Interaction Between the Himalaya and the Flexed Indian Plate - Spatial Fluctuations in Seismic Hazard in India in the Past Millennium?

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Abstract: Between the tenth and early 16th centuries three megaquakes allowed most of the northern edge of the Indian plate to slip 20-24 m northward relative to the overlying Himalaya. Although the renewal time for earthquakes with this large amount of slip is less than 1300 years given a geodetic convergence rate of 16-20 mm/yr, recently developed scaling laws for the Himalaya suggest that the past 200 years of great earthquakes may be associated with slip of less than 10 m and renewal times of approximately 500 years. These same theoretical models show that the rupture lengths of the Himalaya's Medieval earthquakes (300-600 km) are too short to permit 24 m of slip given the relationships demonstrated by recent events. There is thus reason to suppose that recent earthquakes may have responded to different elastic driving forces from those that drove the megaquakes of Medieval times.

An alternative source of energy to drive Himalayan earthquakes exists in the form of the elastic and gravitational energy stored in flexure of the Indian plate. The flexure is manifest in the form of a 200-450 m high bulge in central India, which is sustained by the forces of collision and by the end-loading of the plate by the Himalaya and southern Tibet. These flexural stresses are responsible for earthquakes in the sub-continent. The abrupt release of stress associated with the northward translation of the northern edge of the Indian plate by 24 m, were the process entirely elastic, would result in a deflation of the crest of the bulge by roughly 0.8 m. Geometrical changes, however, would be moderated by viscous rheologies in the plate and by viscous flow in the mantle in the following centuries.

The hypothesized relaxation of flexural geometry following the Himalayan megaquake sequence would have the effect of backing-off stresses throughout central India resulting in quiescence both in the Himalaya and the Indian plate. The historical record shows an absence of great Himalayan earthquakes in the late 16th to early 19th centuries, and colonial records for this period contain few records of earthquakes in central India. Although this may be an artifact caused by a poor recorded history, it is unlikely that Mw>8.2 earthquakes have escaped notice in the Mughal or early colonial histories.

Recent mid-plate earthquakes in India may thus represent a redevelopment of flexural stressing of the Indian plate. Their return also signifies the development of stresses in the Himalaya that will eventually be released in large Himalayan earthquakes.

Keywords: Earthquakes, Plate flexure. Himalaya
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INTRODUCTION

GPS geodesy in the past two decades indicates that convergence between the India and EuroAsian plates cause the Himalaya to contract at a rate of 16-18 mm/year [1-3]. The rate is not precisely defined because the velocity field across the Himalaya merges with the velocity field of Tibet [4], which itself contracts at a rate of more than 1 cm/yr [5-7]. Additional measurements in southern Tibet may permit the local contraction rate across the Himalaya to be further refined, however, for the purposes of this article a maximum convergence rate of 18 mm/yr will be assumed. This convergence rate, if entirely elastic and released in earthquakes can renew the 5-9 m of slip associated with recent great Himalayan earthquakes in approximately 300 -500 years.

