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Entertaining a Great Earthquake in Western Nepal: Historic Inactivity and Geodetic Test for the Development of Strain

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ABSTRACT

A 500-800 km long segment of the Himalaya bordered by the rupture zones of the great Bihar, 1934, and Kangra, 1905, earthquakes has not experienced a great earthquake for at least 200 years, and perhaps for as long as 750 years. The observed rate of occurrence of earthquakes is evidently too low to accommodate Indo/Tibetan slip which must therefore be accommodated by creep or occasional great earthquakes. Creep processes do not appear to be sufficiently fast, at least in central Nepal, where levelling data in the last two decades, and GPS data in the past 3 years, have been interpreted to account for at most 7 mm/year, or 30% of the inferred ≈20 mm/yr convergence signal. The measurement of 19th century geodetic networks in northern India, which have hitherto been neglected, potentially provides an estimate the rate of accumulation of elastic strain in W. Nepal. In view of the possibly disastrous consequences to the many tens of millions inhabitants of northern India and Nepal who would be affected by a great earthquake, an intense effort to explore further the historic record and the geographic limits of historic and future rupture is desirable.

INTRODUCTION

Each year India is believed to approach Tibet by 15-20 mm. This convergence rate has been inferred indirectly from geological and seismological evidence and from global plate-circuit closures (Molnar 1990), and new data from GPS observations promises soon to provide a direct measure of its instantaneous rate. GPS data to date are consistent with a 20 mm/year convergence rate although the uncertainty of the measurements is currently of the same order of magnitude as the 1991-1992 signal (Jackson and Bilham 1994a, b). GPS data between Banglore and Kathmandu 1991-1994 confirm a low rate of relative northward convergence (0±6.5 mm/year, Burgmann et al. 1994), and a rate of NE displacement of the Indian Plate consistent with global plate motions (6 cm/year). A convergence rate across the Himalaya of 20 mm/year yields a renewal time for earthquakes with 5-10 m slip of 250-500 years.

Current methods employed to estimate seismic hazards in Nepal depend on identifying active faults, assigning probable recurrence intervals for earthquakes of a given magnitude on these faults, and estimating at selected nearby sites the probable accelerations from all probable ruptures on these identified faults in a given time window. Necessary refinements include assessing the dispersion and attenuation of seismic waves with distance from each hypothetical earthquake, and assessing soil and geometrical conditions that can result in local amplification of these waves.

The problem with this approach is that although a substantial fraction of the seismic risk expected from future moderate and large earthquakes can be included in this analysis, the contribution from great earthquakes that accommodate most of the Himalayan convergence is not well -represented by surface faulting, and must be entirely estimated from probable renewal times for which we have little guidance. This would not be a serious omission were not the causal fault(s) of these great earthquakes, namely the sub-horizontal faults associated with the Himalayan-detachment of Seeber and Armbruster (1981), fewer than 6 km beneath the surface, and thus the *closest* fault to many villages in Nepal and northern India. This fault (or faults) is believed to separate the Indian plate from an accretionary prism of Himalayan sediments, but its geometry and location are uncertain because micro-earthquakes near it are rare, and its reflected image in seismic refraction surveys is weak. Moreover, because it is horizontal or gently dipping to the north, the detachment surface does not appear on any map of Nepal. The conspicuous throughgoing thrust faults that are mapped along the southern edge of the Himalaya (Main Boundary Thrust, Main Frontal Thrust, Main Dun Thrust etc.) may meet this surface at depth, yet no slip on these great thrust fault systems has been reported during any

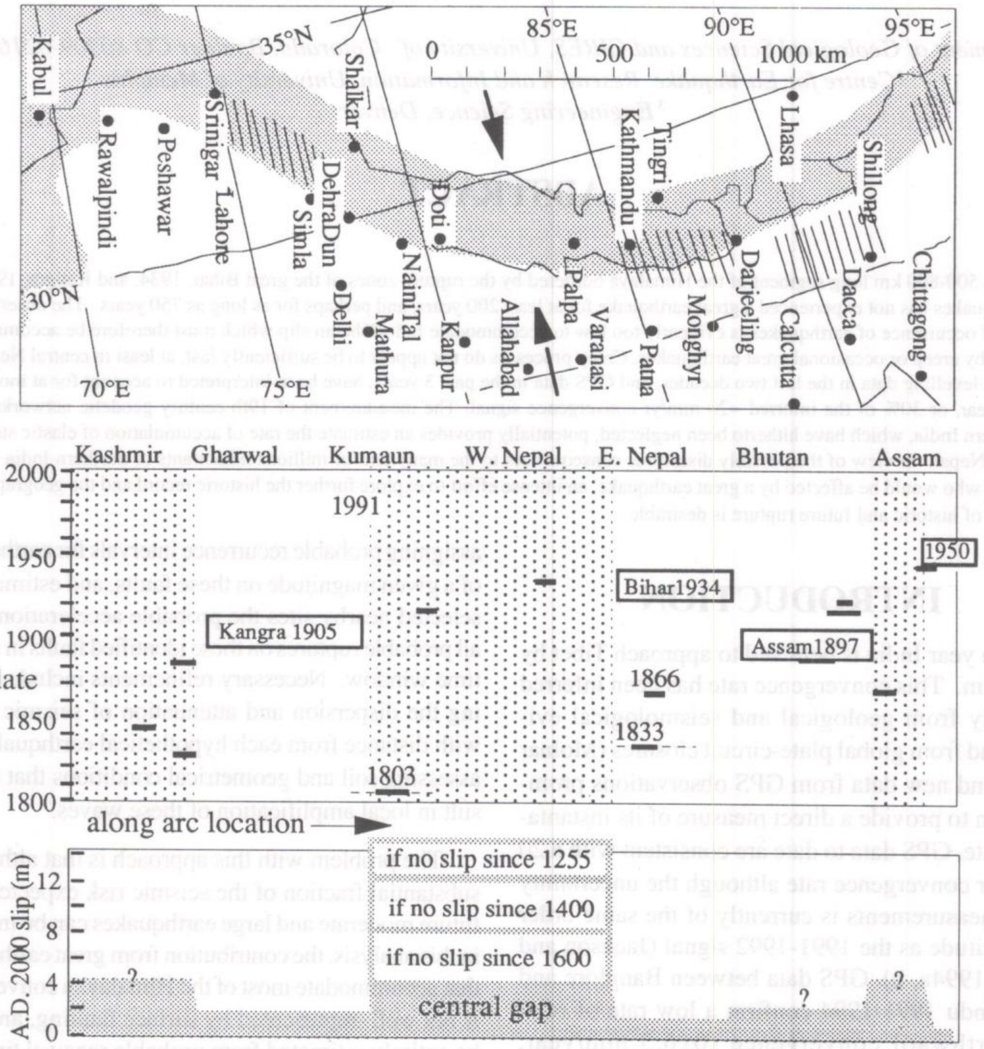

Fig. 1 Himalayan earthquakes since 1800 adapted from Khattri (1987). M>7 events shown as solid bars proportional to magnitude. Uncertainties in the locations of the 1803 and 1833 events are shown with dashed lines. Seismic gaps shaded in central panel; great earthquakes boxed showing approximate rupture areas. Uttar Kashi M=6.5 1991 indicated by dot. Lower panel shows slip available now to drive future earthquakes assuming no creep and uniform Indo/Tibet convergence of ≈20 mm/yr (arrows).

of the four great earthquakes in the past 100 years. Slip on these faults cannot therefore be used as a proxy for slip intervals of great detachment earthquakes. Thus although seismic risk zonation procedures based on mapped faults may be complete, the absence of data to constrain rupture areas, coseismic slip, surface accelerations, or recurrence intervals for earthquakes on a subsurface detachment represents a serious weakness for realistic estimates of seismic risk.

