Implications of recent levelling observations for Tehri and other high dams in the Himalaya

Seismic hazards around the Tehri and other existing and proposed high dams in the Himalaya are a matter of concern to many people. The magnitude and dimensions of the problem appear to increase with every new set of geophysical and geological data gathered from the Himalaya. But the flexibility and readiness of the people involved to improve their designs for the dams transparently in the light of the evolving perceptions about seismic hazards[1–5] is not evident to us at least. Still, we buttress further in this article the evidence for an aspect of seismic hazards in the Himalaya.

A set of repeat geodetic levelling observations[6] obtained in Nepal (Figure 1 and 2 *a*) during the last two decades vividly reveal the ongoing deformation of the Himalayan upper crustal rocks in response to the relative convergence of Indian and Eurasian lithospheric plates. Laterally localized near-surface deformation is superimposed on broader-scale crustal strains (Figure 2). We provide here an explanation for some of the more localized elevation changes observed in Nepal and consider their seismic hazard implications.

The Nepal levelling data

Jackson and Bilham[6] have recently published the results of two successive sets of levelling observations across the width of Nepal along the main north south highway through Kathmandu (Figure 1). The period elapsed between the two sets varied between 2 and 13 years. Figure 2 *a* is a display of the observed annual rates of elevation changes along a line normal to the local trend of the Himalaya. Figure 2 *a* is created by projecting the benchmark positions along the winding highway onto a horizontal straight line oriented along N 10°. Jackson and Bilham[6] have provided an interpretation of the relatively longer wavelength features of the curve displayed in Figure 2 *a* by postulating a slip rate of 5 mm/yr on the detachment (Figure 2 *c*), an intracrustal thrust fault type of surface of separation between the Himalayan rocks above and the relatively northward-moving Indian shield material below[7].

Data from only the southern Nepal are shown in Figure 2 *a* for three reasons. Firstly, distance-dependent random errors in levelling observations grow northward from the southern end of the levelling line[6]. Secondly, as the levelling line approaches the main central thrust (MCT), the effect of plate convergence accommodated along a major ramp in the detachment becomes prominent in the form of a large-amplitude, long-wavelength signal in the elevation change observations[6]. This is not of interest in the present context. Thirdly, most of the river valley projects and high dams that can be envisaged to develop the hydroelectric and irrigation potential of these hills are located in the Lesser and Outer Himalaya.

