Interpreting the style of faulting and paleoseismicity associated with the 1897 Shillong, northeast India, earthquake: Implications for regional tectonism

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[1] The 1897 Shillong (Assam), northeast India, earthquake is considered to be one of the largest in the modern history. Although *Oldham*'s [1899] classic memoir on this event opened new vistas in observational seismology, many questions on its style of faulting remain unresolved. Most previous studies considered this as a detachment earthquake that occurred on a gently north dipping fault, extending from the Himalayan front. A recent model proposed an alternate geometry governed by high-angle faults to the north and south of the plateau, and it suggested that the 1897 earthquake occurred on a south dipping reverse fault, coinciding with the northern plateau margin. In this paper, we explore the available database, together with the coseismic observations from the region, to further understand the nature of faulting. The geophysical and geological data examined in this paper conform to a south dipping structure, but its location is inferred to be in the Brahmaputra basin, further north of the present plateau front. Our analyses of paleoseismic data suggest a 1200-year interval between the 1897 event and its predecessor, and we identify the northern boundary fault as a major seismic source. The Shillong Plateau bounded by major faults behaves as an independent tectonic entity, with its own style of faulting, seismic productivity, and hazard potential, distinct from the Himalayan thrust front, a point that provides fresh insight into the regional geodynamics. *INDEX TERMS:* 7209 Seismology: Earthquake dynamics and mechanics; 7215 Seismology: Earthquake parameters; 7221 Seismology: Paleoseismology; 7230 Seismology: Seismicity and seismotectonics; 7299 Seismology: General or miscellaneous; *KEYWORDS:* earthquake, tectonics, paleoseismology, faulting, seismicity, northeast India. **Citation:** Rajendran, C. P., K. Rajendran, B. P. Duarah, S. Baruah, and A. Earnest (2004), Interpreting the style of faulting and paleoseismicity associated with the 1897 Shillong, northeast India, earthquake: Implications for regional tectonism, *Tectonics*, *23*, TC4009, doi:10.1029/2003TC001605.

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1. Introduction

[2] The northeastern part of Indian subcontinent is one of the most active regions of the world; two great earthquakes have occurred here in 1897 and 1950 (Figure 1). Of these, the June 12, 1897 event has been described as one of the most damaging earthquakes in the recent history. In his study of great earthquakes during 1896–1903, *Gutenberg* [1956] assigned a magnitude of ~8.7 to this earthquake, an estimate based on records of Milne's instruments [*Richter*, 1958]. Although *Oldham*'s [1899] monograph established its status as among the best documented earthquakes of the 19th century, many issues concerning its mechanism remain controversial. A poorly understood aspect is the location and geometry of the causative fault and its relation to the Shillong Plateau. The traditional understanding is that the earthquake occurred on a north dipping fault that crops up on the Shillong Plateau [e.g., *Seeber and Armbruster*, 1981; *Molnar*, 1987; *Kayal*, 2001]. On the basis of the high accelerations and spatial distribution of aftershocks, *Oldham* [1899] suggested that the rupture might have extended from the southern topographic front of the plateau to Gauhati and Goalpara in the north. In one of his reports, *Oldham* [1898] mentions how the northern part of the plateau was subject to a large number of aftershocks, mostly between Goalpara, Tura, and Shillong, regions noted also for the occurrence of landslides and fissures as well as slumping of riverbanks (Figure 2a).

[3] No primary fault rupture was documented, but a couple of secondary faults and fractures developed in the northern part of the Shillong Plateau. Prominent among them is the 20-km-long NW–SE trending Chedrang fault, with a throw of 0–9 m, with its east side up (see Figure 2a for location). How much of this throw constituted coseismic slip is not evident from *Oldham*'s [1898] report. It is likely that the accumulated slip from previous events and scarp degradation due to erosion could have significantly modified its morphology. The E–W trending, 4-km-long Samin fault, with a throw of 3 m, and the 11-km-long Bordwar fracture, with no apparent displacement, are the other coseismic surface deformation features, observed close to the plateau (Figure 2a). Postearthquake triangulation survey [*Oldham*, 1899] indicated a north to northwestward displacement, some points having moved >3.5 m (Figure 2b). The extensive occurrence of landslides, secondary faulting and fissuring on the plateau imply a greater shaking intensity in this region. Oldham's hat-shaped high-intensity zone is primarily based on the distribution of these surface features (Figure 2c).

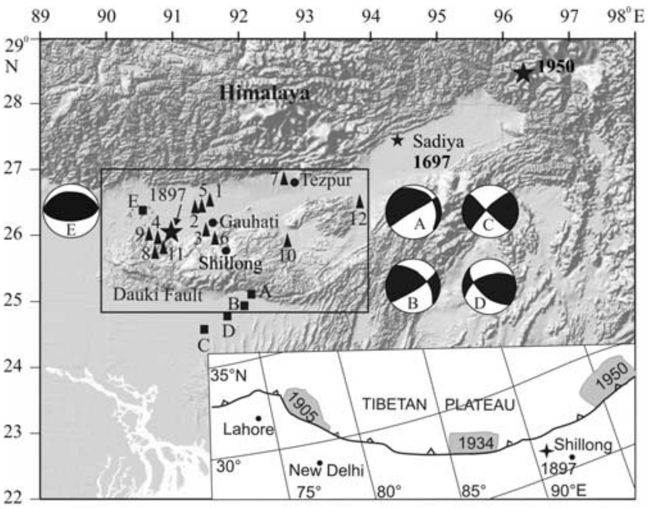

Figure 1. Map of northeast India showing the study area and important locations discussed in the text. Location of the 1897 earthquake is after *Gutenberg* [1956] and focal mechanisms (A-E) are from *Chen and Molnar* [1990]. Features within the box are discussed in the text and enlarged in Figures 2, 3, and 4. Solid triangles numbered 1–12 indicate sites of ancient monuments (temples) and ruins: 1, Madan Kamdev; 2, Hathimora; 3, Kamakhya; 4, Mornoi; 5, Hajo; 6, Umananda (Peacock Temple); 7, Da-Parbatia; 8, Hathimur; 9, Pancharatna; 10, Hojai; 11, Suryapahar, 12, Numaligarh. Inset is of Himalayan frontal arc showing the rupture areas of the 1905, 1934, and 1950 earthquakes [after *Yeats and Thakur*, 1998] (reprinted with permission from *Current Science*).

[4] Despite the generation of a variety of secondary effects, the causative fault was not evident, because of the lack of a primary surface rupture. In *Oldham*'s [1899] paper, he suggested that the earthquake occurred on a shallow, north dipping thrust fault below the Shillong Plateau. In his later writings, *Oldham* [1926] retracted from this view and favored a mechanism controlled by a deep-seated laccolitic intrusion. Later workers were inclined toward Oldham's initial proposal of a north dipping thrust fault, a structure considered as an extension of the Himalayan frontal dècollement [e.g., *Seeber and Armbruster*, 1981; *Molnar*, 1987; *Chen and Molnar*, 1990; *Gahalaut and Chander*, 1992; *Kayal*, 2001]. This was the prevailing understanding, until *Bilham and England* [2001] proposed a steep (50°) SSE dipping reverse fault, close to the northern topographic front of the Shillong Plateau. Deduced from the triangulation data (1860, 1898, 1936), this proposed geometry deviates from that of the hitherto accepted fault models.