The area of the rupture zone potentially active during a great detachment earthquake could be equal to the area of Nepal extending 800 km eastward from Kathmandu, and more than 150 km down-dip, similar to the area of the Ms=8.6 1964 Alaska earthquake. A careful study of historical data might reveal whether or not such a large event has occurred, yet the current incompleteness of the historical record is such that the assessment of the size of known historic earthquakes is poor, and some great earthquakes may have occurred but have not been correctly recognized even during the colonial period of India's history.

That the historical record of Himalayan earthquakes is largely incomplete is cause for concern. However, other disciplines whose further emphasis might illuminate the potential for a future great earthquake are equally poorly pursued. Seismic networks along the Himalaya are currently inadequate to understand the details of seismic release, or the geometries of future slip. Geodetic measurements in northern India which may provide potentially both an estimate of slip in these recent great earthquakes, and an estimate of the relative contributions of seismic and aseismic slip in the past century, have not been subjected to rigorous remeasurement. Geological investigations of liquefaction in regions south of the Himalaya that could provide estimates of the timing of historic and prehistoric great earthquakes, remain to be undertaken.

Given that slip during a great earthquake may exceed 6 m, the occurrence of the recent 1934 earthquake reduces the probability for an imminent event in Eastern Nepal to a low value. No similar great earthquakes have occurred recently in W. Nepal. Aseismic folding, subsurface creep or slow earthquakes can be invoked to eliminate or reduce the potential for great earthquakes and these possibilities are discussed in following sections, however, given our current understanding of Himalayan tectonics one or more future *great earthquakes appear inevitable in western Nepal* and Kumaun.

HISTORICAL ACCOUNTS OF EARTHQUAKES NEAR NEPAL

Prior to the development of seismographs in the late 19th century, materials available for the study of earthquakes in northern India are quite fragmentary. Sanskrit records of earthquakes in early India are largely mythical yet may hold clues concerning regions prone to seismicity (Iyengar 1994). The complex fabric of interpretation (Bhat 1983) developed by the poet/scientist Varahamihira (505 AD) displays considerable familiarity with damaging earthquakes. The Moslem occupations of India resulted in a promising source of written materials for earthquakes in northern India but scholarship of these texts has yet to provide details on earthquake recurrence. Jesuit records in the 15th and 16th centuries may also provide an important source of information on Indian earthquakes, however, many letters and reports from India were lost in the 1755 Lisbon earthquake, or destroyed maliciously in Goa in 1774 by agents charged with their transport to Europe (Correia-Alfonso 1969).

A frequently cited 13th century earthquake in Nepal is described in Nepalese colophons (Regmi 1965; Shaha 1992 p.47). Information on damage during the 7 June 1255 event appears to be restricted to the Kathmandu valley. Palaces, temples and dwellings were badly damaged resulting in the death of one third of the population. The reigning king, Abhaya Malla, died 6 days later as a result of injuries sustained during the event, and earthquakes recur throughout the 3 year reign of his son perhaps indicative of aftershocks or related earthquakes. Events in 1408 and 1681 are listed by Chitrakar and Pandey (XXXX) who cited Regmi, 1965.

The British occupation of India provides an important source of written materials for studying Himalayan earthquakes from the 17th century onward because, as with Jesuit writers, there was considerable correspondence between Europe and India, much of which has survived. The time span is important because, given a convergence rate of 2 cm/year a 300 year window permits the possible recurrence of events with co-seismic slip of more than 6 m, similar to slip during the Bihar 1934 earthquake. Nineteenth century Indian newspapers regularly reported felt earthquakes (eg Srivastava and Ramachandram 1985), and from these and from letters compiled in scientific journals, we know of Himalayan earthquakes in 1803, 1833, 1842 and at other times that must have been of considerable size. The calibration of the magnitude of an earthquake from historical accounts, however, requires clues concerning the simultaneity and intensity of shaking over a wide region, the duration of shaking, and the widespread manifestation of processes associated with substantial accelerations, such as liquefaction phenomena and rockslides, and the occurrence of aftershocks felt over a large region in the months following the event, suggestive of an extensive rupture zone. Even when historic accounts appear to confirm some or all of the phenomenon of better documented great earthquakes like the Bihar event, they may be misleading because of a bias caused by the sparse location of people reporting felt effects.

GREAT EARTHQUAKES BETWEEN 1800 AND 1950

GREAT EARTHQUAKES SINCE1890

Details of great earthquakes of 1897, 1905, 1934 and 1950 have been discussed by several investigators (Oldham 1899; Middlemiss 1910; Dunn et al.1939; Seeber et al. 1981; Seeber and Armbruster 1981; Khattri1987, 1992; Chander 1988, 1989; Molnar 1990; Molnar and Pandey 1989; Chandra 1992; Gupta 1992; Gahalaut and Chander1992). Each of these studies has treated the absence of unequivocal data on the area of the rupture zones of these earthquakes in different ways, yet despite volumes of written materials, the location, rupture area and coseismic slip distribution of these earthquakes are in some cases in dispute by factors of 2. This is largely because surface faulting provides few clues to constrain the extent of the rupture surface. Moreover, aftershocks, the distributions of which are typically used to estimate the dimensions of subsurface rupture, were poorly located for each earthquake. For the Kangra earthquake only do geodetic data provide an estimate of slip (5-12 m) and the levelling data on which the estimate is based (Chander, 1988) are obtained from close to the eastern end of the rupture zone providing a poor estimate of mean slip. Intensity data suggest that rupture may have been quite heterogeneous so that even for this earthquake mean coseismic slip is uncertain. Despite these uncertainties the dimensions of the felt isoseismals and the extensive epicentral damage leaves no doubt that the 4 events were great earthquakes (M>8).

Seeber and Armbruster (1981) interpret the rupture zones of the 3 eastern great events to abut and to underlie the plains of northern India. In this interpretation much of the Himalaya east of Kathmandu has slipped, as have smaller segments west of Dehra Dun. However, reduced rupture areas are permitted by the data resulting in gaps between these events. Molnar (1989) outlines three possible interpretations for the Kangra intensity data: that the Kangra event may have ruptured 280 km, or that two adjoining segments with smaller dimensions slipped unequally, or that two separate segments slipped. Molnar also favours smaller rupture areas for the 1897 Assam event than those adopted by Seeber and Armbruster (1981) with an east-west length for rupture of 200±40 km, and a north-south rupture width of ≈100 km terminated south of the Himalayan foothills. A revised surface wave magnitude for the 1897 event of M=8 is also consistent with a smaller 1987 rupture zone (Abe 1994) but the absence of long period energy in these early seismograms may underestimate magnitude. The absence of evidence for Himalayan slip north of the Shillong Plateau in 1897 means that the Himalayan region to the north may now be a potential site for a great earthquake. In contrast, Pandey and Molnar (1988) estimate a possible rupture length of 200±100 km for the 1934 rupture similar to that determined by Seeber et al. 1981, but prefer a rupture area extended north beneath the Himalaya. Fig. 1 illustrates approximate dimensions of these ruptures and the locations of other events discussed in the text.

