Future Mw>8 earthquakes in the Himalaya: implications from the 26 Dec 2004 Mw=9.0 earthquake on India’s eastern plate margin

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Abstract

The inventory of historical Himalayan earthquakes has grown substantially in the past decade. Some well-known earthquakes have been downgraded in magnitude, or their locations shifted, leading to the conclusion that only 30% of the Himalaya have slipped in the past three centuries. Newly discovered earthquakes occurring in the 10th to 16th centuries may have been much larger than recent events; some of these resulted in ruptures of the frontal thrusts of the Himalaya that did not accompany earthquakes of the past two centuries.

The following observations suggest that the Kangra region, hitherto considered a region relatively safe, cannot be excluded from hosting an imminent major earthquake:

1. The Mw=7.8 1905 Kangra earthquake with a slip of probably less than 4 m and a rupture area of approximately 100x55 km² incompletely released the 9 m of cumulative plate boundary convergence inferred to have developed since c. 1400, when a great frontal thrust earthquake ruptured the western Himalaya nearby.

2. The 1833 Mw7.7 and 1934 Nepal Mw8.2 earthquakes provide a precedent for contiguous and/or overlapping Himalayan rupture, after an interval of only 101 years.

3. The 2004 Sumatra/Nicobar/Andaman earthquake indicates that great ruptures can re-rupture through or past the rupture zones of relatively recent major plate boundary earthquakes.

Thus, the Kangra region, like other parts of the Himalaya, must now be considered vulnerable to a future large earthquake, despite having experienced one 100 years ago.

This reasoning, extended across the Himalaya from the eastern Indian plate boundary in Myanmar to the western plate boundary through Pakistan, Afghanistan, and Baluchistan, reveals a dozen examples of regions that could experience a future Mw>8 earthquake. Potentially the most dangerous of these is the so-called Central Himalayan Gap whose rupture in 1505 may have occurred as a 600-km-long rupture, similar to the tsunamigenic initial phase of the 2004 Sumatra earthquake. Its re-rupture would be catastrophic. The recent Mw=9 Sumatra/Andaman earthquake suggests that we would not be serving society well by viewing seismic risk too conservatively.
Introduction

It is fitting that one hundred years after the most devastating of India's Himalayan earthquakes, the 4 April 1905 Mw=7.8 Kangra earthquake, the seismological community should review progress in understanding earthquakes in the past century, and the perceptions of the potential for future damaging earthquakes in the Himalaya. This review is particularly relevant, coming as it does a few months after the 26 December 2004 Mw=9 earthquake that ruptured approximately half of India's eastern plate boundary, from northern Sumatra, through the Nicobar Islands, to the northernmost islets of the Andamans.

Despite a significant difference in their magnitudes, the Kangra 1905 and Sumatra/Andaman 2004 earthquakes have much in common socially and scientifically. They both took society by surprise, rendering hundreds of thousands homeless, and tens of thousands dead, accompanied by massive local economic losses. The severity and impact of each earthquake was not anticipated by the scientific community, despite the occurrence of a recent severe earthquake that should have alerted them to the potential consequences of a future event. (The Kangra earthquake followed the mid-plate 1897 Mw=8 Shillong earthquake by seven years; the Sumatra/Andaman earthquake followed the M=7.8 Bhuj mid-plate earthquake by 3 years). Finally, in neither location was there any precedent for an earthquake of such severity in India's history.

This threefold comparison is worrisome because seismologists, geologists, tectonophysicists and earthquake engineers have learned much in the intervening century about the earthquake process. Instruments, computational abilities and manpower focused on seismological research have increased enormously. We should not have been surprised by the location and size of the 2004 earthquake, and we should not have been surprised by the size of the tsunami, something that a competent graduate student could have estimated within minutes by making reasonable assumptions. Why was no attempt made by scientists to consider the consequences of slip on all parts of India's plate boundary, to consider worst case scenarios, or to attempt to communicate with political leadership their understanding of potential future earthquake related disasters?
Answers to these questions are outside the scope of this communication, but perhaps they will be considered during the planned conference. Clearly the scientific community is not indifferent to future seismic risk, for that is the reason that it justifies, at least partially, its activities. However, there is often a gulf between what a scientist knows may be possible and what a scientist believes should be done with this information.

