Earthquakes and elevation changes in the Himalaya

Ramesh Chander

Ground elevation changes associated with great earthquakes in the Himalaya appear to contribute significantly to differential uplift of the Outer or Siwalik Himalaya relative to the Lesser Himalaya. The differential uplift of the Higher or Great Himalaya relative to the Lesser Himalaya appears to be the cause of many small and micro-earthquakes of the Himalayan seismic belt.

EVERY earthquake induces ground elevation changes. Usually the changes are subtle and require instrumental observations. But we begin by mentioning two Indian examples where the changes could be observed directly. A scarp of about 3 m, called 'Allah Bund' by the local people, was created over a distance of about 25 km due to the Kuchchh earthquake of 1819 (ref. 1). Similarly, faults with prominent vertical components of slip broke the ground surface at several places in the Shillong plateau during the great earthquake of 1897 (ref. 2). Dams and waterfalls, also signifying ground level changes, were formed along many river courses. Severe flooding occurred in the Brahmaputra downstream of Guwahauti due to ground subsidence induced by the earthquake. Ground tilting led to a notable change in the line of sight between Tura at the western margin of the Shillong plateau and Rowmari in the plains to the west of the plateau[2] (Figure 1). All these different observations of ground elevation changes have been used to estimate the extent of rupture on the subsurface causative fault for the 1897 earthquake[3] (Figure 1).

We discuss in the following paragraphs two distinct ways in which earthquakes appear to be associated with the ongoing relative elevation changes between the Outer (or Siwalik), Lesser and Higher (or Great) Himalaya. Attention is focussed on the Garhwal Himalaya (Figure 2) where suitable observations are available.

The link between earthquakes and elevation changes

The concept of an earthquake cycle[4, 5] is useful for seismically active regions, such as the Himalaya, where great earthquakes occur repeatedly at each site. Basically, it is recognized that the accumulation of earthquake-generating stresses is a relatively slow process taking decades and centuries whereas the process of stress release is a rapid one taking seconds only. The slow process of stress accumulation starts anew after a major earthquake. There are concomitant changes in strains or deformations of rocks during an earthquake cycle. Several types of rheological responses to stresses may be envisaged[4].

Strain changes in rock imply changes in relative positions of particles. Such changes at depth in the source region of an earthquake have corresponding effects on particles at the ground surface[4]. Therefore, during an earthquake cycle, heights and horizontal positions of particles above and around an earthquake source region also undergo slow changes during the stress accumulation phase and rapid, almost instantaneous, changes during the stress release accompanying

