

Apparent Himalayan slip deficit from the summation of seismic moments for Himalayan earthquakes, 1500-2000

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Re-evaluated estimates of the magnitudes of Himalayan earthquakes since 1500 (1) permit a measure of the convergence rate between India and Tibet for the past five centuries. Averaged over the entire Himalaya the calculated rate (≈ 5 mm/yr) is less than one third of the convergence rate observed from GPS measurements in the past decade (18 mm/yr). The missing slip is equivalent to four $M_w > 8.5$ earthquakes, events that are unlikely to have escaped note in the historical written record. The absence of repeated rupture anywhere in the Himalaya permits several explanations for the missing slip, ranging from the extreme view that large earthquakes are in our future, to less hazardous interpretations, related to flaws in the historical data on Himalayan earthquakes.

India's collision with Asia has resulted in the flexure of the Indian sub-continent with a wavelength of approximately 670 km giving rise to flexural stresses responsible for many of the earthquakes of central India (2). The largest of India's earthquakes, however, occur on the northern boundary of the Indian plate where it descends beneath southern Tibet. We know of four Himalayan earthquakes (1505, 1803, 1934 and 1950) whose magnitudes have exceeded $M_w = 8$ (1,3) and numerous magnitude 7 earthquakes, yet for nowhere in the Himalaya have we observed a pattern of earthquakes that has repeated in historical time (4). The absence of a well-documented earthquake cycle anywhere along the Himalayan arc is a considerable impediment to quantifying seismic risk in the Himalaya. In this article we examine the energy released by known earthquakes in the past 500 years in an attempt to quantify what fraction of plate convergence has apparently been released by seismic slip.

The collision velocity between India and southern Tibet in the past decade observed by GPS is 16-18 mm/year (5, 6, 7, 8), a rate that is assumed to have been constant for many thousands of years. Although this is by no means certain, support for a near-constant rate of collision prevailing in at least the past several thousand years comes from geological observations of slip-rate of the frontal thrusts of the Himalaya that indicate convergence rates of 15-20 mm/yr (10-15). In view of the apparent identity between decadal geodetic convergence and several millennia of geological data, we assume that this convergence rate (≈ 1.8 m each century) currently accumulates in the Himalaya as elastic strain that is subsequently released as seismic slip in earthquakes, or as aseismic slip between earthquakes. The assumption is examined later in the article.

The re-evaluation of reported intensities for 20th century earthquakes for which instrumental magnitudes have been determined, and their comparison with the re-evaluated intensities of pre-instrumental earthquakes, has made possible a compilation of a moment-magnitude catalogue for historical earthquakes in northern India (Table 1) that is largely complete for $M_w > 7.8$ since 1501 (ref.1). In that study an empirical relation [1] is first derived to relate the surface-wave magnitude, M_s to observed MSK shaking, i , within an equivalent radius R_i surrounding an earthquake:

$$M_s = -0.297 + 0.65i + 0.0026 R_i + 1.65 R_i \quad [1]$$

and an empirical relation (2) between seismic-moment, M_0 , and M_s is derived for north Indian earthquakes greater than $M_s = 5.94$

$$\log M_0 = 16.0 + 1.5 M_s \quad [2]$$

from these equations, derived for earthquakes in the instrumental period, (ref 1) calculate the moment magnitudes for earthquakes in the pre-seismometer period for which intensity data exist. The seismic moment of twenty six Himalayan earthquakes are available, but for some earthquakes insufficient data exist to evaluate MSK shaking intensity, and these are absent from the catalogue (Table 1). Examples of suspected large earthquakes include a severe earthquake in Bhutan and parts of Assam in 1713, and isolated or unconfirmed reports of large earthquakes in Nepal in 1255, 1408 and 1668 (e.g. ref 16).

Seismic moment is the product of rupture area and slip.

$$M_0 = \mu * \text{slip} * L * W \quad \text{where } \mu = 3.3 * 10^{11} \text{ dyne cm}^{-2} \quad (3) \text{ Aki 1967}$$

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

$$\Sigma M_o = \mu * v_H * L_h * W_h * t \quad \text{dyne-cm} \quad [4]$$

from which the convergence velocity may be estimated (26).

$$v = \Sigma M_o / \mu L_h W_h t \quad \text{cm/yr (for L and w in cm)} \quad [5]$$

The slip rate derived from [5] 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 none of the great earthquakes in the past 500 years do we know of a preceding great earthquake with similar rupture location and area.