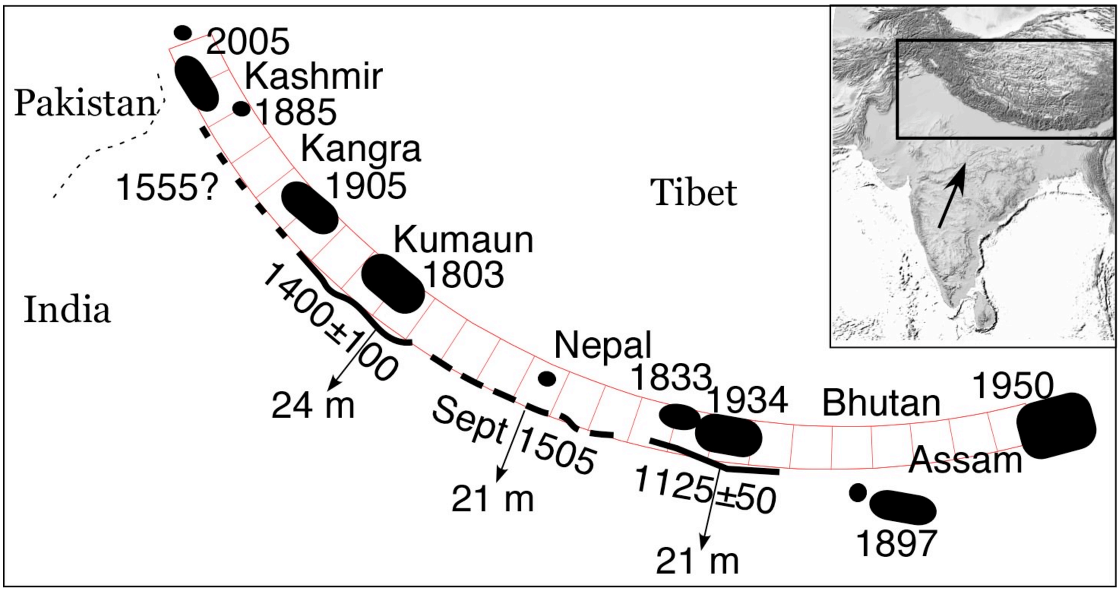

FIGURE 1. Earthquake rupture zones in the Himalaya are shown where inferred from historical and instrumental records. Slip in these earthquakes is believed to be less than 10 m, and only for the Kashmir 2005 earthquake has a surface rupture been identified. In contrast, palæoseismic investigations have identified surface ruptures exceeding 20 m (solid lines). Six hundred km of the central Himalaya slipped >20 m in 1505, and the western Himalaya may have slipped in 1555.

Although less than one third of the Himalaya has slipped in the past 200 years (Table 1), palæoseismic investigations reveal that three large earthquakes occurred in Medieval India (Figure 1): in c.1100, [8], c1400 [9,10] and in 1505 [Yule, personal communication 2007], the last corresponding to a known earthquake that destroyed Agra and numerous buildings in Tibet and Nepal [11]. Each of these earthquakes was associated with slip exceeding 20 m requiring a elapsed time of more than 1100-1300 years for the slip released in these earthquakes to have developed at current rates. This suggests that the predecessors to these megaquakes would have occurred 200BC to 400 AD, a time during which few historical data, and no palæoseismic data currently exist. A large earthquake is supposed to have occurred at the time of the birth of Buddha, however, no details of this event are known [12].

The difference between the recent great earthquakes and the Medieval megaquakes is striking. In each of these megaquakes surface rupture occurred, raising and back-tilting structures at the front of the Himalayan foothills. In contrast, with the exception of the Kashmir earthquake of 2005, no primary surface ruptures were associated with earthquakes in the past two centuries, and although it is possible that surface rupture,

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had it occurred, may have escaped the notice of contemporary observers, palæoseismic trench investigations have not recorded offsets at the times of these known events.

The Medieval megaquakes, due to their large slip and long rupture lengths also dominate the cumulative seismic-moment released in the past 1000 years. A previously published summation of seismic-moment for known **M**>7.5 earthquakes since 1800 concluded that a slip deficit in the Himalaya currently amounts to four **M**>8 earthquakes [13]. However, when the three megaquakes 1125-1505 are included, and the moment-summation extended to 1000 years the moment deficit is much reduced, or entirely eliminated, depending on the rupture lengths and widths assumed for these events (Figure 2). The 1505 rupture length is estimated at ≤600 km from the reports of damage to monasteries in southern Tibet [11], which when combined with its estimated 21 m of slip (Yule, personal communication, 2007) and an assumed 80-100 km wide rupture, yields a magnitude of **M**w8.9-9. The minimum rupture length of the c.1125 earthquake is 180 km (**M**w 8.4), and that for the c.1400 earthquake is ≈250 km (**M**w8.7).