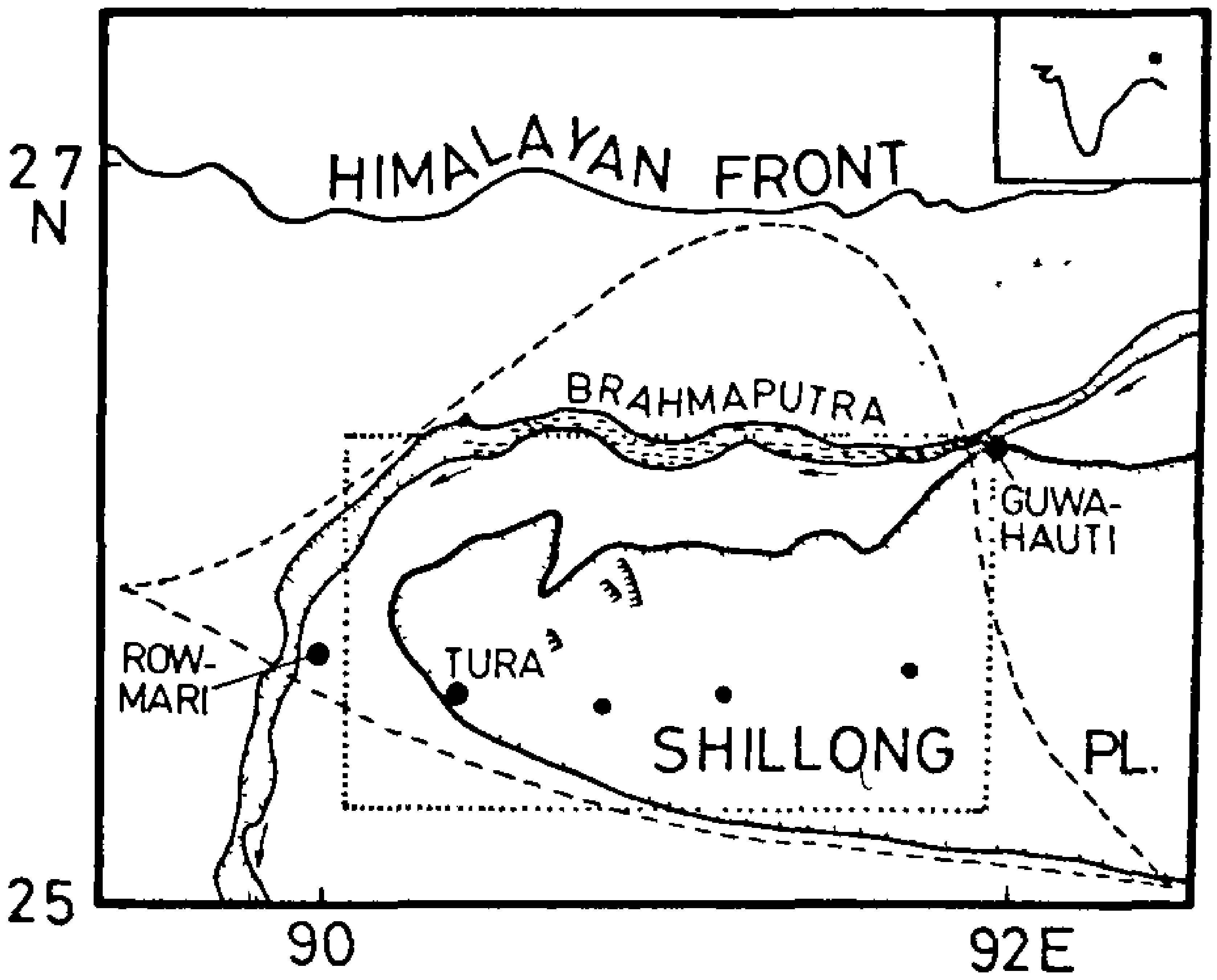

Figure 1. Epicentral region of the great Indian earthquake of 1897 is shown by the dashed line[2]. Thick line with dots marks boundary of the Shillong plateau Section of the Brahmaputra shown by thick lines and dashes experienced flooding due to earthquake-induced subsidence New surface breaking faults are shown by lines with hatching on the side of ground subsidence Unmarked dark dots indicate localities where the earthquake affected river courses The dotted rectangle is the inferred rupture on the causative fault[3]