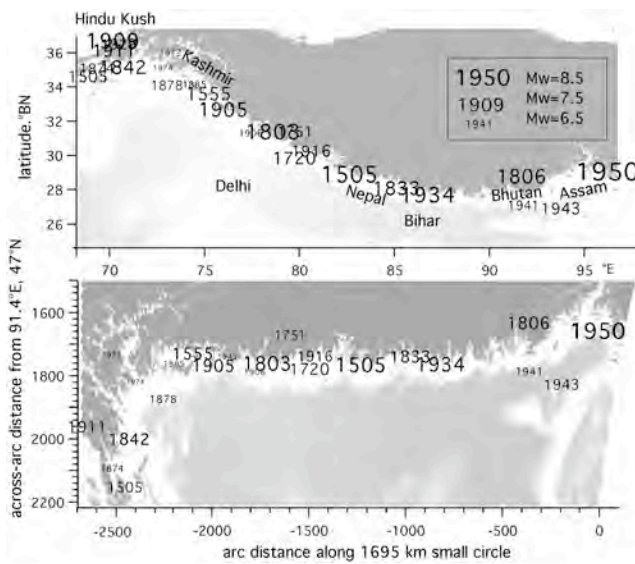


Fig.1 Locations of north Indian earthquakes in Cartesian coordinate view (upper figure), and in an arc-normal/arc-parallel view using a equal azimuth projection that “straightens” the 1695 km radius small circle of the Himalaya (refs. 2,18). Light shading is below 100m and dark shading above 3.5 km. The white region between these two regions along the arc is inferred to be the locked Himalayan plate boundary. The 1751 and 1806 earthquakes and those south of km+1820, and west of km-2300 are excluded in this study.

Hence the velocity we obtain from [5] will underestimate the true velocity. This velocity can be considered a “velocity deficit” absorbed either by an aseismic process in the form of geological deformation (folding, thickening and other forms of plastic deformation) or slow aseismic slip, or it may be recovered in the form of displacement delivered by a future earthquake driven by elastic strain. The instantaneous velocity so obtained provides a measure of the slip deficit, independent from estimates of slip deficit derived from the geodetic velocity and the time of the last earthquake, as has been achieved in earlier studies of Himalayan seismicity (17).

In figure 1 we show the locations of earthquakes in the Himalayan region. The lower panel shows the same earthquakes plotted as arc-normal distance from the center of the small circle that defines the Himalayan arc (18). Summations of seismic moment depend

on the assumed down-dip width of the plate boundary, W_H . The width of the locked plate boundary is inferred from the observation that microearthquakes in the northern Himalaya probably indicate the transition from locked- to stable- sliding of the Indian plate beneath southern Tibet (17). Avouac (15) makes the important observation that this belt of microearthquakes in Nepal follows the 3.5 km contour. The southern edge of the plate boundary is taken to be the Himalayan frontal thrusts, close to the 100 m contour. The distance between these two contours is approximately 80 km although it varies considerably along the arc (Figure 1).

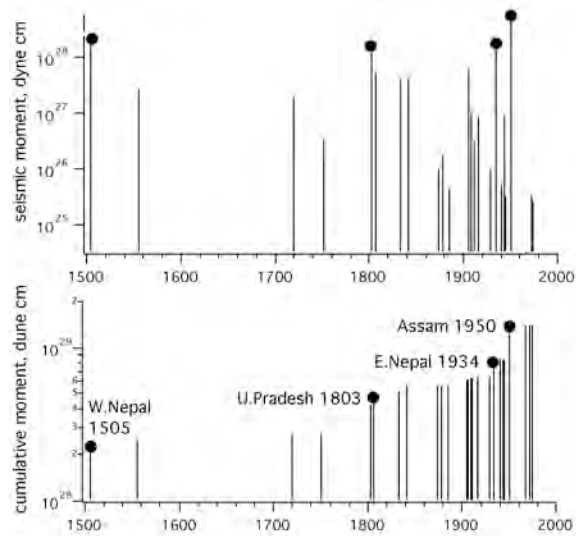


Fig.2 The release of seismic moment with time shows that we are probably missing numerous earthquakes in historical seismic record, especially in the 16th and 17th centuries. The large 1713 earthquake in Bhutan (ref.3), for example, cannot yet be assigned a magnitude. It is also clear that most of the moment release occurs during the largest earthquakes ($M > 8$ indicated by dark circles).