For the entire Himalayan plate boundary length L_h, and width W_h, the mean slip rate v_h mm/yr can be calculated from the sum of the seismic moments of all the earthquakes $\Sigma\mathbf{M}o$ for a given interval of time t,

$$v_H = \Sigma Mo / L_h W_h t\sigma \ \text{mm/yr} \tag{1}$$

Where the length of the Himalaya plate boundary, L_h, is here taken to be 1800 km and the width is 100 km, t=1000 years and σ

The mean slip rate, assuming minimum rupture lengths for the pre-17th century earthquakes is 14.2 mm/yr. Were we to increase this by 20% to account for the large numbers of small and moderate earthquakes missing from the historical record we would obtain a slip rate close to that observed geodetically. The slip rate increases to 25 mm/yr if the plate boundary is narrowed from 100 km to 80 km. If the rupture lengths of the c.1125 and c.1400 earthquakes were each 600 km, the calculated mean slip rate would exceed the 18 mm/yr geodetic convergence rate by 1.5-5 mm/yr, suggesting that the rupture lengths of these earthquakes are not significantly underestimated.

The range of calculated slip rates is thus close to the observed geodetic rate and it suggests that 1000 years is sufficiently long interval to observe a complete earthquake cycle at the Himalayan plate boundary. An inspection of Figure 1 shows that part of the plate boundary has no clear record of rupture in this interval. For example, the region from Bhutan eastwards has no known earthquake, except for some suggestion of an earthquake of unknown size in 1713 [11]. Similarly an earthquake in Kashmir in 1555 may have ruptured a segment of the plate boundary west of the 1905 Kangra earthquake [14,11]. Earthquakes in these regions may have contributed to the 20% of slip considered missing from the historical data base described above.

Our assumption of a 100 km width for the plate boundary may also be inappropriate. The width of the plate boundary is commonly taken to lie between the zone of microseismicity that defines the transition between the locked Indian plate and the zone of aseismic slip beneath southern Tibet, a zone that Avouac [15] notes follows the 3.5 km contour rather closely. This points to a locked width of approximately 90-100 km between here and the start of the foothills of the Himalaya. The transition, however, is rather diffuse and in practice it cannot be an abrupt step function, but a zone of tapered slip. It is not clear how much of this transition zone participates in coseismic slip. An analytic solution in an elastic half-space suggests that it may narrow the effective locked zone to 83 km [4] with a region to the north participating in coseismic slip or immediate post-seismic afterslip.