The rupture zones and magnitudes of pre-1850 earthquakes in western Nepal and the Kumaun Himalaya are less well known. In particular, earthquakes in 1803 and 1833 have been sometimes invoked as possible great earthquakes (Seeber and Armbruster 1981). If they were large and occurred within the largest of the remaining gaps (the central gap of Khattri 1987) they would reduce the potential slip available for future rupture. The following discussion based on newspaper accounts and eyewitness accounts suggests that these events were not great earthquakes.

1 SEPTMBER 1803, 00:30

Considerable damage to mosques and dwellings occurred at Mathura on the Ganges 130 km SE of Delhi. From subsequent repairs it is believed that the 80 m high, 24 sided, 14th century Qutab Minar in Delhi lost part of its summit, and was extensively fractured by the event (Cunningham 1864). The mainshock duration was several minutes in Lucknow, Varanasi and Calcutta (Calcutta Gazette, Sept. 8 & 15, 1803) and several slighter aftershocks followed. Destruction of buildings is reported in the Kumaun Himalaya where rockfalls buried whole villages (Baird-Smith (1843, 1844) citing Hogson). Loss of life was considerable in the villages of Badrinath 79.5W 30.7N and Barabal (Oldham 1883).

The effects near Mathura on the Ganges are clearly liquefaction "very extensive fissures in fields, through which water rose in considerable violence, and in quantity sufficient to be used by cultivators" (Oldham citing Asiatic Ann. Reg. 6, Chronicle, 58, 1803). According to Baird-Smith (1844) water issued from these fissures for 23 days. However, but minor damage only was reported from Lucknow 350 km to the east -"severest shock I ever felt....dislodging of the upper turrets... of several minarets in the city", and none in Varanasi 550 km ESE - "made the furniture in our Bungalows rattle" (Calcutta Gazette, Sept. 15, 1803).

One interpretation of the reports is that a major earthquake beneath the Garhwal/Kumaun Himalaya caused liquefaction near the Ganges as observed during the 1934 event. The shock was felt at Makwanpur, caused Mercalli Intensity VIII damage in Lucknow, stopped pendulum clock and caused fish to be thrown out of the Botanic Garden's tank and other reservoirs in Calcutta (Calcutta Gazette 1803). In the absence of other extensive reports of damage from Kathmandu, Varanasi and Delhi, and weak evidence for a reduction in intensity south and east of Nepal, it is reasonable to suppose that the event occurred near the Kumaun Himalaya. The relatively small impact the event had on agriculture and the relative disinterest shown by the press (although the earthquake occurred at the time of troop movements associated with an incipient 1803 Anglo- Maratha war) suggests that it cannot have approached in magnitude the size of the Bihar 1934 event. An event size of M<7.5 is probably reasonable given current uncertainties. Khattri (1992) assigns 6≤M<7.6 to the event.

26 AUGUST 1833, 23:57

Campbell's November 1833 report from Kathmandu lists 4040 buildings destroyed and 414 killed in the vicinity of Kathmandu with additional hundreds of fatalities and destroyed houses in eastern villages. This number of destroyed houses is substantial, though an order of magnitude less than in 1934. Campbell reports that damage reduced rapidly to the west, and less rapidly to the east. Campbell reports that damage reduced rapidly to the west, and less rapidly to the east. He relates that local Brahmins acquainted with Nepalese chronicles considered it less violent than the earthquake of 1255 when "innumerable towns were utterly destroyed and thousands of their inhabitants killed". In 1833 a fort was damaged at Chisapani in the northern Mahabharat range south of Kathmandu, the passes to Tibet were blocked by landslides, and the Kamala River was dammed by a landslide that burst 4 days after the event flooding the village of Baldeah, north of Darbhanga in the Terai (Bengal Hurkaru, 16 Sept.,1833).

Although felt reports from the plains of India are well distributed there is an absence of detailed reports from remote parts of western and eastern Nepal. Campbell writes in Dec. 1833 that "the most extreme violence of the shock, as far as its occurrence is as yet known, was expended from this side of the Himalayan range on the north, to the course of the Ganges on the south, and from the Arún River (in the Nepal hills) on the east, to the western branches of the Trisúli Ganga on the west, comprising a space of about 200 miles from north to south, and 150 from east to west." This estimate corresponds roughly to the Mercalli Intensity VIII contour shown in Fig. 2 compiled from newspaper reports of 1833 (India Gazette, Bombay Courier, Bengal Hurkaru, and Mofussul Akbar) and from Campbell's accounts (Bilham 1995). The 1833 earthquake may have ruptured a region of eastern Nepal within the inferred rupture area of the 1934 event, but with less slip and smaller rupture area.

Dunn and Auden (Dunn et al. 1939, p.116), apparently basing their information on editorial comment in Prinsep, 1833 or perhaps upon the somewhat speculative account in the Calcutta Courier reprinted in the India Gazette Oct. 6 1833, relate that the 1833 shock was felt in Lhasa, as was the 1934 event. However, members of a Nepalese delegation returning from Beijing via Lhasa at the time did not feel the earthquake in Lhasa. Verbal news of the disaster in Kathmandu was obtained from travellers encountered at Xigatse, but not until they approached Tingri (87°E, 28.5°N) did they meet villagers who had felt the event (Campbell, Nov. and Dec. 1833). Damage became increasingly evident as they approached the Nepal border. At Kyirong (28.45° N, 84.25°E) 60 of 400 houses were destroyed, and at Kuti (=Nyalam, 28.18° N, 86.00) 550 houses were destroyed out of an estimated 600. This suggests that the epicentre may have been close to the Tibet/Nepal border, with a rupture area overlapping or abutting the 1934 rupture (cf. Chen and Molnar 1990, Pandey and Molnar 1988).

