Reassessment of earthquake hazard based on a fault-bend fold model of the Himalayan plate-boundary fault

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At least three great earthquakes of $M \geq 8$ have ruptured the plate-boundary megathrust between India and the Himalaya in the last century. The central Himalaya moves southward as a fault-bend fold at 15 mm/yr or more by infrequent earthquakes that nucleate on the highly-seismic ramp beneath the Himalaya and rupture southward along a thrust flat to the range front. There is a consensus that future great earthquakes will strike the Himalayan front, with the next earthquakes most likely in the 20th-century seismic gaps in Western Nepal, Kumaon, and Jammu-Kashmir. Because of the great increases in population in these regions, losses in the next great earthquake are expected to be catastrophic. A realistic earthquake probability forecast requires establishment of a GPS array in the northwest Himalaya to establish slip rates on the plate-boundary fault and palaeoseismological investigations at the Himalayan front and adjacent Ganga plains to establish earthquake recurrence intervals on individual segments of the fault.

FOUR earthquakes of $M \geq 8$ struck Himalayan foothills in 1897, 1905, 1934, and 1950, resulting in tens of thousands of people losing their lives (Figure 1). Since the last earthquake almost 50 years ago, the population in the Himalayan foothills and adjacent plains has grown enormously, an indication that the losses of life in the next great earthquake could be in the hundreds of thousands[1] or even greater. The most likely sites for the next events are the seismic gaps between the 1905 Kangra and 1934 Bihar–Nepal earthquakes and between the Kangra earthquake and the Taxila, Pakistan, earthquake of AD 25.

Fault-bend folding and the plate-boundary fault

The fault that ruptured to cause at least three of these great earthquakes of the past hundred years is the plate-boundary thrust between the Indian shield and the Himalaya. This fault is only discontinuously exposed at the surface, and no surface faulting is definitely known to have accompanied any of these earthquakes. However, the fault has been imaged directly in multichannel seismic profiles acquired by the Oil and Natural Gas Commission in the search for petroleum in the Himalayan foothills[2]. It has also been imaged in a deep crustal seismic profile in southern Tibet by Project INDEPTH, where it has been named the Main Himalaya Thrust (MHT)[3].

Direct imaging of the MHT is consistent with other evidence that the MHT underlies and controls a fault-bend fold, as defined by Suppe[4]. The MHT includes a ramp beneath the High Himalaya and a flat farther south[5].

