Preparations for future great earthquakes seen in levelling observations along two lines across the Outer Himalaya

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An important set of levelling observations across Central Nepal have been reported in the literature recently. We infer from these observations that recoverable elastic strains are accumulating in the upper crust of the region and will lead to a great earthquake in course of time. Limited levelling data from the Dehradun region in northwestern Himalaya show remarkable similarities to the Nepalese data and require a similar interpretation regarding preparation for the next great earthquake in the region.

GEODETIC observations have been carried out in the Indian region for nearly two centuries[1]. The use of such observations for detecting crustal deformations during a great Indian earthquake was first proposed by Oldham[2]. But, almost a century later, repeat observations for geodetic monitoring of crustal deformations over satisfactorily large areas are not yet available within the Indian territory. Recently, Jackson *et al.*[3] have reported repeat observations along a 350 km long levelling line across Central Nepal (Figure 1). We compare levelling observations along the 80 km long Saharanpur–Rajpur line across the Dehradun Outer Himalaya[4] (Figure 2) with Jackson *et al.*'s[3] observations pertaining to the Outer Himalaya of Central Nepal. It appears that accumulation of elastic strains is currently taking place in the Dehradun and Central Nepal segments of the Himalaya in preparation for the next great earthquakes of the respective regions.

Nepalese levelling data

The levelling line starts at Birganj (Figure 1) on the India–Nepal border and runs northward across the Indo-Gangetic Plains and Outer Himalaya of Central Nepal. It crosses the Mahabharat range and continues via Kathmandu up to Kodari on the Nepal–Tibet border[3]. This entire line has been levelled at least twice. Figure 3 *a* is a display of annual uplift rates after projection of observations on to a line normal to the trend of the Nepal Himalaya. It is adapted from Figure 2 of Jackson *et al.*[3] Since our attention is focused here on the nature of tectonic activity currently going on in the Outer and southern Lesser Himalaya, only observations from the southern part of the Nepalese line are shown in Figure 3 *a*. The main uplift rate signal in the Nepalese observations