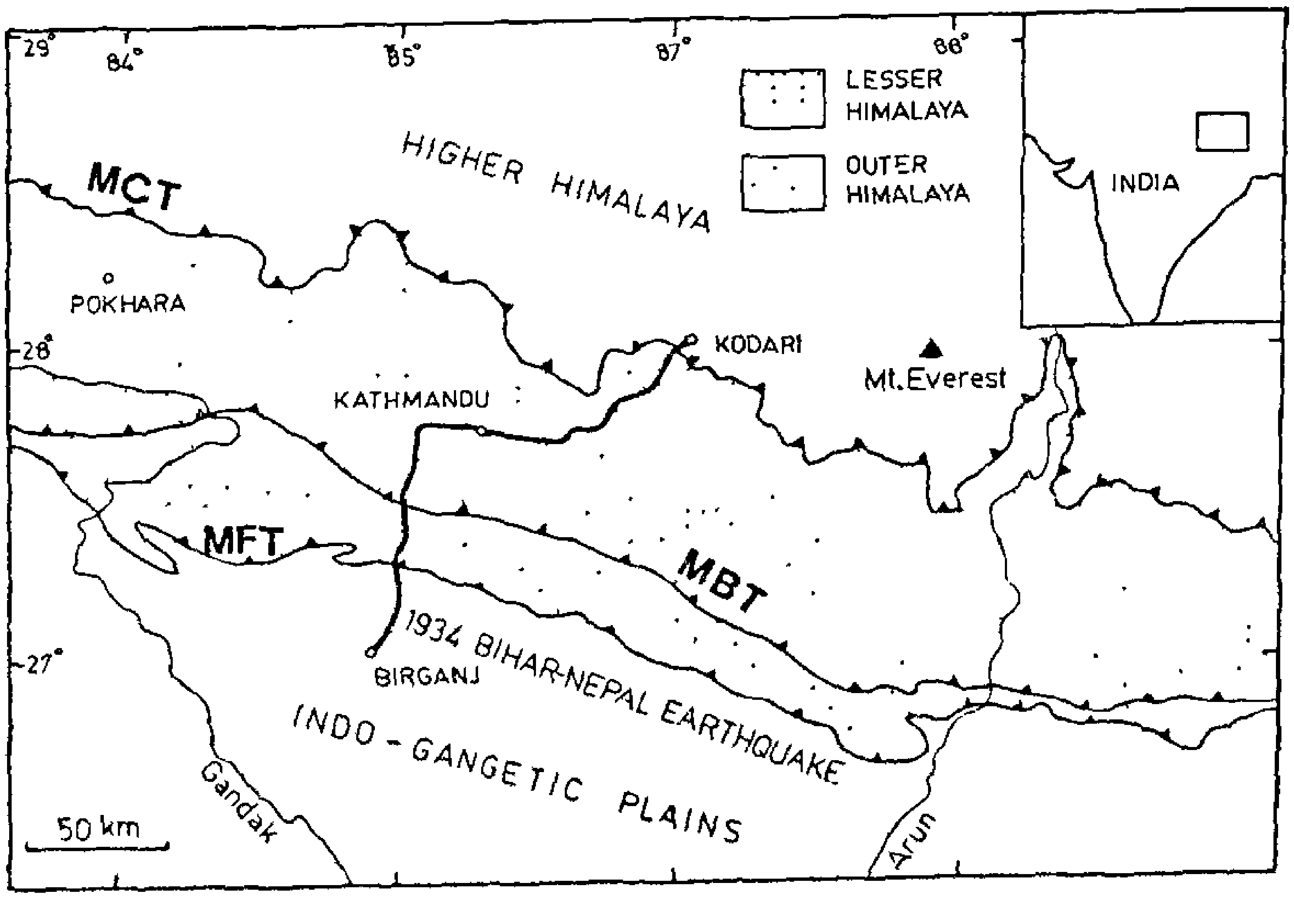

Figure 1. Location of the levelling line in Nepal. MFT – main frontal thrust; MBT – main boundary thrust; MCT – main central thrust.

Imbricate thrusts in the Nepal Himalaya

Several shorter-wavelength signals in the Nepalese levelling data deserve explanation also. We show in Figure 2 *c* our interpretation of the two most prominent of these features on the assumption that they could be associated with slip on relatively steeper near-surface thrust faults. Similar faults could be conceived for other less prominent short-wavelength features in the data. Such shallow-level and relatively steep dipping thrust faults are called imbricate thrust[8]. They occur in suites and are associated with a major, deeper thrust fault dipping at a comparatively gentler angle[8]. Although geological mapping in different parts of the Himalaya is still far from complete, numerous imbricate thrust faults have been mapped already[9, 10]. Since precise locations of benchmarks used by Jackson and Bilham[6] have been masked, it is not possible to associate the imbricate thrusts postulated by us in Figure 2 *c* with specific thrust faults mapped in the Nepal Himalaya. The possibility also exists that the geodetic observations may have revealed imbricate thrusts which are as yet 'blind' or concealed below the ground surface.

Role of imbricate thrusts during a great thrust earthquake

Since the observations reported in Figure 2 *a* were taken during a period when no major earthquake had occurred in the region, they reveal aseismic crustal defor-