[5] Views differ also on the repeat period of similar size ($M \geq 8.0$) earthquakes in this region. On the basis of the liquefaction chronology, *Sukhija et al.* [1999a, 1999b] suggested a regional recurrence of 500 years for large earthquakes in the Brahmaputra Valley. It is not clear whether this inferred interval is source-specific, and this should be an important consideration in a region vulnerable to moderate/large earthquakes from multiple sources. Ascribing features to specific sources may not be easy in such conditions, especially when the data coverage is limited. *Bilham and England* [2001] suggested a source-specific recurrence interval of 3000–8000 years, on the basis of inferred fault slip data, differing significantly from the earlier estimate, derived from the liquefaction chronology.

[6] Much of the field observations on the 1897 earthquake remain scattered in the literature. Although some attempts have been made previously, they have not been fully examined from the point of understanding the fault geometry and the regional tectonism. We believe that a perceptive evaluation of such data, along with the available

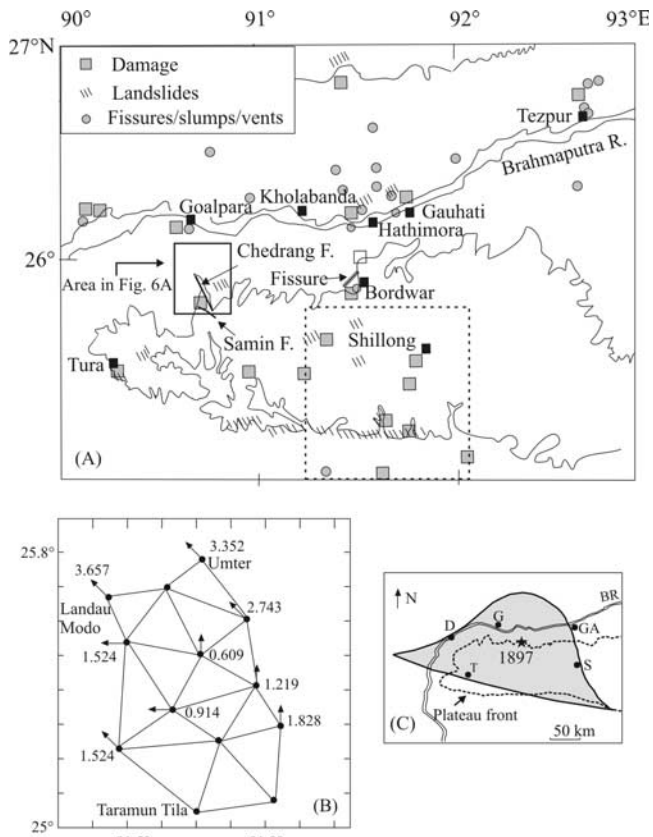

Figure 2. (a) Map of the Shillong Plateau showing surface effects including secondary faults (F) reported by *Oldham* [1899] and modified from *Molnar* [1987]. Area within the smaller box in solid outline shows the location of paleoliquefaction features. Larger box in dashed outline is the area of triangulation survey (1860, 1898) reported by *Oldham* [1899]. (b) Triangulation points showing displacement (in meters) and movement direction. Arrows (not scaled) indicate the direction of movement. (c) The hat-shaped high-intensity zone (shaded) identified by *Oldham* [1899]; star indicates the epicentral location by *Gutenberg* [1956]. Abbreviations are as follows: D, Dhubri; G, Goalpara; GA, Gauhati; T, Tura; S, Shillong; BR, Brahmaputra River. Dashed line denotes the boundary of the Shillong Plateau.

geological and geophysical data may provide a new insight on the overall seismotectonics of the region, and more specifically, the 1897 earthquake. Historic documentation on ancient structures is yet another source of information that has not been adequately used from the perspective of understanding the earthquake recurrence. In this paper we synthesize a variety of data to assess the location and geometry of the fault and present additional database on past earthquake activity. *Oldham*'s [1899] observations form an important frame of reference and a starting point for our present study. Bouguer gravity, seismicity, paleoseismological data, surface/subsurface geology, and morphological characteristics of the region, together with analyses of historical and archaeological information, provide additional constraints. At the end of the discussion, we make two major observations, which have important consequences for the regional tectonics: one, that the 1897 earthquake occurred on a south dipping fault, located farther north of the plateau front in the Brahmaputra Valley, and two, that the penultimate earthquake may have occurred ~1200 years B.P, significantly deviating from the earlier postulations.

2. Earthquake-Related Morphological Changes in the Brahmaputra Valley

[7] The maximum intensity during 1897 was generally observed in and around the Shillong Plateau. Warping, tilting, intense ground motion, and permanent ground level changes were also reported from places like Gauhati and Goalpara, bordering the Brahmaputra River. The earthquake destroyed most masonry buildings; it generated widespread landslips and liquefaction and caused intense sand venting in areas far beyond the plateau margins. In *Oldham*'s [1899] isoseismal map, the highest intensity was equated with X of Rossi-Forel scale. *Gutenberg* [1956] located the epicenter in the middle of this "hat-shaped," highest-intensity zone (Figure 2c). The southern boundary of this zone is rather linear and roughly coincides with the topographic front of the plateau. However, its northern boundary is somewhat circuitous, extending beyond the Shillong Plateau into the Brahmaputra Valley. The peculiar shape of the high-intensity zone could have resulted from the selective amplification in the alluviated valley leading to liquefaction, landslides, and rock falls. A recent reevaluation suggests that Oldham's intensities are likely to have been exaggerated by 1.5 to 3 isoseismal units [*Ambraseys and Bilham*, 2003]. For our discussion, we mainly rely on the coseismic level changes in the Brahmaputra Valley, as reported by *Oldham* [1899]; these regions also partly conform to isoseismal VIII in the recent revised estimates [*Ambraseys and Bilham*, 2003].

2.1. Deformation Within the Brahmaputra Valley as Deduced by *Oldham* [1899]

[8] *Oldham* [1899] documented the coseismic water level changes in the Brahmaputra River rather meticulously, and interpreted them as indications of a general uplift of the region. Maximum changes in the level of the river were recorded at Gauhati (>4.7 m) and Goalpara (5–6.25 m), both on the southern bank of the river. The most definitive indication of the level changes was found near the hill of Hathimora, and to its east, near Kholabanda [*Oldham*, 1899, p. 162] (Figure 2a). Although outpouring of water due to sand venting was a factor, Oldham noted that there could be other factors for these abrupt and significant changes. Oldham suggests two causes for the flooding: (1) subsidence of the rocky floor beneath the river and, (2) formation of a barrier across the river, slightly down stream of Hathimora (due to shaking down of loose material from the banks and consequent filling of the river bed). This part of the river basin was also noted for the diversion of river channels and formation of swamps. According to *Oldham* [1899, p. 107], the pattern of rise and fall of the water level may not have been spatially uniform. He writes

> This way barriers were formed across the stream and on the upstream side water was ponded up to the height of the maximum rise of the next barrier downstream. Thus a greater rise of water level occurred than would have been the case if the raising of the riverbeds had been uniform, while barriers, being composed of loose sand, were more easily scoured away, in such a manner as to leave the water lower than the level to which it had risen immediately after the earthquake, though a little higher than it was before.