Perhaps the most important issue now faced by seismologists is the realization that future great earthquakes in the Himalaya could have a much greater impact on people than the recent tsunami. The population of the Ganga basin is larger than at any time in history, and a future earthquake could equal the 2004 event in magnitude, as we explain in this article. What should be our response to this knowledge? A first hurdle is to achieve a consensus amongst the scientific community on the inevitability of future great Himalayan earthquakes. A second might be to accept that whatever we may dispute concerning the timing, frequency, or severity of these future earthquakes, our findings all point to the need strengthen dwellings in epicentral regions. A third might be the realization that prevention of damage may in fact be less expensive than the enormous cost of reconstruction following these inevitable future earthquakes.

The Kangra earthquake D not a great earthquake.

A great earthquake is defined to be one where Mw³8. For more than 90 years the Kangra earthquake of 5 April 1905 was mistakenly thought to be a great earthquake. This misinterpretation was due largely to Charles Richter rounding up Beno Gutenberg's handwritten magnitude-calculation (M=7.8) to the nearest integer, and partly due to the area of high-intensity shaking (Middlemiss et al., 1910) that extended almost 300 km along the arc, which suggested an earthquake with a M>8 magnitude. The magnitude of the Kangra earthquake is believed now to be Ms=7.8 (Ambraseys and Bilham, 1998; Ambraseys, 2000, Ambraseys & Douglas, 2004).

The combination of an erroneously high magnitude and a large Rossi-Forel intensity VIII area initially favored the notion that 300 km of the Himalayan plate boundary had slipped in a great earthquake, rendering this segment of the Himalaya an unlikely setting for a imminent future great earthquake (Seeber and Armbruster, 1981). However, the downward revised magnitude suggests that further rupture may yet occur in this region. In reducing the magnitude of the earthquake from Ms=8 to Ms=7.8, (a fairly modest decrement typically within the uncertainties in magnitude determination), either the area of the rupture, or the amount of slip must be halved from inferred values. Either the rupture did not span width of the Himalaya, the rupture length was shorter than 300 km, or it slipped less than hitherto thought, or a combination of these. As a result of this seemingly minor error, the conclusions of numerous oft-cited articles require revision, and the motivation of others can be shown to be without foundation.

Numerous studies in the past two decades report attempts to constrain slip at the supposed eastern end of the rupture, based on the availability of leveling data that appear to show significant (15 cm) coseismic uplift at Dehra Dun. The data were acquired immediately after the earthquake and were compared with data obtained one year before the earthquake between Dehra Dun and Mousoorie, and 25 years before the earthquake between Dehra Dun and Saharanpur (Longe, 1907; Burrard, 1906, 1909, 1910a,b&c; Walker 1863). The starting premises in these analyses was that the data were error free and that the Kangra rupture had approached, or passed beyond, Dehra Dun.
A critical review of the raw leveling data show that they contain incontrovertible correlations between height-change and elevation that render them most untrustworthy (Bilham, 2001). The correlations appear to be caused by unsuspected systematic errors related to rod-errors, and/or line-slope refraction errors. Previous investigations had noticed some of this correlation (DeGraaff Huner, 1910, Angus-Leppan, 1984; Chander 1988; 1989, Gahalaut and Chander, 1988) but had not noted the remarkable coincidence that the point that rose highest in the 1905 earthquake was the origin for all local surveys, located at the headquarters of the Survey of India, Dehra Dun. Nor had these investigators noted that height changes decreased almost monotonically with distance from this point, or that the Survey of India had conducted a measurement of horizontal angles in the Dehra Dun region and found no angular changes following the earthquake (Burrard, 1906; Eccles, 1907, 1908). Once systematic vertical errors in the leveling data are taken into account, no significant vertical deformation remains.