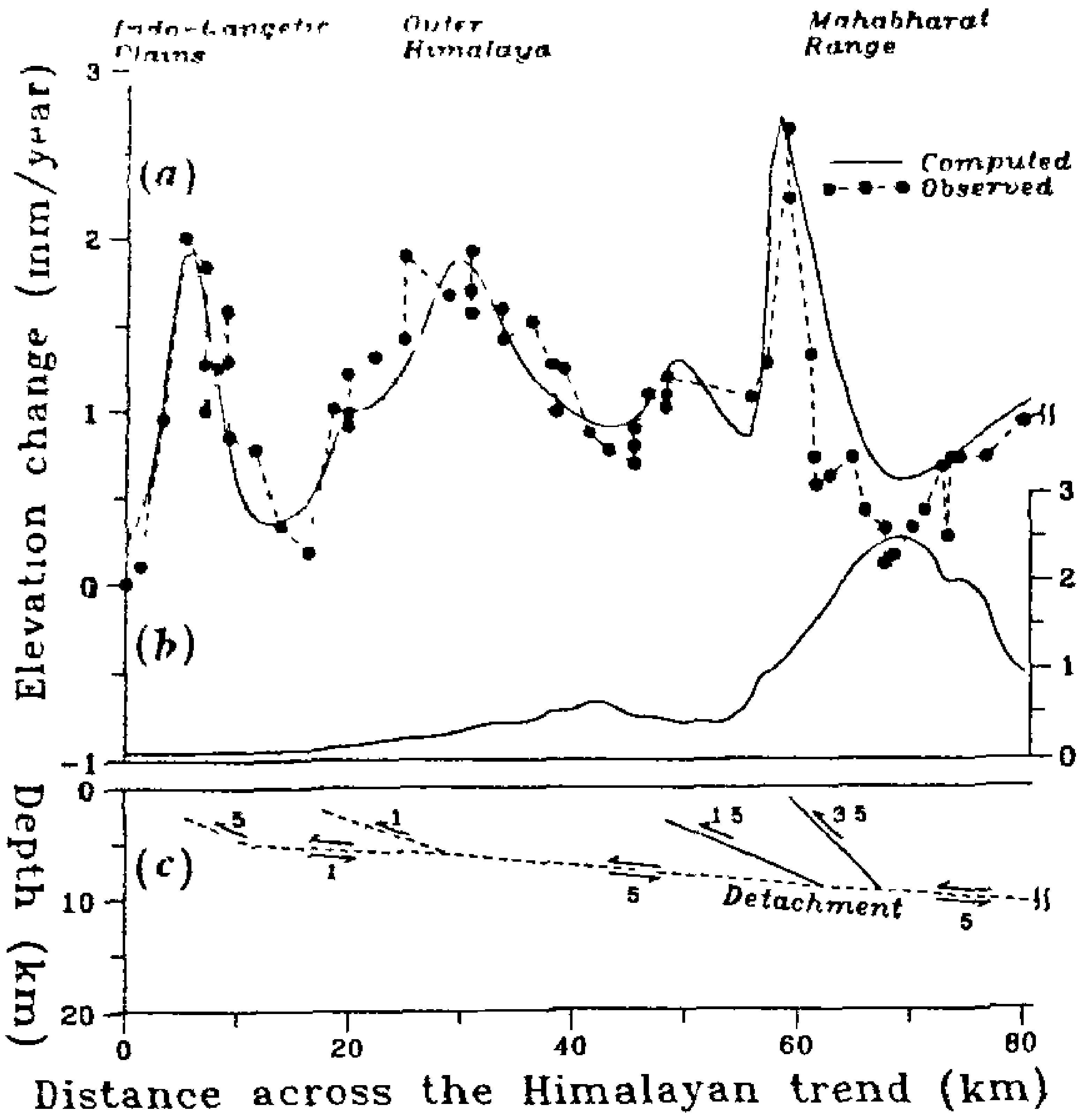

Figure 2. *a*, Comparison of observed and calculated rates of ground elevation changes in southern Nepal. *b*, Profile of topography along the projected line. *c*, The model used to compute the results shown in (*a*). The dotted parts of the fault model were also considered by Jackson and Bilham[6] to explain the long-wavelength features. Solid lines indicate the imbricate faults suggested by us to explain two short-wavelength features in the observations. The numerals shown against faults represent the postulated annual slip rates (mm/yr) on the respective faults to explain the observations.

mation. It is not unreasonable to surmise that these imbricate thrusts will be reactivated also in the next great earthquake of the region. These faults could be loci of large relative slips between rocks across them. Significant ground level changes may occur in regions near their updip terminations. Concomitant high particle velocities and accelerations may be expected in these pockets during great earthquakes. Ample evidence of this has been documented in the literature.

