Ambraseys, N., and R. Bilham, (2003) MSK Isoseismal intensities evaluated for the 1897 Great Assam Earthquake, Bull. Seism Soc. Am. 93 (2) 655-673.

Abstract: **The great 1897 Assam earthquake of 1897 is the largest known Indian intraplate earthquake (8<M<8.1). The earthquake raised the northern edge of the Shillong Plateau by more than 10 m, resulting in the destruction of structures over much of the Plateau and surrounding areas, and causing widespread liquefaction and flooding in the Brahmaputra and Sylhet floodplains. Shaking intensity data for the earthquake are crucial for estimating future earthquake hazards in NE India and Bangladesh since similar earthquakes will no-doubt recur. Yet despite the availability of numerous felt reports, no evaluation of isoseismal contours has been attempted since Oldham's (1898) approximation. We have re-evaluated 365 accounts of the earthquake and quantified 287 on a simplified version of the "MSK 1981" Intensity scale. The re-appraised isoseismals are consistent with the geodetic mechanism for the earthquake and are smaller, less regular, and less elliptical than those inferred by Oldham. They suggest that Oldham's intensities were inflated by 1-1.5 intensity units. The revised intensity data provide new quantitative constraints on the attenuation of perceived intensity as a function of distance in northeastern India.**

Introduction

The earthquake of 12 June 1897 in the Shillong Plateau in north-eastern India is the largest intraplate event in the last two centuries to have occurred in the Indian subcontinent. Although contemporary geodetic data have been used recently to infer the rupture parameters of the earthquake (Bilham & England, 2001), much of what is know about the intensity distribution of the event comes from Oldham's detailed report and his subsequent estimates of aftershock activity (Oldham, 1898; 1901; 1904; 1920). Over the years his report and isoseismal maps have been used to assess the seismic hazard of this part of India, to evaluate the magnitude of the event, and to constrain the location and dimensions of the associated rupture zone (Figure 1).

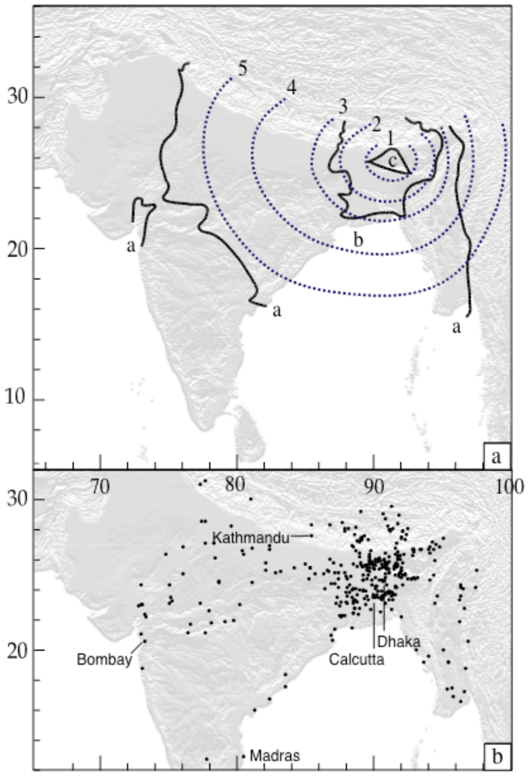


Fig. 1a. Location map for the 1897 Assam earthquake showing isoseismal approximations assigned by Oldham (1899) as dashed incomplete ellipses. Bold lines enclose Oldham's (a) felt area, (b) "area of extensive damage" and (c) "the probable limits of the epicentre", beneath and north of the Shillong Plateau. Fig.1b. Locations of observational data (dots) used to evaluate MSK intensities.

In view of the importance of the 1897 earthquake, we consider a review of the intensities assigned by Oldham to be warranted, especially since we may now incorporate data from Tibet and from published data not utilized by Oldham. This paper is concerned solely with the reappraisal of the intensity distribution of the Assam earthquake, drawing attention to potential pitfalls associated with indiscriminate use of intensity data.

The earthquake

General The earthquake occurred beneath the Shillong Plateau in what was then the district of Assam, in northeast India. For many years the earthquake was considered to have occurred on a gentle north-dipping rupture beneath the Shillong Plateau, linked structurally to the style of Himalayan thrust faulting (Seeber et al., 1981, Molnar 1987; Molnar and Pandey, 1989, Gahalaut and Chander, 1992). This interpretation has recently shown to be untenable. According to recent analyses of geodetic data acquired in 1860, 1897 and 1936, the earthquake occurred on a steep SSE-dipping reverse fault beneath the northern edge of the central Shillong Plateau (Bilham and England, 2001). Rupture is inferred to have extended from 9 km to more than 30 km depth on a 110-km-long, SSE steeply-dipping reverse fault that slipped approximately 15 m. The Chedrang fault, a north-south secondary fault, ruptured the surface at the western end of, and above the main rupture.

The Assam earthquake holds a prominent place among the great earthquakes of the world, not only because of its large magnitude, but also because of the large area over which it caused damage, liquefaction, and landslides. Destruction was widespread on the Shillong Plateau, (the present state of Meghalaya), and in surrounding areas (Figure 1). Much of what is known about the event is exclusively due to Oldham's report, (Oldham 1899).

The earthquake almost totally destroyed settlements and small towns on the western part of the Plateau, and caused heavy damage in surrounding districts, chiefly due to the extensive liquefaction of the ground. The Plateau, which is the only high ground between the Himalaya and the Bay of Bengal, is about 250 km long and 80 km wide and includes, from west to east, the Garo, Khasi and Jaint hills. It stands more than 1,500 m above the plains of the Brahmaputra River which flows along the north and west sides of the Plateau. The Sylhet flood plains bound the Plateau's southern margin where much additional damage occurred. The Plateau receives an average of 11.4 m of precipitation, the second highest rainfall in the world, much of it during the monsoon period.

Instrumental The earthquake occurred at 17h 15m local time (11h 09m GMT) and was recorded by 12 primitive seismographs in Europe at distances between 64° and 72° (Germany, Italy, France and UK). Instrumental readings, however, are not good enough to be used to establish its position, even approximately, and the macroseismic location of the event has been estimated by various authors at 26°N, 91°E. The mean geodetic location is 25.7°N. 91.1°E.

Although 1897 occurred too early to be located instrumentally, its surface-wave magnitude M_S can be estimated from the trace amplitudes recorded by six calibrated instruments operating at the time in Italy (Agamennone, 1897; Cancani, 1897), one in Russia (Kortazzi 1900), and two in the UK (BAAS 1898). Using Abe's method we obtain a value of M_S 8.0 ±0.15). This value is very close to the estimates of 8.2 made by Kanamori and Abe (1979), revised by Abe (1994) to 8.0, and to the unified magnitude m = 8.0 estimated by Gutenberg (1956). By converting Gutenberg's unified magnitude m into M_S through the empirical relation, $M_S = 1.59m - 4.0$, a relation derived for California for M_S estimates based on surface waves with periods close to 20 seconds, Richter (1958) obtains Ms=8.7. Richter's inflated estimate of 8.7 has been adopted by later authors. The geodetic moment estimate is $M_W = 8.1 \pm 0.1$ (Bilham and England, 2001). Here we adopt the value of M_S 8.0 (Ambraseys 2000).

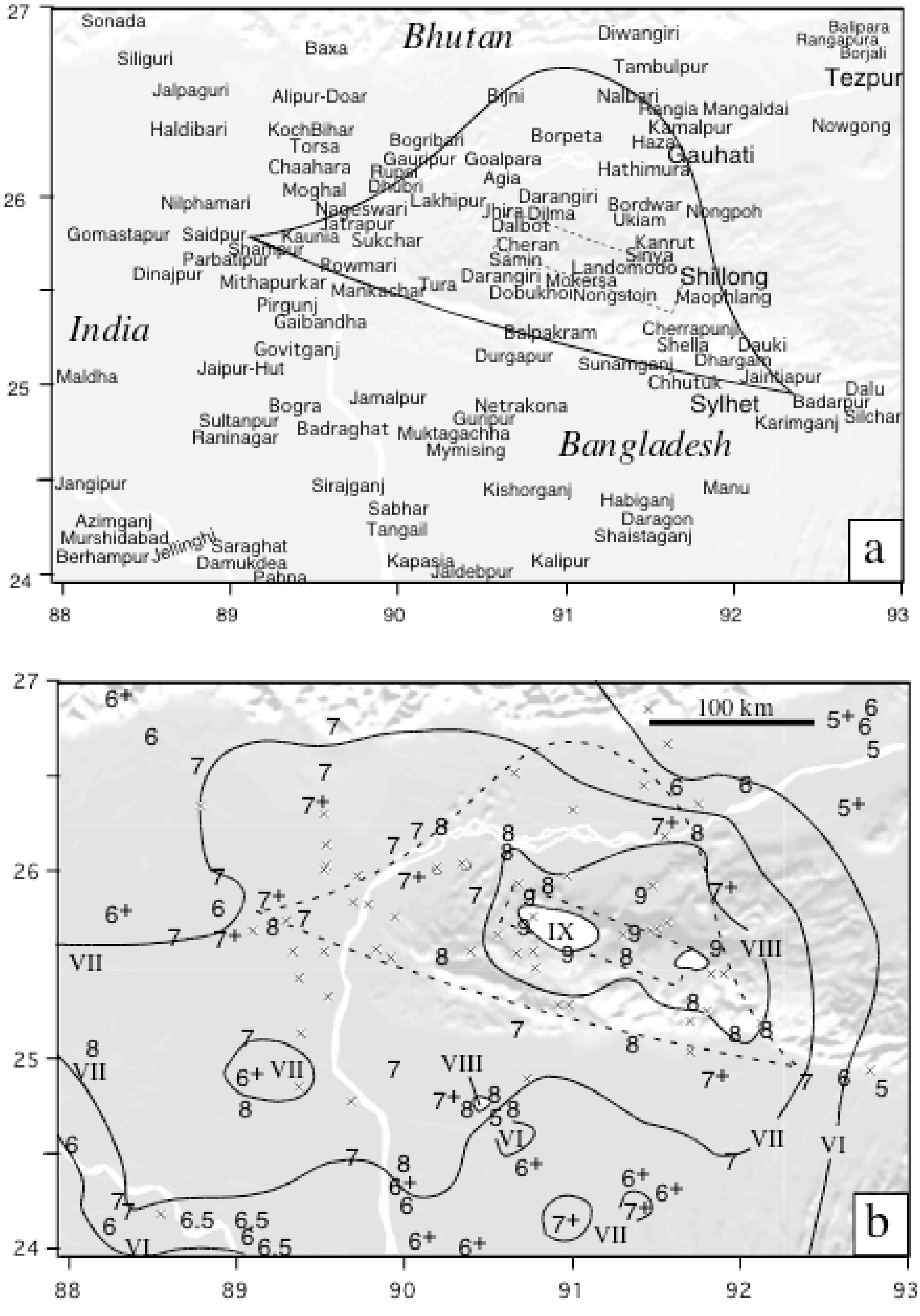


Fig. 2a. Epicentral location map showing Oldham's (1899) epicentral area centered on the Shillong Plateau, and dashed rectangle indicating the inferred 1897 subsurface rupture. Fig. 2b Same area with evaluated MSK intensities, rejected observational data (x), and isoseismal contours evaluated using kriging methods described in the text.

Faulting. In spite of its large magnitude, the earthquake left no vestiges of extensive through-going surface faulting that today could help confirm the attitude of the causative rupture and the extent of the rupture zone. Surface faulting was found by Oldham in the north-west part of the Shillong Plateau (Garo Hills), running for a distance of at least 19 km along the Chedrang fault which strikes 340°E, (measured from 25.81°N, 90.73°E) and showing maximum vertical displacements of about 9.5 m with the east side up, on an approximately vertical exposed fault plane ~~with no indication of the associated dip~~. Other smaller fractures were found south-west of the Chedrang fault near Samin.