The absence of geodetic confirmation for a rupture in the Dehra Dun region, however, conflicts with the curiously high intensities reported by Middlemiss (1910) in that region. An apparent dip in intensities between the two extremes, however, suggested that slip in the rupture may have been small in the region between Dehra Dun and Kangra, and several studies questioned, and confirmed, the reality of these low intervening intensities (Seeber and Armbruster, 1981; Molnar, 1987). A re-evaluation of felt intensities by Ambraseys and Douglas (2004) using the MSK intensity scale confirmed that although Middlemiss' Rossi-Forel contours were 1 to 1.5 intensity units too large near the epicenter, a region of high intensities remained near Dehra Dun with intensities falling as low as MSK V in the region between Dehra Dun and Kangra.

The mystery of the anomalously high intensities near Dehra Dun in 1905 was resolved by predicting shaking intensities generated by an inferred rupture near Kangra (see next section) and subtracting these intensities from newly calibrated MSK intensities (Hough et al, 2005a). The residual intensities revealed, among other things, a broad region of high intensities that were not confined to the Ganga plain but were partially distributed in the Himalayan foothills near and SE of Dehra Dun. The region of anomalous intensities were interpreted as a triggered M>7 earthquake, probably at 30-40 km depth in the Indian plate. The Udaypur 1988 earthquake is an example of the type of deep earthquake that may have been triggered by the Kangra earthquake. Deep earthquakes near the Himalayan front are related to flexural bending of the Indian plate.

Previous investigators had speculated that the Dehra Dun 1905 intensity anomaly was caused by a triggered earthquake (Chander, 1988), but independent support appeared unlikely to be forthcoming. A careful search through surviving European seismograms of the Kangra...
earthquake, however, confirmed seismic phases in the coda of the primary shock that are likely to have originated from this triggered earthquake (Hough et al, 2005a,b).

**Fig. 2** Geodetic GTS control points (Æ) and newly-evaluated MSK Intensities (Ambraseys & Douglas, 2004). Arrows are representative 1±1 mm/yr GPS convergence vectors from Banerjee and Byrgmann (2002). GPS measurements in 2001 (Wallace et al, 2005) provide constraints on the slip, and SE and NW extent of the 1905 rupture (shaded). Its other parameters are not well constrained but approximate the isoseismal contour enclosing MSK VIII. Its NE margin corresponds to the inferred locking line (dashed) that follows the 3.5 km elevation contour (Avouac, 2003), and microseismicity that marks the transition between episodic seismicity to creep of the Indian plate beneath Tibet. Its SW margin follows the strike of the Jawalmucki thrust. Black circles M>5 earthquakes. Dotted line links investigative trenches (open circles) that have sampled the c. 1400AD rupture. The length of the rupture extends from 76.7°E and 79.7°E, an arc distance >400 km (Kumar et al, 2001;2004), that includes the 1803 rupture (Ambraseys and Douglas, 2004).

**Geodetic data from the Kangra region 1846-2001**

The earliest of the several scientific misjudgments associated with the Kangra earthquake was inadvertently introduced by Surveyor General Sir Sydney Burrard, who, following his discovery that no deformation had occurred near Dehra Dun during the earthquake, concluded that there was consequently no cartographic value to measuring trigonometrical points near the Kangra epicenter (Burrard, 1906). This decision was made despite his discovery of >3 m displacements in the epicentral region of the 1897 Shillong earthquake only 7 years previously. Had he authorized a Kangra re-survey he may well have discovered horizontal displacements exceeding 4 m within the primary and secondary triangulation networks then in place above the Kangra rupture zone, and this in turn would have changed our understanding of this important (if not quite "great") earthquake.

As a result of Burrard's decision, trigonometrical points near Kangra were never re-measured by the Survey of India, or at least the results of their re-measurement have never been reported or published. Almost certainly the points were not measured before mid-century Independence, but it is equally certain that the points have been carefully maintained by the Survey of India and used in local surveys, for many of them were found intact or recently repaired. Some crucial primary points have been lost, and data from the secondary triangulation north of the primary network have been unavailable for scientific study. Even now we could learn much concerning the mechanism of the Kangra earthquake were these data made available.