He further adds that the rise in water level remained perceptible (1 foot higher than the normal) even 2 years later, during the months of January and February 1899, a season, generally, of lowest levels. Oldham attributed these anomalous changes to the general uplift of the riverbed, which had not been completely scoured out to the preearthquake level.

2.2. Earthquake-Driven Drainage Modification

[9] The 1897 earthquake caused extensive changes to the drainage system in the Brahmaputra Valley, mostly between 90.5° and 91.5°E (Figure 3). A region where significant elevation changes occurred subsequent to the earthquake [*Oldham*, 1899], this part of the valley is also noted for the profusion of lakes and swamps. Preearthquake topographic maps are not easily available, and our major source of information is a map of 1893, provided by *Allen* [1905]. A comparison of this map with a later version (1911–1913) indicates that the extensive growth of this swampy area is a postearthquake phenomenon, restricted to the northern bank of the Chaulkhowa River. This part of the valley was known for the profusion of fissures (possibly lateral spreads) and sand vents during the 1897 earthquake (Figure 2a) [*Oldham*, 1899; *Molnar*, 1987]. *Das et al.* [1996] noted the eastward migration of the south flowing rivers of Pagladia and Puthimarhi, both abandoning their original courses to join the Brahmaputra River (Figure 3). These changes in the river courses are likely to have been induced by the general uplift in the downstream parts of the valley. Because of its morphologically distinct character, we consider this part of the valley as different from its adjoining areas and refer to it as the central segment (see Figure 3).

[10] A wide stretch of raised alluvial plain occurs between the Chaulkhowa and the Brahmaputra Rivers in the central segment (Figure 3). Field observations indicate

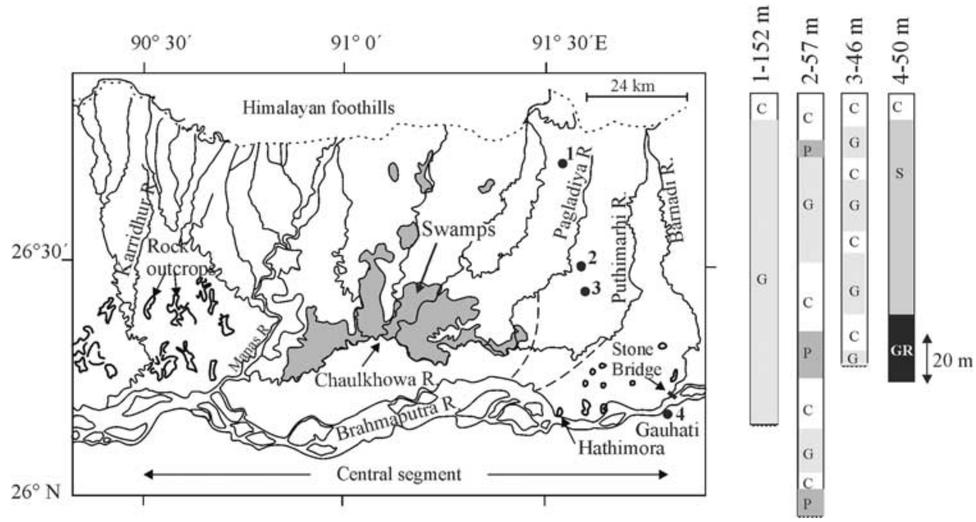

Figure 3. Channel system of the Brahmaputra basin, based on preearthquake maps of the area [*Allen*, 1905]. Shaded area represents the zone of postearthquake swamps and marshes on the basis of the 1911 Survey of India maps. The change in the courses of the Pagladia and Puthimarhi Rivers was a postearthquake phenomenon, discussed in the text. Dashed lines represent the original courses of these rivers on a preearthquake landscape. The stone bridge indicated at the downstream of Barnadi River collapsed during the 1897 earthquake (see text for details). Solid circles numbered 1–4 are boreholes for which lithologs are shown in the side panel, with their respective elevation above the mean sea level (msl) (e.g., well 1 is 152 m above msl). Abbreviations are as follows: C, clay with silt; G, clay with boulders and gravel; P, pebbles with gravel; S, sand; GR, granite (data source is Geological Survey of India and the Directorate of Geology and Mining, Government of Assam).

that large-scale levee deposition along the Brahmaputra basin, possibly aided by river aggradations, currently restricts the southward flow in this part of the valley. Previous workers have suggested that such massive accumulation of sediments may have resulted from a possible rise in the base level of the river [*Goswami*, 1985; *Valdiya*, 1999]. These observations are consistent with the earlier suggestion that the river valley as a whole might have undergone regional uplift [e.g., *Oldham*, 1899; *Morgan and McIntire*, 1959]. Occurrence of elevated beds of "older alluvium" at 4–5 m (occasionally ~8 m) above the present riverbed has been cited as a manifestation of past vertical movements within the river valley [*Kailasam*, 1979].

[11] Limited borehole data available from four wells along a transverse profile from Gauhati to Darranga suggest northward deepening of the Brahmaputra basin (Figure 3). The logs show tens of meters of gravel deposits, intercalated with sand, and none of the wells in the northern flanks reached the basement [*Geological Survey of India*, 1977]. Such mollasse-type deposits are absent in the borehole at Gauhati, which bottomed on the crystalline basement at a much shallower depth. Occurrence of crystalline rocks at shallower level near Gauhati is consistent with what appears to be an exhumed basement under the riverbed that occasionally outcrops in the Brahmaputra Valley (Figures 3 and 4a). Whether these outcrops suggest a deeper fault or they represent a transition zone from the plateau to the valley will remain debatable in the absence of high-quality geophysical data (especially the seismic reflection profiles). Located in the Himalayan foredeep, development of flexural bulges and concomitant tilting is another possibility that must be discounted, but the lack of appropriate data precludes a detailed assessment. However, in the following sections, we present some relevant information indicating that the transition from the plateau to the valley is not gradual, but it could be fault controlled.

3. Signatures of Faulting at the Plateau Margins

[12] The uplift of the Shillong Plateau began around 5.3 million years in the Pliocene Epoch [*Johnson and Alam*, 1991], and its present average elevation is about 1 km, with a maximum of ~2 km. Located in the northeastern flank of peninsular India, the bedrock of the plateau consists of Archaean/Proterozoic gneiss and schist, compositionally similar to the shield rocks [*Evans*, 1964; *Nandy*, 2001] (Figure 4a). Although the whole of the plateau is composed of similar suite of resistant rocks, its northern and southern boundaries seem morphologically quite distinctive. Spectacular gorges, incised river valleys, and waterfalls mark the southern boundary of the plateau, but its northern boundary shows a relatively smoother, staircase-type topography, possibly a result of intense fluvial erosion (Figures 4b and 4c).

[13] The most spectacular structural feature of the southern plateau front is the 300-km-long Dauki fault (Figure 1).