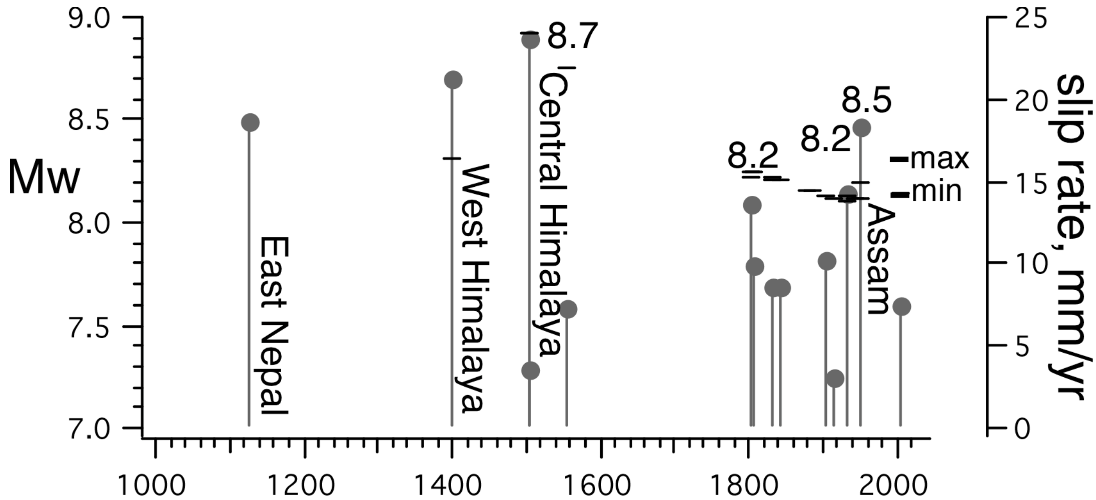

FIGURE 2. Known great earthquakes in the Himalaya since 1000 AD. A range of magnitudes can be assigned to the early events c.1125, c.1400 and 1505. The effective instantaneous slip rate of the Himalaya (dash marks) is calculated from their cumulative seismic moment assuming a 1000 year cycle and a 1800 km x 100 km Himalayan plate boundary area. The slip rate, if adjusted upwards by 20% for the numerous smaller earthquakes that have escaped historical documentation is close to the observed geodetic convergence rate of ≈18 mm/yr.

A further complication in the Himalaya that may render pour current data on earthquakes heterogeneous, is caused by the high rates of erosion particularly in the eastern Himalaya. Monsoon rains result in the removal of mass from the Himalayan accretionary wedge, a critical taper whose shape is maintained by a balance between thrust faulting, internal friction and gravitational forces [16]. Were it not for this erosion the Himalayan wedge would taper like those in submarine environments, rising northward at approximately 2°. Erosion removes on average 3 mm/yr of material from the frontal slopes of the Himalaya, destabilizing the accretionary wedge, and promoting activity on high level thrusts. Out-of-sequence thrusts have been reported recently active in the Sikkim Himalaya [17]. Should these thrust faults break through to the surface they will temporarily short-circuit slip on the basal thrusts, delaying or circumventing basal thrust earthquakes that would otherwise have occurred. It is possible, for example, that some of the recent earthquakes in the historical record for which no surface breaks have been recognized (eg. Kangra 1905, Nepal 1833) may have occurred on out-of sequence thrust faults. It is also possible that slip on other historical earthquakes may have been reduced by previous high level thrusts of which we have no record. Thus the historical record of the past thousand years may be quite inhomogeneous

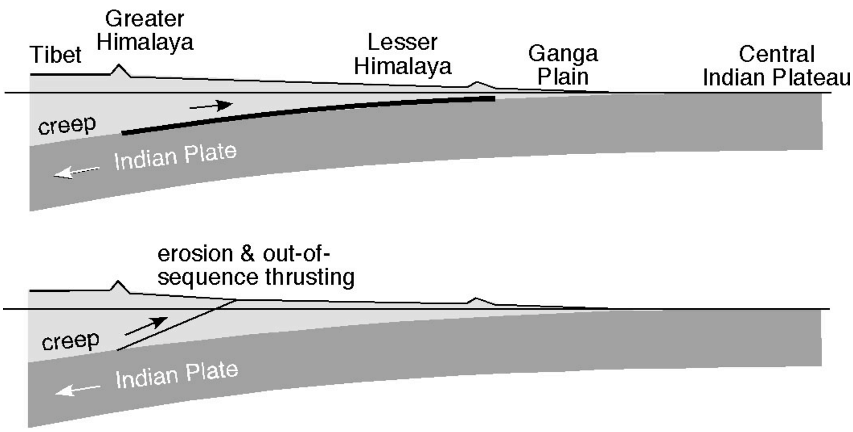

FIGURE 3. Great earthquakes occur on a decollement between the Indian plate and the base of the Himalaya (upper figure). Erosion of the Himalaya has destabilized the 6° tapered accretionary wedge, which in recovering its shape by the mobilization of slip on steep, high-level thrust faults north of the Lesser Himalaya, does so at the expense of slip on the main decollement [17].

Notwithstanding the uncertainties in the Himalayan earthquake record, it appears that the Medieval earthquake sequence was significantly more energetic than the earthquakes that have occurred in the past 200 years. There is also a suggestion that there may have been an absence of great earthquakes in the 17th and 18th centuries.

Listings of earthquakes in the Indian peninsular reveal numerous earthquakes in post 1800 colonial times but very few in the centuries prior to 1800. While this is also true of the Himalaya, there were few colonial centers of population in the Himalaya, whereas Portuguese, Dutch, French and British colonies flourished throughout India from the mid 16th century onward.