To test this assertion, a subset of these primary triangulation points in the Kangra region was selected for GPS re-occupation in a search for deformation attributable to the Kangra earthquake. The observed relative displacements in the Kangra region permit us to exclude the possibility that slip in the Kangra earthquake exceeded 7m and that its rupture zone did not exceed 150 km (Wallace et al, 2005). The preferred rupture width (100 km) and down-dip width (55 km) requires slip of Å4 m on a rupture terminating in the subsurface near the Jawalmucki thrust. The constraints are not strong, but they confirm that rupture did not extend to the frontal thrusts of the Himalaya, a conclusion consistent with the findings of geologists in 1905, who found no evidence for surface rupture.

The 150-year interval between triangulation and GPS remeasurement is unsatisfactory for providing a unique constraint of the Kangra rupture parameters since it includes a substantial period of interseismic deformation. However, the cumulative constraint on coseismic slip, afterslip and interseismic strain at these longitudes is important for estimating the future seismic potential of the region. For example, we can be certain that no significant interseismic creep has occurred in the foothills SW of Kangra in the past 150 years; it is probable that all slip on the foothill faults occurs during earthquakes.
Seismic deficit in the Himalaya.

Figure 3 illustrates all known earthquakes along the Himalayan arc between 1200 and the present from several sources. The rupture dimensions and locations of most of these earthquakes are estimated from Ambraseys and Douglas (2004) who derive an empirical relationship between Ms and seismic moment $M_o$ for northern India and provide citations to source materials.

$$\log M_o=16.0+1.5M_s \quad (M_o \text{ in units of dyne cm}=10^{-7} \text{ Nm}) \quad [1]$$

from which they calculate $M_w=2/3\log M_o -10.63$ (Hanks and Kanamori, 1994).

The northerly limit to rupture is selected to be the transition from locked to stable sliding of the Indian plate characterised by seismicity, uplift and a maximum in the geodetic convergence rate. Knowing $M_o$ and the rupture width of the rupture provides an estimate of the rupture length assuming typical slip vs. length scaling (Wells and Coppersmith, 1994), or for long ruptures from intensity data directly. Locations are inferred from regions of maximum damage (Intensity>VIII) and from instrumental determinations of epicenter.

![Figure 3 Time distance graph of Himalayan ruptures vs. time. The location and date constraints for an inferred earthquake in 1400 (7-26m of slip) between Kumaon toward Dehra Dun are indicated by 2 sigma age ranges (Kumar et al., 2004. Inferred large ruptures are enclosed. There is evidence for at least one large rupture c.1200 AD in eastern Nepal (Rockwell, personal communication, 2002) which may correspond to a prolonged mainshock-aftershock sequence in 1255 recorded in Kathmandu. The 1200 and 1400 ruptures resulted in >8 m of slip on the frontal faults of the Himalaya.](image)

The largest precisely dated historical rupture occurred in the central Himalayan Gap (Khatttri, 1987) in June 1505, a month after a large earthquake in NE Afghanistan, and 50 years before a major earthquake in Kashmir (Ambraseys and Jackson, 2000). The 400-500 km long inferred rupture associated with the 1505 earthquake was assigned from intensity data to have a magnitude of 8.2 (Ambraseys and Douglas, 1505); however, its rupture, according to scaling laws, may have been larger. The c.1400 (Wesnowsky et al., 1999; Kumar et al., 2001) and c.1200 earthquakes (eastern Nepal) known from trench investigations of the Himalayan frontal faults may also have been 8.2<$M_w<$8.7 earthquakes, larger than either the 1905 Kangra or the Bihar/Nepal 1934 ruptures.