This fault marks the contact between the Precambrian basement of the plateau and the thick Tertiary rocks to its south, and its features are expressed well in both in geological and geophysical data. In the Bouguer gravity profiles, it reflects an abrupt change in the gradient (Figures 4b and 4c). Despite its significant morphological and geophysical expressions, the Dauki fault is not known to have generated any major earthquakes during the historical or recent times [*Chen and Molnar*, 1990; *Kayal*, 2001] (Figure 5). Relatively better constrained focal mechanisms [*Chen and Molnar*, 1990] indicate compression in a north–south direction, normal to the trend of the fault (Figure 1). The general low-level seismicity in terms of moderate/large earthquakes associated with this structure is a point to be considered in the overall hazard scenario, an issue discussed later in this paper.

[14] While the fault bordering the south of the plateau is fairly well defined, the location and geometry of the fault coinciding with its northern boundary are less evident. On the basis of spatially limited post-1897 triangulation data, *Bilham and England* [2001] proposed a steep, ESE striking fault, dipping SSW at 57°, roughly bordering the northern topographic front. This 110-km-long fault, which they refer to as the ''Oldham fault,'' is considered to have generated the 1897 earthquake. A recent study using remote sensing data, however, revealed no compelling structural evidence for the existence of the Oldham fault; nor were any offsets or anomalous fracture density detected along the putative fault [*Srinivasan*, 2003].

[15] We examined the available gravity and seismicity data to check whether these conform to any one of the opposing views. On the plateau proper, Bouguer gravity vary from +40 to −50 mgal, for elevations ranging from a few meters to 2000 m; however, in the Brahmaputra Valley, these range from −80 to −200 mgal, for an elevation change of about 80 m. The horst-like nature of the Bouguer gravity and the variations from the plain to the plateau are interpreted to be due to density contrast, possibly related to deep faulting [*Verma and Mukhopadhyay*, 1977; *Kailasam*, 1979]. In his Bouguer gravity map, *Kailasam* [1979] had indicated a fault located to the north of 26°N. Transverse profiles suggest very small changes in the Bouguer gravity values in the area between 25.5° to 26.25°N; however, a sharper gradient is observed farther north (Figures 4b and 4c). Patches of relatively elevated outcrops of Archaean gneiss (the farthest being about 75 km north of the plateau front) are suggestive of the possible extension of the plateau under the Brahmaputra alluvium. Some of these outcrops are fringed by raised ''older alluvium'' (Figure 4a), providing physical evidence for recent vertical movements.

[16] Seismicity recorded by a local network (1986–1999) suggests that most of the earthquakes occur on the plateau and regions to its north in the Brahmaputra basin (Figure 5). Depth distribution of better quality hypocenters within the selected area suggests concentration of hypocenters at depths <30 km, with more events occurring north of 25.5°N. A

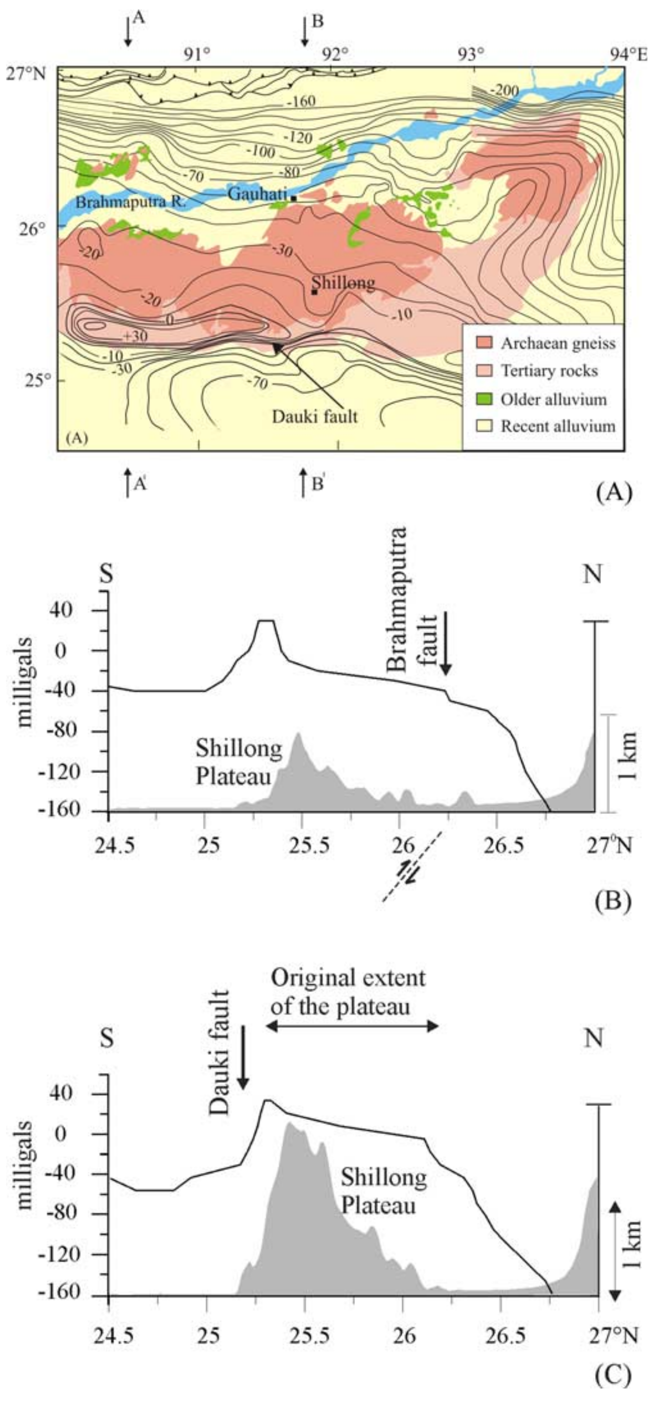

Figure 4. (a) Geology of the region identified in Figure 1, showing patches of raised older alluvium and the Archaean gneissic outcrops. Bouguer gravity contours are in milligals [after *Narula et al.*, 2000]. Arrows indicate the locations of the topographic profiles and cross sections of Bouguer gravity gradient shown in Figures 4a and 4b. (b) Topographic profile and gravity gradient across the Shillong Plateau and the river valley along A-A′ (90.5°E). Scale on right is elevation; scale on left is Bouguer gravity values. (c) Topographic profile and gravity gradient of the Shillong Plateau and the river valley along B-B′ (91.8°E). Scale on right is elevation; scale on left is Bouguer gravity values.

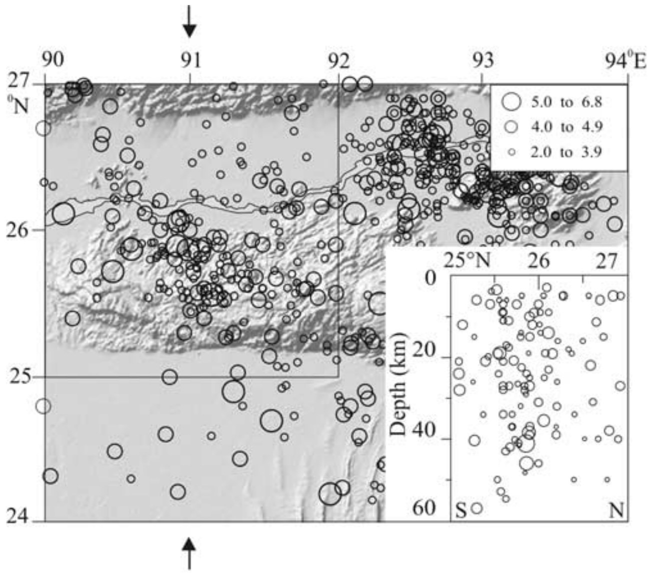

Figure 5. Distribution of earthquakes (1986–1999) in the Shillong region (source is Regional Research Laboratory, Jorhat, Assam). Inset shows depth distribution of earthquakes within area shown in the box. Hypocenters of all earthquakes in the magnitude range from 3.0 to 6.8 (scaled to size) have been projected to 91°E parallel. About 20% of the data was not used because of its questionable accuracy in depth estimates.

large number of these hypocenters, including those deeper than 40 km, seem to fit a steep, south dipping (50°–60°) plane that projects north of 26°N. All of these data compel us to suggest that the fault controlling the northern boundary of the plateau is probably beneath the valley (south of 26.5°N), and we refer to it as the "Brahmaputra fault."