A series of fractures in rock were also found on the northern part of the Plateau (Khasi Hills), about 60 km to the east of the Chedrang fault, probably coseismic, running intermittently for about 9 km and bearing 6°E (25.26°N, 91.44°E).

Oldham suggests that all these ruptures were not primary manifestation of the earthquake but rather the result of internal deformation of the region (Oldham 1899). Oldham describes several freshly ponded regions on the Plateau suggestive of internal tilting, and one clear example of post-seismic flexure of the surface revealed by changing lines of sight recorded by eye-witnesses. However, there is no evidence that a *primary* surface break was associated with the event.

Early attempts to model the causative rupture from tectonic consideration and Oldham's isoseismal map viewed the fault as dipping gently towards the Himalaya (*e,g.* Seeber and Ambusher 1981, Molnar 1987, Gahalaut and Chander 1992). The south-dipping geodetic solution for this earthquake is well-constrained but integrates coseismic and postseismic deformation along the north edge of the Plateau (Bilham and England**,** 2001). A south-dipping fault is consistent with an interpretation advanced by Auden, and by gravity data, which suggest that Shillong Plateau is an inlier horst of peninsular India thrust up between the Himalaya and the Naga Hills (Auden 1949).

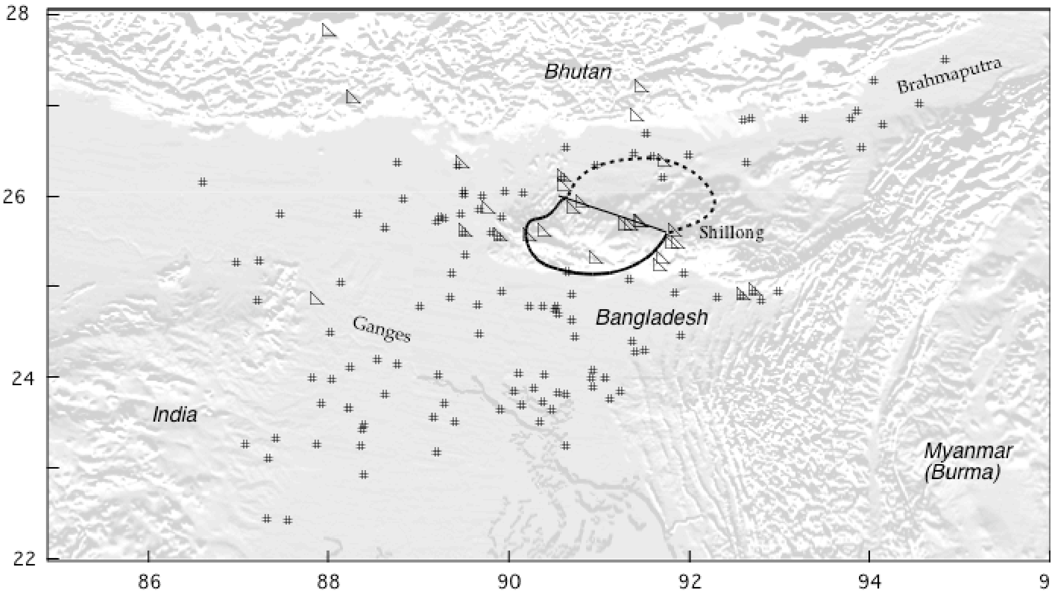


Fig.3 Liquefaction sites (#) and landslide locations (triangles) reported for the 1897 mainshock. Contours for 25 cm uplift (solid line) and 25 cm of subsidence (dashed line) inferred from triangulation (Bilham and England, 2001) are indicated SW and NE respectively of the projected intersection of the subsurface 1897 rupture plane with the surface of the Shillong Plateau

Oldham's intensity assessment. The scale devised by Oldham (1899) to assess intensity consists of 6 grades, viz,

1- The earthquake was only noticed by a small proportion of people who were sitting or lying down or were otherwise favourably placed to observe it [X RF].
2- Theshock was strong enough to be generally noticed, but not to cause any damage [IX RF].
3- The earthquake was universally felt, severely enough to disturb furniture and loose objects, but not to cause damage, except in a few instances, to brick buildings [VIII RF].
4- All or nearly all brick buildings were damaged [VI+RF].
5- The damage to masonry or brick buildings was universal, often serious, amounting in some cases to destruction [IV+ RF].
6- The destruction of brick and stone buildings was particularly universal [II+ RF].

Oldham, who new about the Rossi-Forel scale, did not use it but took his grades to correspond roughly with the (RF) grades which are shown above in brackets [Båth 1970]. In a later publication Oldham, adopting the Mercalli (M) scale, concludes that throughout the greater part of the Garo and Khasi Hills, in the western part of the Plateau, intensities were not less than VIII M, more usually reaching X and in places XII, estimates apparently *based* on evidence of secondary effects such as ground deformations and fractures, changes of level and cumulative damage from aftershocks, [Oldham 1920**]**.

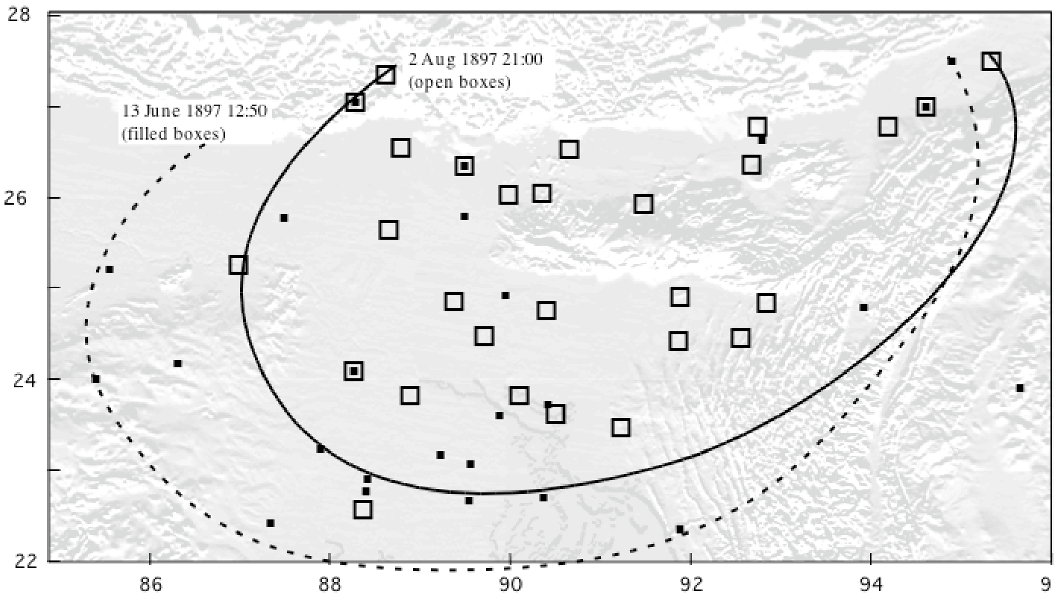


Fig.4 Observations and felt areas for the aftershocks of June 13 1897 (filled squares and dashed line), and 2 August 1897 (open boxes and solid line).

Data from India In spite of its great volume and attention to detail, Oldham's report contains relatively little information that can be used to reappraise intensities. His report, which makes fascinating reading, concentrates chiefly on earthquake effects other than vibrational, such as the rate of propagation of the shock, ground effects, liquefaction, landslides, rockfalls, earthquake sounds, direction of the ground movement and electrical effects, subjects which occupy more than 95 percent of the report, with little or no explicit quantitative information about the extent of damage, loss of life and property caused by the earthquake. He visited only a fraction of the epicentral region personally in a series of traverses across and around the Plateau. His avoidance of detailed damage reports was stated as a deliberate decision on his part to avoid sensationalism, and instead to focus on scientific objectives [Oldham 1884]. In his 1899 report he emphasizes the difficulties of applying the Rossi-Forel intensity scale to destruction in the epicentral region. This suggests that he had notes and access to accounts of damage from throughout the epicentral region.

Apart from Oldham's report and the references he quotes, the main additional sources of macroseismic information that can contribute to the understanding of the engineering effects of the earthquake are the Indian and international press, supplemented by published reports and technical papers. Oldham's subsequent three papers on the Assam earthquake (Oldham 1901, 1905 and 1920) add little. The reports by Luttman-Johnson (1898), Anderson (1900) and in particular the *1898-99* report of the Public Works department are useful, as well as those by La Touche (1897), Gait (1926) and Gorshkov (1961).

Press reports abound, but in the days that followed the earthquake, they are repetitive and carry little useful information, much of it exaggerated or unauthenticated. The press were preoccupied with the famine and plague in India, both of which were at their height at that time (Lambert, 1898), and in particular with the preparations for the celebration of the Diamond Jubilee of Queen Victoria (23 June 1897). Details about the effects of the earthquake were clearly delayed from being published as there had been a "natural disinclination to mar the Jubilee by giving undue prominence to misfortunes in one part of the Empire" [The Times, 19/07/1897]. Articles such as those we can find in London in the Indian press *e.g. Bengalee, Englishman, Indian Daily News, Indian and Eastern Engineer,* the *Madras Times,* the *Allahabad Pioneer Mail* and *Indian Weekly News,* and the *Times of India* are useful, but these newspapers did not start publishing reliable reports for some time. When reports were published they revealed less loss of life and less damage than originally reported. A consequence of this delay is that articles in the world press, drawing from early press reports, tend to give a rather exaggerated picture of the situation. In what follows, because of their large number, press reports are not quoted.

Besides these sources of information, many more written at second hand long after the event have been found, but they do not add anything of importance and they are not cited.

Data from Tibet. Observations from Tibet, extracted from unpublished *Gaxia* (local government) archives in Tibetan and translated into Chinese have been published by Chen (1982). They include 42 reports of damage and repairs to various places, chiefly to monasteries, orders about relief measures and customs control, petitions for tax relief as well as official prayers for averting future earthquakes. Some of this information, with small additions, was published, by Xie and Cai (1987). We shall have occasion to refer to this material later. It is interesting, however, to see that even today the living Tibetan tradition deals with the impending threat of an earthquake by official prayers, as in the case of the recent Bhuj earthquake of 2001 in Gujarat [Tribune News 2001].

One of the problems with information from Tibet is that it is not always possible to locate sites mentioned in the texts. Tibetan place-names in modern maps are given in Chinese, not always in standard Romanized spelling, which is quite different from the traditional British rendering based on the Survey of India systems, or from the new Pinyin Chinese form. Some Chinese names are translations of Tibetan names whereas others are phonetical approximations.

Landor *(1898)* gives some information from Garbyang, *in Uttar Pradesh*, where he felt the earthquake. From Garbyang he marched north-east to the sources of the Brahmaputra River in Tibet, following its course up to a point north of Gyirong, 600 km north-west of the Plateau. In his travels he did not hear nor notice any effects of the earthquake.

Oldham's intensity distribution map.

On his map Oldham, with very few exceptions, does not show individually the intensity points he used to produce the contours of his isoseismal map (Figure 1). The highest isoseismal, marked 1 (corresponding approximately to Intensity X, Rossi-Forrel), which has a radius of 160 km, includes the regions in which serious damage occurred to buildings. Within this innermost isoseismal, Oldham defines the boundary of what he calls the epicentral area, that contains the Shillong Plateau, defined in the south by the towns of Rangpur, Tura, Cherrapunji and Silchar, and in the north by Dhubri, Bobgalgaon, Gauhati and Shillong, an area which extends to the north across the Brahmaputra river valley, towards the hills of Assam and Bhutan. The epicentral area was drawn so as to enclose the districts in which ground cracks were observed, or dislocations measured by the trigonometrical survey, as well as places at which large numbers of aftershocks were felt. It is not clear whether maximum damage was also one of the considerations (Bilham and England 2001)..

Isoseismals 2 (IX RF) and 3 (VIII RF), of radius 300 and 500 km respectively, encompass most of the valley areas along the Ganges, Brahmaputra rivers and in the Sylhet plains. Isoseismals 4 (VI+ RF) and 5 (IV+ RF) cover areas of a radius of 720 and 1030 km respectively.

