EARTHQUAKE POTENTIAL OF THE MAIN HIMALAYAN THRUST IN NORTHWEST INDIA: EVIDENCE FOR WESTWARD DECREASE IN SLIP RATE

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Introduction

Great earthquakes of M≥ 8, at least three on the northern edge of the Indian plate, struck the Himalayan foothills in 1897, 1905, 1934, and 1950, resulting in tens of thousands of people losing their lives (Fig. 1). Since the last earthquake 50 years ago, the population in the foothills and adjacent plains has grown enormously, and hundreds of thousands of people could die in the next great earthquake. We model the source fault, the Main Himalayan Thrust (MHT), as a crustal-scale ramp, where earthquakes nucleate, and a flat, where a few of these earthquakes propagate toward the Himalayan front as M ≥ 8 events. This fault is largely a blind thrust, with no surface faulting reported for the 1905 or 1934 earthquakes.

Ramp-flat model

Direct imaging of the MHT is consistent with other evidence that the MHT underlies and controls a crustal-scale fault-bend fold (Yeats and Thakur, 1998). The MHT includes a ramp beneath the High Himalaya, a flat farther south, and another ramp at the Himalayan front. Earthquake distribution, fault-plane solutions, and seismic profiles acquired by the Indian Oil and Natural Gas Corporation suggest that the flat dips 6° ± 3° N, whereas the down-dip ramp, which coincides with a zone of high seismicity including the 1991 Uttarkashi earthquake (m_b6.6) and 1999 Chamoli earthquake (m_b6.3), dips 5°-29° N (Fig. 2), based on earthquake fault-plane solutions. This is consistent with a dip of 9°± 4° in the Project INDEPTH deep crustal seismic profile in southern Tibet.

The axial surface at the inflection between ramp and flat projects upward to the Earth's surface and separates north-dipping thrust plates of the High and Tethyan Himalaya from a zone where the thrusts are folded. The presently-inactive Main Central thrust (MCT) zone is deformed above both ramp and flat, and klippen occur in flexural-slip synclines. The simple, convex-south map trace of the axial surface, together with the zone of seismicity, maintains a constant distance from the Himalayan Front fault (HFF), and the HFF is expressed at the surface as a series of fault-propagation folds overlying a frontal ramp.

The steeper fault dip on the two thrust ramps in comparison with the thrust flat requires a greater uplift rate in the High Himalaya and near the Himalayan front than in the intervening thrust flat. The evidence suggests that the rates are higher in the High Himalaya and at the front of the Sub-Himalaya and lower within the Lesser Himalaya. The longitudinal profiles of major antecedent rivers crossing the Himalaya and terraces of the antecedent Kali Gandaki River in Nepal have steepest gradients in the High Himalaya above the zone of high seismicity and much lower gradients to the north and south. Swath topographic profiles across the Nepal Himalaya show that the relief, a measure of the degree of incision of rivers, is greatest in the High Himalaya, another indicator of high uplift rates over the structural ramp. Uplift rates above the frontal ramp near the HFF of Nepal are as high as 15 mm/yr.

Slip rate

Balanced cross sections based on seismic and well data show a shortening rate of 14 ± 2 mm/yr for the Kangra re-entrant (Fig. 2) and 11 ± 5 mm/yr for the Dehra Dun re-entrant to the southeast, consistent with the earlier estimates. West of 73° E, where the Himalayan front bends sharply to the WSW in Pakistan, shortening estimates based on balanced cross sections range from 7 to 14 mm/yr in the Potwar Plateau. Errors arise from uncertainties in the age of initiation of thrusting and from possible additional shortening on out-of-sequence thrusts north of the subsurface well and seismic data set on which the rates are based. Holocene rates are 21.5 ± 1.5 mm/yr in the frontal Himalaya of central Nepal, 18 ± 3 mm/yr in western Nepal, and ≥ 11.9 ± 3.1 mm/yr in the Doon Valley of India. Global Positioning System (GPS) data from 1991 to 1995 in Nepal and older land-based trigonometric surveys reveal a shortening rate across Nepal to be 17.7 ± 2 mm/yr. Thus the long-term rates based on balanced cross sections with timescales of 10^6 to 10^7 yr are consistent with Holocene rates with timescales less than 10^4 yr and geodetic rates in Nepal with time scales <10 yr.

