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

Roger Bilham[1,]* and Nicholas Ambraseys[2]

[1]CIRES and Geological Sciences, University of Colorado Boulder 80309-0399, USA
[2]Department of Civil Engineering, Imperial College, London

Re-evaluated estimates of the magnitudes of Himalayan earthquakes since 1500 (ref. 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 half-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 $M_w = 8$ (refs 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[5–8], 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[9–15]. 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. These assumptions are 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 (eq. (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:

$$M_s = -0.297 + 0.65i + 0.0026R_i + 1.65R_i, \tag{1}$$

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

$$\log M_0 = 16.0 + 1.5M_s. \tag{2}$$

From these equations, derived for earthquakes in the instrumental period (ref. 1), we 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, the data are insufficient 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.

$$M_o = m^*\text{slip}^*L^*W \text{ where } \quad m = 3.3^*10^{11} \text{ dyne cm.} \tag{3}$$

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

*For correspondence. (e-mail: bilham@colorado.edu)

Table 1. List of earthquakes in the Himalayan region from Ambraseys and Douglas[1]. Moment and cumulative seismic moment are given in dyne-cm and plotted in Figure 2. 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 × 80 km. Thus in the absence of large earthquakes, the cumulative slip velocity decreases with time (Figure 3)

Event	M_w	Lat. (°N)	Long. (°E)	Year	Month	Day	Moment	Cum moment	Rate (mm/yr)
Lo Mustang	8.2	29.5	83	1505	June	6	2.14E + 28	2.14E + 28	79.2
Srinagar	7.6	33.5	75.5	1555	September		2.69E + 27	2.41E + 28	8.1
Uttarpradesh	7.5	30	80	1720	July	15	1.91E + 27	2.60E + 28	2.2
Uttarpradesh	8.1	31.5	79	1803	September	1	1.51E + 28	4.11E + 28	2.5
Nepal	7.7	27.7	85.7	1833	August	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	April	4	6.03E + 27	5.10E + 28	2.3
Bashahr	6.4	31.5	77.5	1906	February	27	5.13E + 25	5.10E + 28	2.3
Uttaranchal	7.3	29.9	80.5	1916	August	28	8.32E + 26	5.19E + 28	2.3
Uttaranchal	6.5*	30.3	80	1926	July	26	6.00E + 25	5.19E + 28	2.3
Nepal-Bihar	8.1	27.6	87.1	1934	January	15	1.82E + 28	7.01E + 28	3.0
West Nepal	7*	28.5	83.5	1936	May	7	1.00E + 27	7.11E + 28	3.0
Shillong	6.8	27	92	1941	January	21	5.01E + 25	7.12E + 28	3.0
Uttaranchal	6.5*	30.3	80	1945	June	4	6.00E + 25	7.12E + 28	3.0
Chamba	6.3	32.8	76.1	1945	June	22	3.16E + 25	7.13E + 28	3.0
Assam	7.3*	28.8	93.7	1947	July	29	8.30E + 26	7.21E + 28	3.0
Assam-Tibet	8.5	28.7	96.6	1950	August	15	5.62E + 28	1.28E + 29	5.3
Anantnang	5.6	33.6	75.3	1967	February	20	3.16E + 24	1.28E + 29	5.1
West Nepal	6.5*	29.6	81.1	1980	July	29	6.00E + 25	1.28E + 29	5.0
Uttarkashi	6.8*	30.8	78.8	1991	October	21	1.80E + 26	1.29E + 29	4.8
Chamoli	6.4*	30.5	79.4	1999	March	29	5.20E + 25	1.29E + 29	4.8

*Indicates magnitude adapted from other catalogues.

$$M_o = m^* v_H^* L_h^* W_h^* t \quad \text{dyne-cm}, \tag{4}$$

from which the convergence velocity may be estimated (see ref. 27).

$$v = M_o / m L_h W_h t \quad \text{cm/yr} \qquad (\text{for } L \text{ and } w \text{ in cm}). \tag{5}$$

The slip rate derived from (eq. (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.