Tibetan isoseismal map. Chen (1982) shows an intensity distribution map of the Assam earthquake in Tibet. It shows large intensities extending to urban centers, all the way up to the Tsangpo (Brahmaputra) River, north of the Himalaya close to Lhasa. However, we could find no supporting evidence for this in Chen's Tibetan sources. For a few of the places in Chen's map for which we have information, not only from Tibetan but also from the British borders' customs commissioner,we find that Chen’s intensities are grossly overestimated. It is probable that Chen's map has been derived from Oldham's isoseismals with extrapolation into Tibet.

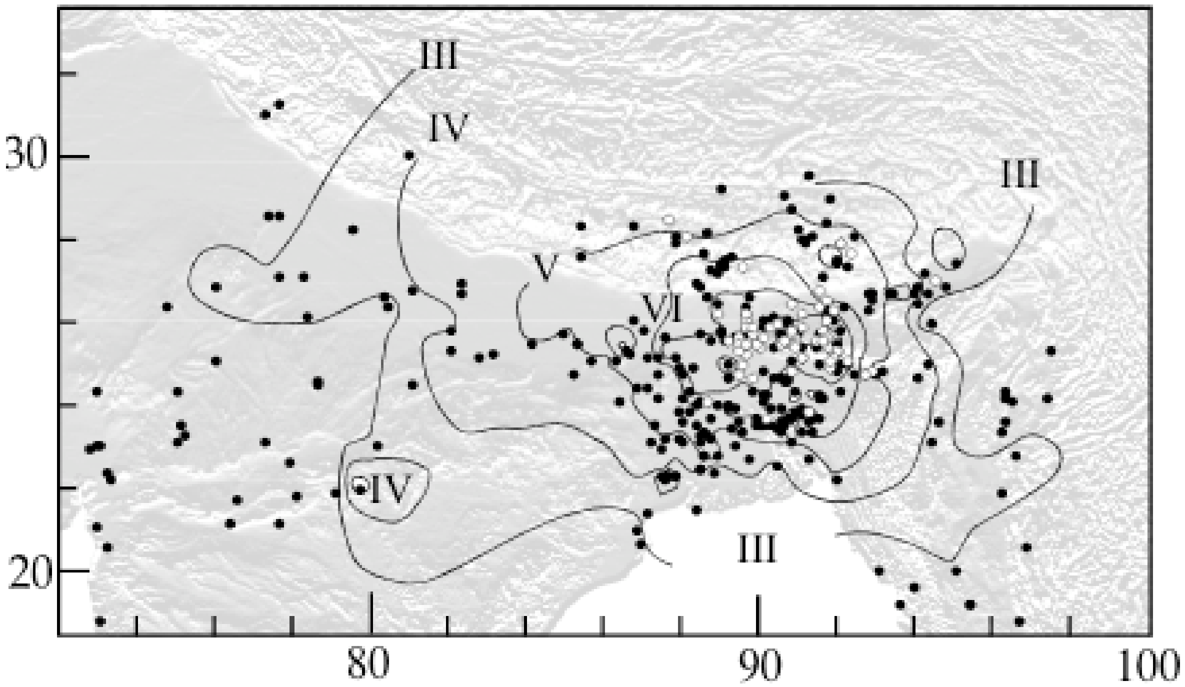


Fig. 5 MSK isoseismals for the 1897 earthquake showing points (dots) used in contouring. Open circles indicate where data were inadequate to assess intensity. The approximate isoseismal radii are $r_{iii} \approx 830$ km, $r_{iv} = 540$ km, $r_v = 370$ km, $r_{vi} = 250$ km, $r_{vii} = 170$ km and $r_{viii} \approx 90$ km. The highest intensities (MSK=IX) are found in two patches above the rupture zone (Figure 2). See text for contouring methodology.

Reappraisal

Building stock The vulnerability of the building stock exposed to the earthquake varied enormously. In India kiln-brick structures laid in lime mortar were limited to churches, government, railway buildings and in rural centers chiefly to factories and tea estates.

At the turn of the 19th century, in towns, and to a lesser extent throughout rural areas, *pukka,* or better built constructions were of kiln brick, and occasionally of stone, laid predominantly in clay mortar, and plastered. *Pukka* construction was generally used for more substantial houses, covered with corrugated sheets or thatch. However, in most cases for which we have detailed damage descriptions, heavy damage to brick buildings was due to either poor construction, or to differential settlement of their foundations.

In villages in the Brahmaputra plains, particularly to the north of the Shillong Plateau, brick was used sparingly only for external walls up to the window sill, the rest of the wall consisting of bamboo and lath or adobe, covered with corrugated sheets or thatch.

South of the Shillong Plateau in the Sylhet plains, rural houses were mostly *kuccha*, built chiefly of sun-dried mud, adobe bricks and lath. The usual type of bungalow was of poorly burnt thick bricks, with thatch roofs, which become particularly heavy during the monsoon season. Tea factories and certain bungalows had steel girder frames.

On the Plateau (500-1600 m) and in some parts of the Brahmaputra valleys *pukka* was used for more substantial houses, some of them two to three storys high, built on sloping ground. In equal numbers there were wooden frame works, with walls of grass covered with plaster, and log huts. For the different types of local construction see Gosain [1966].

To the north of the Brahmaputra plains in northern Bhutan, Sikhim and Tibet, buildings and their foundations were quite different from those in north-eastern India. The country changes considerably in character compared with that to the south, with hills and rugged and precipitous ranges instead of alluvial plains.

Tibet is the highest country in the world, lying at the heart of the Himalayas *and* varying in height between 3000 to 5000 m. It was, and still is very thinly populated and with a significant proportion of the people being nomadic, making their living by subsistence agriculture and herding. No railways exist in Tibet, and at the time of the earthquake the roads were virtually non-existent, with the inhabited areas in the late 1890s largely restricted to monastic settlements.

Monasteries are fortress-like, sited on hilltops, built with very thick walls of stone laid in mud without many external windows, and with internal sun-dried brick walls. They are built mostly on rock with skyscraper-like sloping external walls and their down-slope facing walls rise precariously to tens of metres. Roofs are covered with heavy clay tiles or more commonly with beaten earth resting on sparingly used wooden rafters. Local dwellings were vulnerable structures, only one story high, mostly made of dry-stones with the gaps stopped with turf, or of alternating layers of turf and stones. Rooves are covered with wood slats held on by stones (for more details see Collection, [1989]).

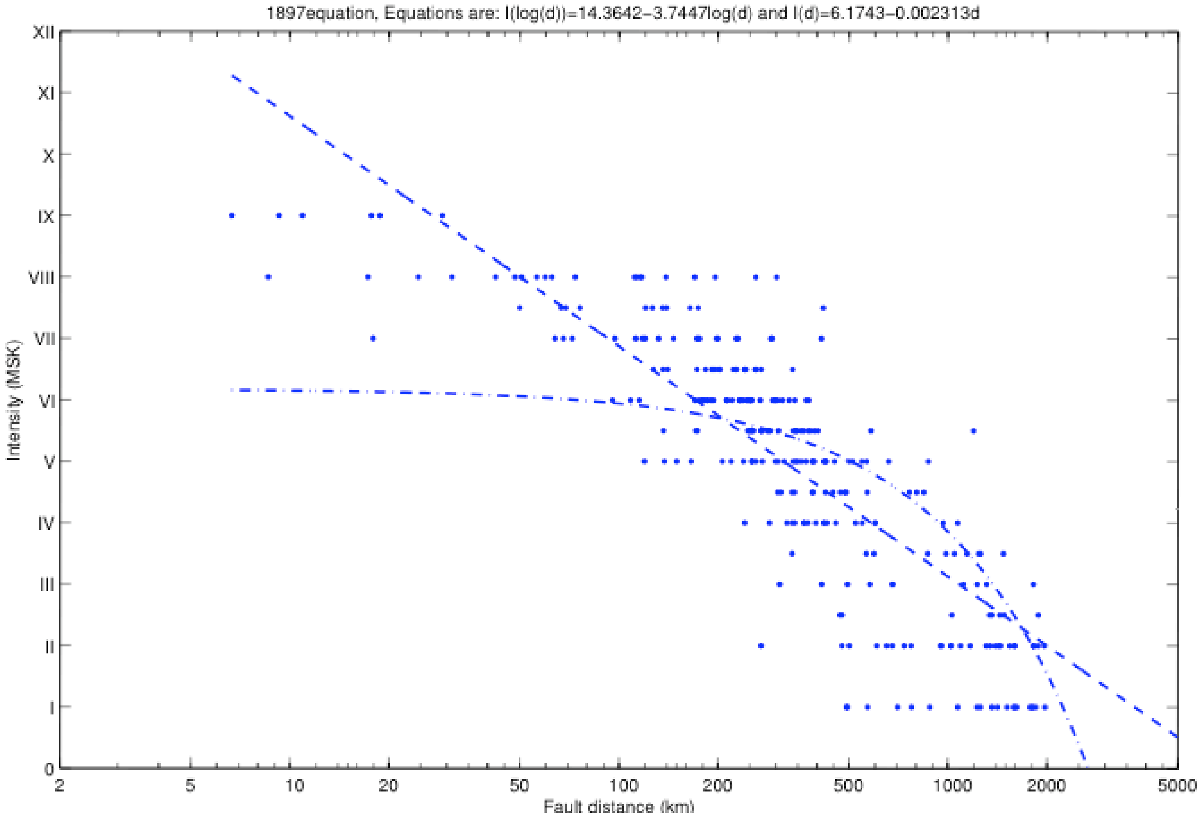
In south-eastern Tibet, near the borders with India, in Raunchily Prudish, Bhutan, Sikhim and Nepal, more wood was used in houses, chiefly to support the roof structure, with rubble masonry, non-bearing walls, filling in the space between wooden supports, a method widely used in other parts of the Himalaya and the Northwest Frontier area in Pakistan [Ambraseys et al., 1981]

Foundation conditions The epicentral area of the Assam earthquake consists of large areas with different geologic site conditions; from predominantly soft rock on the Shillong Plateau, to loose saturated sands and silts in the Brahmaputra Valley and even morass in the Sylhet plains, areas which under normal conditions are covered by *bills* (extensive and very shallow bodies of water).

Information from the *Bengal* Railway Department shows that the earthquake did little or no damage to the Assam-Bengal railway where it ran across the Sylhet plain through *tilahs* (low hills), and through ground well above the river level, which at the time of the earthquake had risen considerably due to recent rains. On the plains damage due to foundation failures was enormous. Where the line crossed on embankment *pahar* (low-lying ground) and flood plains, which was the case along much of its route, the earthquake caused embankments to sink slowly into their foundations. In one case a whole train, engine and wagons, sunk with the bank into the ground [Anderson 1900].

Ground motions Short-period ground motions on the Plateau and vicinity were violent and of large amplitude; water was not thrown out of containers and few tall structures were not overturned. Long-period ground motions were reported from large distances and were apparently responsible for damage sustained in isolated cases by flexible structures such as timber-frame houses, minarets, and dwellings built on thick alluvial saturated deposits. Slow oscillatory movements persisted long enough to cause water to slosh from ponds, suspended objects to sway, and people to experience nausea.

Early Structures Many free-standing monoliths on the Khasi and Jaintia hills were overthrown. The shock broke down most of the piers of the Sil Sako, an ancient bridge, not far from Hajo, 14 km north-west of North Gauhati, which marks the bed of a river that has long since left it and taken another course. The temple of Siva, near Tezpur, collapsed [Barua1988]



Upthrow Oldham reports many cases of stones being projected from the ground on the Shillong Plateau and to its north and cites this as evidence for high accelerations in the epicentral region. Over the years these observations have been attributed exclusively to the vertical ground acceleration exceeding gravity.