There is little doubt that the 1833 event was smaller than the 1934 event based on the minimal liquifaction features at Monghyr and Chapra in 1833, and their widespread manifestation throughout Bihar in 1934 (Andrews 1935). Dunn et al. (1939), largely from fatality and damage statistics, also conclude that the 1833 event had isoseismals of similar form but lower intensity . However, a significant feature mitigating loss of life in 1833 was the existence of the two large foreshocks: the first a moderate event 5 hours before the mainshock, and the second a significant event 15-25 minutes before the mainshock, which drove many people outside with great anxiety. As a result the re-

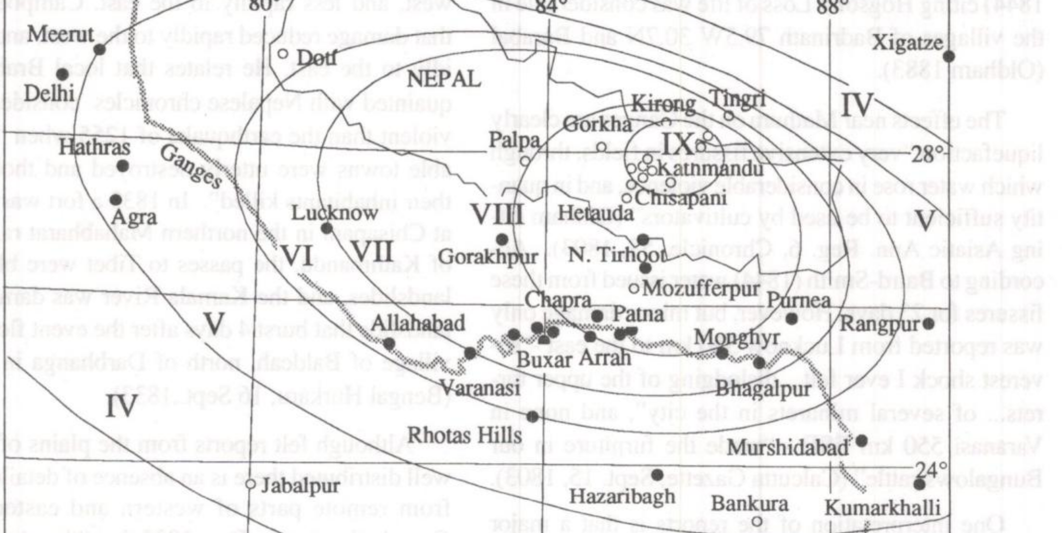

Fig. 2 Locations reporting the 26 August 1833 earthquake. Solid circles from newspapers and open circles from Campbell, 1833. The shaded ellipse corresponds to the rupture area adopted by Khattri placed in a location corresponding to maximum damage reported by Campbell. However, the location of the rupture is probably uncertain to ±1 degree, and the rupture area could be a factor of 2 or more larger.

ported ratio of destroyed buildings to fatalities in the Kathmandu Valley was *10 in 1833* and *3.6 in 1934*. There were 20 times more fatalities (8519) reported in 1934 compared to 1833 (414), but it is certain that reporting in rural Nepal was far from complete in 1833. Isoseismal areas in 1833 compared to isoseismal areas for more recent events suggest that the 1833 earthquake had a moment magnitude of 7.7±0.2 (Bilham 1995).

NO RECENT GREAT EARTHQUAKES IN W NEPAL AND KUMAUN

The accounts of earthquakes in 1803, 1810, 1826 and 1866 (Oldham, 1883) evidently do not qualify these events as great earthquakes. The 1833 intensity data support the notion that an M 7.6±0.2 earthquake occurred within or close to the mainshock region of the 1934 event (Fig. 2). The 1803 event may have been similar in size to the 1833 event and may have been centred in the Kumaun Himalaya although intensity data are sparse. Thus no great earthquakes have occurred in the past 200 years in W. Nepal and the Kumaun Himalaya, a region termed the central gap by Khattri (1987). The length of this zone according to Khattri may be as long as 800 km, which would be consistent with Molnar and Pandey's (1989) conservative estimates for historic rupture areas. If larger estimates are permitted for the rupture zones of the Kangra and Bihar events (Seeber and Armbruster 1981) the length of the gap can be reduced to perhaps 500 km. These estimates are equal or longer than any of the rupture zones of great earthquakes that have occurred in the past 100 years and, were the gap to fail in a single event, it would possibly be associated with greater slip, and consequently recur less frequently than adjoining great earthquakes (see below). Khattri (1987, 1992) points to structural features of the Indian plate near the centre of this region (the Faizabad ridge at 82°E) whose presence elsewhere along the arc appear to have terminated ruptures, and which if operative in the next great earthquake might prevent a rupture larger than 400 km developing. A 250-400 km-long rupture would be similar to other events in the Himalaya (a characteristic rupture length), yet based on our current understanding there are no strong reasons to favour the possibility of one, two or three ruptures filling this 500-800 km segment.

If we suppose that great earthquakes in the past century have completely released the accumulated plate displacement in those regions, and that the convergence rate between Tibet and India is at least 20 mm/year, the slip available to drive future rupture is less than 2 m in these regions (Fig. 1) rendering them probably impotent to host another great event for several centuries. However, the rupture zone dimensions of segments that ruptured in 1897, 1905, 1934 and 1950 are far from certain so that the along-arc lengths of these areas of minimal seismic hazard (from great earthquakes) are not well constrained. The possibility that a major earthquake in eastern Nepal in 1833 was followed a century later by a great earthquake in approximately the same location raises additional concern that simple estimates of slip potential may be misleading.

If slip has not occurred in the region of west Nepal for 200 years, as appears to be admitted by the historical data, the minimum slip in a future earthquake, or sequence of earthquakes, is ≈4 m, assuming a convergence rate of 20 mm/year (Fig. 1). Less than 1 m of potential slip has developed in the Kangra and Bhutan regions and less than 70 cm in the Bihar region. The incomplete history of seismicity prior to 1800 does not permit any conclusion concerning the maximum slip that may occur in western Nepal, however, if an earthquake has not occurred in the region since the historic 13th century event the slip during future rupture may exceed 15 m. Such a conclusion is consistent with the absence of substantial damage to the Qutab Minar in Delhi during the same period (Cunningham 1864).

RUPTURE AREA AND MEAN COSEISMIC SLIP

Great earthquakes are more effective in allowing slip between two plates than smaller events because the amount of displacement in an earthquake, assuming constant failure conditions (stress drop or strain at failure) and ignoring the effects of friction and rupture dynamics, is proportional to the area of the zone over which rupture occurs. The length of the central-gap permits several failure scenarios, and in this section we attempt to establish the size of one or several earthquakes that could permit the plate boundary to slip, assuming no aseismic processes to be active. We summarize the effects of creep in a following section. Although several empirical curves have been developed relating rupture area, slip, and earthquake magnitude, these relations are for equidimensional ruptures and are based on observational data from a broad spectrum of tectonic settings (Kanamori and Anderson 1975; Wyss 1979; Scholz 1990).

The length and breadth of the central gap (W. Nepal and Kumaun) permits several failure scenarios, and it is possible to estimate the magnitude of potential sequences of earthquake from the above empirical relations. However, the aspect ratio of each rupture zone influences the mean slip in ways that the above relationships do not predict . Thus, in this section we calculate the maximum slip that can occur on a 6 degree dipping thrust fault (an average dip for the Himalayan detachment) terminating 4 km below the Earth's surface for various rupture areas and aspect-ratios. Magnitude and mean slip are calculated for ruptures with a broad range of lengths and widths, and these are then compared to the worldwide rupture-are/moment magnitudes to estimate an appropriate failure strain for the Himalaya.