One possibility is that these apparent periods of low seismicity are real. The other is that they are artifacts of the historical record. and that earthquakes in the 16th and 17th centuries were simply not recorded or that records of events in these times have not survived. Since we have no way of proving either case, we discuss a possible causal connection linking mid-plate seismicity to Himalayan megaquakes.

Elastic energy and the Himalayan Earthquake Cycle

The earthquake cycle in the Himalaya is driven by elastic energy resulting from India's convergence with Asia. In simple models of the process [18], strain is concentrated at the transition between the creeping Indian plate and the locked decollement at approximately 15 -18 km depth and decays from this point (the locking line) towards the surface within the Himalaya and Tibet, and downwards into the descending Indian plate [4]. More complex models of the process incorporate tapered slip, more realistic geometries and depth-dependent rheologies [19-21].

Elastic models of the earthquake process in the Himalaya have yielded a scaling law linking the length of earthquake rupture to the amount of slip anticipated in a Himalayan earthquake [4]. The strain at failure, and hence the amount of slip, depends on the recurrence interval between earthquakes. For those earthquakes that have occurred in the past 200 years a recurrence interval of 500 years appears appropriate, yet the Medieval megaquakes require a significantly longer renewal time. One possibility is that the megaquakes (Mw>8.3) release a different reservoir of elastic energy that that available to great earthquakes where Mw<8.2. A possibly suggested in [4] is that a large volume of southern Tibet can participate in driving these great earthquakes due to the longer rupture zones with which they are associated. We discuss here an alternative reservoir of elastic energy - the gravitational and elastic energy of India's flexural bulge

Flexure of the Indian plate

The weight of the Himalaya, and the end loading stress caused by India's northward motion result in the downwarping of the Indian plate and the generation of a bulge to its south [22]. The bulge is responsible for the central Indian plateau beneath which a gentle rise in the Moho and the underlying high density mantle causes a positive gravity anomaly. The anomaly was recognized during the late 19th century Survey of India and named the hidden range. An outer trough lies south of the flexural bulge causing compressive stresses near the surface of the plate, and it has been suggested that earthquakes of peninsular India are to a large degree caused by the downward, and subsequent upward flexing of the Indian plate as it streams northwards through the flexural stress system at a rate of ≈18 mm/yr [23].

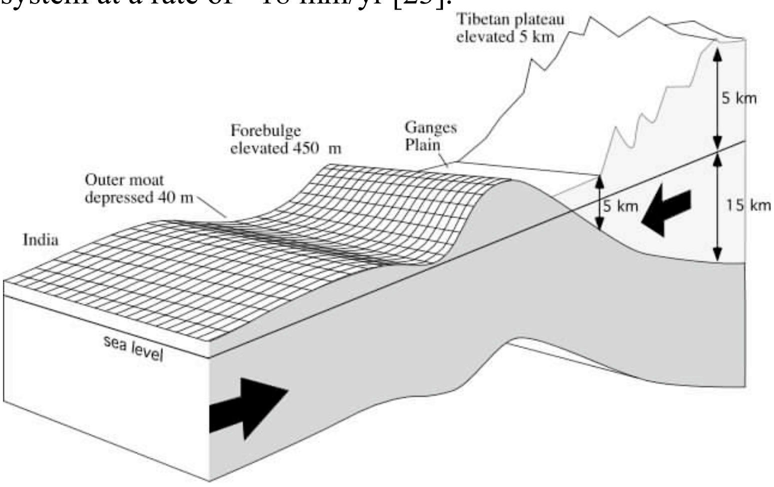

FIGURE 5. Flexure of the Indian plate results in a region of downwarping (depressed ≈40 m) bordered to its north by a 450-m-high, ≈650-km-wide bulge, which is itself bordered by the downwarped plate to the north. The plate is found at a depth of 4-6 km near the Lesser Himalaya. The flexural forebulge has weakened the upper surface of the plate where it descends beneath the Ganges