However upthrow of objects during an earthquake does not necessarily imply vertical accelerations greater than 1g. Given appropriate conditions, such as thin alluvial overburden, the upthrow of objects of the size observed in the Assam earthquake may occur when bedrock accelerations are significantly smaller than 1g [Bolt 1977].

Ground velocities Oldham presents numerous examples of thrown objects from which he infers that ground velocities may have exceeded 3 m/s. Until recently such velocities were considered excessive; however, they have now been recorded in the ChiChi 1999 earthquake and other well-instrumented epicentral regions.

Overturning of trees Isolated cases of large trees being brought down by the earthquake are not always an indication of the severity of the ground motion. As in the case of high winds, overturning depends on the species and age of the tree, on the degree of saturation of the soil at the time of the earthquake and in particular on whether the tree was leaning over to begin with. At the northern end of the Chedrang fault trees are shown tilted by what appears to be a drape fold in soils over the subsurface bedrock fault. A tree fractured at a height of roughly 1.5 m is depicted in Oldham's text.

Liquefaction The earthquake occurred early in the monsoon season, after two days of heavy rains, and the country had been already waterlogged, with rivers overflowing, disrupting communications [Luttman 1898]. Rain started again immediately after the event. The consequent transient rise of the water table, and in general an increased pore pressure in soils is typical in the monsoon period, and had often had led to landslides and apparent liquefaction without an earthquake.

Liquefaction and spreading of the ground caused by the earthquake was severe and widespread throughout the Brahmaputra Valley and the Sylhet plains. In places the phenomenon continued for half an hour following the main shock, and in the plains the ground water gradually rose to the surface and flooded large areas (Figure 3). In many cases houses of all types, levees and embankments bridge piers sank bodily, their tops alone remaining above ground, and liquefied sands filling river-channels, water tanks and wells [Davison 1936].

From available descriptions of ground effects one can identify ground failures on level ground caused by lateral spreading, loss of bearing capacity and excessive ground settlements, eruption of sand boils and mud volcanoes, and flows on sloping ground where, the earthquake shaking apparently acted as a trigger for the initiation of retrogressive failures. It is clear that special conditions, such as heavy rainfall preceding and following the earthquake and the rise of artesian pressure enhanced the liquefaction potential of the sandy deposits in an area equivalent to the size of Scotland or the state of Maine.

Had the earthquake occurred in any of the earlier months of the year, the local authorities believed that damage would have been much less severe [Anderson 1900].

Subsidence and uplift Oldham's 1899 account describes changes to navigation along the Brahmaputra River. Shoaling is described at Goalpara and near Dhubri. The stretch of the river between these two locations and Hathimura and Gahauti that normally required careful pilotage had apparently deepened, facilitating navigation. Flexure of the surface of the Shillong Plateau was observed in at least two places: eyewitness accounts describe hitherto obscured distant views rendered visible after the earthquake. Minor ponding was observed by Oldham during his traverse of the Plateau, and a significant but transient lake developed near the northern end of the Chedrang Fault. Although their interpretation of subsurface slip erroneously favoured the conjugate plane of the focal mechanism solution, Gahalaut and Chander (1997) invoked these observations in a qualitative sense to constrain the approximate vertical deformation field for the earthquake

In Figure 3 we show contours of inferred vertical displacements calculated from the best fitting dislocation model determined from the triangulation data (Bilham and England, 2001). It appears that the earthquake resulted in less than a meter of subsidence along the Brahmaputra north of the Ganges, which corresponds to the stretch where navigation of the river became easier after the earthquake. The Gahauti region is inferred to have subsided 30 cm. Similarly regions of shoaling correspond approximately to where null or minor uplift may have occurred. We note, however, that shoaling can be caused by liquefaction of the river bed or slumping of the banks, and that had this impeded flow near Dhubri it would have temporarily raised the river level upstream. Temporary ponding elsewhere, may also be the result of massive spreading, slumping and liquefaction of river deposits.

Maximum subsidence, north of the surface projection of the causal reverse-fault rupture, near the northern edge of the Plateau amounted to more than 1.5 m. Tributary streams flowing northward to the Brahmaputra from this region of subsidence would have been back-tilted, and their lessened gradients may have resulted in flooding in this region, exacerbated by heavy rains. However, Oldham's account contains scant data from this region and none of utility in confirming these conclusions.

Significant uplift of the mouth of the Krishna River valley where it debouches onto the plains appears to be responsible for ponding near the Chedrang fault (Tandey, 1927). Within hours of the earthquake a lake several km long and up to 0.5 km wide was formed that persisted until 1908 when it had almost completely filled with silt (Playfair, 1909). Parts of this area have recently been excavated in a successful search for paleoseismic liquefaction features associated with previous earthquakes (Sukhija et al. 1999). The distributed ponding on the plateau observed by Oldham may be related to the southward tilt of its surface during the earthquake. In the northern parts of the Plateau this is calculated to have exceeded 10^{-4} radians SSE.

Vertical deformation south of the plateau in what is now northern Bangladesh is inferred to be less than 10^{-6} radian, although river gradients are sufficiently low to be sensitive to these minor changes, as suggested by the following account from south of the Garo Hills: "The river for the whole of Sunday flowed the opposite way to the usual stream, and below my bungalow, where I could easily cross it on my elephant, there are (now) between twelve and fifteen feet of water" (*Englishman,* June 28, 1897).

Landslides Figure 3 shows the distribution of known slides triggered by the earthquake and by its aftershocks. Most of these slides occurred on the Shillong Plateau, particularly on the Cherra Hills and around Cherrapunji, with great resulting loss of life. It is said that other, presumably smaller slides were triggered on the foothills of the Himalaya from southern Sikhim and Bhutan to as far east as western Arunachal, a distance of 450 km. Most of the slides in the hills to the north of the Brahmaputra plains occurred in hillsides, carrying trees and undergrowth with them, leaving behind them patches of clean rock faces. Widespread landslide failure also occurred following the Assam earthquake of 15 August 1950 far to the east of the 1887 event [Rao, 1953].

The occurrence of landslides in the immediate vicinity of thShillong Plateau and far outside the epicentral region, particular in the Himalaya, was probably more due to the terrain being destabilized by the monsoon rains rather than high intensities. The propensity for slope instability in both cohesive soils and soft rocks was aggravated by the transient increase of pore pressures caused by heavy rainfall. In previous years, during the same season, large land slips and rockslides had also occurred without earthquake triggering, particularly along the foothills of the Himalaya, and in eastern Nepal [Holland, 1896; Morris, 1935].

Standing waves Sloshing of water and standing waves have been reported in the far-field from many parts of the region. Assuming that *pukars* (water storage tanks in Assam and the Sylhet plains) were 1-10 m long and 1-3 m deep and that small rivers during the monsoon period were 15-25 m wide and 2-5 m deep, we can estimate the periods of the ground motion that could set up standing waves under sustained ground motions. These would be from 2-6 s in the first and 4-10 s in the second instance, periods well outside the range of the natural period of rural dwellings, which typically have a 0.1-1 s spectral response.

Aftershocks Many aftershocks were felt at different places over a wide area through the end of 1898 (Oldham 1900; Montessus de Ballore, 1904). Three relatively large aftershocks whose occurrence would have occasioned great destruction had there remained any undamaged houses on the Shillong Plateau, occurred on 12 June at 20:10, 13 June at 07:30 and 17:20 (GMT). They were recorded by a Milne instrument at Shide in the UK, which recorded also the belated aftershock of Aug 2 at 15:40, which caused some concern in the region.

Figure 4 shows the extent of the felt areas of the shocks of 13 June at 07:30 and 2 August 15:40. The must been of considerable magnitude as they were perceptible with an intensity II MSK over areas of about 400 and 340 km respectively in the plains of the Ganges and Brahmaputra, chiefly to the south and west of the Shillong Plateau. Few of the observers who reported the first of these aftershocks also reported the second aftershock, although the felt areas overlapped significantly. Their magnitude, assessed from equation 1 (see below), is estimated to have been $6.0<M_S<6.4$).

Loss of life No precise estimate of the loss of life is available, and early totals issued by the press (>6,000) cannot be authenticated in subsequent reports. For the epicentral region information seems to be definite. In spite of its large magnitude and the relatively high population density of some parts of the epicentral region, the total number of people killed from the collapse of buildings was only 788, of which 27 were on the Shillong Plateau [Oldham 1899], about 300 in the Sylhet Plains to the south of the Plateau, and a very small number elsewhere, chiefly from the collapse of masonry dwellings in Dacca, Dhubri, Goalpara, and Hoogli. In addition, approximately 620 were allegedly killed by landslides near Cherra Hills and in the lower part of the Someswari Valley, north of Durgapur [Oldham 1899], 17 in the mines of Cherrapunji, and 117 at Chela, 14 km south of Cherrapunji [Davison 1936].

The total number of people killed as a result of the earthquake amounts to 1,542 with the following distribution by district: 916 in the Khasi and Jainta hills, 545 in Sylhet, 29 Kampur, 27 Garo Hills, 12 Darrang, 5 Goalpara, Nowgong 3, Silchar 3, Sibsagar 2 [Gait 1898]. We found no reports of loss of life among members of the various Christian missionary stations in Assam and in the Sylhet Plains [Luttman 1898].

Cost Little is known about the total economic loss caused by the earthquake. It was large enough to result in regional costs that exceeded the annual revenue for Bengal, requiring the Government of India to make an application for a grant from the Imperial Treasury to meet the cost for reconstruction of public buildings [BAAS]. For the repair of roads and buildings of the Public Works Department alone, more than 35 lakhs of rupees (£250,000 Sterling of 1899), or about £10 million of 1999, were required [Gait, 1898]. The total cost of the earthquake was probably many times this sum, particularly to private property, but details are lacking.

Intensity assessment Macroseismic information about the Assam earthquake from India and Tibet is rather poor and subject to misinterpretation. Despite the large number of sites (325) for which there is some macroseismic information, there are only 132 sites for which the data allow assessment of intensity, and not always unambiguously. *Pukka*, *kuccha* and the Tibetan style of buildings are not included in any of the intensity scales, which are chiefly designed for European conditions. There are very few standard type of buildings over the area, and these vary greatly in vulnerability, making it difficult to map out intensity according to any modern scale. Of the 325 sites, the distribution of which is shown in Figure 8, damage to 114 sites was inferred to be due to liquefaction of the ground, and to 24 sites was the result of landslides, sites for which no attempt was made to assess intensities.

For the purpose of reassessing intensity and reducing subjectivity it is important to distinguish between damage caused by vibrational, dynamic or inertia loading, and damage caused by indirect, secondary effects, such as foundation spreading, liquefaction, slides, rockfalls and aftershocks.

Compression ridges and ground cracks in flat or sloping soil deposits are caused by strong ground movements, strong enough to overcome the yield resistance of the soil mass and cause permanent deformation. These permanent displacements are produced because the materials through which acceleration pulses travel have a finite strength, and shear stresses together with high pore water pressures induced by rapid shearing may bring about failure. The result is that this partial or total soil failure will cause permanent ground displacements, but at the same time will prevent large bedrock accelerations from reaching the surface. Liquefaction may suppress surface accelerations completely, causing structural damage from excessive differential settlement rather than from ground shaking.

As a diagnostic feature of intensity, therefore, ground deformations of non-tectonic origin are questionable. Also landslides, spreading and liquefaction of the ground may be influenced by conditions other than ground accelerations, making appraisals of intensity on the basis of such ground effects misleading.

In the case of the Assam earthquake, and with the exception of the Shillong Plateau, most if not all of the large intensities were assigned by Oldham to sites in areas of widespread liquefaction, in spite of the fact that on nearby higher ground, damage was often much less serious.

Inasmuch as we are not in a position to be rigorous in our definitions of various ratings, we used a simplified version of the Medvedev-Sponheuer-Karnik (MSK 1981) intensity scale by disregarding criteria relating to ground effects and to damage of modern types of construction. Intensities, by definition, can be assessed only in steps of one whole intensity unit and the MSK scale gives the assessor enough leeway to use his own judgement without being constrained by a scale that is too specific.