One important conclusion derived from this evolving time-space diagram of Himalayan earthquakes is that nowhere, with the possible exception of the Kumaon region, do we see the repeat of a great earthquake in Himalayan history. This suggests that the recurrence interval for great Himalayan earthquakes is possibly 500-900 years. Given a geodetic convergence rate in the Himalaya of 14-19 mm/year, this implies that when such earthquakes occur they release at least 8 m and possibly as much as 16 m of slip on the
frontal faults. That none of the earthquakes of the past two centuries have produced slip on the frontal faults suggests that they may have been abnormally small events.

Figure 3b. Symbols are MSK intensity VIII or greater reports data for recent earthquakes (Ambraseys and Douglas, 2004), and possible locations for the 1505 and 1555 earthquakes based on Ambraseys and Jackson, (2001). Although intensity data can be invoked to justify the 500 km length of the 1505 rupture, the data from 1555 are limited to the Kashmir valley, and the only evidence of its possible magnitude comes from the numerous aftershocks reported in historical sources. The double arrow shows the along arc coverage of five trenches that show evidence for rupture circa 1400 (Kumar et al., 2004) The 1803 earthquake could have ruptured a longer length of the arc toward Kangra, but except for the possible rupture in 1555 no historical, or geological data yet constrains earthquakes to the west. Excavations of the Taxila archaeological site near Islamabad suggest that destructive earthquakes occurred during the period of its occupation.

A significant finding (Figure 3b) is that the western 1200 km of the Himalaya appears to have slipped between 1400 and 1555. A gap remains between the Kangra epicenter and Kashmir that may have been filled by the 1555 Kashmir earthquake but data for this event are limited in their spatial coverage (Ambraseys and Jackson, 2001). The length of the 1400 rupture is known from five sites and abuts, or slightly overlaps, the inferred 1505 rupture. The M=8.2 1803 earthquake is located near the intersection of these two earthquakes and appears to have re-ruptured the eastern 150 km of the 1400 rupture, If so this represents a 400 year return period for MÄ8 earthquakes here.

Of interest for characterising future slip in the Himalaya are the 1833 (Mw=7.7) and 1934 (Mw=8.1) earthquakes that occurred in Nepal. These earthquakes were either contiguous or overlapping events separated by a century, and provide a pattern that must be considered in evaluating seismic hazards in the Kangra region. The 1833 earthquake consisted of three distinct shocks within 5 hours (Bilham, 1995), and the location of these are not well constrained. Intensities suggest that the largest of these events occurred in the northern part of the Himalaya and, like neither of the Kangra earthquakes (two earthquakes in 15 minutes), did not rupture to the southern foothills. If the 1833 Nepal earthquake is analogous to the 1905 Mw=7.8 Kangra earthquake it is conceivable that a larger earthquake could occur in or near the Kangra region at any time.

**Slip deficit in the Himalaya**

The convergence rate across the Himalaya has been reported by several investigators using GPS methods. The rate was initially reported as 18-20 mm/year (Bilham et al., 1977) from 5 years of data, consistent with geological rates of 20±3 mm/year inferred from the deformation near the frontal thrusts of the central Himalaya (Lave and Avouac, 2000). Subsequently Jouanne et al., (1999) and Wang et al., (2001) reported rates of 16-18 mm/year across the central Himalaya. and although rates as low as 14±1 mm/year are reported from the west by Banerjee and BYrgmann, (2001), this low rate conflicts with the 18.8±3 mm/year rate published by Jade et al., (2004) from approximately the same region. One reason for the scatter in the convergence rates may be the paucity of regularly observed GPS sites in southern Tibet.