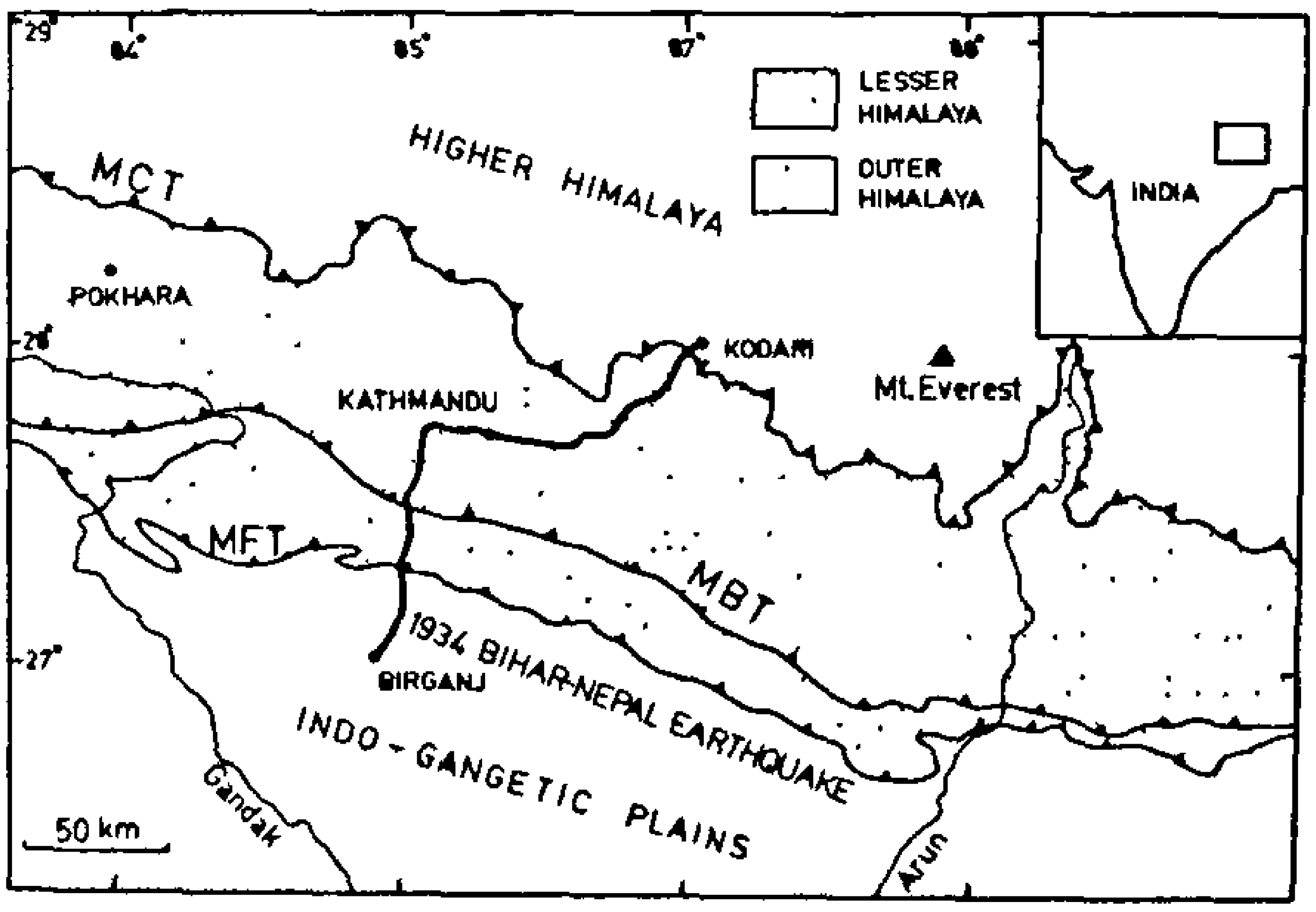

Figure 1. Simplified geologic map of the Central Nepal Himalaya[23]. The thick line shows the route along which repeat levelling was carried out in Central Nepal[3]. The segment of the Himalaya affected by the great 1934 Bihar–Nepal earthquake is indicated. MFT, Main Frontal Thrust; MBT, Main Boundary Thrust and MCT, Main Central Thrust.