The elastic models used to investigate slip as a function of rupture area consist of 6 degree northward-dipping rectangular faults (frictionless dislocations) embedded in an elastic half space subjected initially to a north-south strain of 100 microstrain. The failure strain chosen, though reasonable, is quite arbitrary, and calculated values scale linearly with failure strain. Thus for a failure strain of 200 μstrain the coseismic slip in the model will be double those shown in Table 1. We later show that the few slip data we have suggest that a failure strain of 200-300 microstrain may be appropriate for Himalayan events. The dislocation area in each model is divided into 49 contiguous patches (7 each along-strike and down-dip) to permit variable slip to occur on a rupture surface pinned at its sides and at its leading and trailing edges (Fig. 3). Smaller numbers of patches tend to estimate poorly the reduction of slip near the edges of the rupture zone. The shallowest edge of the dislocation in each case is at 4 km corresponding to the depth of the Indian Plate beneath the Siwalik Hills. The models underestimate the slip of real ruptures which presumably taper to low values of slip over a distributed region near their edges (cf.. Cowie and Scholz 1992). These effects are assumed second-order corrections to the general relation explored here and are therefore neglected. The computations use a 3-D boundary element code (Crouch and Starfield, 1983; Gomberg and Ellis 1994) to calculate the amount of down-dip slip on each patch needed to minimize the stress in the medium surrounding the patch. The mean slip in Table 1 is calculated by averaging the slip calculated for each patch across the fault plane. Maximum slip, of course, occurs on the central patch. Calculations were undertaken for areas measuring as little as 25 km by 25 km to areas as large as 800 km by 200 km corresponding to moderate earthquakes and great thrust earthquakes respectively. Numerical values of maximum and mean slip are calculated for a homogeneous elastic medium with a Poisson's Ratio of 0.25 and a Young's Modulus of 7×10^{10} Nm^{-2} for a range of rupture areas in Table 1. In Table 2 these results estimated for a failure strain of 200 μstrain are converted to Magnitude, Mw using the relation $Mw=2/3(\log Mo)-10.7$ (Kanamori) where $Mo=\mu*slip*L*W$ and $\mu=3.3\times10^{10}$ N/m^2.

Table 1 illustrates the importance of rupture area and aspect ratio in facilitating intraplate slip. For each doubling in the length of the side of an equidimensional rupture mean slip increases by more than a factor of 2. Elongation of a ruptures beyond an aspect ratio of 2 is inefficient at increasing slip. It is evident that 2.3 times as many 50 km x 50 km events must occur on each patch to release the same amount of slip as one event on a 100 km x100 km rupture, hence to fill the single larger rupture requires more than 9 times as many smaller events. Similarly, more than 80 times as many earthquakes on 25 km x 25 km ruptures (mean slip =0.30 m, maximum slip 0.42 m) would need to occur to release the same slip as a single 100 km x 100 km rupture.

From the above geometrical property of a shallow rupture, and accepting the assumption that failure occurs for all rupture areas at similar failure strains, we confirm analytically the well-known result that small earthquakes ($M<7$) are inefficient at absorbing intraplate slip. The approximate magnitudes for earthquakes associated with rupture areas shown in Table 1 are calculated in Table 2 for a failure strain of 200 μstrain. If we assume that an M=7 event (a major earthquake) is associated with rupture dimensions of 50 km x 25 km, and that an M=8.5 event (a great earthquake) is associated with rupture dimensions of the order of 200 km x 150 km we should need to have 24 of major events to rupture the same dimensions as one great event. The mean slip in each of the major earthquakes (0.4 m) is 7.75 times less than that in the great earthquake (3.1 m), thus 186 major earthquakes are needed to replace one great earthquake. Thus to avoid a single great earthquake occurring say every 300 years (releasing 6 m of accumulated slip at a plate convergence rate of 20 mm/yr by a rupture occurring at a failure strain of 200 μstrain) we should need to have a major earthquake within the rupture zone of the equivalent great earthquake at a rate of approximately one per one or two years and the earthquakes would need to rupture repeatedly the same patches of each rupture zones many (≈8) times. The occurrence of major earthquakes (M≤7.5) in western Nepal and Kumaun Province is perhaps 4 per century and there is no evidence for repeated moderate or major events, which means that those that have occurred have done little to diminish the potential for a future great earthquake. Thus unless creep occurs (see following section), a great earthquake is inevitable.

From Table 1 it is evident that coseismic slip continues to grow if the length or width of a fault increases, but that equidimensional ruptures permit the most slip for a given rupture area. One of the unknown parameters in the model is the strain at failure. The failure strain is not known for the Himalaya and is likely to vary with depth, but from the values in Table 1, and from the inferred rupture areas and slip of Himalayan events it is possible to estimate a range of possible values. Thus for an earthquake with a rupture area of 200±100 km along strike, and 100±50 km down dip, a mean slip of 5±3 m can be obtained for a range of failure strains from 100-800 μstrain. It would appear that a failure strain of ≈250 μstrain is consistent with the mean 7 m slip inferred to have accompanied the Kangra earthquake (Gahalaut et al. 1994) if the down-dip width of this event equalled 150 km. The general relationship between rupture area and earthquake magnitude noted by Wyss is approximated for equidimensional ruptures associated with 200-400 ustrain at failure (Fig. 5), although the slope of the model results differ from unity, the slope appropriate for an infinite elastic medium, because of the asymmetry in the model as the rupture approaches the free surface.

Table 2 permits an estimate of the number of M 8 earthquakes that could occur to fill the central seismic gap. Assuming a maximum rupture width of 150 km, a maximum length of 800 km, and a failure strain of 250 μstrain, and assuming that all events fill the seismogenic width of 150 km, the following combinations of events are possible: one M=8.9 earthquake with 10 m mean slip, two M=8.7 earthquakes each with 9.3 m of mean slip, or 4 M=8.5 earthquakes each with a slip of 7.5 m.

CREEP WITHOUT EARTHQUAKES

Data from a levelling line between India and Tibet passing through Kathmandu indicate minor regions of uplift that are significantly above the noise level, one

Table 1 Mean slip and maximum slip (in parentheses) in meters for ruptures of varying along strike-length (columns across) and down-dip width (rows) in kilometers. Failure strain = 100 ustrain. For model geometry see text.

width\length	50	100	200	400	800
25	0.40 (0.51)	0.42 (0.53)	0.43 (0.53)	0.43 (0.53)	0.44 (0.53)
50	0.68 (0.97)	0.87 (1.18)	0.97 (1.21)	1.00 (1.21)	1.01 (1.21)
100	0.98 (1.42)	1.61 (2.35)	2.09 (2.84)	2.33 (2.92)	2.40 (2.92)
150	1.07 (1.52)	2.03 (3.04)	3.06 (4.44)	3.70 (4.89)	3.94 (4.92)
200	1.09 (1.58)	2.26 (3.37)	3.83 (5.74)	5.05 (7.00)	5.62 (7.16)

Table 2 Moment magnitudes (Mw) corresponding to slip shown in Table 1 for a failure strain of 200 μstrain. (Using Mo=μ*slip*L*W and Mw=2/3(log Mo)-10.7)

width\length	50 km	100 km	200 km	400 km	800 km
25 km	7.0	7.2	7.4	7.6	7.8
50 km	7.3	7.6	7.8	8.0	8.2
100 km	7.6	8.0	8.2	8.5	8.7
150 km	7.8	8.1	8.5	8.7	8.9
200 km	7.8	8.3	8.6	8.9	9.1