Hence the velocity we obtain from (eq. (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]. The conver-

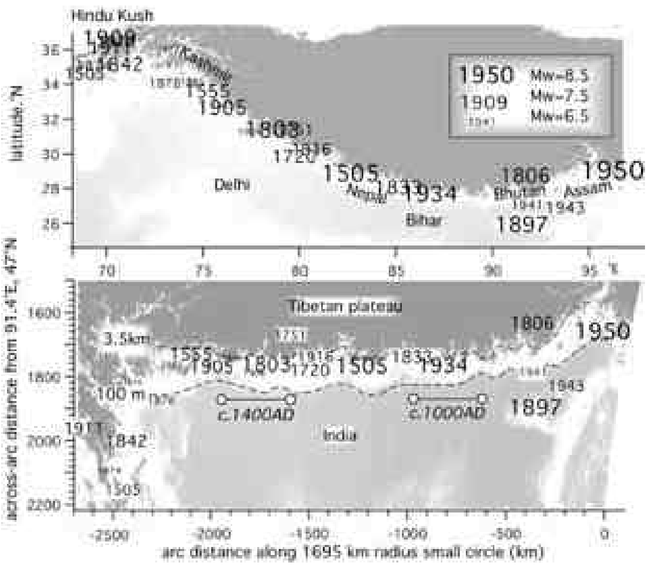

Figure 1. Significant earthquakes 1500–1950 plotted on a Cartesian projection (top) and on an oblique Mercator projection (below) centered on the pole that defines a 1695 km small circle fit to the edge of the Tibetan plateau. Dark shading indicates elevations >3500 m, and light shading indicates elevations <100 m. The white area between the two areas (dashed lines) indicates the width of the locked plate boundary whose cumulative moment-release is discussed in this article. The two bars indicate the inferred rupture lengths of great earthquakes (>10 m of slip) recently exhumed in trench excavations across Himalayan frontal thrusts[29,30].

sion of summations of seismic moment to slip rate 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).

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 (eq. (5)) a 500 year slip rate < 5 mm/yr, less than one third of the inferred convergence rate (Figure 3). 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

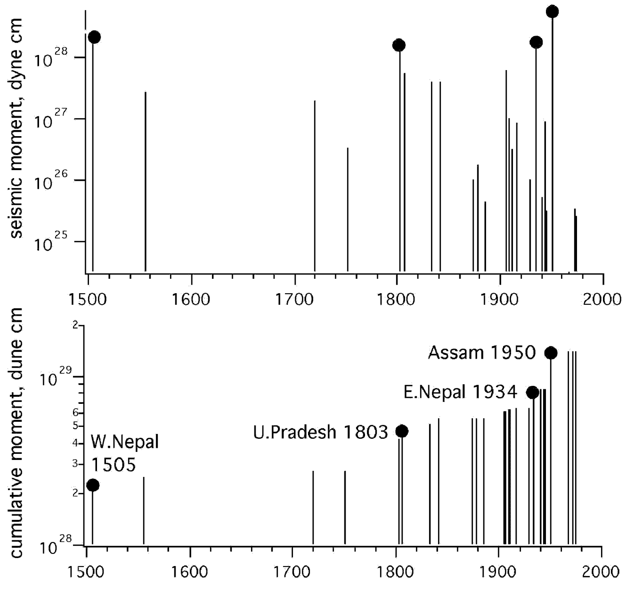

Figure 2. Seismic moment vs time for the Himalayan arc. The cumulative plot of seismic-moment (lower panel) emphasizes how most of the historical moment is released by great earthquakes.

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.

Alternatives to four overdue *M* > 8 earthquakes

Though the case for overdue $M_w > 8$ 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[20]. 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 by small and moderate earthquakes 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[22]. 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[23–25]. The northernmost 300 km of the 26 December 2004 $M_w = 9.3$ Sumatra–Andaman earthquake exemplifies this slow slip[28], and had such slip occurred in historical Himalayan earthquakes it would have passed undetected. However, since the Himalayan thrust faults are considerably shallower (<20 km) than the region of slow slip in the Andaman segment of the Sumatra earthquake (20–40 km), we consider that significant slow moment-release in the Himalaya is unlikely.

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 *et al.*[26] argue for low friction during southward propagation of Himalayan ruptures, through the 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 (Assam 1950) has occurred in the instrumental catalogue. 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' (Figure 4). 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.

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.

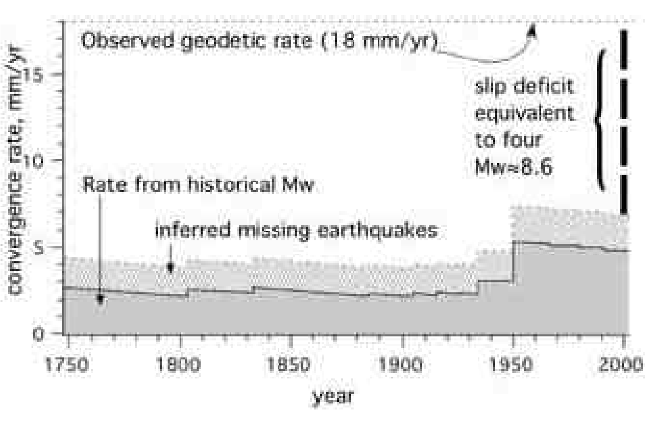

Figure 3. Convergence rate inferred from seismic-moment release, compared to the convergence rate estimated from GPS data in the past decade. Earthquakes that are missing from the historical record are anticipated to contribute no more than an additional 20% to plate boundary slip. Each earthquake increments the curve upward, and in the absence of earthquakes the graph will trend toward zero. Four $M > 8.6$ earthquakes are needed to reconcile the historical and recent estimates of convergence rate.