If we assume an along-arc length of 2200 km, and exclude those events that did not occur on the plate boundary (as defined in the lower panel of Figure 1), we obtain a cumulative moment release of 1.3×10^{29} dyne-cm, from which we determine from [5] a 500 year slip rate < 5 mm/yr, less than one third of the inferred convergence rate. It is usual to increase the seismic moment by 10-20% to account for small earthquakes not recorded in the historic record, but the resulting slip velocity remains less than 6 mm/year. To bring the seismic moment to that required by the geodetic slip rate requires the equivalent of four $8.2 < M_w < 8.6$ earthquakes. Despite the gaps in the data evident in Figure 2 it is unlikely that four large earthquakes would have escaped detection in the past 500 years.

The most obvious explanation for the discrepancy (assuming that no substantial earthquakes are missing in the 500 year record), is that 500 years is insufficient time to record a complete earthquake cycle in the Himalaya. Yet this conclusion brings with it the unwelcome inference that several $M_w > 8$ earthquakes are overdue.

If we divide the arc into three regions: the western 600 km, the central 1000 km and the eastern 600 km, we obtain slip rates of 2.5, 3.9 and 7.8 mm/yr respectively, confirming that most of the moment release occurs during the largest earthquakes, and again suggesting that large earthquakes are missing from the seismic record in the western and central segments of the Himalaya.

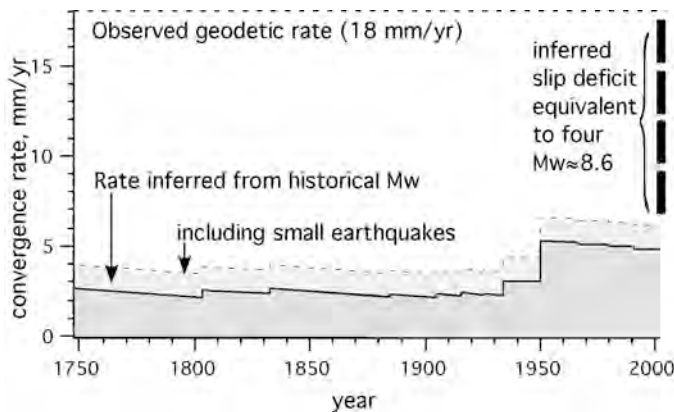


Figure 3. The slip rate derived from historical Himalayan earthquakes with inferred Mw amounts to less than one third the geodetic convergence rate (Table 1). It is unlikely that four Mw=8.6 earthquakes could have escaped notice in the historical record since 1500. Alternative explanations for the apparent slip deficit are examined in the text.

Alternatives to four overdue M>8 earthquakes

Though the case for overdue Mw>8 earthquakes is compelling, especially in those segments of the arc that have not experienced a great earthquake for many centuries, four explanations permit plate boundary slip to have occurred without causing widespread devastation. The first is that creep processes may prevail at the plate boundary. The second is that moderate earthquakes may release a substantial amount of plate boundary slip. Third, slow earthquakes may release large amounts of slip without radiating seismic energy. Fourth, it is possible that the magnitudes of Himalayan earthquakes are systematically underestimated by observed intensities.

Geodetic measurements indicate that creep on the decollement between the Himalaya and the Indian plate occurs only north of the Greater Himalaya, but detailed measurements of this process exist only in the Nepal Himalaya at present. Geodetic measurements suggest that during the interseismic period, the Siwalik, Lesser Himalaya, and central ranges are transported bodily northward, effectively locked to the Indian plate. However, two examples of creep have been described - one on the Nahan thrust in the Dehra Dun region (19), and the other associated with uplift recorded in the lesser Himalaya of Nepal (10). The second of these accounts for less than 3% of the convergence signal, since it appears to be driven by the strain field developed in the Greater Himalaya, rather than by creep propagating southward on the decollement.

Although seismic moment release on some plate boundaries can be significant (21),

the case for moderate earthquakes making a substantial contribution to moment release in the Himalaya is weak. The reason for this is that moderate earthquakes in the past century are confined largely to the transition zone between the locked and creeping Indian plate. A fundamental assumption in seismic moment summation calculations is that all the earthquakes considered in the summation occur on the plate boundary. These northerly earthquakes occur on out-of-sequence thrusts at higher levels in the Himalaya, and may indeed "short-circuit" the plate boundary. But in the long-run these earthquakes are too far north to contribute to slip on the plate boundary, where the secular geological rate is observed to equal the present-day geodetic rate. The slip derived from missing earthquakes is thus thought to contribute less than 20% of the convergence signal (dashed line in Figure 3). Some moderate earthquakes do occur in the southern Himalaya but these are near the base of the Indian plate (e.g Udaypur, 1988).