[17] A model developed by *Gahalaut and Chander* [1992] had suggested an E–W trending fault (close to 26.25°N), gently dipping to the north. The fault proposed in this study falls close to this location, but we infer that its movement may be taking place on a steep south dipping plane, as also evident from the modeling of all the available geodetic data [*Bilham and England*, 2001]. As cited in *Oldham*'s [1899] memoir, a postearthquake repeat triangulation (1860, 1898) carried out northward over an area east of 91.5°E meridian from the southern margin of the plateau for a distance of about 60 km showed that the survey points moved 60 cm to 3.60 m, in a generally north to northwesterly and westerly directions (Figure 2b). It is also reported that these stations showed elevation changes ranging from ∼1 m to 8 m. A general northward trend in displacement of the survey points is consistent with a faulting style in which the plateau region moves up dip on the south dipping fault. As noted by *Oldham* [1899], surface effects of the earthquake were most striking within the Brahmaputra Valley and part of the plateau proper south of 26.5°N (Figure 2a). It is therefore reasonable to assume that this part of the plateau, to which the surface deformation and most of the secondary failures are confined is the hanging wall block.

[18] The above interpretation significantly differs from the earlier suggestions of a north dipping thrust, a mechanism that involves thin-skinned wedge transport, originating from the Himalayan front [e.g., *Seeber and Armbruster*, 1981]. *Bilham and England* [2001] have suggested that with high angle-reverse faults bordering its south and north, the Shillong Plateau resembles a "pop-up" structure. Their inference questions the interpretation by *Seeber and Armbruster* [1981] and the suggestion that the 1897 earthquake ruptured a 550-km-long segment of the Himalaya, an issue discussed later in this paper. In the next section, we examine the repeat period of large earthquakes in the source zone of 1897 earthquake, another crucial issue in the regional geodynamics.

4. Earthquake Recurrence: Evidence From Liquefaction Features

[19] The 1897 earthquake generated massive liquefaction in the meizoseismal area, particularly within the Brahmaputra Valley [*Oldham*, 1899]. Identifying older generation liquefactions and dating them, therefore, would provide constraints on the previous earthquakes in this region; the well-documented 1897 features could be used for calibrating the older ones in terms of spatial distribution and dimensions. Previous workers conducted paleoliquefaction studies along the Krishnai and Chedrang Rivers, a region known for the 1897 coseismic secondary rupture [*Sukhija et al.*, 1999a, 1999b] (Figures 2a and 6a, for locations). These studies indicated evidence for at least two older earthquakes during 1450–1650 A.D. and 700–1050 A.D. Our reevaluation of the published data suggests that the liquefaction features identified in this area can also be placed in two groups, on the basis of their relative sizes. While the younger features (1450–1650 A.D.) are characterized by ∼10-cm-wide vents, the width of the older vents (700–1050 A.D.) is ≥50 cm. We find that the dimensions of the older vents, as reported by *Sukhija et al.* [1999a, 1999b], are comparable to those identified as the 1897 features.

[20] We conducted an independent study at two locations along the Chedrang River (fault), near Dilma and Jira (Figure 6a), an area studied by earlier workers for paleoliquefaction features associated with the 1897 earthquake. We highlight here the salient features of some interesting sedimentary features, exposed at two sites, namely, Dilma-1 and Dilma-2. The 4-m-thick section at Dilma-1 revealed a 50-cm-wide sand dike that had disrupted the bottommost clay layer (Figure 6b). This section consists of two texturally different types of emplaced sands; one is fine- to medium-grained brownish sand, and the other is much finer-grained, whitish sand. Both these sand units can be termed as sills as they have not broken through the top layer of host sediments consisting of gritty brownish sand. The stratigraphic relation of these units indicates that the sill composing of the whitish sand has been emplaced into the brownish sand, and it assumes a domal shape in the middle of the section (Figure 6b). The boundary of the older sill is quite distinct in the lower part of the section. Toward the top, it appears to have been mixed with the host sediments

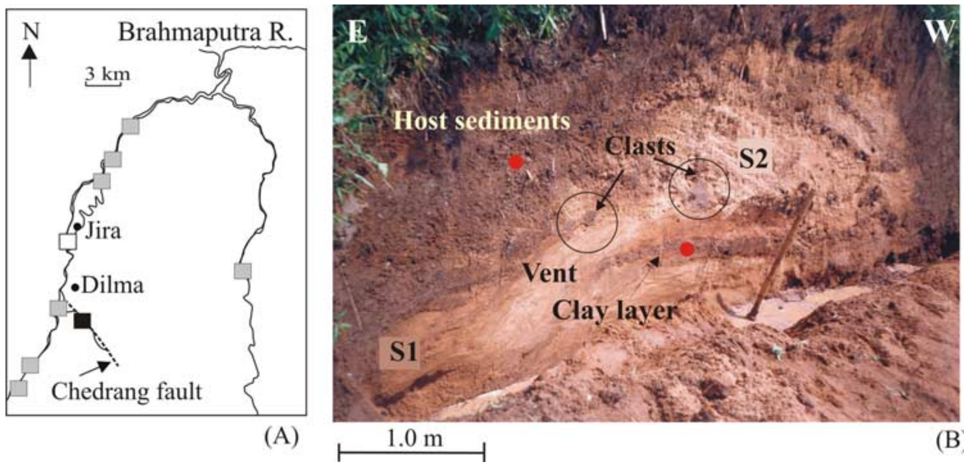

Figure 6. (a) Locations of paleoliquefaction sites around the Chedrang River. Sites investigated by *Rastogi et al.* [1993] and *Sukhija et al.* [1999a] and the present study are shown by open, shaded, and solid squares, respectively. Both the sites discussed in the text (Dilma-1 and Dilma-2) are within the area identified by the solid square. (b) A view (facing north) showing the paleoliquefaction feature exposed at Dilma-1 located on the western bank of the Chedrang River. S1 is the older sill and S2 is the younger sill. Broken clay layer and clasts of clay are scattered within the feature. Samples collected from the ruptured clay layer and the host sediments (locations shown by red dots) yielded calibrated ages of 2170 ± 140 years B.P and 1250 ± 80 years B.P., respectively. The section shown here is 1 m below the surface.

consisting of gritty brown sand and has partly assimilated into the younger sill. The characteristics such as well-defined conduit, upward directed flow structures, and rip-up clasts within the main body of the intrusion (shattered fragments of the clay stratum) suggest that these have resulted from earthquake-induced soil liquefaction [e.g., *Obermeier*, 1998; *Tuttle and Schweig*, 1995].