Thus although the rate may be as low as 14 mm/year the average rate appears to be at least 16 mm/year and possibly close to the 20 mm/year required by geological data. This slip is eventually manifest as seismic or aseismic slip of the basal faults beneath the Himalaya. Geodetic data suggests that aseismic slip at present is negligible; hence the slip must occur seismically.
A measure of seismic slip along an entire plate boundary can be obtained by summing the slip that occurs in every earthquake and by dividing this sum by the total time over which the summation was taken (Brune, 1968). Slip in an earthquake can be calculated when its seismic moment is known.

\[ M_o = \mu \cdot \text{slip} \cdot L \cdot W \] \hspace{1cm} [2]

For the entire Himalayan plate boundary length \( L_H \), and width \( W_H \), slipping at velocity \( v_H \) mm/yr, the sum of the seismic moments of all the earthquakes within a given time \( t \) (in years) is

\[ \Sigma M_o = \mu \cdot v_H \cdot L_H \cdot W_H \cdot t \hspace{1cm} \text{dyne-cm} \] \hspace{1cm} [3]

from which the convergence velocity may be estimated.

\[ v = \frac{\Sigma M_o}{\mu \cdot L_H \cdot W_H \cdot t} \hspace{1cm} \text{cm/yr} \] \hspace{1cm} (for \( L \) and \( w \) in cm) \hspace{1cm} [4]

The area of the plate boundary is calculated directly from the separation of the smoothed location of the 3.5 km contour and the smoothed location of the 200 m contour along the Himalaya between the epicenter of the 1950 Assam and the Kunar 1842 earthquakes. The slip rate derived from [4] assumes that the duration of time for which earthquakes are available greatly exceeds the interval between repeating earthquakes on the plate boundary, i.e. the minimum condition is that the earthquake cycle is much shorter than the history of available earthquakes. For the Himalaya this minimum condition is not met; for only one of the great earthquakes in the past 500 years do we know of a preceding great earthquake with similar rupture location and even this event (in 1803) had a different inferred rupture area. Hence we are likely to underestimate the slip rate, but the amount by which we do this gives us an idea of the number of earthquakes that are either missing from the historical record or are yet to happen in the future.

Figure 4 illustrates a plot of the past 250 years of velocity vs. time estimated from [4]. Large earthquakes instantaneously raise the apparent Himalayan convergence rate; in the absence of (all) earthquakes, the apparent convergence rate decays to zero. To account for missing slip represented by the numerous small earthquakes not documented in the historical earthquake record we increase the numerical estimate by 30% (Ambraseys and Sharma, 1999). Despite this precaution, the convergence rate estimated from the cumulative seismic moment in the Himalaya (7 mm/year) falls far below the rates inferred from GPS measurements across the arc (≈18 mm/year). The missing slip is equivalent to four \( M=8.6 \) earthquakes (Bilham and Ambraseys, 2004).
The Sumatra/Andaman earthquake

The 26 December 2004 Sumatra/Andaman earthquake permitted 1200 km of the Indo/Andaman plate boundary to slip in a single rupture with a duration of approximately 9 minutes. Of interest to the present discussion is that it traversed, or bypassed, the 1847 (Hochstetter, 1866), 1881 and 1941 rupture zones with little apparent regard for the principles of seismic gap theory. Though the rupture zones of these previous $7.5 < M_w < 8$ earthquakes did not arrest the northward propagation from the mainshock, they appear to have slowed it. In the first 3 minutes the rupture propagated approximately 650 km at 2.5 km/s, generating the coherent wavefront of the damaging tsunami and high intensity shaking in the epicentral region. North of the Nicobar Islands it propagated a further 550 km northward more slowly, resulting in relatively low perceived intensities and a complex low amplitude tsunami.

The earthquake occurred on a plate boundary with oblique slip at approximately 14 mm/year. Focal mechanisms before the 2004 earthquake reveal that the oblique slip is partitioned into pure thrust faulting on the subduction zone and strike-slip faulting in a back arc region east of the epicenter. The mechanism of the mainshock was pure thrust faulting accompanied by aftershocks both in the subduction zone and in the back arc strike slip regime. The thrust faulting, as in the Himalaya, resulted in uplift near the frontal faults and subsidence above the down-dip termination of the rupture. The Andaman Nicobar archipelago was tilted down to the east during the earthquake: the Sentinel Islands and westernmost Andaman Islands are in the uplifted footwall, and the Nicobars in the part of the footwall associated with subsidence.