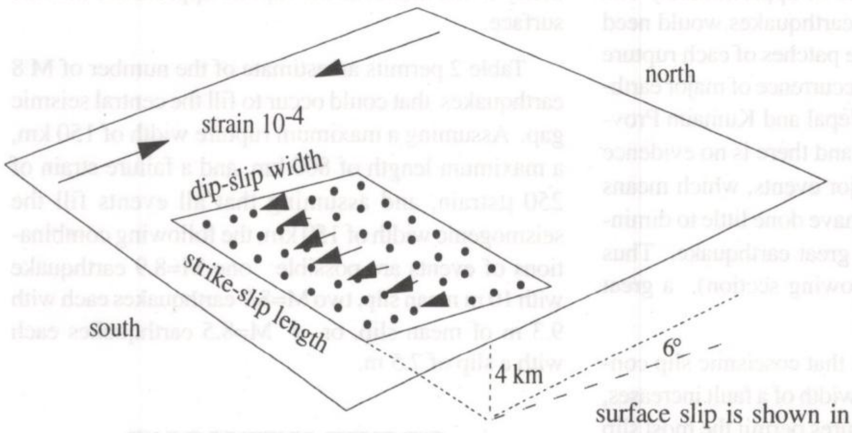

Fig. 3 Half space model to investigate growth of slip related to rupture area and aspect ratio. Dots show the centers of the 49 patches used to determine slip. A typical slip distribution is shown for the central row.

south of the Himalayan foothills and a broad region of uplift near the Tibetan border (Jackson and Bilham, 1994b). The rates of uplift are small (2-7 mm/year) but they have persisted for at least 15 years indicating that part of the ≈20 mm/yr of Himalayan shortening may be manifest as local uplift. No significant seismicity has occurred near the levelling line during the period of deformation so that we have little to guide elastic models of uplift caused by slip on subsurface faults, or even whether elastic processes are operative. The broad wavelength of the observed deformation indicates that its origin, if localized by fault processes must lie at least at depths of 4 km in the Terai and 8 km beneath the greater Himalaya. Alternative mechanisms that could be responsible for the uplift include plastic or elastic deformation of a shallow fold system, or pressure-solution processes resulting in local surface contraction. A simple geometry for subsurface slip is shown in Figure 5, and several other presented by Jackson and Bilham, 1994a.

GPS data obtained between 1991 and 1994 (Bürgmann et al. 1994; Gaur et al. 1994) indicate that convergence between Bangalore and Kathmandu is 0±6.5 mm/year, consistent with the low creep rate near the Siwalik range required by the levelling data. Current GPS networks (Anzidei 1994; Jackson and Bilham 1994b) are too sparse to detect the spatial inhomogeneity in uplift evident in the levelling data (Fig. 6).

A GEODETIC TEST FOR CREEP ALONG THE HIMALAYA

Nepalese levelling data and GPS data permit between 0% and 30% of the Himalayan convergence signal to be manifest as (harmless) creep. However, this

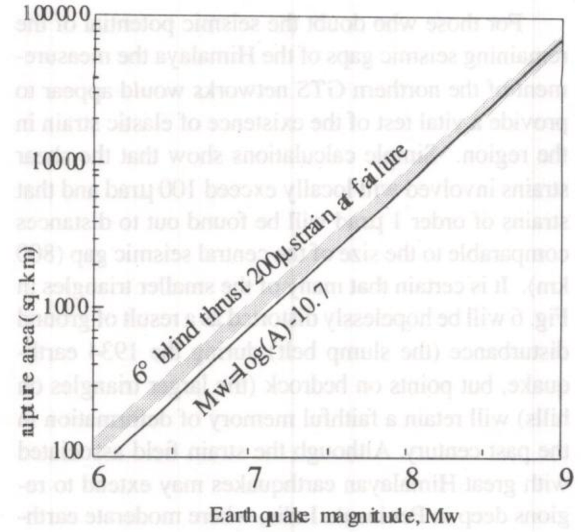

Fig. 4 Comparison between Mw calculated from the boundary element model for equidimensional ruptures (shaded) and empirical fit to worldwide data (Wyss, 1985). The upper bound of the shaded region corresponds to 200 μstrain at failure, the lower bound to 400 μstrain. Non-equidimensional ruptures are associated with smaller magnitudes for a given rupture area than the corresponding equidimensional rupture

leaves 70-100% of the ≈2 cm/year convergence signal to be absorbed plastically or elastically in the rocks of the Himalaya. If the storage is elastic it can be released occasionally during earthquakes, thus the missing 30% merely delays the time of a future great earthquake. Because the existence or not of stored elastic energy is crucial to seismic risk estimates, we would like to know more about its magnitude and distribution. Fortunately, a test of the presence or absence of stored elastic strain is possible, at least for that developed in the past 150 years.

The geodetic test to be described is also effective in assessing whether or not elastic energy associated with plate convergence in the past 150 years has been released by slow earthquakes (Sacks and Linde 1981; Beroza and Jordan 1990). These events have been recognized to occur in some seismic environments as events whose seismic moment based on slip and rupture area calculations, far exceeds the seismic moment determined from radiated seismic energy at periods of less than ≈100 s. Such events may be considered to be fast creep events with large amounts of aseismic slip accompanied by little or no seismic radiation.

The Great Trigonometrical Survey of India conducted between 1805 and 1870 resulted in the relative positions of many thousands of control points being established to approximately 10 ppm accuracy in distance and 1-3 ppm in angular position (Gaur et al. 1994). Fortunately these data and descriptions of the original monuments are well documented in the Journals of Asiatic Society of Bengal and official reports, and are freely available in many libraries throughout the world. Each great earthquake subsequent to the completion of the survey has deformed locally part of the Indian Plate, and any creep or plastic deformation that may have occurred within the Himalaya will have suppressed the development of elastic strain. A systematic remeasurement of the old survey points will thus reveal the location and form of elastic strain developed within northern India since the original measurements were undertaken. The scientific targets of these measurements are threefold: to measure the elastic strain associated with the 4 documented great Himalayan earthquakes, to measure the visco-elastic strain developed subsequent to these events, and to measure the development of strain associated with Indo-Asian convergence near suspected seismic gaps.

Although the original measurements took many years using theodolites, and many of the original survey points have been lost, it is relatively easy to measure the new relative locations of surviving points using GPS geodesy. GPS methods are 10-100 times more accurate and 10-100 times faster than the original surveys. The methodologies of GPS field work and processing are now well-established and an initial start has been made on these important measurements by several groups in India. Fortunately, the new measurements do not require the infrastructure of a large organization and university groups offer a cost effective alternative to the National Survey Departments of India and Nepal, who are typically disinterested in sub cm position accuracy

However, despite the simplicity and accuracy of GPS geodesy, none of the epicentral regions and surroundings of historic great earthquakes have been measured with GPS methods (Gaur et al. 1994). Nor have measurements been applied extensively to the Himalaya to provide a network to monitor coseismic changes associated with the next great earthquake. Were this event to occur in the next year we should know little more geodetically about the rupture parameters of this earthquake than we do about the 1897 earthquake almost 100 years ago.