It is important to note that stresses throughout the plate, in the absence of additional stressing from topographic or tectonic loads, are in many places approaching failure, and that the thickness of the plate result in tensile and compressional fiber stresses far exceeding those needed to fracture rock. The release of a 1000 years of accumulated stress along India's northern edge in the Medieval earthquake sequence would have considerably reduced the in-plane stress that supports the flexed Indian plate. Had this occurred it would have reduced stresses throughout the plate. In the subsequent few hundred years stresses would gradually be returned to their previously high values resulting in the resumption of earthquakes in the Himalaya and in the Indian plate. In this view the great earthquakes that have occurred in the past 200 years mark the end of a region of quiescence and the beginning of a period of increasing seismic severity that will culminate in a another sequence of megaquakes 300-500 years hence.

Calculations show that the geometric change in shape of the bulge is likely to be very modest - an elevation reduction of a few cm at most. moderated by viscous flow in the mantle. However, the accompanying in-plane stress changes are likely to exceed 1 or 2 bars in places, a value that elsewhere is known to retard aftershocks, and which would require several hundred years for their re-development.

However, it is not clear to us that the Indian plate would in fact slip 10 m northward as a result of 20 m of slip in an earthquake rupture in the Himalaya. For example, were the Indian plate significantly higher modulus than the overlying Himalayan materials we could imagine that the slip in these large earthquakes, in an absolute sense, would occur mainly in the hanging wall. This would result in an incremental end load on the Indian plate equivalent to adding a layer of rock 1-2 m thick (assuming a 6° dipping decollement) causing an incremental elevation of the flexural bulge. This would act in an opposite sense to releasing the in-plane stress that supports the flexural bulge.

The resolution to our speculation may require additional data both on the rheology of the descending Indian plate and of the viscosity of the underlying mantle. Clearly the underlying mantle acts to supress elastic changes in flexural geometry, and in so doing may establish propagating signals into the plate that may manifest temselves in delayed stress changes elsewhere in the plate.

Discussion & Conclusions

Earthquake related stresses in the Himalaya are unable to cause significant stress changes directly in the Indian plate to the south. However, changes in end-loading stress, almost certainly accompany long ruptures, especially those that permit a significant fraction of the northern edge of Indian plate to slip. When this occurs, as is speculated to have occurred between 1125 and 1505, it will tend to change the geometry of the flexural bulge. A reduction in the amplitude of the flexural bulge would retard the timing of earthquakes in central India, and these earthquakes would not be brought back to their former state of imminence until the flexural geometry is re-established by further plate motion.

The historical earthquake data available to us, though consistent with such a scenario occurring in the 16th and 17th centuries, are equally consistent with the data for this time period having been lost. Similarly too little is know of the rheology of northern edge of the buried Indian plate to constrain the response of the flexed Indian plate to a sequence of large contiguous earthquakes. Although the historical record of Indian earthquakes is unlikely to improve in the next century, there is little doubt that improved rheological constraints may be available following the next large earthquake in the Himalaya, that may enable us to address this interesting question analytically.

If in fact the flexural bulge is beginning to tighten following a historial period of partial relaxation, we may anticipate that it will be accompanied by a corresponding spate of mid-plate seismicity in central India and the Himalaya.