The 2004 rupture has several implications for Himalayan earthquakes. The length of the 2004 rupture is 60% of the arc length of the Himalaya. Could the Himalaya slip in a rupture this long, or longer? We have no precedent historically for such a rupture, but then, neither did we for the Andaman plate boundary prior to 2004.
A long Himalayan rupture may have to re-rupture segments of the arc that have already ruptured. Is it possible for this to occur in the Himalaya? Consider the following quantitative argument. Prior to the 2004 earthquake the largest of three historical earthquakes traversed by the 2004 rupture was the 1881 Mw=7.9 Car Nicobar earthquake (Ortiz and Bilham, 2002). The 125 interval between a Mw=7.9 and its subsequent re-rupture as part of a Mw=9 earthquake, means that the 1881 rupture zone could have accumulated a 1.4-1.75 m slip deficit because the Andaman plate converges with the Indian plate obliquely here at 14±3 mm/year (Paul et al., 2001). In 100 years the Kangra region has developed a similar slip deficit (1.4 m) with its measured convergence rate of 14 mm/year. Hence re-rupture of the Kangra region appears possible, and should it do so in a similar-sized rupture-zone (100 km x 55 km) it could now (2005) release sufficient slip to drive a Mw=7.5 earthquake. It could also, by analogy with the Andaman-Nicobar sequence, be part of a larger rupture.

Figure 5. Urban population and slip potential in the Himalaya, based on elapsed time since the last major earthquake in various sectors along the arc since 1400 and the GPS-derived convergence rate across the Himalaya. The height of each trapezoid is proportional to the current slip potential in meters, and the numbers refer to the potential size of Mw should the same segment length slip as is currently believed to have occurred in the last earthquake. The slip potential in the eastern Himalaya is tentative since the effects of the 1897 Shillong earthquake are uncertain and we know of no great historical earthquakes in Bhutan with the exception of a possible event in 1713 (Ambraseys and Jackson, 2003).

A revised slip potential map

In 2001 we estimated the present-day slip potential of the Himalaya by assuming that the currently observed convergence rate had prevailed for 200 years, and by calculating the accumulated slip that would be released at various points along the arc since the last earthquake at each of those points, should an earthquake occur there today (Bilham et al., 2001). The extension of the historical record to 1500, and geological evidence for surface rupture in a large earthquake in 1400 (Wesnousky et al 1999, Kumar et al, 2001) permits a revised estimate of this slip potential (Figure 5). Its accuracy depends on the following assumptions: that we know of all significant earthquakes since 1500, that present geodetic convergence rates have prevailed for the past 500 years, and that no slow earthquakes have released slip during or after large earthquakes.

In the 2001 analysis we made no attempt to estimate the along-strike rupture length of potential future ruptures. Despite the different along-arc lengths of segments shown in Figure 5, the segment estimates do not necessarily represent the segment size of future earthquakes. Each trapezoidal figure represents the slip developed since the previous known earthquake at that location. We have no way of knowing whether a future earthquake will rupture the same area. Using the slip and rupture area of each of these regions we can estimate the magnitude of an earthquake should it occur today using equation [2].
We know less about earthquakes in the eastern Himalaya than in the west, and it is possible that we have underestimated seismic slip potential there. The 1897 earthquake reduced stresses in the region, but only for a 120 km long segment of eastern Bhutan. We know with certainty of no large earthquakes in western Bhutan with the exception of the 1713 earthquake that damaged several monasteries. The along-strike extent of this earthquake is unknown (Ambraseys and Jackson, 2003).

The consequences of the western Himalaya slipping in its entirety between 1400 and 1555 is that a 1200 km length of the Himalaya has matured sufficiently to experience two or more M>>8 ruptures. The total length, and the presence of relatively modest earthquakes in the intervening 500 years, suggest that the western Himalaya may be in a stress state somewhat similar to the Andaman plate boundary prior to 2004. Although we have no historical examples of simultaneous rupture of contiguous segments of the Himalaya, we would, given the recent M=9 earthquake on India's Andaman boundary, be foolish to ignore the possibility that a similar great earthquake in the Himalaya.