Oldham[11] surveyed the changes in the ground surface brought about in the Shillong plateau region during the great earthquake of 12 June 1897. He reported surface-breaking faults near the northern border of the Shillong plateau. He estimated relative ground level changes of up to about 12 m near these faults. Although Oldham[11] estimated that the faults were subvertical, Gahalaut and Chander[12] have surmised that they could be imbricate to the major mid-crustal thrust fault in which the main rupture of this earthquake occurred. The 1897 earthquake caused the ponding of south-flowing rivers in the southern part of the Shillong plateau[11]. This too could be explained with coseismic activity on imbricate thrust faults under southern Shillong plateau[12]. Finally, Oldham[11] argued lucidly from the evidence of boulders thrown into air during the earthquake that ground acceleration exceeding g (acceleration due to gravity) occurred during that earthquake. We suggest that slip on a nearby imbricate thrust was involved in this case also. It is important to recall that Oldham[11] has given exactly the same explanation for these observations. However, he used the phrase 'secondary and tertiary reverse faults' instead of 'imbricate thrust faults'. The hazard implication of this observation of high acceleration has been remarked by Khattri[2] also.

Byrne *et al.*[13] investigated the source of the 1945 Makran earthquake and suggested that prominent uplift along a narrow coastal belt could be due to slip on a shallow fault imbricate to the deeper detachment-type plate boundary in the Makran subduction zone. Barrientos and Ward[14] and Plafker[15] also referred to significant activity on imbricate thrusts extending up from the main plate boundary thrust faults associated with the great Chile earthquake of 1960 and the great Alaska earthquake of 1964.

Implication of imbricate thrusts for civil engineering structures in the Himalaya – the concept of the nearest active fault

An important consideration for the design of a critical civil engineering structure, such as a dam or a nuclear reactor, especially from the standpoint of seismic hazards, is the distance of the site from the nearest active fault. Ordinarily, the distance between an engineering site and a surface-breaking active fault is determined on a geological map. However geodetic and other geophysical techniques, such as earthquake observations, can lead to identification of subsurface active faults also. Geodetic techniques have the advantage that even aseismically active faults can be detected.

Recent investigations of great Himalayan earthquakes have led to the consensus that they occur by extended ruptures in the detachment[7, 12, 16–20]. The depth of the detachment has been estimated to be less than 5 km under the main frontal thrust (MFT) and about 17 km under the MCT[7, 16, 18, 19, 21–23]. Thus, there is at least one active fault beneath every engineering site in the Outer and Lesser Himalaya. If some faults imbricate to the detachment could be active in this Himalayan domain, as has been remarked elsewhere on geological grounds[1, 10, 24–26] and shown to be the case in the Nepal Himalaya through geodetic observations, then they could be potentially even nearer to an engineering site than the detachment.

On the Tehri dam site

The Kumaun–Garhwal Himalaya, including the region around Tehri dam site in Garhwal (Figure 3), has been investigated geologically, especially in the recent decades. The monograph by Valdiya[10] is an important source book for the geology of the Lesser Himalaya of the Kumaun–Garhwal region. Valdiya[1, 10, 24–29] and others[30–32] have documented geomorphic and other geological evidence for neotectonic and even continuing tectonic deformation in different longitudinal and transverse segments of the Kumaun–Garhwal Himalaya. This includes suggestions about possible deformation along imbricate thrusts. See the discussion section below for a limitation of the geologi-