[21] We interpret this feature to have resulted from multiple liquefactions, in which the younger feature (event II) crosscuts the older sill (event I). Radiocarbon dating of peat samples obtained from the host sediments yielded a calibrated age 645–980 A.D. (1250 ± 80 years B.P.) and that the lower most ruptured layer of clay was dated at 535–530 B.C. (2170 ± 140 years B.P.) (Figure 6b and Table 1a). We consider these dates as the maximum and minimum age bounds for the older sill. Age of the younger feature could not be constrained, but arguably, it may have formed during the 1897 earthquake, assuming that no major earthquakes have affected this area in the intervening period.

[22] In another section (Dilma-2), located a few meters west of the above site, we observed further evidence for crosscutting relation of sand dikes of different vintages. Although we did not obtain any datable material from this site for constraining the minimum age, the accelerator mass spectrometry date of a peat sample from the ruptured clay layer suggests its formation during 2501 ± 75 years B.P. (B.C. 810–400) (Table 1a). This is similar to the age obtained for the ruptured clay layer in Dilma-1, and we assume that the age ranging from 2170 ± 140 years B.P. to 2501 ± 75 years B.P. is the maximum bound of the older dike. Thus our data suggest that the penultimate earthquake that generated the older sill may have occurred between 1250 ± 80 years B.P. and 2501 ± 75 years B.P. Averaging the radiocarbon dates published by *Sukhija et al.* [1999a], using the statistical method suggested by *Pinter* [1996], we obtained an age of 1208 ± 40 years B.P., which also agrees with our independently derived chronology for the Dilma features.

Table 1a. Radiocarbon Age Data for the Samples From Sites at Dilma, Chedrang, Assam (India)[a]

Sample	Laboratory	Material	^{14}C Age, Years, B.P.	Calendar Age, B.P. (2σ Range)	Calendar Year (2σ Range)
D1-1897-1	BS-1900	charcoal	2170 ± 140	2486–2481	535–530 B.C.
D1-1897-2	BS-1901	charcoal	1250 ± 80	1305–971	645–980 A.D.
D2-1897-1	NZA 14919	charcoal	2501 ± 75	2761–2347	810–400 B.C.

[a]Calendar years were estimated following *Stuiver et al.* [1998]. First two samples (conventional radiocarbon ages) were dated at Birbal Sahni Institute of Paleobotany, Lucknow, India, and the age of the last sample (accelerator mass spectrometry date) was obtained from Rafter Radiocarbon Laboratory, Wellington, New Zealand.

[23] The above age also conforms to a concurrent radiocarbon date (1220 ± 100 years B.P.) obtained by *Rastogi et al.* [1993] from a tree trunk embedded in a sandblow excavated near Dilma (see Figure 6a for location of the trench). Their studies also confirm that the ~1200-year-old sand dikes are larger in size (width ≥50 cm) and are ubiquitous in this region. Only the 1897 earthquake is historically known to have generated such large features in this region, and we believe that the older feature, with comparable size, may also be related to the same source. The smaller and younger liquefaction features (average width ~10 cm; 1450–1650 A.D. years B.P.) discussed by *Sukhija et al.* [1999a, 1999b] probably belong to a distant earthquake, an inference we derive from the relation between dimensions of the liquefaction features and distance to sources [e.g., *Obermeier*, 1998]. In the next section we analyze the historical data to seek additional constraints on the past seismicity of this region.

5. Historical and Archaeological Constraints on Past Seismicity

[24] Remains of monuments and temples, the oldest of which belong to a period covering circa fifth century to tenth century A.D., lie scattered over an extensive area in the Brahmaputra Valley, testifying to the fact that a rich culture had flourished here several centuries ago. From the widespread nature of destruction to temples in the Brahmaputra Valley, *Barua* [1966] suggested that only some major earthquakes could have caused such widespread destruction. In a region where history stretches to periods far beyond the probable timing of the penultimate earthquake, chronological constraints can be obtained from monuments and other heritage structures, whose history is well documented. As demonstrated below, such a study has proved to be very useful to complement the results from paleoliquefaction studies.

5.1. Chronological Constraints on the Pre-1897 Earthquake

[25] A catalogue of ancient monuments [*Chaudhury*, 1964] indicates that ruins of almost all of the stone temples discovered around Dhubri, Goalpara, Barpeta, Gauhati, Nowgong, and Tezpur belong to circa ninth-tenth century A.D (see Figure 1 for locations). Historical data also reveal that during the ninth-eleventh century A.D., there was a wave of reconstruction activity in Assam. For example, a copper plate inscription of 835–860 A.D. near Gauhati mentions the reerection of a "lofty white temple, which had fallen down" [cf. *Barua*, 1966]. Later generation construction in the contemporary style and inscriptions on some of these temples testify to their rebuilding. These reconstructions seem to have followed a massive destruction, and the timing is in agreement with that of the large earthquake (~1200 years B.P) inferred from the paleoliquefaction studies, discussed earlier.

[26] The case of a circa sixth century A.D. structure, the ruins of one of the oldest temples in Assam, is also quite instructive. Located at Da-Parbatia, near Tezpur, what remains here today is only a small doorframe in stone, dating back to the fifth-sixth century A.D. The ruins consist of the remains of a brick-built temple (circa eighteenth century A.D.), erected upon the ruins of a stone temple of circa sixth century A.D. The former collapsed during the earthquake of 1897, revealing stone doorframe of the older structure [cf. *Barua*, 1966]. Coexistence of these structures, which follow distinctly different styles of construction, suggests multiple episodes of destruction, and the earlier one was presumably caused by a post-sixth century (825 and 835 A.D.) earthquake. Such ancient ruins are not just confined to the vicinity of Tezpur and Gauhati, they are also found in other places along the Brahmaputra Valley [*Banerji*, 1923; *Chaudhury*, 1964] (see Figure 1 for locations), suggesting that the destruction was not localized. It is reasonable to believe that only an earthquake could have caused such widespread and massive destruction.

[27] References to earthquake damage are also found in ancient books such as *Kalikapurana* and *Yoginitantra* (late ninth and sixteenth century A.D., respectively) (referred by *Iyengar et al.* [1999]). Both these texts mention destruction to the temple of Kamakhya (seventh-eighth century A.D.) situated on the top of Nilanchal Hills, about 8 km from the town of Gauhati (Figure 1; location 3). On the basis of this cue, we studied a section, excavated at the temple of Kamakhya, which confirmed the aforementioned textual evidence of destruction. The most revealing aspect of this ~2-m-deep section is the occurrence of a layer of debris, broken bricks, pottery, and a jumble of carved stones with alternating levels of bricks (Figures 7a and 7b). The modern temple sits at the present surface level, on a foundation made of bricks. Below this is a layer of sand, underlain by another layer of bricks, presumably the remnant of the temple, destroyed during the 1897 event. The cluttered middle horizon below this level reflects massive destruction of the previously existing temple structure (sixth–eighth century A.D.). Historic records of earthquake damage discussed earlier correspond to this period. Samples of pottery from this assorted layer and the bricks from the bottommost layer yielded thermoluminescence (TL) dates of 1194 ± 120 years and the 1464 ± 150 yr, respectively (Figure 7 and Table 1b). These dates probably correspond to minimum and maximum age limits for the penultimate earthquake. The pottery appeared to have been used for temple rituals and therefore yields a younger age, whereas the bricks used for construction of the temple would provide the original date of firing. The mean value (with error margin) agrees with the 1200-year-old event, recognized from paleoliquefaction data and historical records. This assumption is corroborated also by contemporaneous reports of damage to other local monuments of the same vintage and epigraphical evidence, suggesting destruction to structures around the eighth century A.D. (Table 2).