Using finite-element modeling, the distribution of strain across the diffuse mobile zone between stable India and Eurasia results in a residual shortening rate between India and the Himalaya to be 18 mm/yr in the Nepal and Assam Himalaya dimishing gradually westward to 10 mm/yr immediately east of the syntaxial bend and 3-5 mm/yr in the Potwar Plateau farther west (Fig. 1). The shortening rate decreases northwestward in part because shortening in the northwest Himalaya is taken up by the Karakoram right-lateral strike-slip fault with a slip rate in its southern segment of 30 +/- 10 mm/yr, and in part due to increasing obliquity of India-Himalaya convergence westward.

GPS shows that most present-day convergence in Nepal is being taken up in the High Himalaya and farther north. The Lesser Himalaya and Sub-Himalaya, characterized by low instrumental seismicity, are moving at a velocity close to that of the Indian plate, indicating that the thrust flat is locked and accumulating elastic strain, whereas the northern part of the ramp slips aseismically. This leads to the conclusion that intermediate-size earthquakes on the structural ramp beneath the High Himalaya are adding to strain centered at the top of the locked flat to its south. The structural ramp has higher seismicity because it is closer to the isotherm marking the onset of quartz plasticity. Great earthquakes are produced when an intermediate-size earthquake on the ramp triggers slip on the stronger flat to the south, which ruptures all the way out to the Himalayan front.

Earthquakes within the hangingwall with strike-slip fault-plane solutions and smaller events with nodal planes considerably steeper than the megathrust at the ramp are an expression of hangingwall deformation that accommodates some of the strain that otherwise would be taken up on the megathrust flat. Hangingwall earthquakes, including the 1975 Kinnaur normal-fault earthquake are evidence that the hangingwall, part of the South Tibet block, is extending E-W. The curvature of the HFT and MHT shows that Himalayan convergence should be increasingly oblique to the northwest, although nodal-plane solutions of earthquakes on the thrust ramp show strain release normal to the Himalayan arc, evidence of strain partitioning. Because of the curvature of the arc and E-W extension of the South Tibet block, the dip-slip component decreases northwestward, as predicted by finite-element modeling. However, we know only that intermediate-size earthquakes are dip slip; earthquakes of M > 8 on the MHT could be dip slip or oblique slip.

Recurrence intervals for great earthquakes

How frequently would earthquakes the size of the three megathrust-flat earthquakes occur? If the slip per event were 5m for 1905 Kangra, 6.2m for 1934 Bihar-Nepal, and 9m for 1950 Assam, and all long-term slip on the megathrust flat were coseismic, the recurrence interval for earthquakes on the same segment of fault would be 250-450 years for a slip rate of 20 mm/yr in central Nepal and 500-900 years for a slip rate of 10 mm/yr in northwest India close to the western syntaxis. Recurrence intervals would be somewhat longer if strain release from hangingwall reverse-fault or strike-slip earthquakes were included.

Paleoseismological observations north of the Shillong Plateau, near or within the rupture zone of the 1897 earthquake, document a recurrence interval of 500 ± 100 years. Kathmandu, Nepal, was destroyed by a great earthquake in 1255 AD, 679 years before the 1934 earthquake. Trenches across the HFF and across a nearby strike-slip fault in southeastern Nepal show a surface rupture that could have accompanied the 1255 earthquake, although these trenches showed no evidence for the 1934 earthquake.

A gap for great earthquakes separates the 1934 and 1905 events; earthquakes in 1803 ($6 \leq M \leq 7.6$) and 1833 (M 7.7 ± 0.2) are not large enough to fill this gap. Kashmir was struck by intensity XII events in 1250 BC and 1555 AD, an interval of 2800 years. Northern Pakistan was struck by only one intensity XII earthquake, in 25 AD. Historical records from Kangra and the western Doon Valley report only the 1905 earthquake in the last 900 years.

The inferred longer historical recurrence interval in the northwest Himalaya, together with the paleoseismological recurrence interval in Shillong, is consistent with finite-element modeling and with a decreased amount of arc-normal component of convergence due to increased obliquity. Although this reduces the probabilistic earthquake hazard somewhat, the apparent absence of a great historical earthquake east of the 1905 event indicates that this seismic gap is at greater risk than those regions that ruptured in the last century.