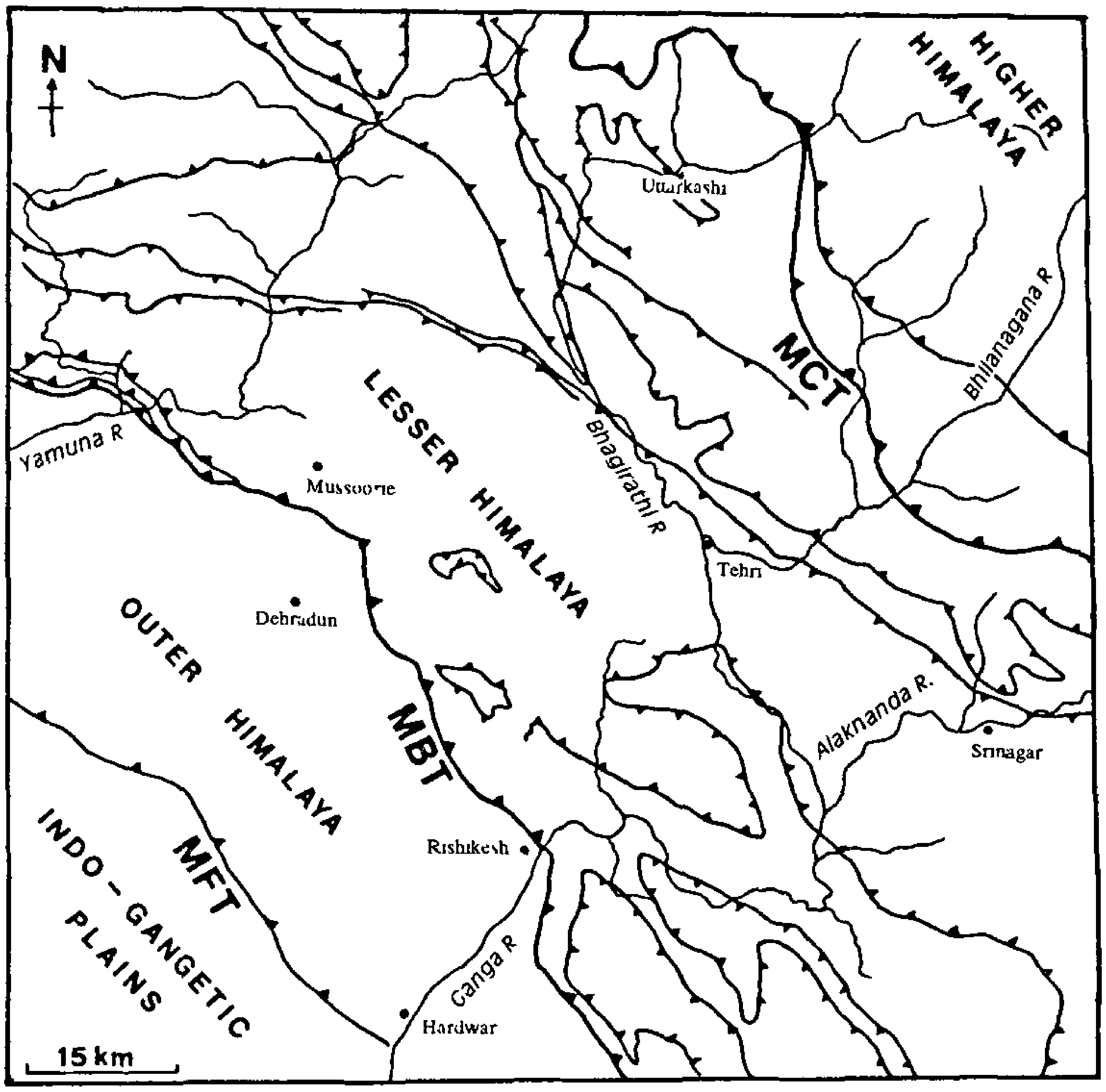

Figure 3. A randomly selected geological map of a section of the Lesser Himalaya showing some of the mapped thrust faults (after Valdiya[10]). Smaller unnamed faults hading northerly are imbricate faults.

cal inference regarding the activity of faults.