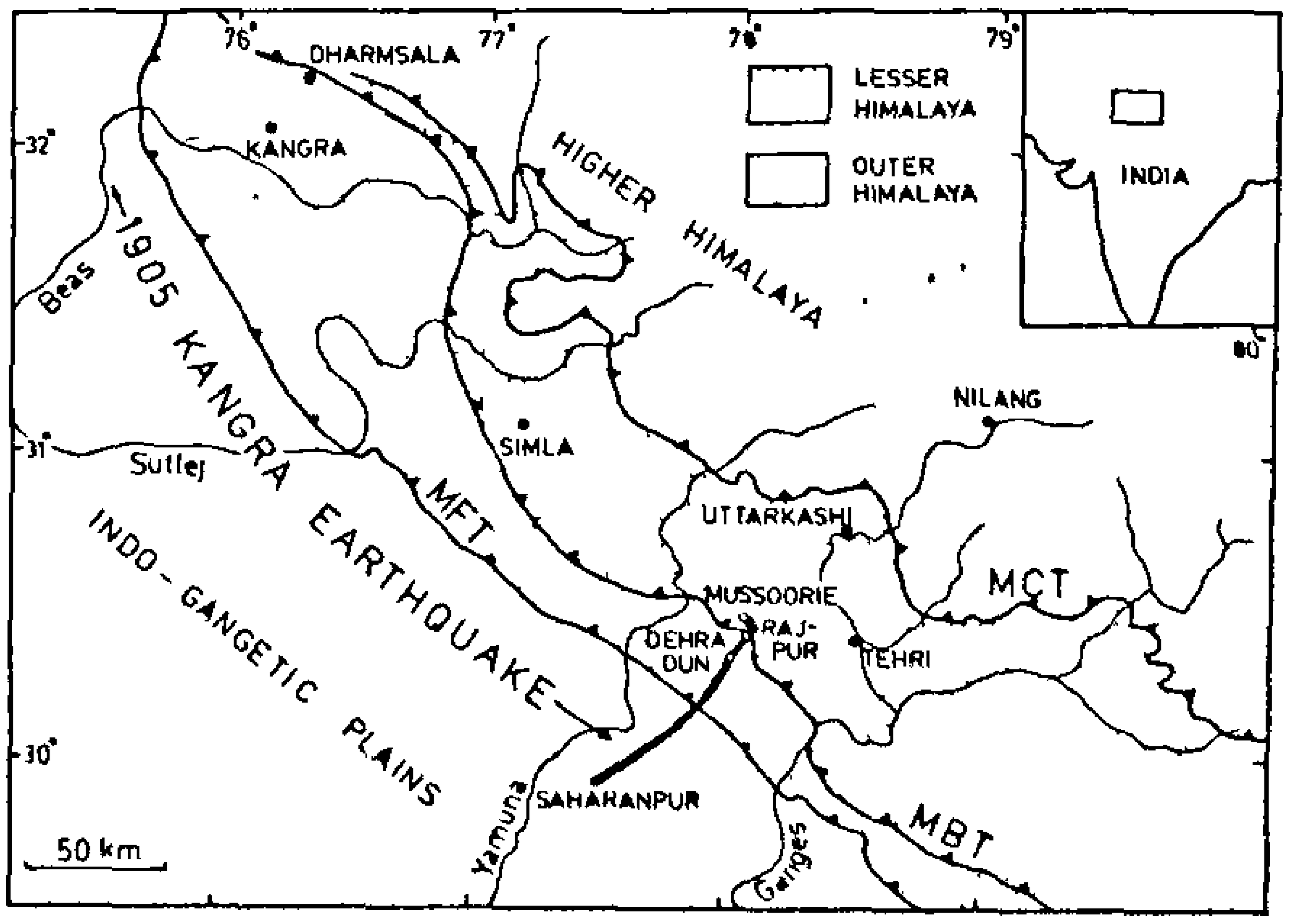

Figure 2. Simplified geologic map of northwestern Himalaya[23]. The thick line denotes the levelling route along which the observations of elevation changes are reported[14,21] in the region. The segment of the Himalaya affected by the great 1905 Kangra earthquake is indicated. Abbreviations used are as in Figure 1.