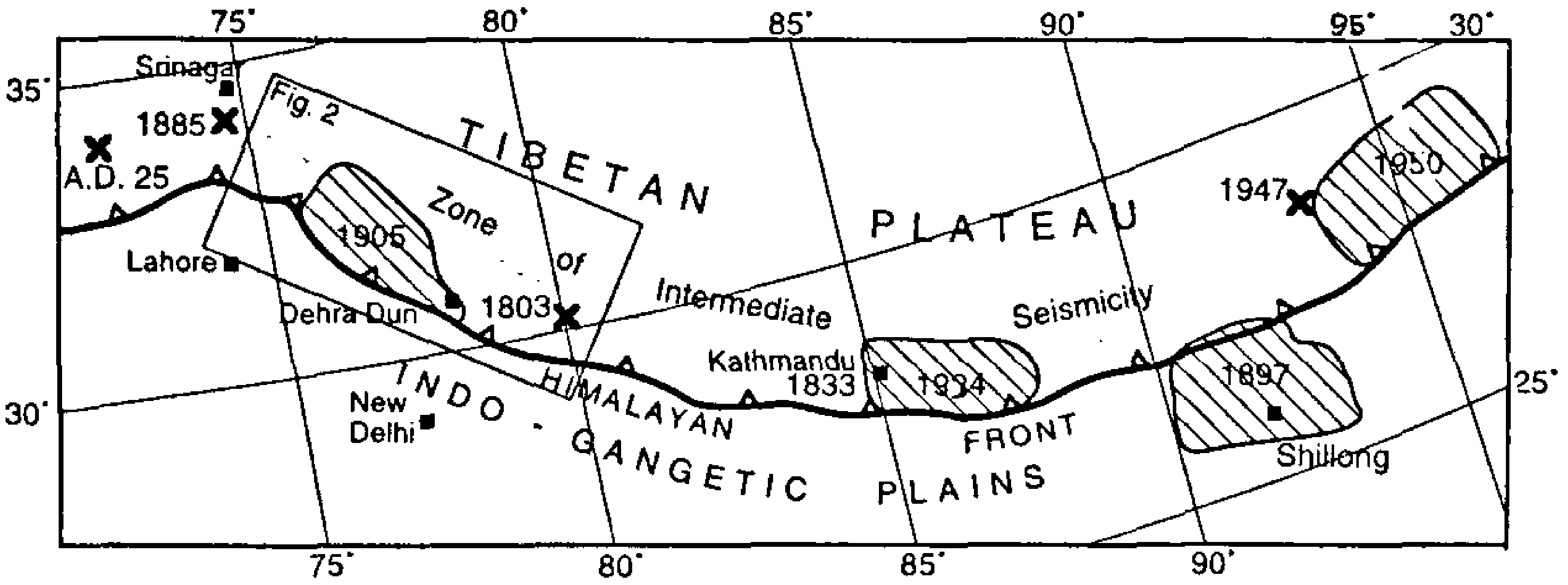

Figure 1. Sketch map of Himalaya showing Himalayan front (solid line with triangles), zone of high instrumental seismicity (dotted band), meizoseismal zones of four great earthquakes along Himalayan front (lined pattern), and location of other large earthquakes of interest, including the great earthquake of AD 25 at Taxila, Pakistan. Box shows location of Figure 2.

We first discuss the evidence consistent with a fault-bend fold model, and then we discuss the long-term slip rate on the MHT, which has major implications for future great earthquakes in the foothills of the Himalaya.

Earthquake distribution, fault-plane solutions, and multichannel seismic lines suggest that the flat dips 6° ± 3°N, whereas the down-dip ramp, which coincides with a band of high seismicity including the 1991 Uttarkashi earthquake, dips 10°–25°N (refs 6–8) (Figure 2). The axial surface at the inflection between ramp and flat projects northward to the surface and separates predominantly inactive north-dipping thrust plates of the High and Tethyan Himalaya from a zone of thrusts with highly-convoluted map traces, klippen, and windows[9] (Figure 3). The simple, convex-south map trace of the axial surface maintains a constant distance from the Himalayan Front fault (HFF), and the HFF may be a series of fault-propagation folds (as defined by Suppe and Medwedeff[10]) marking the southern edge of the basal flat. The presently-inactive Main Central thrust (MCT) zone (Chail, Jutogh, Vaikrita thrusts) is complexly folded above both the ramp and the flat, which results in a sinuous map pattern above the flat, where fault dips are low, but a straighter map pattern above the ramp, where dips are steeper. In Kumaon and Nepal, the band of high seismicity is beneath and south of the MCT, leading some to suggest that the MCT is itself active. But Thakur[9] showed that farther west, in Himachal Pradesh and Jammu-Kashmir, the MCT is much closer to the Himalayan front, where it is called the Panjal thrust, whereas the zone of high seismicity underlies the Tethyan Himalaya.

In the High Himalaya, only the axial surface of the fault-bend fold is active at crustal scale; it moves relatively northward through the hangingwall as the megathrust drives southward and upward over the ramp and rotates to a lower dip over the flat. The fault-bend fold model shows the axial surface as a sharp kink or chevron fold; however, the data are consistent with a more gradual change in dip from ramp to flat, as shown by Bilham *et al.*[11,12]. A fault-bend fold requires a back-limb, formed by the northward slope between the High Himalaya and the region to the north, an outcome of higher uplift rates in the High Himalaya. This is imaged in a 100-km-wide swath topographic profile as a decrease in maximum altitudes > 1 km between the High Himalaya and southern Tibet[13].