If slow earthquakes occur, or if a substantial component of an historic great earthquake is caused by slip that does not radiate seismic energy, this would result in the seismic-moment of historic earthquakes being underestimated. For example, a substantial slow component might effectively result in a $M_w=8.6$ earthquake being manifest as a $M_w=8.2$ earthquake in the historical catalog. Slow earthquakes have been recorded as down-dip components to great shallow ruptures in subduction zones, but not as slow components on the main seismic rupture (22,23,24).

Slow earthquakes imply reduced frictional sliding, and some investigators have suggested that gently-dipping ruptures may be accompanied by modes of failure that do not permit seismic radiation to escape into the body of the Earth. Brune (25) argues for low friction during southward propagation of Himalayan ruptures through a processes of ripple detachment of the fault surfaces. Avouac (15) argues that the decollement may have low friction as suggested by an electrical resistivity anomaly suggestive of high fluid pressures on the plate boundary. The recent ChiChi earthquake was associated with large slip on a shallow dipping fault.

The relationship between M_s and M_w established by Ambraseys and Douglas (1) is assumed to be linear for $M_w > 8.2$, however, only one earthquake larger than 8.2 has occurred in the instrumental catalogue (Assam 1950). It is possible that for large earthquakes that propagate along the arc for more than 300 km (either as single or multiple ruptures) the felt intensity does not increase in amplitude but is sensibly influenced by the closest part of the rupture area. This would have the effect of the M_s/M_w scale saturating at large M_w . The great 1505 earthquake in the central Himalaya may have been an earthquake whose M_w was underestimated in this way. According to

the intensities of the five extant accounts in India and Tibet the magnitude of this earthquake was $M_w=8.2$, yet the widespread reports of damage in southern Tibet and the southern Ganges plain suggests that its rupture area was large, probably filling the entire "central seismic gap". A rupture length of 600 km with a down-dip width of 70-90 km given normal scaling laws should be associated with 7-15 m of slip. This would result in a moment magnitude of around $8.6 < M_w < 8.8$. Thus, the 1505 earthquake could have released 8-16 times more slip than implied by its intensity-derived magnitude of $M_w=8.2$. Had the 1505 earthquake been $M_w=8.7$ it would have decreased the inferred slip deficit in Figure 3 to 10 mm/year. The M_w of other Himalayan earthquakes would thus need to be increased to bring the apparent release rate closer to the observed convergence rate.

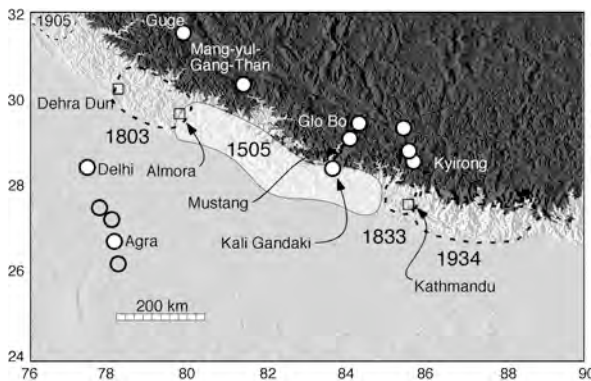


Fig. 4 A sketch of the abutting ruptures for four significant historical earthquakes in the central Himalaya. The 1833 event consisted of three principal shocks none of which may have occurred on the plate boundary. Intensities in the 1505 earthquake were recorded unambiguously at some sites (white circles) and with less certainty at others (open circles). The 1505 earthquake was probably a multiple rupture. The dark shading indicates >3500 m, the probably northern edge of Himalayan ruptures.

If a $M_w=8.6$ earthquake in the Himalaya radiates only as much energy as a $M_w=8.2$ earthquake, this is potentially a useful property of great Himalayan earthquakes. However, shaking from long ruptures, or multiple ruptures, is likely to increase the duration of shaking, causing damage to some structures that would otherwise stand, and increasing the severity of liquefaction in some lowland areas, since liquefaction effects are known to depend on shaking duration, in addition to intensity.

Conclusions

Quantitative estimates of the moment-magnitudes of numerous Himalayan earthquakes permit us to compare the observed geodetic convergence rate with that inferred from the release of seismic moment in the past 500 years. Earthquakes have apparently released less than one-third of the geodetic convergence, admitting several interpretations.

The simplest explanation is that we are missing four great earthquakes from the historic record. Alternatively, because we know of no repeating earthquake in the Himalaya we can be certain that the earthquake-cycle is longer than the 500 year record examined in this article, and that these (and other) $M > 8$ earthquakes will occur in the next few hundred years, both as repeats of historical ruptures, and as gap-filling earthquakes in intervening regions.

