeast Himalaya region, *Geomatics, Nat Hazards Risk*, **1(3)**, 273-281 **(2010)**

17. Kayal J.R., Microearthquake Seismology and Seismotectonics of South Asia, McGraw Hill Publication, India **(2008)**

18. Kayal J.R., Microseismicity and source mechanism study, Shillong Plateau, northeast India, *Bull.Seismol. Soc. Am.*, **77,** 184-194 **(1987)**

19. Khattri K. and Wyss M., Precursory variation of seismicity rate in Assam area, India, *Geology*, **6**, 685-688 **(1978)**

20. Khattri K.N., Wyss M., Gaur V.K., Saha S.N. and Bansal V.K., Local seismicity in the region of Assam gap, Northeast India, *Bull.Seismol. Soc. Am.*, **73**, 459-469 **(1983)**

21. Kumar V., Megalithic Cultural tradition amongst the Khasi and Jaintia tribes of North-East India, *The Tribal Tribune*, **6 (4)**, 1-4 **(2014)**

22. Morino M., Kamal A.S.M.M., Muslim D., Ali R.M.E., Kamal M.A., Rahman M.Z. and Kaneko F., Seismic event of the Dauki Fault in 16th century confirmed by trench investigation at Gabrakhari Village, Haluaghat, Mymensingh, Bangladesh, *J. Asian Earth Sci.*, **42**, 492–498 **(2011)**

23. Murthy M.V.N., Talukdar S.C., Bhattacharya A.C. andChakravorty C., The Dauki fault of Assam, *Bull. ONGC*, **6(2)**, 57-64 **(1969)**

24. Nayak G.K., Rao V.K., Rambabu H.V. andKayal J.R., Pop-up tectonics of the Shillong Plateau in the great 1897 earthquake (Ms 8.7), Insight from the gravity in conjunction with the recent seismological results, *Tectonics*, **27**, TC1018 **(2008)**

25. Oldham R.D., Report on the Great Earthquake of 12 June 1897, *Memoir Geol.Surv. India,***29**, 379 **(1899)**

26. Oldham T., The Cachar earthquake of 10th January, 1869, by the late Thomas Oldham edited by OldhamR. D., *Memoir Geol.Surv. India,***19**, 1-98 **(1882)**

27. Pandey A. and Chadha R.K., Surface loading and triggered earthquakes in the Koyna-Warna region, western India, *Phys. Earth Planet In.*, **139**, 207 – 223 **(2003)**

28. Rajendran C.P., Rajendran K., Duarah B.P., Baruah S. and Earnest A., Interpreting the style of faulting and paleoseismicity associated with the 1897 Shillong, northeast India, earthquake, Implications for regional tectonism, *Tectonics*, **23**, TC4009 **(2004)**

29. Rao N.P. and Kumar M.R., Uplift and tectonics of the Shillong plateau, Northeast India, *J. Phys. Earth,***45**, 167-176 **(1997)**

30. Rastogi B.K., Chadha R.K. and Rajgopalan G., Paleoseismicity studies in Meghalaya, *Curr. Sci.*, **64(11&12)**, 933 - 935 **(1993)**

31. Saha D.K., Naskar D.C., Bhattacharya P.M. andKayal J.R., Geophysical and Seismological Investigations for the Hidden Oldham Fault in the Shillong Plateau and Assam Valley of Northeast India, *J. Geol. Soc. India*, **69**, 359-372 **(2007)**

32. Sarma K.P., Shillong super group, A new lithostratigraphic unit in the basement – cover precambrian rocks of the shillong plateau, northeast India, *Int. J. Geol., Earth & Environ. Sci.*, **4 (2)**, 158-171 **(2014)**

33. Sharma M.L. and Shipramalik, Probabilistic seismic hazard analysis and estimation of spectral strong ground motion on bed rock in north east India, Proceedings of the 4th International Conference on Earthquake Engineering, Taipei, Taiwan **(2006)**

34. Srinivasan V., Deciphering differential uplift in Shillong Plateau using remote sensing, *J. Geol. Soc. India,***612**, 773 – 777 **(2003)**

35. Srinivasan V., The Dauki fault in Northeast India, Through Remote Sensing, *J. Geol. Soc. India*, **66**, 413-426 **(2005)**

36. Sukhija B.S., Rao M.N., Reddy D.V., Nagabhushanam P., Hussain S., Chadha R.K. and Gupta H.K., Timing and return period of major paleoseismic events in the Shillong Plateau, India, *Tectonophysics*, **208**, 53–65 **(1999a)**

37. Sukhija B.S., Rao M.N., Reddy D.V., Nagabhushanam P., Hussain S., Chadha R.K. and Gupta H.K., Paleoliquefaction evidence and periodicity of large pre-historic earthquakes in Shillong Plateau, India, *Earth Pl. Sci.Lett.*, **167**, 269–282 **(1999b)**.

38. Sukhija B., Reddy D., Kumar D. and Nagabhushanam P., Comment on “Interpreting the style of faulting and paleoseismicity associated with the 1897 Shillong, northeast India, earthquake: Implications for regional tectonism” by C. P. Rajendran et al, *Tectonics*, **25**, TC2009 **(2006)**.

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