5.2. Antiquity of Penultimate Earthquake: Further Evidence From the River Valley

[28] Ancient Brahmaputra Valley is known for stone bridges, and at least one of them existed until the 1897 earthquake, near Gauhati [*Hannay*, 1851; *Barua*, 1966].

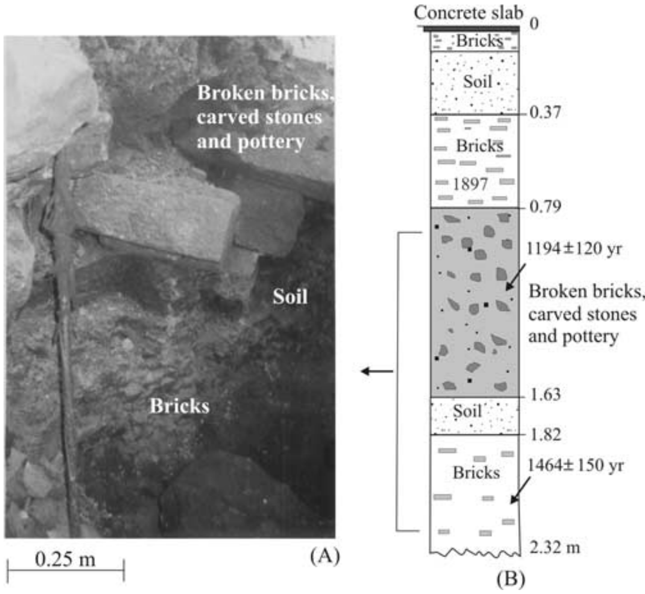

Figure 7. (a) Photograph showing a pit excavated at the bottom of the southern compound wall of Kamakhya temple; top part of the section is not represented in the photograph. (b) Log showing complete stratigraphy with different levels of temple foundations and corresponding thermoluminescence (TL) dates. The upper bricks layer represents ruins due to the 1897 earthquake (on the basis of temple documents); however, the TL value for this level was close to zero (see text for more details). Section of the log shown in the photograph is indicated.

Built across one of the presently dry channels of the Barnadi River, this bridge, which we refer to as Barnadi bridge, located about 10 km NW of Gauhati, collapsed during the earthquake (see Figure 3 for location). The design and style of architecture of this bridge are coeval with that of the ancient stone temples built during a long period from the fifth to 10th century A.D. [*Hannay*, 1851]. Thus it is likely that the Barnadi bridge and several other smaller stone bridges built across the rivers near Gauhati were constructed around that period. Historical accounts testify to the fact that an invading cavalry in 1205–1206 used the Barnadi bridge, to cross over to Bhutan and Tibet [cf. *Hannay*, 1851]. Captain Dalton examined this bridge in 1851 and wrote (as quoted by *Hannay* [1851])

> The structure is of solid masonry, built without lime or mortar. . .the superstructure being a platform with a slight curve 140 ft long and 8 ft in breadth composed of slabs of stone six feet nine inches long and ten inches thick, numbering five in the whole breadth, resting on an understructure of sixteen pillars, three in a row, equally divided by three large solid buttresses; with a half buttress projecting from a circular mass of masonry forming the abutments at each end of the road, there being in the whole, 21 passages for the water.

Hannay [1851] presents a sketch of this bridge that illustrates most of these features. According to the historians, no other large stone bridge fitting Captain Dalton's description is known to have existed within this kingdom and they have little doubt that the structure that collapsed completely in 1897 is indeed the same as that existed during the aforementioned expedition by the invading army [*Gait*, 1905; *Barua*, 1966, p. 141]. Although the exact age of this bridge is not known, as a first approximation, it seems reasonable to believe that an 1897-type earthquake had not occurred in this region at least for 690 years.

[29] The court chronicles mention of an earthquake in 1697 A.D., which occurred at Sadiya in the Upper Assam region (Figure 1). A record of this earthquake reads as follows [cf. *Iyengar et al.*, 1999]:

> In the month of Puh 1618 (A.D. 1697) Bandar Phukan of the Chetia family constructed a fort at Puingdang under the orders of the king which took two months. In the same year there was an earthquake, which continued for six months in an abortive fashion, from Phagu to Saon. The earth was rent asunder at Sadiya, and magur and kawai fish appeared in the breaches. As sands and water appeared at that place, the sides of the hills crumbled down.

This remarkable description suggests this event to be a major earthquake, followed by a long and significant sequence of aftershocks. However, the fact that the Barnadi bridge survived this earthquake, to be destroyed only in 1897, is an indication that the 1697 earthquake was much smaller or that it was distant. Historical data suggest that the maximum damage occurred in the town of Sadiya, located at least 300 km east of the 1897 source in the Upper Brahmaputra Valley (Figure 1). Interestingly, this site figures prominently in the discussion of the great earthquake of 1950 (M 8.6), as well. The 1950 earthquake with its epicenter at Rima, outside the Indian border (Figure 1), had also affected the Upper Brahmaputra Valley because of liquefaction, bank failure, subsidence, and landslides in the catchment area, besides completely destroying Sadiya Town [*Poddar*, 1950]. Taking into account error margins in

Table 1b. Data on Thermoluminescense Dating and Estimated Ages of the Samples From the Base of the Temple Wall at Kamakhya, Gauhati, Assam (India)[a]

Sample	Laboratory	Material	Average Dose Rate, mGy/yr	Equivalent Dose, Gy	Estimated Age, ka
KS2	...	pottery	4.27 ± 0.60	4.993 ± 0.009	1194 ± 120
KS3	...	brick	4.27 ± 0.60	6.145 ± 0.038	1464 ± 150

[a]Procedures used in this analysis were similar to those described by *Aitken* [1985]. Thermoluminescense was measured with Riso TL/OSL (model TL DA-15) reader (located at Manipur University, Imphal, India). The dose rate was determined on the basis of assaying Th and U by alpha counting techniques and the K content using inductively coupled plasma-atomic emission spectrometer (ICP-AES).