To employ intensity usefully, each observation must reflect the mode of observed vibrational effects within a given location and not the maximum observed, which will tend to inflate estimates. Taking account of information derived almost entirely from arbitrarily selected localities of maximum intensity or allowing secondary effects to affect intensity estimates, may result in deceptive intensity maps which depict the distribution of low-lying areas, river valleys liable to liquefaction and regions prone to landslides and rock-falls.

There is evidence that when field data are sufficient and of good quality, the variation of intensity within a given small area is significant and shows a divergence by one to one and a half intensity grades from the mode of the observed intensities. This large variance, which is real, arises from the heterogeneity of near-surface geology, and non-uniform vulnerability of dwellings, as well as from the bias of field observations which tend to report extreme, and occasionally exaggerated, effects (Ambraseys and Finkel 1987).

We now summarize observations for some for sites in India to which Oldham assigns his highest intensity "1", equivalent to Rossi-Forrel X. We provide examples of typical revised intensities in each of Oldham's isoseismal areas. At the end of each entry we show in brackets the revised intensity we assigned this location in the MSK scale.

Within Oldham's isoseismal 1 (=Intensity X Rossi-Forrel) **:**

Nowgong is situated on the Kalang River, a branch of the Brahmaputra. Oldham does not mention any damage here but places the town within isoseismal 1. In fact there was some damage at this location. However, it was not caused so much from shaking as from ground cracks, some of them 1.0 m wide, running parallel to the river, suggesting spreading and slumping of the ground. A long stretch of the bank slid into the river drowning 41 people, but houses away from the river front suffered unspecified but minor damage [V+].

Further up the valley at *Rupahi* (?), a bazaar on the bank of the river slumped bodily into it, causing the death of 29 persons [Luttman 1898].

Shillong is at an altitude of 1500 m, built mostly on rock with houses then of rubble masonry filled in with mud covered with corrugated iron roofs; all these came down. Also better built buildings such as the Government house, the local church and the Telegraph Office were demolished, and the low quality of masonry was evident from the stones of the walls found lying piled around the base. Houses made of wood or masonry laid in lime mortar fared much better, and only half of these were destroyed. Many of these houses had suffered from past earthquakes to the extent that before the Assam earthquake, it was considered unsafe to build upper storied houses. The only building with upper stories was the Government Printing Press which collapsed killing 10 people. Only two Europeans were reportedly killed [La Touche, 1897; Lambert, 1898; Luttman, 1898] [IX].

Sylhet is situated in the lowlands of the Sylhet plain (now Bangladesh), on the north bank of the river Surma, a region that liquefied extensively. Following the earthquake the region was surfaced by large fissures and mud volcanoes. Most houses, both adobe and thatched, were demolished, killing 55 people [Luttman 1898]. Some of the public buildings were more or less damaged, but many of them were left standing while a few, such as the *pukka* mosque on the river front and the school were left undamaged [Stuart 1919]. Several, but not all, of the buildings were affected, as much by foundation failure as by shaking [Oldham 1899] [VII+].

Gauhati is built partly on granites exposed on the south bank of the Brahmaputra River. Slumping and spreading of the ground between these exposures, particularly in the lower part of the town was widespread and all masonry buildings were destroyed, resulting in five fatalities. However, houses on wooden or bamboo posts with lath and plaster walls escaped serious damage. Buildings with iron posts were barely damaged at all [Luttman 1898] [VIII].

At*Goalpara*, on the south bank of the Brahmaputra River, the earthquake was followed by a surge that destroyed the bazaar and all *pukka* houses, flooding much of the town; loss of life was very small but details are lacking. Further south in the part of the town that was not flooded, and in spite of the liquefaction of the ground, a few brick houses were left standing with some damage [La Touche, 1897; Luttman, 1898] [VIII].

Tura, a station in the Garo Hills, was badly damaged. Most dwellings consisted of a wooden frame, filled in with lath and plaster, with roofs of thatch or corrugated sheets, with wooden floors, raised from the ground on masonry plinths or on piles driven into the ground, a method of construction that prevails to this day. Much of the damage here was due to the collapse of masonry plinths. Landslides occurred in sloping ground while flat ground was cracked and in places slid, damming water courses and forming small lakes. Houses were built on rather steep hillsides and a number of them were destroyed by landslides [Luttman, 1898] [VII] .

The small near-by road station of *Chamari*, was only slightly damaged.

Mymensingh is built on soft deposits on the west bank of the Brahmaputra River, where ground fissures were abundant. There was less ground fissuring and liquefaction in the town as in other places east of the river, but all two-storied brick buildings and many one story adobe houses were destroyed. The earthquake left the city in widespread ruin [Luttman, 1898; Oldham, 1899] [VIII].

At *Madhupur*, a hamlet situated about 10 km north of Mymensingh, there was less damage [Oldham1899] [VI+].

Much of *Dhubri*, which is built on reclaimed land next to the Brahmaputra River, sunk and the ground was fissured. A 400 m stretch of the waterfront settled by 1.5 m, and where the town was not flooded by the rising of the water table, it was subsequent flooded by the rising of the river. Local houses, particularly those on low ground, were ruined by widespread liquefaction but only 1 person was killed [La Touche, 1897]. In contrast almost all of the public buildings built on piles, aling with several better-constructed dwellings on higher ground, survived the shock with relatively little damage [Oldham 1899] [VII+].

The village of *Jemardahat*, about 3 km south of the Brahmaputra *River*, opposite Dhubri, was totally destroyed. Most of its houses sunk into their foundation and were filled with liquefied sand which came through the doorways. The *accounts* are insufficient to assess intensity [Oldham1899].

In *Koch Bihar*, which is built on the lowlands of the confluence of the Brahmaputra and Tista rivers, most brick houses were damaged beyond repair, many of them by the fissuring of the ground which opened in their vicinity. In the town 8 people were killed and the Maharajah had a narrow escape. However, on high unfissured ground in the town, one building, as well as other brick buildings a few kilometres to the north of the town belonging to the PublicWorks Department, escaped with only a few cracks [Luttman, 1898; Oldham,1899] [VII+].

At *Chaahara* (Dinhata 26.13N 89.53E), 20 km south of Koch Bihar, and *Torsa* (26.33N 89.48E), a few km south-east of Koch Bihar, damage is said to have been negligible [Oldham 1899] [IV].

Rungpur, west of the river Tista, is built partly on clays and partly on loose sands with the water table at a depth of only about 1 m. As a result of the earthquake the ground everywhere was fissured and almost every brick house was damaged beyond repair, but the railway station building was not seriously damaged. Also in several cases, houses built on clays escaped with little damage. The damage was not due so much to the actual shock as to its secondary effects on the ground [Oldham, 1899; Luttman, 1898] [VII+].

For *Diwangiri* the only effects reported were landslides, and no intensity can be assigned to the locality. At *Susa* there is no evidence of damage but the region was infested with landslides.

Within Oldham's isoseismal 2 (=IX RF)

Early news in the press from *Darjeeling* indicated that houses, the number of which is not given, were destroyed, while others were damaged. Later reports correct this information saying that only a number of houses were damaged, while much later reports indicate that damage was superficial - cracked walls and toppled chimneys [Lambert, 1898]. No damage was reported to the narrow-gauge hill railway [Luttman, 1898] [VI+]. At *Tezpur* there is no evidence of any serious damage apart from a few cracked walls. [TL] [V].

Within Oldham's isoseismal 3 (≈VIII RF)

In Calcutta, which had a population of over one million at the time, damage was limited to cracking of some walls, and the collapse of parapets and porticos of two to three storey houses in the European part of the city, which caused the loss of a few lives. Factory chimneys were not affected and house chimneys suffered slight damage. Three church spires were broken off near the top, and only two of the monuments in the Old Cemetery were affected. The firing of a cannon salute on the occasion of the Jubilee was abandoned in Calcutta and at all other places, as it was considered likely to cause additional damage [Luttman, 1898] [IV+]

Despite early press reports to the contrary, there is no evidence that *Kohima* suffered any damage [Luttman, 1898; Oldham, 1899] [V]

At *Wokha* in Nagaland, 300 km east of Shillong Plateau the shock was felt by few people [II+]

Examples from the far-field within Oldham's isoseismal 6 (≈II-IIIRF).

At *Garbyang* in NW Nepal (30.12°N, 80.86°E), 1100 km west from the Shillong Plateau, the earthquake was felt by Landor. From Garbyang, Landor marched north-east to the sources of the Brahmaputra River in Tibet which he followed up to a point north of Gyirong, 600 km north-west of the Plateau. He did not learn of or notice any effects of the earthquake (Landor 1898) [III+].

In *Ahmadabad* the person who reported the event did not feel it himself but reported that it had been felt by others. He adds that not one person in a thousand noticed anything. [Oldham, 1899] [I]

There are a few separate reports from the region of *Baroda* and to the east, probably from sites on thick alluvium, which mention the shock as having been felt, though this area also includes a large number of negative reports [Oldham 1899] [I].

Newly available data from Tibet

In Tibet, which is outside and to the north of the area mapped by Oldham, damage was reported from sites on the Great Himalaya close to Bhutan, from the districts of *Mönyul* and *Yadong*, the name by which the Assam earthquake is referred to in Tibetan sources.

Damage was reported from the sparsely inhabited part of north-eastern Arunachal Pradesh and Mönyul, north of the Shillong Plateau, where at *Kangar* and *Tawang*, at an elevation of about 4000 m, where a few houses were destroyed, killing three people. The scripture halls of the main temple and minor temples in the region were destroyed, injuring several monks. Several roads were carried away or blocked by slides [**Chen 1982**] [VI+]

Some damage was also reported from the north, in Cona (Tsona 27.99N 91.98E) county where the Kunzi monastery needed some repairs after the earthquake [Chen 1982] [V+]. Further west in Tibet, in the region of *Lakang* (28.00N 91.04E), *Shengge* (28.07N 90.07E), *Luozha* (28.07N 90.97E) and *Darma* (28.19N 91.20E), damage was small without loss of life or injuries [Chen 1982] [V+ to VI]]

In *Sang* and *Lin* many houses collapsed due to the fact that they had previously been abandoned and damaged by heavy rains before the earthquake [**Chen 1982**] [V+].

Between Sikhim and Bhutan, in the *Chumbi* Valley which leads to one of the passes into India, some official residences, barracks and houses were damaged, and the postal system of runners (*messengers*) was discontinued for some time, presumably due to landslides. The main building of the *Kagovi* monastery collapsed and its high compound walls were cracked. At *Natang* and *Gantok* in neighbouring Sikhim, a few houses were ruined [VI+], and a stone bungalow collapsed at *Langrang* [VI]. The monastery of *Xiayadong* needed repairs after the earthquake [V+] while the monastery of *Zhashen* was only slightly affected [IV+]. Little damage was done at *Yadong*, where the few houses are of wood, with walls of rough stone laid in mud, but a pendulum clock in one of the houses did not stop [V+]. However, a landslide buried 70 people, and a number of isolated dwellings in the region caved in. The *Gajun* temple suffered some reparable damage. At *Duozong* the combination of previous flooding and the earthquake damaged the water canals in the region.

To the east of theChumbi valley, in the area of *Paro* in neighbouring Bhutan, there was some unspecified damage [V+]. North of Yadong, the *Dongkar* temple needed repairs [V+], but at *Pali,* in the northern part of the Chumbi valley, contrary to rather exaggerated reports, there was little or no damage [V+]. In all, we find that in the upper Chumbi valley 14 local houses were ruined and 101 damaged. In the lower valley 13 dwellings were heavily damaged and 143 were moderately damaged. In the whole of the Chumbi Valley and Pali fewer than 75 houses were destroyed or damaged beyond repair and only 5 people were killed.