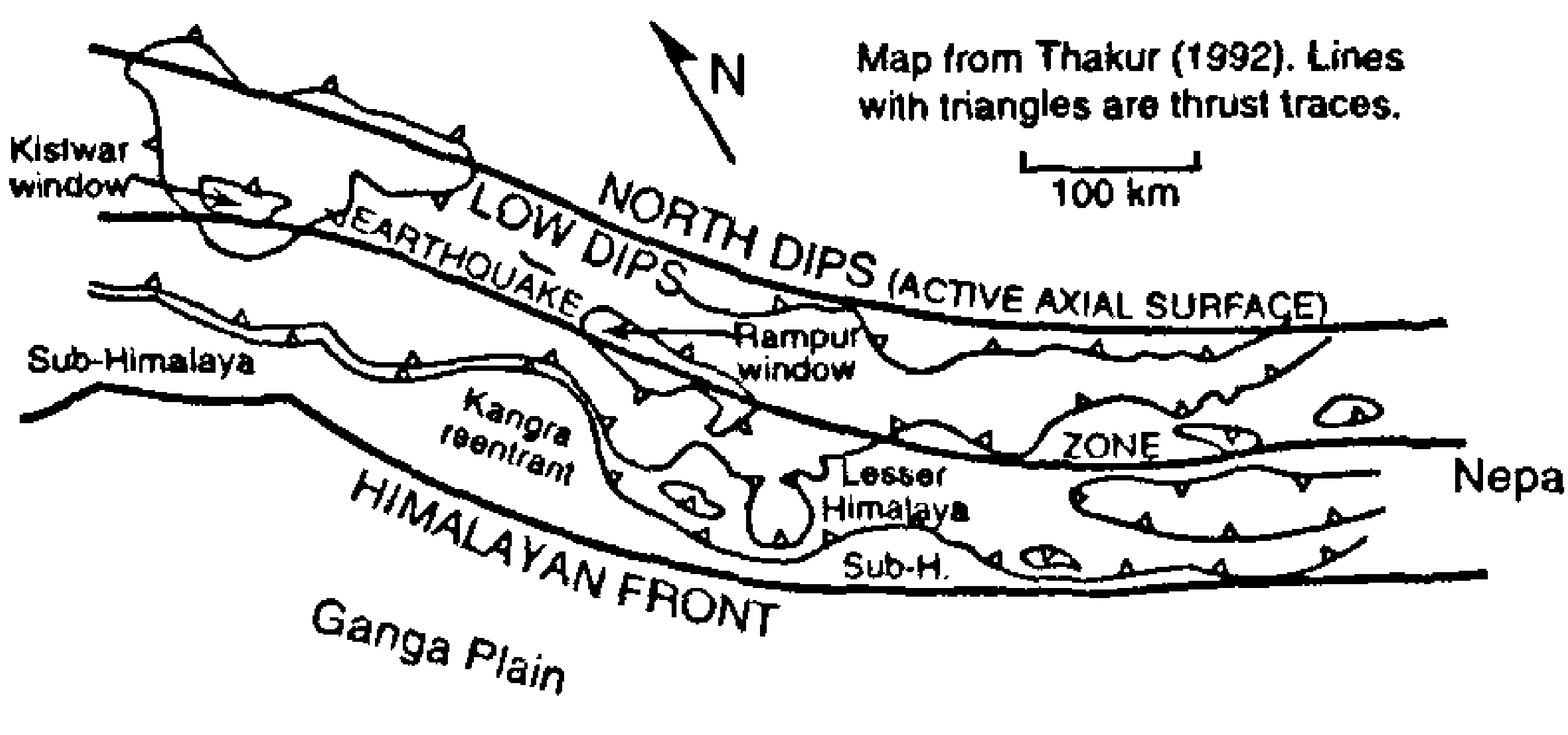

Figure 2. Tectonic map of northwest Himalaya showing major thrust structures (solid lines with open triangles), Himalayan front, as marked by Himalayan Front fault or by frontal anticlines, zone of high instrumental seismicity and intermediate-size earthquakes, and active axial surface separating predominantly north dips of thrusts and zone of klippen and windows where thrust dips are lower. Map simplified from Thakur[9].