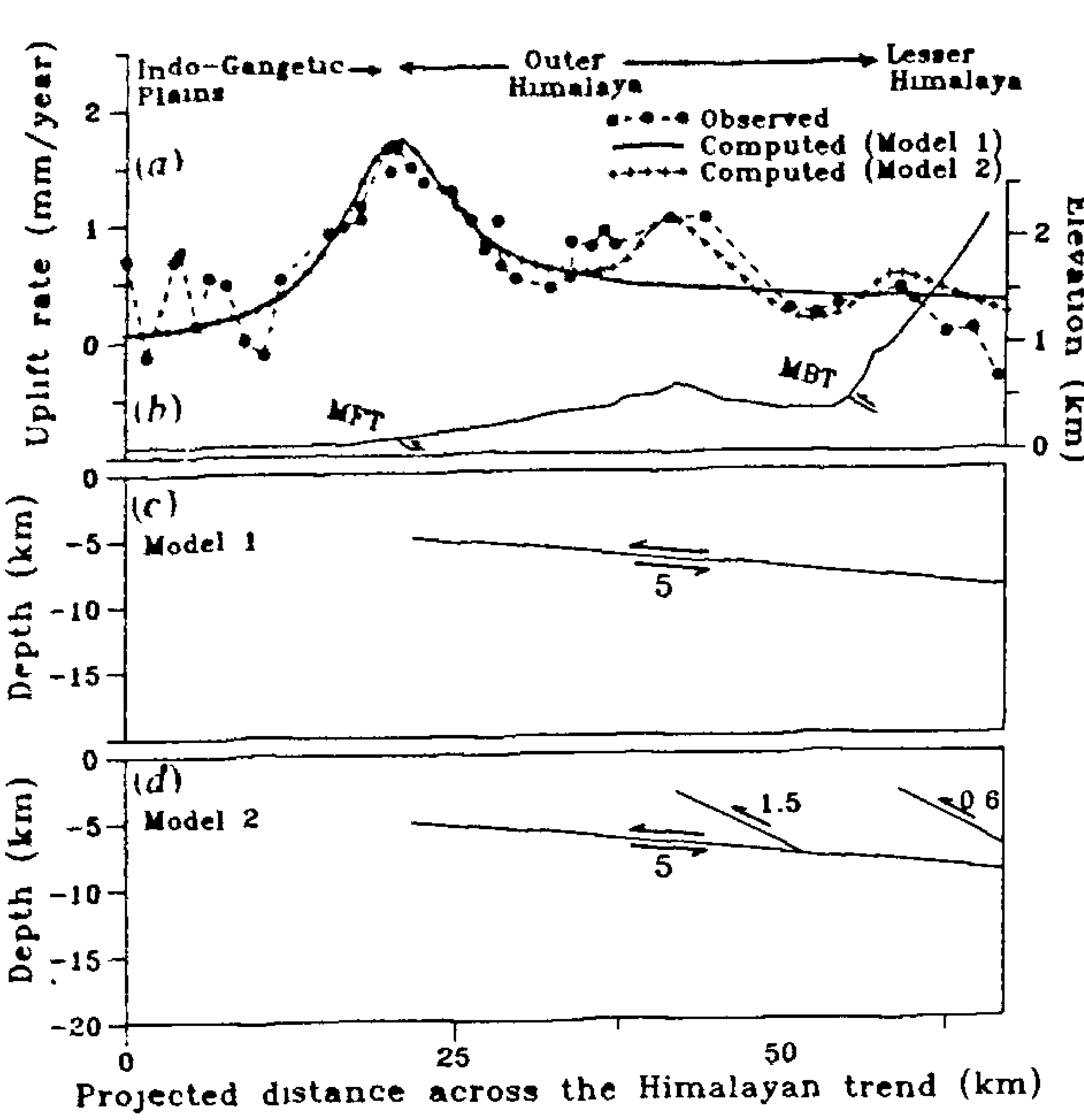

Figure 3. (a), is a comparison of the observed[3] and calculated uplift rates along the southern section of the Nepalese levelling line (b) shows the topography along the levelling line The calculated uplift rates in (a) are the result of slip in mm/year on the faults of the models shown in (c) and (d). The single fault in (c) and the main fault in (d) correspond to the detachment[7] on which the slip of 5 mm/year is indicated.

is also from this part of the line.

The numerical calculations for interpreting these data were carried out by adopting the elastic dislocation theory[5,6] to predict surface uplift rates for an assumed uniform rate of slip on a fault buried in an elastic half space. The two models shown in parts c and d of Figure 3 can explain the main uplift rate signal closely and the remaining observations to varying degree.

The most important and common feature of both these fault models is the buried low angle thrust fault dipping at 5° and extending southward up to the limit of the Outer Himalaya at a depth of 5 km. We equate this fault with the detachment[7] surface separating the Himalayan rocks from the underthrusting Indian shield material. The two additional faults in the model of Figure 3 *d* may be taken to simulate imbrication[8] under the Outer and southern Lesser Himalaya. The estimated slip rate on the detachment is 5 mm/year in both models and is firm within ±0.5 mm/year.

Uplift rate evidence for accumulation of elastic strains

This estimate of the slip rate on the detachment has to be compared with the rate of 18 ± 7 mm/year estimated by Molnar[9] for horizontal crustal shortening in the Himalaya in response to the convergence of Indian and Eurasian plates. This crustal shortening could involve both folding as well as slips on thrust faults in the Himalaya. An important limiting case would be that in which the crustal shortening is ascribed to slip of 18 ± 7 mm/year on the detachment.

We now explore the implication of these two different estimates of slip rate on the detachment by making the following assumptions. Firstly, we assume that the observed uplift rates arise from two competing deformations of the upper crust, namely, permanent aseismic deformations and recoverable elastic strains. The possibility of aseismic slip on buried faults in the Higher Himalaya has been mooted in the literature[7]. Although specific observational evidence has to be collected, still we entertain the possibility, based partly on the Nepalese levelling data, that even in the Lesser and Outer Himalaya, some of the ongoing, plate tectonics driven slip on the detachment is producing permanent aseismic deformations in the upper crust. Secondly, we assume that both types of deformations occur simultaneously due to slips on buried upper crustal faults in response to the continuing convergence of the Indian and Eurasian plates. Of course, the detachment is the most important of these faults and we consider only its slippage in writing the equations to follow. Thirdly, we assume that uplift rates due to both of these deformations can be estimated theoretically[10–15] using the above mentioned elastic dislocation theory[5,6]. Finally, it follows from the elastic rebound theory of earthquakes[16] that the ground elevation changes associated with the accumulation of elastic strains prior to an earthquake should have signs opposite to those for the ground elevation changes due to strain release during an earthquake.

Let V_a and V_e represent slip rates on the detachment that lead to accumulation of permanent aseismic and recoverable elastic strains in the upper crustal rocks of the Outer and southern Lesser Himalaya. Then the following two equations should hold.

$$V_a + V_e = 18 \pm 7 \text{ mm/year}, \quad (1)$$

$$V_a - V_e = 5 \text{ mm/year}. \quad (2)$$

Thus $V_a = 12 \pm 4$ mm/year and $V_e = 7 \pm 4$ mm/year, after rounding off in view of many uncertainties in the observations[3] and the foregoing assumptions for writing these equations.