Conclusions

The 1905 Kangra earthquake fell short of permitting the entire down-dip width of the Himalaya to slip near longitude 77¡E. This leads to the conclusion that an additional earthquake is required to permit slip on the main frontal faults there. Approximately 1.4 m of slip has developed since 1905 in the 100-km-long Kangra rupture zone so that re-rupture of the region could presently sustain a damaging earthquake with Mw=7.5.

A somewhat worse scenario can be envisaged that would permit re-rupture to accompany a contiguous or enveloping rupture to the NW or SE with a much larger magnitude. If we are missing no significant earthquakes in the historical record since 1400, this future earthquake could exceed Mw=8.6 with 9 m of slip. We have no historical insight to exclude an even larger earthquake of the sort that occurred in the Nicobar/Andaman region.

![Figure 6. A map of India showing M>4 earthquakes since 1960. The black bars indicate 200-600 km-long segments of the Indian plate boundary that have not slipped recently. The 2004 Sumatra -Andaman earthquake reminds us that eventually these boundaries must fail, and that we are remarkably ignorant presently concerning the timing and total rupture length of past ruptures in the region.](image)

The century for which we have instrumental seismic data provides few constraints in our estimation of the geometries of Himalayan ruptures. Dissappointingly, no precise geodetic constraint or aftershock study exists even for the largest earthquakes: 1905 (7.8), 1934 (8.2) and 1950 (8.5). Felt intensities and empirical estimates based largely on intensity data and instrumental magnitude provide our strongest constraints on rupture areas and locations, with resulting uncertainties of many tens of km. For earlier earthquakes we have only intensity data, with coverage that worsens for each century we step backwards in time. These historical data permit us to infer that great earthquakes in the Himalaya do not rupture the same point on the plate boundary more frequently than once every 400 years, and possibly much longer. That the past several centuries are not anomalous is supported by the observation that none of the past 200 years of earthquakes are associated with surface rupture, and where surface rupture has been identified in trench excavations of frontal faults, the slip in single events...
approaches or exceeds 10 m. Five hundred year renewal times must elapse between such large slip-events if geodetically observed convergence rates of 16-20 mm year have prevailed.

The present-day slip deficit in the Himalaya (Figure 4) suggests that central Himalayan populations in the past several centuries may have witnessed earthquakes that are atypically small. Earthquakes in 1400 and 1505 may be more typical of the long term behaviour of the plate boundary, each rupturing apparently at least 400 km, with inferred magnitudes similar to the 1950 Assam earthquake. Fault slip investigations in the Himalaya using geological trenches are currently sparse, and a high priority is to search the frontal faults of the Himalaya for repeated rupture and dateable liquefaction features, to learn more about the recurrence interval and along-arc length of previously undiscovered great earthquakes.

This article has focused on the Himalayan plate boundary and in particular on the seismic setting of the 1905 Kangra earthquake. India's other plate boundaries have not been discussed because less is known of their historical slip. North of the Andamans, through Myanmar to Assam, a thousand kilometers of India's eastern plate boundary awaits detailed study. In the west a huge slip deficit is apparently present on the 1000-km-long transform plate boundary. Apart from the Chaman earthquake of 1892 and the Mach/Quetta sequence of 1931-5, we know of no major earthquakes between Himalayan latitudes and Karachi (Ambraseys and Bilham, 2003). A large earthquake here would have limited moment release because the width (defined by the depth of transform microseismicity) of the plate boundary is a factor of five less than the Andaman plate boundary. Nevertheless, rupture of the entire boundary is calculated to have a moment release equivalent to a Mw=8.3 earthquake. The absence of recent historical earthquakes in Baluchistan is also cause for concern. Although it is possible that aseismic slip processes here may be absorb some fraction of plate boundary slip, the occurrence of the 1892 and 1935 earthquakes suggests that seismic slip prevails, and that we should expect ruptures with magnitudes in the range 7.5<Mw<8.

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