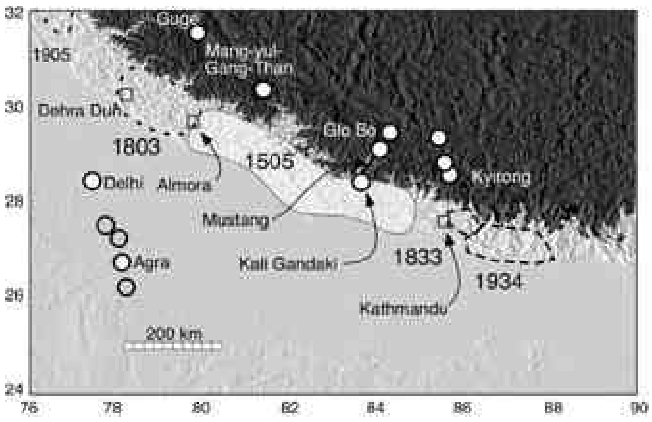

Figure 4. Estimates for the rupture areas of earthquakes between 1500 and 1934 in the central Himalaya. Evidence for the c. 1400 earthquake rupture[29] extends west from the $M_w = 8.2$ 1803 rupture, and a c. 1000 AD rupture[30] has been identified near the center and east of the 1934 rupture. White circles indicate reports that permit an intensity assessment for the 1505 earthquake[3]. Grey circles indicate felt reports for which no intensity can be assigned. Although a recurrence of the 1505 earthquake is considered timely (the central gap identified by Khattri[31]), re-rupture of the 1400 region would also not be unexpected[32].

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 not have survived in the archival record, historical earthquakes may have been underestimated in magnitude, and slow slip or aseismic creep may permit plate boundary slip without seismic radiation. Two great earthquakes have been identified from the offset of sedimentary structures in trenches exhumed across the main frontal faults of the Himalaya: a > 20 m slip c, 1000 AD earthquake in Eastern Nepal[29], and a > 12 m slip event c 1400 AD in the Garhwal Himalaya between Dehra Dun and Kangra[30]. The lateral extent of these ruptures awaits further study.

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. Thus 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 × 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 Himalayan arc would be of considerable value in estimating the probable timing and location of future earthquakes.