Table 2. Earthquake Chronology in the Brahmaputra Valley From the Historical Data[a]

Year of Earthquake	Location/Effects	Intensity/Size
Ninth century (between 825 and 835 A.D.)	Destruction of temples and palaces from Dhubri in the west through Gauhati to Tezpur in the east [*Banerji*, 1923; *Chaudhury*, 1964]. Location is near Gauhati-southern Brahmaputra Valley.	Very large earthquake; magnitude ≥8.0; location and timing of the earthquake are based on the present study.
1663 A.D.	Earthquake felt at Gauhati; probably a local earthquake; no damages reported [*Gait*, 1905].	Probably a mild tremor.
1697 A.D.	Earthquake strongly felt at Sadiya (27°48N; 94°38′E), about 300 km east of Gauhati. Massive damage; appreciable aftershock sequence; ground fissuring and liquefaction at the town of Sadiya [*Iyengar et al.*, 1999]. Either this earthquake occurred at the 1950 source zone or it could be an independent source in the upper Brahmaputra Valley or Himalaya.	Very large earthquake; magnitude ≥8.0;
1930 A.D.	Earthquake at Dhubri (25°57′N; 90°00′E); liquefaction and ground failure within the alluvial tract of north Bengal and NW Bangladesh and western Brahmaputra Valley [*Gee*, 1934].	Moderate earthquake; $M \sim 6.5$
1870–1880 A.D.	Series of tremors occurred near Gauhati, followed by a relatively quiet period, starting from 1880, until the 1897 event [*Keatings*, 1877, 1878; *Bapat et al.*, 1983].	Minor earthquakes; none of them damaging.
12 June 1897	Total destruction in the valley (Tezpur in the east to Goalpara in the west) and many parts of the Shillong Plateau including monuments and stone bridge near Hajo.	Very large earthquake; magnitude ≥8.0

[a]The medieval records include moderate earthquakes of 1548 A.D. (Garhgaon, SE of Sibsagar; 26°45′N; 94°50′E; about 300 km east of Gauhati) and 1596 A.D. (Gajala; modern location uncertain), minor earthquakes of 1642 A.D. and 1649 A.D. that occurred in the Upper Assam [*Iyengar et al.*, 1999]. Large earthquakes reportedly also occurred in the higher Himalayas during 1713 and 1806 near Upper Assam at 27.5°N; 93.0°E and 28.5°N; 92.0°E, respectively [*Ambraseys and Jackson*, 2003].

radiocarbon dating, it is likely that the sand vents in the Lower Brahmaputra Valley, near Chedrang, bracketed between 1450–1650 A.D. years B.P., were formed by the 1697 earthquake.

6. Conclusions and Implications

[30] Several important points need to be considered in assessing the mechanism of the 1897 earthquake: the geometry of the causative fault, recurrence of large earthquakes, and their relation to the regional tectonics, among the key issues. In this paper, we have addressed these compelling questions to arrive at a fresh seismotectonic perspective on this earthquake. An evaluation of the coseismic deformation associated with the 1897 earthquake indicates that the Brahmaputra Valley was severely affected. Geomorphologic modifications including coseismic level changes and postearthquake development of marshes and swamps are particularly evident in the central segment of the valley. Damage intensity and density distribution of deformation features such as fissures, dikes, etc., are also dominant in this part. We have used these observations together with shallow stratigraphy, surface geology, and available gravity and seismicity data to postulate that the causative fault may be located within the river basin.

[31] The Bouguer gravity values in particular are indicative of a fault that projects around 26.25°N, and there is less evidence of a fault close to the present range front, as suggested by *Bilham and England* [2001]. Inference of a steep south dipping fault that projects north of 26.0°N is also supported by the depth distribution of earthquakes. Geological observations are consistent with the interpretation that the present northern topographic front may represent a receded range. We believe that the original plateau boundary, extending under the alluvium, is spatially coincident with the proposed "Brahmaputra" fault. This structure may have been responsible for the 1897 earthquake, although no coseismic rupture was reported. Any expression of a rupture that may have developed here is unlikely to have been preserved in its original condition in this rapidly changing fluvial environment.

[32] The combined evidence obtained from geological, archaeological and historical data are explicit on the occurrence of a large earthquake ($M > 8.0$) in the 1897 source zone, about 1200 years ago. This observation contradicts the 3000–8000 year repeat period proposed for great earthquakes in this region, by *Bilham and England* [2001]; it also questions the 500-year-interval suggested by *Sukhija et al.* [1999a]. However, our analysis of data indicates that an earthquake of comparable magnitude occurred in the Upper Brahmaputra Valley, which has generated liquefaction features of smaller dimensions in the 1897 source zone. This earthquake, historically dated at 1697 A.D., may have occurred near the 1950 event, or at an independent source within the upstream part of the valley, close to Sadiya.

[33] Presence of a south dipping reverse fault at the northern plateau boundary, with repeated movements independent of the Himalayan thrust from the north, has important implications for regional tectonism and seismic hazard. It has long been considered that the 1897 earthquake originated on a gently north dipping fault, a part of thin-skinned deformation extending from the Himalayan front, until *Bilham and England* [2001] presented the steep south dipping fault model. According to an earlier proposal by *Seeber and Armbruster* [1981], the 1897 earthquake ruptured a 550-km-long segment of the Himalaya, filling the gap between the ruptures associated with great earthquakes of 1934 and 1950 (Figure 1, inset). Following this argument, it has been suggested that the 1897 rupture has lowered the potential for a large earthquake in this segment of the Himalaya. There are two interrelated issues to be addressed here: one, whether the rupture length was indeed 550 km, and two, if this can be treated as a rupture on the Himalayan segment. Originally, *Oldham* [1899] estimated that the length of the 1897 rupture zone was not more than 160 km. With the exception of *Seeber and Armbruster* [1981], all others who have interpreted Oldham's data tend to be similarly conservative on the rupture length. For example, *Molnar* [1987] suggests 200 ± 40 km, and *Gahalaut and Chander* [1992] posit 170 km. Our own estimate does not exceed 200 km. Even if the actual rupture length remains debatable, the recent observations including what is presented here establish the fact that the faults bordering the plateau are controlled by mechanisms unrelated to the thin-skinned tectonics, and therefore treating the 1897 earthquake as part of the Himalayan tectonics would not be realistic.

[34] Another point of concern is the role of the Dauki fault in the regional seismic hazard. Although there are explicit references to the occurrences of damaging earthquakes in the Brahmaputra Valley and its upstream parts, there are no suggestions of similar events from the southern side of the Shillong Plateau, at least for >1000 years. Recent seismicity maps of the region also indicate relatively low-level activity along the Dauki fault and regions to its immediate north. Considering the visible geological evidence of large vertical movements, the current quiescence of this structure is quite intriguing. Although aseismic creep may be reckoned as a possible mechanism, in the absence of microearthquake activity close to the fault, this seems less likely. Another possibility is that part of the Dauki fault could be episodically moving antithetically in response to the activity on the northern boundary fault, and the lower rate of erosion helping to retain its high elevation. Relying on *Oldham*'s [1899] observation that the movement during the 1897 earthquake was not restricted to a single fault, it is quite tempting to suggest that there may have been some antithetic movements on the Dauki fault. Future studies should also consider the role of tectonic denudation in generating the present geomorphologic and structural fabric of the Shillong Plateau. Isostatic response to differential unloading and bedrock uplift is an issue that must be addressed in this context.

[35] The important question in the context of the regional seismic hazard assessment is if the Dauki fault is presently locked, and if it is capable of generating large earthquakes. We have no data specific to this structure, but the historic and paleoseismologic data presented in this paper suggest that the fault bordering the north of the Shillong Plateau holds potential to generate large earthquakes during intervals of about 1200 years. To suggest a lower potential associated with the Dauki fault may not be tenable, considering its long elapsed time. Thus the assumption of a 3000-year interval for these boundary faults, as proposed by *Bilham and England* [2001], may not be an accurate representation of the earthquake potential in this region.

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