References

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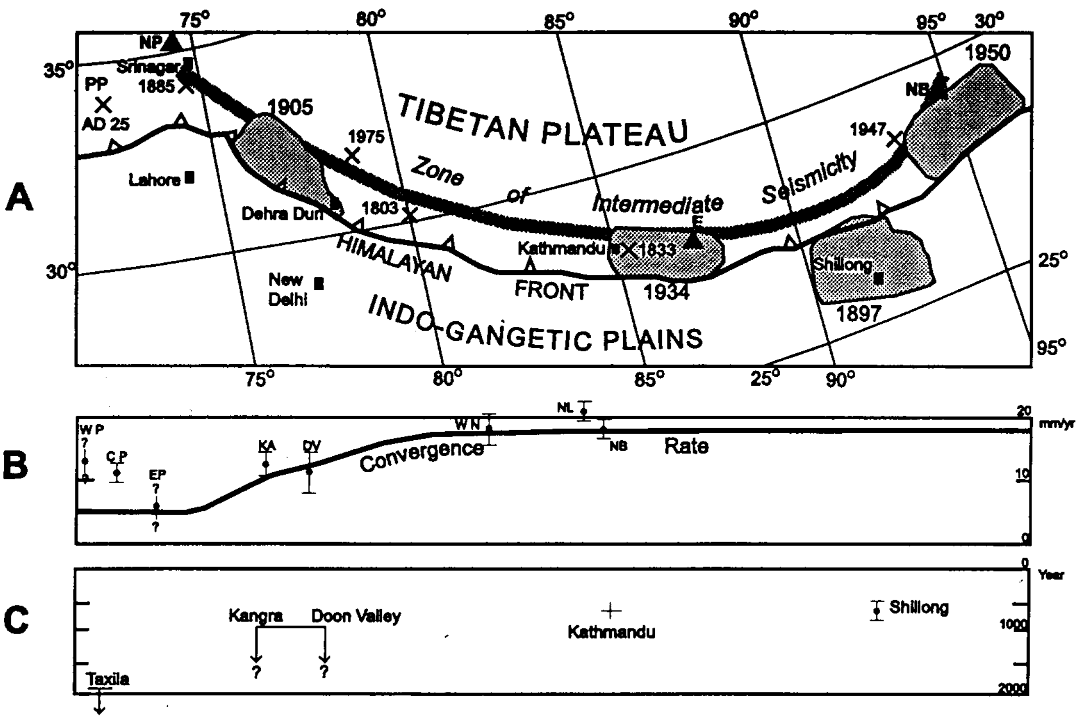

Figure 1. A. Map of Himalaya showing Himalayan front (heavy line with triangles), zone of intermediate seismicity (gray band), rupture zones of four great earthquakes (shading), and epicenters of other earthquakes discussed in text. PP, Potwar Plateau; NP, Nanga Parbat; E, Mt. Everest; NB, Namche Barwa. B. Convergence rate across the Himalayan front relative to longitude in top diagram. Solid line bassed on finite-element modeling. Vertical symbols: convergence rates. WP, Western Potwar; CP, Central Potwar; EP, Eastern Potwar; KA, Kangra; DV, Doon Valley; WN, Western Nepal; NL, Central Nepal from Lavé and Avouac; NB, Central Nepal from Bilham et al. Queries where uncertainties not stated. C. Recurrence interval for great earthquakes relative to longitude. Shillong and Kathmandu supported by paleoseismic data; Kathmandu and points farther west supported by historical data.

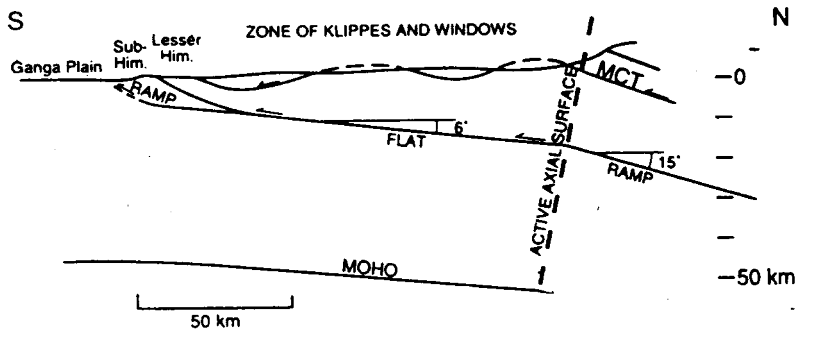

Figure 2: Cross section showing ramp-flat model of Main Himalayan thrust (MHT). Active axial surface bounds a north-dipping ramp marked by high seismicity and a low-dipping folded flat which is locked except for great earthquakes such as the 1905, 1934, and 1950 events. The Main Central thrust (MCT), an inactive ductile shear zone, marks the active axial surface in Nepal, but is south of it farther west in India. Short lines with circles mark representative nodal planes of earthquakes near the active axial surface. The frontal ramp is marked by fault-propagation folds at the Himalayan front (HFF). MBT, inactive Main Boundary thrust. Shading: Sub-Himalaya and crystalline rocks above the MCT. Topography not to scale.