The 1991 Uttarkashi earthquake[33] and recent seismicity observations[34–35] provide further confirmation about the active or ongoing tectonics of the Garhwal region. There was damage at Tehri during the great Kangra earthquake of 1905 (ref. 36). The rupture models proposed by Seeber and Armbruster[7], Chander[19] and Gahalaut and Chander[16] suggest that the detachment under the NW Garhwal Lesser and Outer Himalaya slipped during the earthquake. Epicentres of many small and microearthquakes have been located within about 10 km of the Tehri dam site through observations made[34, 35] in the 1980s. Composite fault plane solutions for some of these earthquakes suggest activity along high-angle reverse faults within the upper 15 km of the crust[34, 35]. These seismologically inferred reverse faults too could be properly called imbricate thrusts. However, in the absence of sufficiently detailed geological mapping as well as the inevitable uncertainties in the estimates of hypocentral coordinates it is not possible to associate these seismologically inferred imbricate thrusts with specific geologically mapped faults of the region. Still in our opinion this is an evidence showing that at least some imbricate thrusts are active today close to the Tehri dam site.

Detailed designs for Tehri dam and appurtenant structures have been made already. Still we suggest that, in view of the magnitude and importance of the project, detailed repeat geodetic observations should be undertaken around the Tehri dam site to supplement the geological and seismological observations and to detect if in addition any buried or exposed faults near this site also are currently creeping aseismically as in the Nepal Himalaya. If such observations have been taken already by governmental agencies, then the results should be published so that interested scientists outside these agencies, may also assess them. The published levelling observations for the Saharanpur-Dehradun–Mussoorie highway[36, 37] are not relevant for this purpose because of the distance between the site and the closest benchmark.

Discussion

Bomford[38] in his well-known book on geodesy specifically recognized that geodetic surveys are useful at civil engineering sites to mark points on the ground with great accuracy. Bomford[38] also underlined the use of repeat geodetic observations for crustal deformation studies. Our analysis above illustrates the application of geodetic observations for identifying the locales of ongoing crustal deformation in the Himalayan setting specifically. Combining the results of sufficiently detailed geodetic observations with the geological and seismological observations should help in settling the question of the nearest active faults for various dam sites with greater confidence.

The main advantage of geodetic methods is that we can detect activity which has occurred during the period between successive occupations of the benchmarks. The geological procedures, on the other hand, indicate activity without being very specific about their dates except when geochronological evidence regarding the activity is forthcoming. Geodetic observations should complement seismicity observations by identifying currently active faults.

We recall here that geodetic observations have been collected in India for nearly two centuries[39]. But only a very small subset of these are repeat observations with a possible bearing on crustal movements in respective regions. There are three prime requirements when geodetic observations are to be used in this way. Firstly, the benchmarks should be closely spaced. Secondly, the reference benchmark should be well outside the region of suspected crustal deformation. Thirdly, the reoccupation of benchmarks should be at sufficiently short intervals of time. To the best of our knowledge there are no repeat geodetic observations in India which fit these requirements entirely. Repeat geodetic observations in connection with the 1897 Shillong plateau[11] and the 1934 Bihar–Nepal[40] earthquakes suffer from the fact that they were within or close to the epicentral tracts. Repeat levelling along the Saharanpur-Dehradun–Mussoorie line has revealed[36, 37] changes during and subsequent to the Kangra earthquake of 1905. But the large distances between benchmarks, the long time gaps between successive observations and the desirability of shifting the reference benchmark at Saharanpur to a bed rock site further south have been remarked[41]. Finally, repeat geodetic observations to measure aseismic fault movements in the Hardwar[42], Kangra[43] and Mandi[44] regions had too limited a spatial extent in our opinion.

An important reason why geodetic methods have not been employed widely for dam site investigations is that in the past the procedures were slow and relatively costly. However, with the availability of the global positioning system these factors should no longer be disadvantages or deterrents for carrying out geodetic surveys as envisaged.

Conclusion

Our interpretation of recent levelling observations in the Nepal Himalaya suggests that a part of the current interseismic upper crustal deformation may be localized along shallow imbricate thrust faults. We have emphasized three implications of these geodetic observations and analyses. Firstly, similar imbricate faults may be slipping aseismically elsewhere in the Himalaya also. Secondly, during great earthquakes of the respective regions, coseismic slip along such faults may lead to locally strong ground motion with attendant large displacements and high accelerations. This could be a threat to nearby civil engineering structures, such as dams, as well as smaller, non-engineered constructions, such as individual houses in villages. Thirdly, there is need to expand repeat geodetic observations in all Indian segments of the Himalaya.

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