Several alternative explanations are possible: historical earthquakes may have escaped archival prior to or since 1500, historical earthquakes may have been underestimated in magnitude, and slow slip or aseismic creep may permit plate boundary slip without seismic radiation.

Given our ignorance concerning the recurrence interval for great Himalayan earthquakes, the reconciliation of the geodetic/geological convergence rate with that recorded by historic earthquakes should not be expected to be exact. We do not attempt in this article to revise seismic estimates for Himalayan seismic hazard, although we note that the "central Gap" is inferred to have developed 9 m of slip, comparable to the slip inferred to have occurred in 1505. We cannot exclude the possibility that an elapsed period of 500 years may represent all, or a substantial portion, of the earthquake cycle in the western Nepal and Kumaon. A longer recurrence interval would increase the amount of slip in the central gap to more than 9 m, raising the estimated M_w for a repeat of the 1505 earthquake to exceed $M_w = 8.7$ (> 9 m of slip on a 600 km x 80 km rupture).

Data suitable for characterizing the recurrence interval for Himalayan earthquakes must be considered a priority research target. Information on the recurrence interval may come from historical archival research, from the exhumation of Himalayan frontal faults, or from the search for simultaneous liquefaction features in the Ganges, Punjab and Brahmaputra plains. A record of shaking events extending back 2-3 millennia along the entire Himalaya arc would be of considerable value in estimating the probable timing and location of future earthquakes.

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Table 1 List of earthquakes in the Himalayan region from Ambraseys and Douglas, (2003). [* indicates magnitude adopted from other catalogues.] Moment and cumulative seismic moment are given in dyne-cm. The inferred slip rate is calculated in elapsed time starting in the year 1500, and assigning the cumulative seismic moment to the inferred area of the entire Himalayan plate boundary 2200 km x80 km. This in the absence of large earthquakes the cumulative slip velocity decreases with time.

event	Mw	Lat°N	Long°E	year	monthday	moment	cum moment	rate mm/yr
Lo Mustang	8.2	29.5	83	1505	Jun.	6 2.14E+28	2.14E+28	79.2
Srinagar	7.6	33.5	75.5	1555	Sep.	2.69E+27	2.41E+28	8.1
Uttarpradesh	7.5	30	80	1720	Jul.	15 1.91E+27	2.60E+28	2.2
Uttarpradesh	8.1	31.5	79	1803	Sep.	1 1.51E+28	4.11E+28	2.5
Nepal	7.7	27.7	85.7	1833	Aug.	26 3.80E+27	4.49E+28	2.5
Srinagar	6.4	34.1	74.6	1885	May	29 4.27E+25	4.50E+28	2.2
Kangra	7.8	33	76	1905	Apr.	4 6.03E+27	5.10E+28	2.3
Bashahr	6.4	31.5	77.5	1906	Feb.	27 5.13E+25	5.10E+28	2.3
Uttaranchal	7.3	29.9	80.5	1916	Aug.	28 8.32E+26	5.19E+28	2.3
Uttaranchal	6.5*	30.3	80	1926	Jul.	26 6.00E+25	5.19E+28	2.3
Nepal-Bihar	8.1	27.6	87.1	1934	Jan.	15 1.82E+28	7.01E+28	3.0
W. Nepal	7*	28.5	83.5	1936	May	7 1.00E+27	7.11E+28	3.0
Shillong	6.8	27	92	1941	Jan.	21 5.01E+25	7.12E+28	3.0
Uttaranchal	6.5*	30.3	80	1945	Jun	4 6.00E+25	7.12E+28	3.0
Chamba	6.3	32.8	76.1	1945	Jun.	22 3.16E+25	7.13E+28	3.0
Assam	7.3*	28.8	93.7	1947	Jul	29 8.30E+26	7.21E+28	3.0
Assam-Tibet	8.5	28.7	96.6	1950	Aug.	15 5.62E+28	1.28E+29	5.3
Anantnang	5.6	33.6	75.3	1967	Feb.	20 3.16E+24	1.28E+29	5.1
W. Nepal	6.5*	29.6	81.1	1980	Jul.	29 6.00E+25	1.28E+29	5.0
Uttarkashi	6.8*	30.8	78.8	1991	Oct	21 1.80E+26	1.29E+29	4.8
Chamoli	6.4*	30.5	79.4	1999	Mar.	29 5.20E+25	1.29E+29	4.8