Conducting a search for strain fields associated with the last several earthquakes will reveal the along-strike dimensions of these ruptures, and whether significant Himalayan slip has occurred since the original surveys. The signals include coseismic strain, slow earthquakes, post-seismic relaxation and interseismic creep since ≈1850. The remeasurements would not, however, illuminate the size of strain-release processes prior to the original surveys, except perhaps through the delayed effects of viscous relaxation. It is for this reason that a careful study of viscous relaxation associated with the 1897, 1905 and 1934 events would be of great value because this would provide an estimate for the time constant of relaxation in the region. This in turn would indicate whether the post-seismic relaxation effects from pre-18th century earthquakes remain accessible to measurement.

A sample of the density of control points of the Great Trigonometrical Survey (GTS) network near the western end of the Bihar earthquake is shown in Fig. 6. The great event of 1934 will have shifted many of these points by several meters but their systematic remeasurement has yet to be reported. If we assume no creep beneath the Himalaya in western Nepal, the general features of the coseismic field from the 1934 Bihar earthquake in this region will be a shear signal resulting from slip during the earthquake. Creep, if it is uniform along strike will have no effect on this signal, however, if it is locally significant it will tend to result in local strain perturbations in proportion to the scale and rate at which it has occurred. If aseismic creep in the past 150 years has caused the detachment beneath west Nepal to slip 4 m, the shear strain developed near the end of the Bihar rupture will be reduced. More complex combinations of aseismic and seismic slip, and visco-elastic relaxation can be developed to match the observed strain fields once they are measured.

For those who doubt the seismic potential of the remaining seismic gaps of the Himalaya the measurement of the northern GTS networks would appear to provide a vital test of the existence of elastic strain in the region. Simple calculations show that the shear strains involved will locally exceed 100 μrad and that strains of order 1 μrad will be found out to distances comparable to the size of the central seismic gap (800 km). It is certain that many of the smaller triangles in Fig. 6 will be hopelessly distorted as a result of ground disturbance (the slump belt) during the 1934 earthquake, but points on bedrock (the larger triangles on hills) will retain a faithful memory of deformation in the past century. Although the strain field associated with great Himalayan earthquakes may extend to regions deep in Peninsula India, where moderate earthquakes have recently occurred, our current ignorance about the seismic cycle in the Himalaya leaves a causal relationship conjectural.

THE EFFECTS OF THE NEXT GREAT EARTHQUAKE

There is a perceived reluctance among some seismic engineers in Nepal and northern India to admit a worst case possibility of a certain M>8 event in western Nepal and Kumaun Province. The size of historical earthquakes and the delaying effects of creep can be questioned. However, there is no doubt that great earthquakes are a permanent, if intermittent fixture, of some segments of the Himalaya, and by analogy, the entire arc. Thus the hazardous nature of the northern plains of India is beyond dispute and it is certain that an M≥8.5 earthquake, were it to occur in the next few decades, would constitute one of the worst disasters in history.

The reason for concern is that the population of the northern plains of India and Nepal is now 4-10 times greater than it was during the last great earthquakes in the region. Large cities in the region have quadrupled their population since 1950 and several are approaching super-city status (>2 million). Aggravating the problem is that construction methods in the cities (where much of this increased population now reside) is inadequate to resist the highest accelerations anticipated from a great earthquake (Arya, 1992;

Bilham, 1994). In the Assam earthquakes and in the Bihar earthquake are found reports of stones and buildings thrown into the air indicating vertical accelerations greater than 1 g. Typical design accelerations applied in the Himalaya are less than 0.5 g, and even for ongoing engineering projects (e.g. Tehri Dam), lower accelerations (0.3 g) are erroneously considered acceptable (Gaur 1980, 1994). The recent M 6.4 Northridge earthquake in Los Angeles confirms that accelerations can exceed 1 g even for quite small earthquakes. The application of such low design accelerations in a region where a M>8 earthquake is anticipated must be considered irresponsible.

As an example of the ambivalent acceptance of possible future seismicity consider Kathmandu, the rapidly growing capital of Nepal currently with a population exceeding 1 million. Seismic resistant building codes are applied to limit the height of construction in Kathmandu to about 15 m, yet reinforcing rods protrude skyward above current roof levels, presumably in the hope that pressure from the business community will lift seismic height restrictions in the city. Construction methods are weakly supervised by engineers in that most of the residential construction is undertaken by contractors where improved profits attend the use of inexpensive building materials: low quality bricks, weak cement and brittle steel. Lower stories of multistorey buildings are constructed to maximize window space for commerce, resulting in a soft lower level that is the first to fail during seismic shaking. Electrification in the old parts of Kathmandu where narrow streets and wooden houses remain, now constitute a major fire hazard that was significantly less during the 1833 and 1934 earthquakes. The absence of an adequate piped-water system means that fires may not be extinguished for days following an earthquake. Finally, although liquefaction of soil layers was not widespread in the Kathmandu valley in the 1934 earthquake, perhaps due to the absence of extensive sand layers in the lake sediments on which the city is built, it did occur along the banks of the

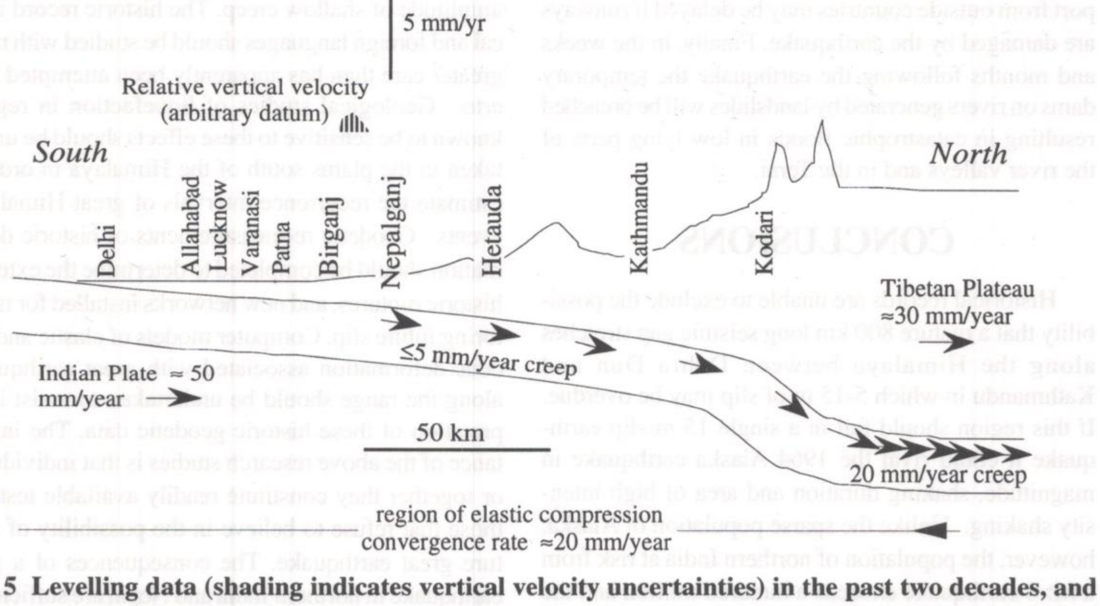

Fig. 5 Levelling data (shading indicates vertical velocity uncertainties) in the past two decades, and GPS data in the past three years indicate that creep rates beneath the Lesser Himalaya are probably less than 6 mm/year. Kathmandu Valley levelling data are omitted since they are contaminated by groundwater withdrawal. On of several possible geometries for subsurface slip is sketched. A bold line indicates a possible locked zone that may be associated with future rupture. Triangles represent GPS observation points with observed northward velocities.