Slip rate

Lyon-Caen and Molnar[14] estimated a slip rate of 15 ± 5 mm/yr based on the rate of migration of the flexure of the Indian shield due to the load of the advancing MHT, which they estimated from the rate of onlap of Siwalik strata onto the Indian shield. Convergence rates across the Pakistan Sub-Himalaya based on retrodeformable cross sections are 13 mm/yr in the western Potwar Plateau[15], at least 9–14 mm/yr in the central Plateau[16], and 7 mm/yr in the eastern Plateau[16]. These uncertainties may be caused by the uncertainty in the age of initiation of thrusting in various parts of the Plateau. Using the same technique, Powers[2] determined a shortening rate of 14 ± 2 mm/yr across the Sub-Himalaya of the Kangra re-entrant of northwest India. These should be considered as minimum rates, because additional shortening could be occurring on out-of-sequence thrusts north of the subsurface seismic and well data on which the rates are based.

Avouac and Tapponnier[18] determined a residual convergence rate across the Himalaya of about 18 mm/yr after removing the slip rates on structures north of the Himalaya from the India–Eurasia plate rate. Using finite-element modeling, Peltzer and Saucier[19] obtained a convergence rate of 18 mm/yr in the Nepal and Assam

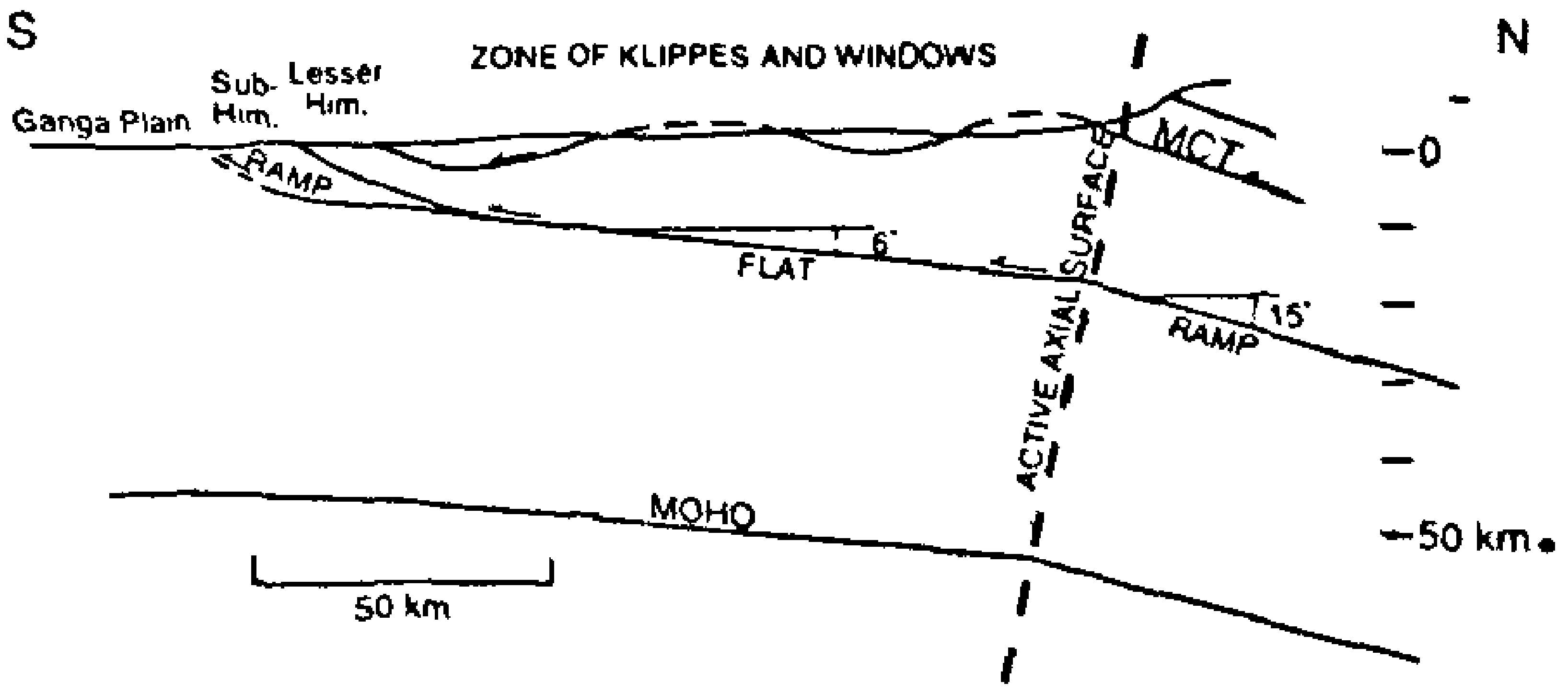

Figure 3. Fault-bend fold model of active Himalaya. Active axial surface separates a north-dipping ramp marked by high seismicity and intermediate-size earthquakes and a low-dipping flat which is locked except for great earthquakes such as the 1905, 1934, and 1950 events. The Main Central Thrust (MCT) is between the active axial surface and the zone of high seismicity in Kumaon and Nepal, but is south of those features farther west in Himachal Pradesh and Jammu-Kashmir. The frontal ramp produces fault-propagation folds at the Himalayan front.

Himalaya, diminishing gradually westward across Kumaon and Himachal Pradesh to 10 mm/yr in Jammu.

How do long-term slip rates based on geology compare to short-term rates based on seismicity and geodesy? The slip rate based on seismic moment release during the last century is 17 mm/yr (refs 8, 20). Uplift rates based on leveling data from Nepal and horizontal velocities based on Global Positioning System (GPS) data from 1991 to 1995, also from Nepal, show a north-south contraction of the Himalaya of 17.7 ± 2 mm/yr consistent with a slip rate on the MHT of 20 ± 3 mm/yr (refs 11, 12). Thus the long-term and short-term rates are consistent, except for the rate based on tectonic geomorphology, which was estimated as no more than 5 mm/yr at the Himalayan front in Nepal[21]. However, this low estimate may be due to an over-estimation of the age of the Quaternary erosion surfaces being deformed; these surfaces have not yet been dated by radiocarbon or thermoluminescence.