North of Sikhim and Nepal in Tibet, damage in the *Gamba* county, at *Ronddi* and *Lilung* was slight or non-existent [IV+]. At *Lilung* the damage was caused by avalanches and the flood from the breaching of the water supply canals. The shock was felt at *Qiongjie* county, at *Kyirong* where after the earthquake the water canal was damaged, at the *Baimo* temple, and to the north, on the Tsangpo (Brahmaputra) river, at *Xigatze* and *Lhasa* [IV] where the earthquake was generally felt but from where there is no evidence that it cause great concern or any damage [IV]

Epicentral Intensity. Maximum intensity in any destructive earthquake in a rural area in the Eastern Mediterranean, Middle East and the Indian subcontinent appears to be effectively the same. That is it "saturates" at intensity VII-VIII MSK at which all adobe, rubble stone masonry and *pukka* houses are destroyed or damaged beyond repair. Any town or village would thus appear equally, but no more, devastated at so-called higher intensities.

The vulnerability of *kuccha*, timber-framed and lath constructions is *low,* but intensity scales are not designed for these types of construction, *so* their degree of damage cannot be used easily as a qualitative description to assess intensity. Also the fact that only one of these types of construction is predominantly available for observation makes it difficult to assess epicentral intensity greater than VII-VIII MSK

Intensities higher than *VII-VIII MSK* can only be assessed from the behaviour of modern buildings for which intensity scales have been calibrated. Such structures did not exist in 1897. For these reasons any attempt to estimate epicentral intensity for the Assam earthquake would be highly subjective, and, in our estimation, unjustified.

Distribution of intensity We have interpreted macroseismic data for 365 sites, of which 78 provide insufficient information to allow intensity assessment. Of the remaining 287 sites, 39 are in Tibet. At 46 sites in India the shock either was not felt or was barely perceptible. Figures 1B and 5 illustrate the distribution of sites; open circles in Figure 5 indicating those for which no intensity could be assessed.

The method of contouring intensity data cannot be separated from the method of information collection and intensity assignment. If the information is not sufficient to provide modal intensities, then the method of contouring should be allowed to work with modal values from a series of overlapping small unit areas. This procedure is particularly important when a few isolated high intensities exist within a background of many sites of much lower intensity, and conversely when isolated low intensities exist within a background of "not felt". The latter situation has a considerable bearing on the determination of the radius of perceptibility (III MSK), which is often grossly overestimated by taking into consideration the furthermost location from which the shock was reported, even by a single observer [Nuttli 1973, Ambraseys 1988]. We have suppressed the interpolation of the Intensity III contour where data are sparse (in Tibet and near the Bay of Bengal).

We use a modified kriging algorithm to contour the intensity data [Olea, 1999]. By this procedure local variants of intensity between isoseismals become averaged and damped out by the surrounding regional intensity and only those anomalies that become fortified through association gain an encircling contour.

Figures 2b and 5 show the intensity distribution of the 1897 earthquake according to the simplified MSK scale. Contours in the epicentral region differ considerably from those shown by Oldham, with no indication of a northward extension of the epicentral area towards Bhutan. Isoseismal are elongated along the Ganges plains to the west and to a lesser extent to the south. To the west of the Shillong plateau the very rapid attenuation of intensity seems to be genuine, supported by a considerable number of negative reports, albeit from a sparsely inhabited area. It is not clear whether isolated pockets of high intensities are due to exaggerated reports that escaped scrutiny, or due to genuine enhancement of the ground motions due to local soil conditions.

Figure 6 shows the decay of perceived intensity with distance. Using the preliminary attenuation relation we have derived in this study from a two-stage regression for large earthquakes in northern India :

$$I = -3.21 + 2.61M_S - 4.87\log(d^2 + 41^2)^{0.5} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

we find its magnitude is 8.0, and that the "epicenter" of the earthquake was at 25.42°N, 91.74°E, close to the centre of the Shillong plateau.

Discussion

The assessment of long-term seismic hazards in India remains largely qualitative, and reliable intensity data from earthquakes with known magnitude remain an important source of data for estimating the size, location and tectonic implications of past and future earthquakes. This is particularly true for the heavily populated region in the Ganges/Brahmaputra plains where no large earthquake has occurred recently.

Just as instrumental calibrations are needed for seismometers, appropriate calibration functions must also be developed for eyewitness observations of epicentral accelerations. Our "calibration functions" for surviving intensity observations of the great Assam earthquake of 1897 have taken into account late 19th century construction methods, and local ground conditions where these are known. Reports where one or other of these are unknown have been ignored. Regrettably, many of the raw materials available to Oldham to assess intensities are not available for re-assessment. We have supplemented his observations with additional materials from India and in particular, with data from Tibet, that were unavailable to Oldham. Altogether 348 reports are available, not all of which provide useful constraints on intensities.

In determining the intensity of an historical earthquake at a place, and in assigning to that place an intensity rating in any scale, allowance must be made for the vulnerability and rate of aging of buildings, compared to dwellings in those countries for which the scale was originally developed. From our analysis of a number of earthquakes in India and adjacent regions it appears that for rural and to a lesser degree urban areas existing intensity scales are not appropriate, particularly before the 1960s, and that they must be used with caution.

One of the striking conclusions that can be drawn from field observations of earthquakes before the 1960's is the comparative ease with which local types of dwellings in rural Indian, Pakistan and the Middle East, particularly adobe, brick and masonry laid in inferior mortar, are damaged beyond repair, and with the ease with which they are rebuilt. Timber and lath constructions appear to be almost indestructible and their occasional total collapse claims very few fatalities. Because the majority of houses in the epicentral area of the 1897 earthquake were constructed from timber and lath methods, fewer than 1500 people were killed.

A half century later, the much larger earthquake of 15 August 1950 in Assam (M=8.6) devastated the mountainous region further upstream the Brahmaputra River, affecting a large area in Assam and Tibet [Chen 1982 vol.2,]. Like the earthquake of 1897 it occurred during the monsoon period, causing damage very similar to that of the of the 1897 earthquake, much of which was due to secondary effects. The total loss of life in 1950 was only 1,526, out of which 500 people were drowned a few days after the earthquake by the flooding of rivers which followed the bursting of natural dams produced by numerous landslides [Poddar 1953; Gee 1953; Kingdom-Ward,1897].

Similar effects accompanied the M_S=8.2 Bihar-Nepal earthquake of 1934, which occurred in eastern Nepal, north of the densely inhabited part of Ganges Plain west of the Shillong 1897 earthquake. Here again widespread liquefaction and ground failures in the Ganges and Brahmaputra alluvial valleys were responsible for the great extent and degree of damage sustained in the region, in spite of which loss of life did not exceed 7,500 [Auden et al., 1939].

Oldham admits that his isoseismals for the 1897 earthquake are simplified and diagrammatic, representing their probable shape had local conditions been everywhere uniform. Clearly they should not be used for assessing hazard, nor for locating the epicentral area of the event. We note, moreover, that intensities from other large earthquakes near the Ganges Plain are felt at larger distances in an east-west direction, south of, and parallel to, the Himalaya, than to their north or to their south. This preferential distribution, absent in Oldham's isoseismals, is caused by the amplification of ground motions leading to ground failure in the thick and saturated sediments of the Ganges and Brahmaputra flood plains, but is partly aggravated by the absence hitherto of macroseismic information from Tibet.

Observations of liquefaction (Figure 3) depend both on the presence of liquefiable deposits, and on whether or not information, if liquefaction occurred, was observed and reported in the field studies. In Figure 3 we omit locations where ground cracks were reported due to shaking, incipient sliding, or cracks behind collapsed steep river banks. The resulting reduced data set shows that liquefaction, as expected, occurred in the low-lying flood plains of the Brahmaputra River in the north, in the region between the Ganges and the Brahmaputra rivers in the west and, in the Sylhet flood plains in the south.

Saturated sand deposits of less than about 15 m in thickness, with a minimum standard penetration resistance ($N^{60}{}_{1}$) of 10, at short source distances, and 5 in the far-field, are likely to liquefy in an earthquake of magnitude M_S, given by:

$$M_S = 4.68 + 0.0092R_f + 0.9\log R_f \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2)$$

where R_f is the source distance of a site in km [Ambraseys 1988**]**. It is interesting to note that the median value of M_S calculated from the liquefaction distribution illustrated in Figure 3, is 8.1±0.4, close to the instrumental and geodetically inferred magnitudes.

We find that non-vibrational intensity reports (soil failure and ground deformation) tend to indicate erroneously high intensities compared to those indicated by building damage. Since their inclusion would inflate the assessment of intensities we ignore ground deformation information. Moreover, in our re-constructions of isoseismals (Figures 2b & 5) we desist from embracing isolated points of maximum intensity where these are surrounded by numerous points of lower intensity since, were we to do so, we would bias isoseismals towards higher estimates [Ambraseys 1988; Hough et al 2001].

Ground motions reported in this earthquake clearly show the difference between the severe short period (0.1-0.5 s.) ground movements caused by smaller earthquakes at a short distance, not discussed here, and the long period movements enhanced by thick sediments (2-8 s.) produced by large earthquakes over a large area, differences which intensity-scales and design ground response spectra do not take into consideration. In the absence of long-period structures throughout the region, and with the presence of loose saturated deposits, these long periods produced effects such as nausea, sloshing of water, overturning of free-standing slender objects and widespread liquefaction, effects that are not indices of high acceleration. However, a repetition of the Assam earthquake today would have a great impact on modern multi-story buildings, bridges and other long-period structures, in the near- and far-field.

Oldham's extension of high intensity isoseismals significantly north of the Brahmaputra River into Bhutan is probably unjustified. Macroseismic data for the epicentral area to the north of the Brahmaputra are scarce but damage due to liquefaction here was widespread. It followed the flood plains of Manas River system which runs along the north-south axis of the northern part of the epicentral area and drains into the Brahmaputra River to the south. It is possible that Oldham was persuaded by not only by the abundant liquefaction here, but also by the large number of aftershocks reported from this area, and because of the rockfalls and slides were reported from the foothills of the Himalaya. The reappraised macroseismic data do not suggest greater intensities north of the Shillong Plateau than south of the range. The curious "Mexican-hat" epicentral contour of Oldham is now seen to be a somewhat symmetric "French bèret" with an east-west long axis, tilted slightly counter-clockwise.

From the position of the higher isoseismals, it appears that the epicentral area is in the west-central part of the Shillong Plateau, with intensities decaying to the north and south at the same rate. Significantly, the highest intensities (MSK=IX) overlie the subsurface rupture indicated by the geodetic data (Bilham and England, 2001**).**

The absence of evidence for surface fault rupture is curious for a M=8 earthquake although we note that no surface faulting occurred in the 26 January Bhuj M=7.6 earthquake, which had a similar depth and mechanism to the 1897 event. Unlike the Bhuj region where no significant topography exists, the projected fault plane (the Oldham fault) intersects the northern surface of the Plateau near a prominent NNE facing escarpment. The surface of the Plateau increments to lower elevations in steps along its northern edge marked by waterfalls and escarpments with elevations of several hundred meters. The absence of marker horizons in the crystalline surface rocks, and the presence of talus at the base of the escarpments that divide these levels is possibly responsible for faulting not to have been mapped in this northern region. Given their limited personal traverses of the northern edge of the Plateau, distributed deformation within the heavily-forested northern edge of the Shillong Plateau may have escaped detection by Oldham and his colleagues. However, as in the case of the Bhuj earthquake, it is probable that co-seismic surface faulting did not occur in 1897, except where noted in the Chedrang river valley.

The geodetic solution requires a rupture plane between 9 and 40 km depth, extending to the base of the continental crust, which is here found at depths of about 45 km (Maggi et al 2000). Oldham, on the basis of the timing of observers at telegraph stations, placed the location of aftershocks at a depth of 9 miles, similar to the depths of aftershocks in the 26

January 2001 Bhuj reverse faulting earthquake (Bodin et al., 2001). The doubtful accuracy of Oldham's depth observations do not exclude the occurrence of more shallow aftershocks.