Much more important than the estimated magnitudes of the partitioned slip rates is the fact emerging from this analysis that a significant part of the total estimated convergence rate of 18 ± 7 mm/year (ref. 9) is currently causing accumulation of recoverable elastic strains in the upper crust.

Elastic strain accumulation is for a great earthquake

Several recent analyses of available seismological data[7,9,11,14,17–20] from the Himalaya reveal a systematic pattern as follows. A more or less continuous belt of small and moderate magnitude earthquakes lies in the northern Lesser Himalaya close to the Main Central Thrust (MCT). The causative ruptures of great Himalayan earthquakes lie in the detachment and extend widthwise from this seismic belt southward up to the Outer Himalaya[7,14]. Both the southern Lesser Himalaya and the Outer Himalaya appear virtually aseismic during intervals between great earthquakes.

The main uplift rate signal of the Nepalese levelling data (Figure 3 *a*) is also in the Outer and southern Lesser Himalaya. Moreover, it has been observed during a period in which no great earthquake has occurred in the region. Therefore, this uplift rate signal implies strain accumulation for the next great earthquake of Central Nepal.

Levelling data from the Dehradun region

The only other significant repeat levelling observations for the Himalaya are reported for a few benchmarks along the Saharanpur–Mussoorie highway[4,21]. This line is about 80 km long in projected distance and traverses the Indo-Gangetic Plains and Outer Himalaya of the Dehradun region. The first levelling observations on this line were carried out between Saharanpur and Dehradun during 1861–62. The observations were extended via Rajpur to Mussoorie during 1903–04. After the Kangra earthquake of 1905, the complete line from Saharanpur to Mussoorie was relevelled in 1905–07 (ref. 21). The difference in the heights of benchmarks deduced from these two surveys was attributed to the Kangra earthquake[11,14,21]. Levelling was repeated during 1926–28 and 1974–76 again[4]. Uplift rates between Sahranpur and Rajpur estimated using levelling observations of the last three surveys[4] are compared with the Nepalese observations in Figure 4.

Major similarities in uplift rate data from the two profiles across the Outer Himalaya

The Nepalese[3] (Figure 1) and Indian[4] (Figure 2) levelling lines are separated by a distance of about 1000 km Still, in spite of the sparseness of Indian data, the relative highs and lows of the projected uplift rate profiles are remarkably similar across the Outer Himalaya in both cases (Figure 4). Also, the magnitudes of uplift rates are quite comparable in both profiles.

Implication for the Dehradun region

The immediate deduction from the similarities in the Nepalese[3] and Dehradun[4] data (Figure 4) and the above analysis of the former data is that recoverable elastic strain should be accumulating for a great earthquake in the latter region also. The last such earthquake of this region was the Kangra earthquake of 1905. Because of lack of suitable other constraints the deduced slip rates cannot be used to provide a useful estimate of return periods of such earthquakes in the region. Hence the time of occurrence of the next great earthquake cannot be predicted with confidence. But, Middlemiss[21] drew two closed isoseismals of intensity RF VIII in the Kangra–Dharmsala and Dehradun regions. Since RF IX and RF X intensity isoseismals were drawn only for the former region but not for the latter, it is conceivable that strain was released in the 1905 earthquake more completely in the Kangra–Dharmsala region than in the Dehradun region. Prudence in the matter of estimating earthquake risk requires us to assume that the next great earthquake in the Dehradun region may occur sooner rather than later on this account. But we emphasize that the date of the earthquake cannot be predicted from the available data.