1. Ambraseys, N. N. and Douglas, J., Magnitude calibration of north Indian earthquakes. *Geophys. J. Int.*, 2004, **158**, 1–42.
2. Bilham, R., Bendick, R. and Wallace, K., Flexure of the Indian Plate and intraplate earthquakes. *Proc. Indian Acad. Sci.* (*Earth Planet Sci.*), 2003, **112**, 1–14.
3. Ambraseys, N. and Jackson, D., A note on early earthquakes in northern India and southern Tibet. *Curr. Sci.*, 2003, **84**, 571–582.
4. Bilham, R., Earthquakes in India and the Himalaya: tectonics, geodesy and history. *Ann. Geophys.*, 2004, **17**, 839–858.
5. Bilham, R., Larson, K., Freymueller, J. and Project Idylhim members, GPS measurements of present-day convergence across the Nepal Himalaya. *Nature*, 1997, **386**, 61–64.
6. Larson, K., Bürgmann, R., Bilham, R. and Freymueller, J., Kinematics of the India-Eurasia collision zone from GPS measurements. *J. Geophys. Res.*, 1999, **104**, 1077–1093.
7. Banerjee, P. and Burgmann, R., Convergence across the northwest Himalaya from GPS measurements. *Geophys. Res. Lett.*, 2001, **29**.
8. Wang, Q. *et al.*, Present-day crustal deformation in China constrained by global positioning system measurements. *Science*, 2001, **294**, 574–577.
9. Lyon-Caen, H. and Molnar, P., Constraints on the structure of the Himalaya from an analysis of gravity anomalies and a exural model of the lithosphere. *J. Geophys. Res.*, 1983, **88**, 8171–8191.
10. Molnar, P., Structure and tectonics of the Himalaya: Constraints and implications of geophysical data. *Annu. Rev. Earth Planet. Sci*., 1984, **12**, 489–518.
11. Molnar, P., A review of the seismicity and the rates of active underthrusting and deformation at the Himalaya. *J. Him. Geol*., 1990, **1**, 131–154.
12. Molnar, P., Inversion pro les o f uplift rates for the geometry of dip-slip fault at depth, with examples from the Alps and the Himalaya. *Ann. Geophys*., 1987, **5**, 663–670.
13. Lave, J. and Avouac, J. P., Fluvial incision and tectonic uplift across the Himalayas of Central Nepal. *J. Geophys. Res*., 2001, **106**, 26561–26592.
14. Wesnousky, S. G., Kumar, S., Mohindra, R. and Thakur, V. C., Holocene slip rate of the Himalaya Frontal Thrust of India – Observations near Dehra Dun. *Tectonophysics*, 1999, **18**, 967–976.
15. Avouac, J.-P, Mountain building, erosion and the seismic cycle in the Nepal Himalaya. *Adv. Geophys*., 2003, **46**.
16. Wright, D., *History of Nepal*, Ranjan Gupta, Calcutta, 1877, 1966 reprint, p. 271.
17. Bilham, R., Gaur, V. K. and Molnar, P., Himalayan seismic hazard. *Science*, 2001, **293**, 1442–1444.
18. Bendick, R. and Bilham, R., How perfect is the Himalayan Arc? *Geology*, 2001, **29**, 791–794.
19. Sinvhal, H., Agarwal, P. N., King, G. C. P. and Gaur, V. K., Interpretation of measured movements at a Himalayan (Nahan) thrust. *Geophys. J. R. Astron. Soc.*, 1973, **34**, 203–210.
20. Jackson, M. and Bilham, R., Constraints on Himalaya deformation inferred from vertical velocity elds in Nepal and Tibet. *J. Geophys. Res*., 1994, **99**, 13897–13912.
21. Ambraseys, N. N. and Sharma, The assessment of total seismic moment. *J. Earthquake Eng.*, 1999, **3**, 439–461.
22. Wobus, C., Heimsath, A., Whipple, K. and Kip Hodges, Active out-of-sequence thrust faulting in the central Nepalese Himalaya. *Nature*, 2005, **434**, 1008–1011.
23. Linde, A., Gladwin, M., Johnson, M., Gwyther, R. and Bilham, R., A slow earthquake sequence on the San Andreas fault. *CSIRO Exploration and Mining*, 1996, **383**, 65–68.
24. Lowry, A. R., Larson, K. M., Kostoglodov, V. and Bilham, R., Transient fault slip in Guerrero, southern Mexico. *Geophys. Res. Lett*., 2001, **28**, 3753–3756.
25. Dragert, H., Wang, K. and James, T. S., A silent slip event on the deeper Cascadia subduction interface. *Science*, 2001, **292**, 1525–1528.
26. Brune, J. N., Brown, S. and Johnson, P. A., Rupture mechanism and interface separation in foam rubber models of earthquakes: A

possible solution to the heat flow paradox and the paradox of large overthrusts. *Tectonophysics*, 1993, **218**, 59–67.
27. Brune, J. N., Seismic moment, seismicity and rate of slip along major fault zones. *J. Geophys. Res.*, 1968, **73**, 777–784.
28. Bilham, R., A flying start, followed by slow slip. *Science*, 20 May 2005.
29. Lave, J., Yule, D., Sapkota, S., Bassant, K., Madden, C., Attal, M. and Pandey, R., Evidence for A Great Medieval Earthquake (–1100 AD) in the Central Himalayas, Nepal. *Science*, 2005, **307**, 1302–1305.
30. Kumar, S., Wesnousky, S. G., Rockwell, T. K., Briggs, R. W., Thakur, V. K. and Jayangondaperumal, R., The Himalaya frontal thrust of India is not Blind. *J. Geophys. Res.*, 2005, in press.
31. Khattri, K. N., Seismic hazard in Indian region. *Curr. Sci.*, 1992, **62**, 109–116.
32. Bilham, R. and Wallace, K., Future $M_w > 8$ earthquakes in the Himalaya: Implications from the 26 December 2004 $M_w = 9.0$ earthquake on India's eastern plate margin. *Geol. Surv. India Spl. Pub.*, 2005, **85**, 1–14.

ACKNOWLEDGEMENTS. We thank Sue Hough and Peter Molnar for helpful discussions of aspects of this work. This study was partly supported by NSF grant EAR-0003449.