rivers, and it is likely that bridges in the city will fail, in addition to extensive damage to approach roads and even the airport runway. Relief to the city will be hampered by the certain closure of all highways south and north by rockslides and avalanches. A consequence of the restricted transport mobility within the valley and into and out of the valley is that water supplies following the earthquake will be compromised and epidemic diseases may develop that will threaten earthquake survivors in subsequent months.

Given that Kathmandu is the centre for administration of the Nepal it follows that a catastrophic event in the city will be catastrophic for the entire country. Thus relief to stricken villages and towns outside Nepal may be delayed for months, partly because of widespread damage to roads, partly because of the collapse of central administrative infrastructures, and partly because the demands for assistance in the capital will outweigh the cries for assistance from outlying provinces. Judging from previous events 1833 and 1934, the approach roads and railways to Nepal will themselves be the subject of earthquake damage and relief from India will be delayed by the need to assist as a priority the inhabitants of its northern cities. Air support from outside countries may be delayed if runways are damaged by the earthquake. Finally, in the weeks and months following the earthquake the temporary dams on rivers generated by landslides will be breached resulting in catastrophic floods in low lying parts of the river valleys and in the Terai.

CONCLUSIONS

Historical records are unable to exclude the possibility that a mature 800 km long seismic gap stretches along the Himalaya between Dehra Dun and Kathmandu in which 5-15 m of slip may be overdue. If this region should fail in a single 15 m-slip earthquake it could rival the 1964 Alaska earthquake in magnitude, shaking duration and area of high intensity shaking. Unlike the sparse population of Alaska, however, the population of northern India at risk from a M>8 earthquake exceeds a hundred million and the mortality and economic effects of an earthquake exceeding M=8 affecting northern India and Nepal would be unprecedented.

Several factors can be invoked to reduce the inferred size and imminence of a great earthquake affecting W. Nepal and the Kumaun Province of northern India. The region can be broken into 2 or more subregions that can fail independently in as many as four M≥8 events, the region could be deforming aseismically, or a great earthquake may have occurred shortly before the 18th century and be as yet undiscovered in the historic record, hence delaying its future occurrence by many hundred years. Some of these possibilities appear unlikely. Aseismic creep near Kathmandu appears insufficient to prevent the accumulation of displacements from plate convergence although we have no data from points elsewhere along the central seismic gap.

Measurement programs can be envisaged that would provide improved and missing data to resolve some of these uncertainties. For example, GPS measurements of the northern 200 km of the Great Trigonometrical survey of India would enable us to assess the developing strain field associated with future rupture. Additional measurements between the Lesser Himalaya and the northern exposure of the Indian craton would more precisely define the distribution and amplitude of shallow creep. The historic record in local and foreign languages should be studied with much greater care than has apparently been attempted hitherto. Geological studies of liquefaction in regions known to be sensitive to these effects should be undertaken in the plains south of the Himalaya in order to estimate the recurrence intervals of great Himalayan events. Geodetic re-measurements of historic deformation should be completed to determine the extent of historic ruptures, and new networks installed for monitoring future slip. Computer models of elastic and viscous deformation associated with great earthquakes along the range should be undertaken to assist interpretation of these historic geodetic data. The importance of the above research studies is that individually or together they constitute readily available tests for those that refuse to believe in the possibility of a future great earthquake. The consequences of a great earthquake in northern India and Nepal are sufficiently catastrophic for there to be little place for indifference to these studies.

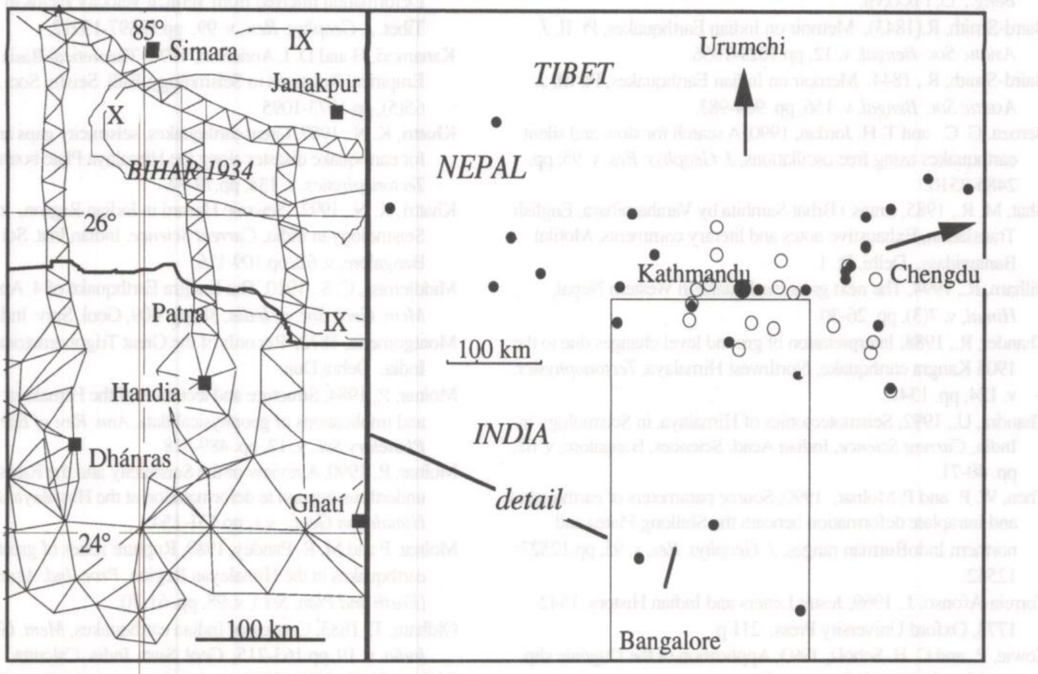

Fig. 6 Triangulation control points described by Montgomerie (1872) and GPS points measured in 1992 (named). Triangles indicate astrogeodetic points that have presumably been rafted ≈5 m north since their first measurement. Intensity ≥IX contours are shown for the Bihar earthquake from Dunn et al., 1939. Position changes since the 19th century survey have not yet been determined. (Right) GPS measurements in from Anzidei (circles),1994), and Jackson and Bilham, 1994 (dots). Long-baseline GPS links arrowed.

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