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REFERENCES

1. Bettinelli, P., J.P. Avouac, M. Flouzat, F. Jouanne, L. Bollinger, P. Willis, and G.R. Chitraker, Plate motion of India and interseismic strain in the Nepal Himalaya from GPS and DORIS measurements, Journal of Geodesy, doi: 10.1007//s00190-006-0030-3, 2006.
2. Banerjee, P. & Burgmann, R. Convergence across the northwest Himalaya from GPS measurements. *Geophysical Research Letters* **29** (2002).
3. Jouanne, F. et al. Current shortening across the Himalayas of Nepal. *Geophysical Journal International* **157**, 1-14 (2004).
4. Feldl, N and R. Bilham, Great Himalayan Earthquakes and the Tibetan Plateau, *Nature* **444**, 165-170. doi:10.1038/nature05199;
5.Wang, Q. et al. Present-Day Crustal Deformation in China Constrained by Global Positioning System Measurements. *Science* **294**, 574-577 (2001).
6. Zhang, Pei-Zhen, Shen, Zhengkang, Wang, Min, Gan, Weijun, Bürgmann, R, Molnar, P, Wang, Qi, Niu, Zhijun, Sun, Jianzhong, Wu, Jianchun, Hanrong, Sun, Xinzhao, You, Continuous deformation of the Tibetan Plateau from global positioning system data**,** Geology 2004 32: 809-812
7. Chen, Q., J. T. Freymueller, Z. Yang, C. Xu, W. Jiang, Q. Wang, and J. Liu (2004), Spatially variable extension in southern Tibet based on GPS measurements, J. Geophys. Res., 109, B09401, doi:10.1029/2002JB002350.
8. Lave, J. & Avouac, J. P. Active folding of fluvial terraces across the Siwaliks Hills, Himalayas of central Nepal. *Journal of Geophysical Research* **105**, 5735-5770 (2000).
9. Kumar, S., S. G. Wesnousky, T. K. Rockwell, R. W. Briggs, V. C. Thakur, and R. Jayangondaperumal (2006), Palæoseismic evidence of great surface rupture earthquakes along the Indian Himalaya, *J. Geophys. Res.*, *111*, B03304, doi:10.1029/2004JB003309.
10. Wesnousky, S. G., Kumar, S., Mohindra, R. & Thakur, V. C. Uplift and convergence along the Himalayan Frontal Thrust of India. *Tectonics* **18**, 967-976 (1999).
11. Ambraseys, N. & Jackson, D. A note on early earthquakes in northern India and southern Tibet. *Current Science* **84**, 570-582 (2003).
12. Bilham, R. Earthquakes in India and the Himalaya: Tectonics, geodesy, and history. *Annals of Geophysics* **74,** 839-858 (2004).
13 Bilham, R. & Ambraseys, N. Apparent Himalayan slip deficit from the summation of seismic moments for Himalayan earthquakes, 1500-2000. *Current Science,* **88,** 1658-1663, (2005).
14. Iyengar R.N., Sharma D. (1998) Earthquake history of India in medieval times, *Rep. Central Build. Res. Inst.*, 124pp, Roorkee.
15. Avouac, J. P. Mountain Building, Erosion, and the Seismic Cycle in the Nepal Himalaya. *Advances in Geophysics* **46**, 1-80 (2003).
16. Davis, Dan; Suppe, John; Dahlen, F. A. Mechanics of fold-and-thrust belts and accretionary wedges, J. Geophys. Res., 88, Issue B2, p. 1153-1172

17. Mukul, M., Jaiswal, M., Singhvi, A. K., 2007. Timing of recent out-of-sequence active deformation in the frontal Himalayan wedge: Insights from the Darjiling sub-Himalaya, India: Geology, 35 (11), p.999-1002
18. Savage, J. C. A dislocation model of strain accumulation and release at a subduction zone. *Journal of Geophysical Research* **88**, 4984-4996 (1983).
19. Vergne J., R. Cattin and J.P. Avouac, On the use of dislocations to model interseismic strain and stress build-up at intracontinental thrust faults, *Geophys. J. Int.,*147, 155-162, 2001.
20. Perfettini, H. & Avouac, J. P. Stress transfer and strain rate variations during the seismic cycle. *Journal of Geophysical Research* **109** (2004).
21. Cattin, R. & Avouac, J. P. Modeling mountain building and the seismic cycle in the Himalaya of Nepal. *Journal of Geophysical Research* **105**, 13389-13407 (2000).
22. Watts, A. B., Isostasy and Flexure of the Lithosphere, Cambridge University Press pp.458.
23. Bilham, R., R. Bendick, and K. Wallace, (2003). Flexure of the Indian Plate and intraplate earthquakes, *Proc. Indian Acad. Sci. (Earth Planet Sci.)*,**112**(3) 1-14