The analysis of the frequency of felt aftershocks carried out on Oldham's data by the Montessus de Ballore, suggests that most of them were reported from the Shillong Plateau and from the region south of the Brahmaputra. Less strong shocks were also reported from outside of this area, chiefly from the north of the Plateau from as far north as Bhutan, and few from locations south of the Plateau (Montessus de Ballore, 1904). However this information comes from a small number of discontinuously reporting sites, most of them located north of the Plateau. Although many aftershocks were felt north of the Brahmaputra River, we conclude that this does not support Oldham's contention that the epicentral area extended north of the river (Oldham 1899).

The revised isoseismals from the great Assam 1897 M=8 earthquake do not differ significantly from those other Indian earthquakes with comparable magnitude. MSK intensities in Dhaka and Calcutta, the largest cities near the Shillong Plateau, for the 1897 earthquake were VI and V respectively. It is possible that local intensities may have differed in these settings by approximately ±2 intensity units depending on local soil conditions. The large area over which loose deposits liquefied and the size of the area over which the shock was felt, are similar to those produced by the large earthquakes of New Madrid 1811, Kangra 1905, Kansu 1920, Bihar-Nepal 1934 and Assam 1950.

Our revised isoseismal areas are significantly smaller than equivalent intensities derived by Oldham. For example, the radius of his 4th isoseist (allegedly equivalent to RF VI) lies between our MSK Intensity III and IV radii, and his 3rd isoseist (RF VII-VIII) is similar in radius to our MSK Intensity IV (Table 1). i.e. Oldham's intensities are apparently inflated by roughly 1.5 intensity units. This comparison is of interest because previous investigations have assumed that Oldham's Rossi-Forrel equivalents could be converted to their approximate Mercalli Intensity equivalents for the derivation of relations between shaking area and magnitude (Johnston, 1996).

The 1897 earthquake is the first earthquake in India for which an instrumental estimate of earthquake magnitude (Ms=8.0±0.02, Ambraseys, [2000]), a geometric seismic moment from geodesy (Mo=8.1±0.1, Bilham and England, [2001]) and isoseismal areas (Table 1), are available. A physical relation between the area within a given isoseismal contour and moment magnitude has been proposed by Frankel (1994) with the form

$$\log Mo = a + b\log(A) + c\sqrt{A} \quad \ldots\ldots\ldots\ldots\ldots\ldots.. \ (2)$$

where A is the Mercalli intensity area in km^2, and where the coefficients a, b and c have been fit to numerous earthquakes in intracontinental regions by Johnston (1996). In Table 1 we show that Johnston's 1996 coefficients, were they applicable to this earthquake, would result in an inferred intensity moment, Mi, more than an order of magnitude smaller than observed: $6.7<Mi<6.9$. The discrepency follows from Oldham's much larger isoseismals for the earthquake that were among those used to derive Johnson's coefficients. Using Oldhams inferrred area we find, as one would expect, that Johnson's coefficients yield a correct magnitude (Table 2).

The implication of these comparisons (Table 1 and 2) is that the coefficients of Johnson's (1996) derivation are inappropriate for India, and possibly for other intracontinental zones. A missing ingredient in quantifying the true relation between intensity and distance in Indian earthquakes is the occurrence of a recent large earthquake monitored by strong motion accelegraphs at a variety of distances, and in a variety of near surface conditions. Regrettably only one strong-motion instrument recorded the 26 January 2001 Bhuj earthquake, and this was at a distance of 1500 km. Until a suitable array of instruments records a future earthquake, studies of the sort we have undertaken provide an important data base to estimate intensity-attenuation relations.

Conclusions

In summary, the lessons learned from the study of the Shillong earthquake are:

- In determining intensities of historical earthquakes allowance must be made for the effects of the vulnerability of the local building stock and extreme soil conditions.
- Intensities assigned to a particular location must represent the mode and not the maximum value of the observed intensity.
- Maximum intensity in any destructive historical earthquake in rural areas in the Eastern Mediterranean, Middle East and northern Indian "saturates" at intensity VII-VIII MSK and any town or village would thus appear equally, but no more, devastated at higher intensities.
- Saturation of the scale at higher intensities makes assessment of “epicentral” or maximum intensity questionable..
- Liquefaction, landslides and rock-falls are not criteria suitable for the assessment of intensity.
- Isoseismal maps of early earthquakes need re-appraisal from original data before they can be used to constrain source dimensions.
- Intensity results from different earthquakes can be compared only when their assessment has been made with the same rules and criteria.
- Isolated points of low intensity within a background of "not felt” should not be allowed to define isoseismals, particularly the contour of perceptibility.
- In drawing isoseismals pockets of isolated high intensity may be ignored
- The shape and dimensions of far-field isoseismals of large earthquakes is influenced by the presence of large rivers and alluvial valleys as well as by the level of the underground water table at the time of the earthquake.
- Provided the majority of sites are on competent foundation materials, high intensity isoseismals may be used to constrain the dimensions of the seismic source .

A comparison between the radii of our estimated MSK isoseismals and Rossi–Forel isoseismal equivalents to Oldham's 1897 isoseists, suggests that Oldham's intensity estimates were inflated by approximately 1.5 intensity units. Reasons for this unwitting inflation are listed above. One of the consequencies of this inflation is that shaking in the 1897 earthquake may have influenced subsequent derivations of the quantitative relations between attenuation and intensity in intracontinental areas. Using our newly derived MSK isoseismal areas, and Johnston's (1996) globally derived attenuation coefficients, for example, an unreasonably low Mo≤6.9 magnitude would be assessed for the 1897 Mw=8.0 Assam earthquake. It would appear possible that similar biases in historically derived intensities in other historical earthquakes may have biased Johnston's (1996) coefficients.

In conclusion, we note that the 1897 M=8.0 Shillong earthquake ruptured a 110-km-long fault beneath the northern edge of the Shillong Plateau, and that the Dauki fault, along its southern margin could sustain a similar earthquake. Although this fault has accomodated strike-slip motion in the past it is probable that it now slips with a substantial vertical component. The recurrence of large earthquakes on this fault is conjectural since none has occurred in recorded history, however, aseismic motions have not been reported, and were it to slip in strike-slip sense alone, the surface of the Plateau would be tilted down to the north (Bilham and England, 2000). Our re-evaluated intensities have important consequencies for estimating the consequencies of an earthquake on the Dauki fault, on villages and cities near the Shillong Plateau.

Our re-evaluated intensities suggest increased attenuation as a function of distance from the epicenter compared to intensities estimated by Oldham. However, our re-evaluated intensites integrate the combined effects of acceleration, duration and shaking-frequency, whose effects now on the housing stock of large cities (Dakka, Calcutta, or Chittagong) will be different from those on structures prevailing in 1897.

Since 1897, populations in surrounding India and Bangladesh have increased tenfold with much of this population now living in urban environments. The style of urban construction now dominant in these urban settings was unknown in 1897. Specifically, fundamental frequencies in many structures are now closer to probable future shaking frequencies from a potential large future Plateau earthquake. Intensities of shaking would be roughly a half-intensity unit higher than in 1897 for cities remote and south of the Plateau were the Dauki fault to slip in an 1897-sized earthquake. For towns such as Sylhet near the Plateau the accelerations could be more than two intensity units higher.

Acknowledgements

We would like to thank Prof X. Zhou for providing Chinese translations of Tibetan documents and Miss Jo Skinner for the translation of Chinese texts. Also John Douglas for helping with the kriging. We thank Susan Hough for critically reviewing the article, and for subsequent helpful discussions. Thanks are also due to the British and Science Museum Libraries in London for newspapers. RB was funded by the National Science Foundation.

Figures

Fig. 1a. Location map for the 1897 Assam earthquake showing isoseismal approximations assigned by Oldham (1899) as dashed incomplete curves. (Approximate radii are: r_5 = 1000 km; r_4 = 720 km, r_3 = 500 km; r_2 = 300; r_1 = 160 km) Bold lines enclose Oldham's (a) felt area, (b) "area of extensive damage" and (c) "the probable limits of the epicentre", beneath and north of the Shillong Plateau. Fig.1b. Locations of observational data (dots) used to evaluate MSK intensities.

Fig. 2a. Epicentral location map showing Oldham's (1899) epicentral area centered on the Shillong Plateau, and dashed rectangle indicating the inferred 1897 subsurface rupture. Fig. 2b Same area with evaluated MSK intensities, rejected observational data (x), and isoseismal contours evaluated using kriging methods described in the text.

Fig. 3 Liquefaction sites (#) and landslide locations (triangles) reported for the 1897 mainshock. Contours for 25 cm uplift (solid line) and 25 cm of subsidence (dashed line) inferred from triangulation (Bilham and England, 2001) are indicated SW and NE respectively of the projected intersection of the subsurface 1897 rupture plane with the surface of the Shillong Plateau.

Fig.4 Observations and felt areas for the aftershocks of June 13 1897 (filled squares and dashed line), and 2 August 1897 (open boxes and solid line).

Fig. 5 MSK isoseismals for the 1897 earthquake showing points (dots) used in contouring. Data from white circles were not found useful (see text). The approximate isoseismal radii are r_{III} ≈830 km, r_{iv} = 540 km, r_v= 370 km, r_{vi} = 250km, r_{vii} = 170 km and r_{viii} ≈ 90 km. The highest intensities (MSK=IX) are found in two patches above the rupture zone (Figure 2b). See text for contouring methodology.

Fig. 6. Rate of decay of perceived intensity with epicentral distance. Linear and logarithmic least-squares fits to the data shown. Each distance is calculated from the closest point of the inferred rupture indicated by the geodetic solution.

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SC Statesman, Calcutta [22.6.1897]
TI Times of India, Bombay (1897 various numbers)
TL The Times, London [14 June-19 July 1897]
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Table 1. Locations, coordinates and MSK Isoseismal eastimates for the Shillong Plateau (Great Assam) earthquake, of 12 June 1897.