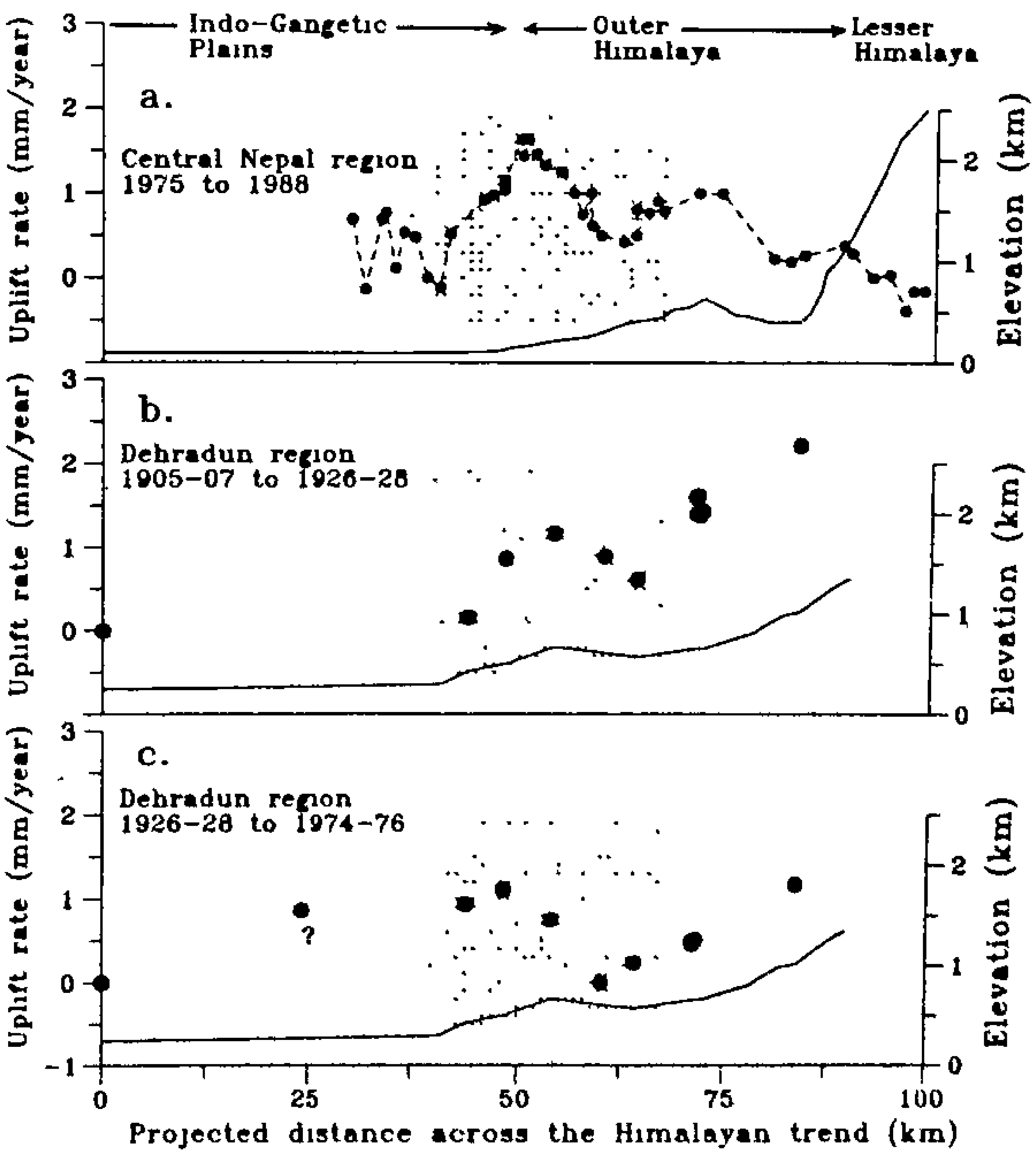

Figure 4. Comparison of uplift rates along Nepalese and Indian levelling lines. The periods between the levelling observations on which these rates are based are indicated The shaded portions highlight data from the Outer Himalaya The topography along the levelling line is also shown

Action required

The above discussion of Nepalese and Indian levelling observations underscores the need for systematic application of geodetic techniques for earthquake studies in India. Triangulation observations for measuring horizontal shifts of surface points in response to the slips on the detachment and associated faults would greatly improve the quality of interpretation for the Himalaya. Moreover, the length of survey lines normal to the strike of the Himalaya should be increased substantially for both vertical and horizontal controls. The Saharanpur–Mussoorie line should be extended via Tehri and Uttarkashi to Nilang in the Higher Himalaya in the first instance (Figure 2). The reference benchmark of the line should be shifted from Saharanpur at least as far south as the nearest bedrock outcrop. Also the number of benchmarks for which elevation changes are estimated should be increased considerably. Finally, systematic reoccupation of benchmarks should be carried out at frequent intervals of 3–5 years. Similar lines should be set up and resurveyed in other segments of the Himalaya falling within the Indian territory. The relatively high cost of geodetic work would be still less in the long run than the savings that may accrue in terms of reduced loss of lives and damage to property during a great earthquake if suitable prognostic features emerge from comparison of successive observations along one or more lines. Seismologists have pinned their hopes for prognostication on geodetic observations for a long time[22]. Maybe we can succeed in India.

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