If the dip of the MHT is known, its slip rate may be estimated from the rate of uplift of its hangingwall. The steeper dip of the MHT at the ramp beneath the High Himalaya and near the Himalayan front would result in a greater uplift rate there than over the intervening thrust flat. To determine the uplift rate of a body of rock with respect to the centre of the Earth, the rate of change of the eroding Himalayan surface would be added to the denudation rate based on fission-track dating and an assumption of constant geothermal gradient. Molnar[8] summarized the evidence for uplift rate, including palaeoclimatic evidence, which suggests that the rates are higher in the High Himalaya and the front of the Lesser Himalaya and lower within the Lesser Himalaya. Molnar[22] noted that terraces of the Kali Gandaki River in Nepal mapped by Iwata *et al.*[23] show evidence of greater uplift rates within the High Himalaya than in regions to the north and south. Seeber and Gornitz[24] observed that the longitudinal profiles of major antecedent rivers crossing the Himalaya have steepest gradients in the High Himalaya above the zone of high seismicity and much lower gradients to the north and south. The swath topographic profile of Masek *et al.*[13] shows that the maximum relief (the difference between maximum and minimum altitudes, a measure of the degree of incision of rivers) is greatest over the structural ramp, another indicator of high uplift rates over the ramp.

Fission-track ages of apatite from the Gangotri granite in the Higher Himalaya of Garhwal indicate a denudation rate of about 2 mm/yr for the past 2 my (ref. 25). To this must be added the true uplift rate based on palaeoclimatic evidence. High denudation rates based on similar evidence have been reported from Nanga Parbat in the western Himalayan syntaxis[26] and the Namche Barwa region in the eastern syntaxis[27]. Nakata[21] found evidence for uplift rates in the Sub-Himalaya of Nepal above the frontal ramp as high as 4 mm/yr.

Recurrence intervals for great earthquakes

Geodetic evidence[11,12] shows that most present-day convergence in Nepal is being taken up in the High Himalaya and farther north; Kathmandu, south of the High Himalaya, is moving at a velocity close to that of the Indian plate. This leads to the conclusion that intermediate-size earthquakes on the structural ramp beneath the High Himalaya are adding to strain on the flat to the south, which is completely locked, supported also by the low instrumental seismicity of the flat. The structural ramp has high seismicity because it is at higher temperatures and is closer to the isotherm marking the onset of quartz plasticity[28]. 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. On the other hand, earthquakes within the hangingwall such as the 1975 Kinnaur normal fault earthquake[29], earthquakes with strike-slip fault-plane solutions[30], and smaller events with nodal planes considerably steeper than the megathrust at the ramp[31,32] deform the hangingwall and accommodate some of the strain that otherwise would be taken up on the megathrust flat.