Aboo Mt	24.48	72.78	1
Achalpur	21.25	77.51	2
Agartala	23.83	91.38	6
Agia	26.08	90.62	8
Agra	27.17	78.08	3.5
Ahatguri	26.83	93.86	5
Ahmadabad	23.09	72.59	1
Ajmer	26.44	74.64	2
Akhaura	23.87	91.27	6
Akyab	20.12	92.93	2
Alipura	23.62	89.82	6
Alipur-Doar	26.5	89.53	7
Allahabad	25.43	81.92	5
Allanmyo	19.35	95.28	2
Anand	22.53	73.02	3
Atharabari	24.36	90.02	8
Azimganj	24.23	88.3	7
Badarpur	24.88	92.62	6
Bagula	23.32	88.65	5
Baidi	29.1	90.47	4
Balasor	21.5	86.97	4
Balipara	26.83	92.73	6
Bangalore	12.97	77.62	2
Banka	24.55	86.97	5
Bankipur	25.61	85.15	5
Bankura	23.24	87.07	4
Bardwan	23.23	87.87	4
Bareilly	28.36	79.42	3.5
Barisal	22.7	90.37	4
Baroda	22.31	73.19	1
Baxa	26.75	89.58	7
Benares	25.31	83.01	4.5
Berhampur	24.09	88.25	6
Betul	21.92	77.9	1
Bezwada	21.13	86.72	2
Bhakalpur	25.25	86.97	5
Bhamo	24.25	97.27	3
Bhartpur	27.22	77.53	3
BiharSharif	25.2	85.53	5
Bilimora	20.68	73.07	2
Birda	24.58	78.48	3
Bobbili	18.57	83.37	2
Bogribari	26.2	90.2	8
Bombay	18.92	72.9	1
Borjali	26.77	92.75	6
Budge-budg	22.48	88.73	3
Burhanpur	21.32	76.27	2
Buxar	25.57	84.02	5
Calcutta	22.57	88.35	4.5
Chandbali	20.77	86.8	3
Chandpur	23.22	90.66	5.5
Chaphara	27	82.2	5
Chapra	25.78	84.78	5.5
Cherrapunji	25.28	91.73	8
Chihindwara	22.05	78.94	1
Chiknagul	24.93	93.05	5
Chittagong	22.35	91.88	5
Coconada	16.95	82.22	2
Colgong	25.26	87.23	5.5
Comillah	23.47	91.22	7
Cona=Tsona	27.98	91.98	5.5
Dabhoda	23.15	72.82	2
Dacca	23.71	90.41	7
Damra	25.9	90.83	8
Damukdea	24.03	89.07	6
Damxoi	28.47	91.55	4.5
Daragon	24.28	91.54	6.5
Darjiling	27.04	88.26	6.5
Darma	28.19	91.2	5.5
Debra	22.4	87.55	4.5
Degyi	28.03	87.67	5.5
Dehegam	23.18	72.85	2
Delhi	28.66	77.23	2.5
Deogarh	24.49	86.69	5
Dhargam	25.12	91.98	8
Dhubri	26.02	89.98	7.5
Diburghar	27.48	94.91	4.5
Dilma	25.87	90.72	9
Dinajpur	25.63	88.64	7
Dongkar	27.57	89	5.5
Doqoi	28.83	90.67	4.5
Dumka	24.27	87.25	6
Durgapur	25.14	90.68	7
Faizabad	26.78	82.2	4.5
Faridpur	23.6	89.88	5
Gamba	28.27	88.53	4.5
Gantok	27.32	88.62	6.5
Garbo	28.37	90.83	5.5
Garbyang	30.12	80.85	4
Gauhati	26.18	91.75	8
Gauripur	26.18	90.12	7
Gaya	24.82	85.05	4.5
Ghaziabad	28.67	77.47	2.5
Giridi	24.17	86.28	4.5
Goalpara	26.18	90.62	8
Goalundo	23.83	89.8	6
Godda	24.83	87.21	5.5
Golaghat	26.51	93.97	5
Gomastapur	25.78	88.33	6.5
Gombardangal	22.88	88.8	6
Guripur	24.76	90.56	8
Gwalior	26.22	78.2	3.5
Habiganj	24.38	91.41	6.5
Harirampur	23.62	89.93	6
Haza	26.25	91.58	7.5
Helem	26.83	93.33	5
Henzada	17.63	95.53	2
Hoshangabad	22.75	77.77	2
Howrah	22.58	88.38	5
Hugli	22.9	88.4	5
Isvarganj	24.68	90.58	5
Jabalpur	23.18	79.98	3
Jaidebpur	24	90.43	6.5
Jaintiapur	25.13	92.17	8
Jaipur	26.92	75.87	3.5
Jaipur-Hut	25.1	89.07	7
Jalpaguri	26.53	88.77	7
Jamalpur	24.92	89.94	7
Jamalpur	25.32	86.53	7
Jangipur	24.47	88.03	6
Jellinghi	24.13	88.77	6.5
Jessor	23.16	89.21	4
Jhenidah	23.54	89.18	5.5
Jorhat	26.76	94.21	4
Jorra	28.2	92.33	5
Kalewa	23.2	94.3	4
Kalipur	24.06	90.97	7.5
Kalna	23.22	88.37	5.5
Kandi	23.95	88.05	6
Kangkar	27.54	91.9	6.5
Kanpur	26.47	80.33	2.5
Kapasia	24.03	90.13	6.5
Karimganj	24.86	92.36	7
Kasva	23.74	91.15	6.5
Katha	24.17	96.38	3
Kathmandu	27.7	85.31	5
Katwa	23.64	88.23	5.5
Kaunia	25.78	89.48	7
Khana	23.32	87.83	5.5
Khandwa	21.83	76.38	1
Kharagpur	22.35	87.4	2
Khulna	22.82	89.62	5
Kindat	23.72	94.47	4
Kishorganj	24.43	90.77	6.5
Kohima	25.07	94.17	5
Kotah	25.17	75.87	2.5
Kotgarh	31.32	77.53	1
Krishnagar	23.4	88.55	6.5
KuchBihar	26.33	89.48	7.5
KyaukPyu	19.37	93.5	1
Kyirong	28.4	85.31	4
Lakang	28	91.04	5.5
Lakhimpur	27.24	94.11	3
Lalitpur	24.68	78.47	1
Langrang	27.42	88.85	6
Lemyethna	17.58	95.23	2
Lhasa	29.65	91.13	4
Lilung	28.44	86.63	4.5
Lobpur	24.82	87.85	6
Luckeerserai	25.18	86.15	5
Lucknow	26.87	80.97	4
Lumding	26.78	93.2	5
Luozha	28.08	91.01	5.5
Machilipatnam	16.19	81.14	2
Madhipura	25.93	86.85	5.5
Madhupura	25.85	90.43	7
Madras	13.08	80.27	1
Magura	23.49	89.42	5.5
Magwe	20.14	94.92	3
Maldha	25.03	88.15	8
Mandalay	21.98	96.13	3.5
Mangaldai	26.43	92.04	6
Manipur	24.79	93.94	5
Manu	24.44	91.95	7

Mawlu	24.47	96.22	2.5
Meherpur	23.78	88.64	5
Midnapur	22.42	87.32	5
Mirzapur	25.27	82.63	4.5
Mogok	22.92	96.5	3.5
Mogra	23.83	91.27	8
Mokersa	25.53	90.98	9
Monohordi	23.78	90.67	6
Moweswar	23.98	87.82	5.5
Muktagachha	24.76	90.25	7.5
Munger	25.38	86.47	7.5
Munshiganj	23.49	90.38	6
Murshidabad	24.18	88.32	7
Myelat	20.75	96.75	2
Myitkhina	25.4	97.38	1
Mymising	24.75	90.4	8
Nabinagar	23.88	90.96	6
Nadiya	23.4	88.38	5.5
Nahakaung	24.27	96.23	2
Naihati	22.9	88.47	5
Naini	25.9	81.93	3.5
Nalhati	24.32	87.9	5
Namtang	27.3	88.82	6.5
Narainpur	26.92	93.93	5
Naraniganj	23.62	90.5	6
Narsinagar	23.97	91.1	6
Narsindhi	23.93	90.78	6.5
Nawabganj	23.67	90.17	6
Nilphamari	25.94	88.85	7
Nimach	24.47	74.9	1
Noachali	22.8	91.15	4.5
Nongpoh	25.9	91.93	7.5
Nongstoin	25.52	91.33	8
Nowgong	26.35	92.69	5.5
Pabna	24.01	89.24	6.5
Pali	27.72	89.16	5.5
Panchkura	22.38	87.73	2.5
Parbatipur	25.65	88.97	7.5
Patna	25.61	85.14	4
Pegu	17.43	96.5	2
Piploda	23.62	75	2
Purbasthali	23.45	88.4	6
Purniah	25.77	87.47	6
Qonggyaixoi	29.05	91.68	4
Raipura	23.98	90.95	6.5
Rambrai	25.65	91.38	9
Ramgopalpur	24.72	90.55	8
Rangapura	26.81	92.65	5.5
Rangia	26.42	91.63	6
Rangoon	16.78	96.22	1
Rangpur	25.74	89.25	7.5
Raniganj	23.6	87.13	5
Raninagar	24.75	89.03	8
Raoti	23.24	74.83	1
Ratlam	23.35	75.07	1
Rongdi	28.19	87.73	4.5
Ru	19.72	93.87	2
Rupganj	23.8	90.57	6
Rupsi	26.13	89.98	7
Sabhar	24.34	90	6.5
Sahibganj	25.23	87.67	8
Saidpur	25.78	88.9	6
Saikupa	23.68	89.3	6
Sakalipur	23.68	87.92	5
Samin	25.68	90.72	9
Saraghat	24.1	89.1	6.5
Saugor.Isl	21.6	88.23	4
Sehore	23.2	77.12	2
Senge	27.47	92.11	6
Sengge	28.07	90.97	6
Seoni	22.09	79.56	5.5
Shaistaganj	24.26	91.45	7.5
Shampur	25.7	89.22	8
Shigatse	29.28	88.89	4
Shigatze	29.27	88.9	4
Shillong	25.57	91.87	9
Sibsagar	26.99	94.63	3.5
Silchar	24.83	92.85	5
Siliguri	26.7	88.5	6
Simla	31.11	77.17	2.5
Sirajganj	24.46	89.7	7
Sonada	26.97	88.32	6.5
Sonamuki	23.3	87.42	5
Srinagar	23.55	90.35	6
Sultanpur	24.8	89.05	6.5
Sunamganj	25.06	91.37	8
Supul	26.12	86.59	5.5
Surat	21.2	72.82	2.5
Susa	27.17	91.5	5.5
Sutna	24.57	80.9	3.5
Sylhet	24.9	91.88	7.5
Tagaung	23.5	96.07	1
Tangail	24.23	89.98	6
Tawang	27.58	91.88	6.5
Tezpur	26.62	92.8	5
Thayetmo	19.32	95.27	1
Tiggaing	23.75	96.18	1
Tindharia	27.78	88.46	5.5
Tinpahar	25	87.82	6
Torsa-Darora	23.44	90.92	4
Toungo	18.92	96.52	1
Tura	25.52	90.23	8
Ukiam	25.85	91.42	9
Utripur	26.75	80.17	3.5
Vishnupur	23.08	87.33	4.5
Vizagapatan	17.7	83.33	2
Wokha	26.1	94.32	2
Xiayadong	27.43	88.91	5.5
Yadong	27.48	88.91	5.5
Yandoon	17.05	95.68	2
Yatung	27.42	88.93	6

Table 2 Areas (km^2) and radii (km) corresponding to Oldham's third, fourth and fifth isoseists (and their stated Rossi-Forel equivalents) compared to MSK areas and radii estimated in this study. The comparison shows that Oldham's stated Rossi-Forel equivalents embraced unjustifiably larger areas compared to newly evaluated MSK intensities.

Oldham	RF equivalent	Oldham area	MSK Intensity	MSK area	radius$_{\mathrm{Old}}$	radius$_{\mathrm{MSK}}$
			Intensity IX	810	79.76	28.46
2nd Isoseist.	VIII-IX	6,361	Intensity VIII	10,054	950	100.3
			Intensity VII	76,952		277.4
			Intensity VI	162,098		402.6
			Intensity V	376,313		613.4
3rd Isoseist.	VII-VIII	902,567	Intensity IV	861,275	950	928
4th Isoseist.	VI	1,286,796	Intensity III	1,798,714	1134	1341
5th isoseist.	IV-V	2,895,291			1702	

Table 3 Estimated area of perceived MSK intensity and inferred magnitude using Johnson's (1996) coefficients (a, b and c) for the Mw=8.0 Assam 1897 earthquake. A, r, MA and Mr are the precise area, approximate radius, and corresponding Mo magnitudes estimated from re-evaluated MSK intensities in this article using equation 3 and coefficients a,b, and c from Johnson 1996. Log(O) is the log of the area estimated by Oldham for approximate Rossi-Forel isoseismals (3,4, and 5) corresponding to the range shown in columns Oldi and OldRF. Oldham's isoseismals yield an approximate correct magnitude for this earthquake, whereas the corrected isoseismals yield a value that is too low by an order of magnitude. Asterix indicates contours whose closures in Tibet were interpolated.

MSK	logA	log(πr^2)	Log(O)	a	b	c	MA	Mr	Mold	Oldi	OldRF
VIII	4	4.41	5.96	24.05	0.44	0.00586	6.9	7.2	10.8	3	VII-VIII
VII	4.89	4.96	5.96	23.22	0.559	0.00328	7.2	7.3	9.08	3	VII-VIII
VI	5.21	5.29	6.11	20.23	1.032	0.00176	6.8	6.9	8.32	4	VI
V	5.58*	5.63	6.11	19.83	0.788	0.0026	6.5	6.6	7.70	4	VI
IV	5.94*	5.96	6.46	18.1	0.971	0.00194	6.4	6.5	7.75	5	IV-V
III	6.25*	6.34	6.46	17.59	1.021	0.00139	6.5	6.7	7.00	5	IV-V
					Average	Mo	6.7	6.9	7.97		