Jackson and Bilham[33] conclude from their data that a slip deficit of 13 ± 8 mm/yr is accumulating beneath the Nepal Himalaya. How frequently would earthquakes the size of the three megathrust flat earthquakes occur? Assume a slip rate of 15 mm/yr. If the slip per event were 5 m for 1905 Kangra, 6.2 m for 1934 Nepal–Bihar, and 9 m for 1950 Assam[8], and all long-term slip on the megathrust flat were coseismic, the recurrence interval for earthquakes on the same segment of fault would be a few hundred years[8,33]. However, the seismic moments on which slip estimates are based are poorly constrained because of uncertainty about fault area, and, in the case of the Assam earthquake, in the possibility of some moment release by strike-slip faulting[8]. The interval would be slightly longer if strain release from hangingwall earthquakes were included.

This recurrence interval is consistent with recurrence of great earthquakes at Kathmandu, Nepal, which was destroyed by an earthquake in 1255 AD and again damaged in 1934, with intervening earthquakes in 1408 and 1681 (ref. 34). An earthquake gap exists between the 1934 and 1905 events; earthquakes in 1803, 1810, 1826, 1833 and 1866 do not appear to be large enough to fill this gap[34]. There is no historical evidence for any 1905-size earthquake in Jammu and Kashmir between 1905 event and the Taxila earthquake of AD 25 except for earthquakes in 1828 and 1885 in Kashmir[35], which may have been considerably smaller than the 1905 event.

Historical records from Kangra report only the 1905 earthquake in the last 900 years. This may be explained by a lower convergence rate in the northwest Himalaya, as modeled by Peltzer and Saucier[19], or by an underestimation of the 5 m slip during the Kangra earthquake.

Resolving the uncertainty in probabilistic forecasts of great earthquakes

There is a consensus among scientists studying Himalayan earthquakes that there will be more earthquakes of $M \geq 8$ in the near future. However, there are major unresolved problems that prevent a more accurate forecast on which planning and preparation by society can be based. These are: (i) a possible westward decrease in the India–Himalaya convergence rate from the rate established in Nepal to the northwest Himalaya, and (ii) uncertainty about the repeat time of $M \geq 8$ earthquakes at any given place along the MHT.

A westward decrease in the India–Himalaya convergence rate is suggested by the finite-element model of Peltzer and Saucier[19], due in part to right-lateral strike-slip on the Karakoram fault to the north. A decreased rate would explain the long recurrence interval between the AD 25 Taxila, Pakistan, earthquake and the present, and the absence of any records of a great earthquake in the Kangra region except for the 1905 event. Rates based on balanced cross sections are limited to the northwest Himalaya and the Potwar Plateau-Salt Range, and these show no monotonic westward decrease in convergence rate. Furthermore, the GPS network in Nepal shows no decrease in convergence rate westward across Nepal[11,12]. It is straightforward matter to establish a GPS network across the northwest Himalaya of India that is tied into the Nepal network. No more than three years of reoccupation of these stations should establish whether the convergence rate is the same along the Himalaya or whether it decreases westward.

Recurrence intervals of $M \geq 8$ earthquakes need to be determined directly by palaeoseismological investigations along the Himalayan front. The historical recurrence interval of great earthquakes in the northwest Himalaya appears to be longer than that predicted by the apparent convergence rate, but this may be due to inadequate study of historical records. Palaeoseismological investigations should consist of (i) trenching the Himalayan Front fault to search for direct evidence of prehistoric fault ruptures, and (ii) study of overbank deposits of major rivers in the Ganga plain near, but south of, the Himalayan front to search for evidence of palaeoliquefaction comparable to that observed in the 1934 Biha Nepal earthquake.

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