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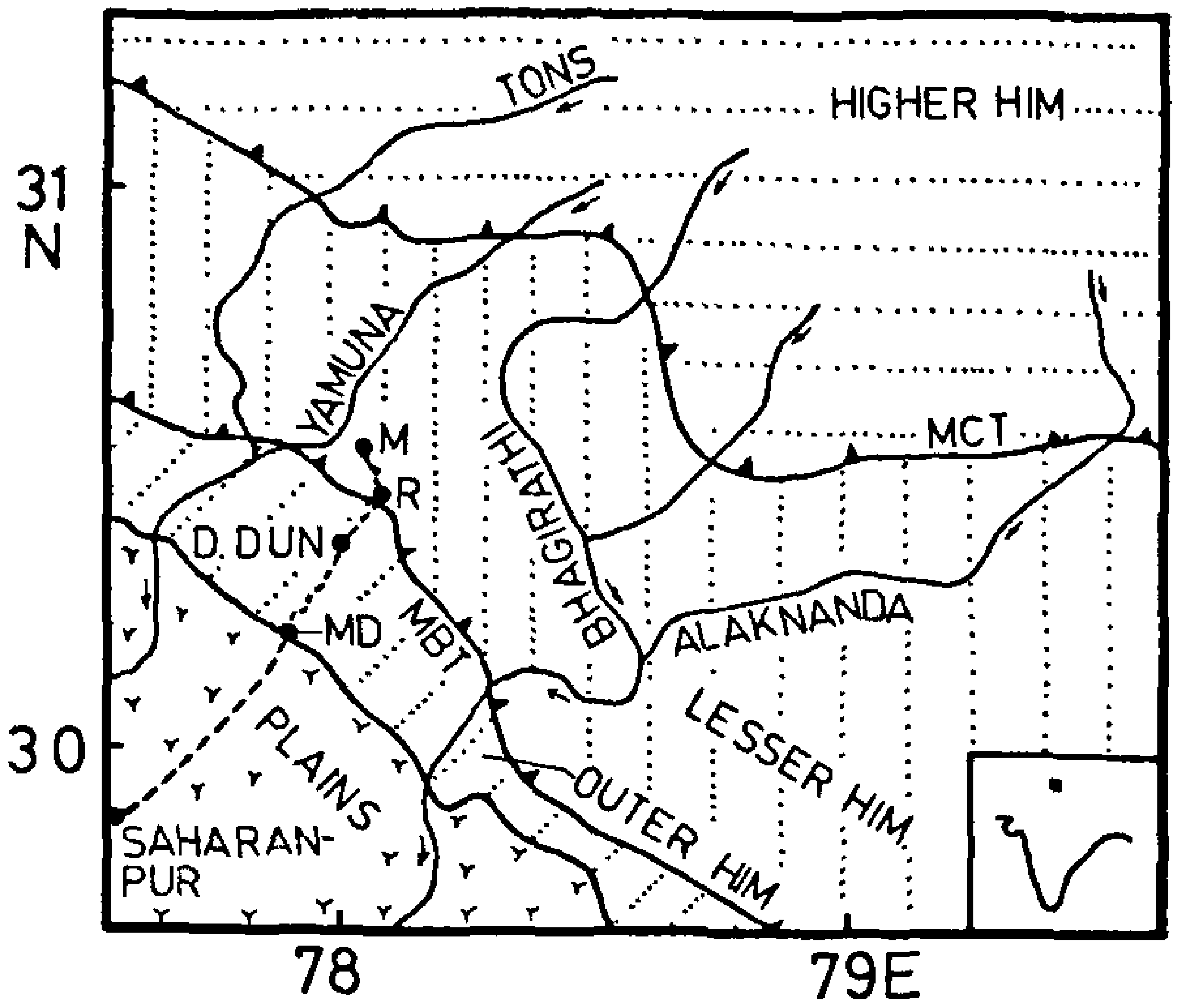

Figure 2. Map of the Garhwal Himalaya MBT and MCT denote the Main Boundary and Main Central Thrusts. M, R and MD denote localities of Mussoorie, Rajpur and Mohand The thick dashed line is the Saharanpur–Mussoorie road

the earthquake. The level changes before, during and after an earthquake are called pre-, co- and post-seismic elevation changes[4, 5].

Elevation changes in the Garhwal Himalaya

Coseismic elevation changes during the 1905 Kangra earthquake

Provided they are suitably large, the ground elevation changes linked with the earthquake cycle in a seismically active region may be measured geodetically. Precision geodetic levelling was carried out along the Saharanpur–Dehra Dun road first in 1861–62 (ref. 6) (Figure 2). The measurements were extended from Dehra Dun to Mussoorie in 1903 (ref. 6). The great Kangra earthquake occurred on 4 April 1905. It caused extensive damage in parts of Garhwal Himalaya also. The precision levelling was repeated between Saharanpur and Mussoorie during the 1905–07 period. Heights above sea level of bench marks located across the width of the Outer Himalaya, between Mohand and Rajpur, had increased by 10 to 14 cm (Figures 2 and 3). The increase of bench mark heights decreased towards Mussoorie in the Lesser Himalaya and Saharanpur in the Indo-Gangetic Plains[6] (Figures 2 and 3).

Middlemiss[6] associated these height changes with the Kangra earthquake. Chander[7] and Gahalaut and Chander[8] used these data to infer about the earthquake source. Our preferred model is that the earthquake occurred on a 280 km × 80 km area of a thrust fault dipping at about 5° to the northeast[7]. This fault area stretched between Kangra and Dehra Dun in the longer dimension and was buried mostly beneath the Lesser Himalaya. The depth of burial was about 10 km at the southwestern long edge. The rocks above the fault moved up and to the southwest relative to those below by about 5 m (ref. 7). This major fault is probably the same surface which separates the underthrusting Indian shield rocks from the Himalayan rocks above[7, 9] (Figure 4).

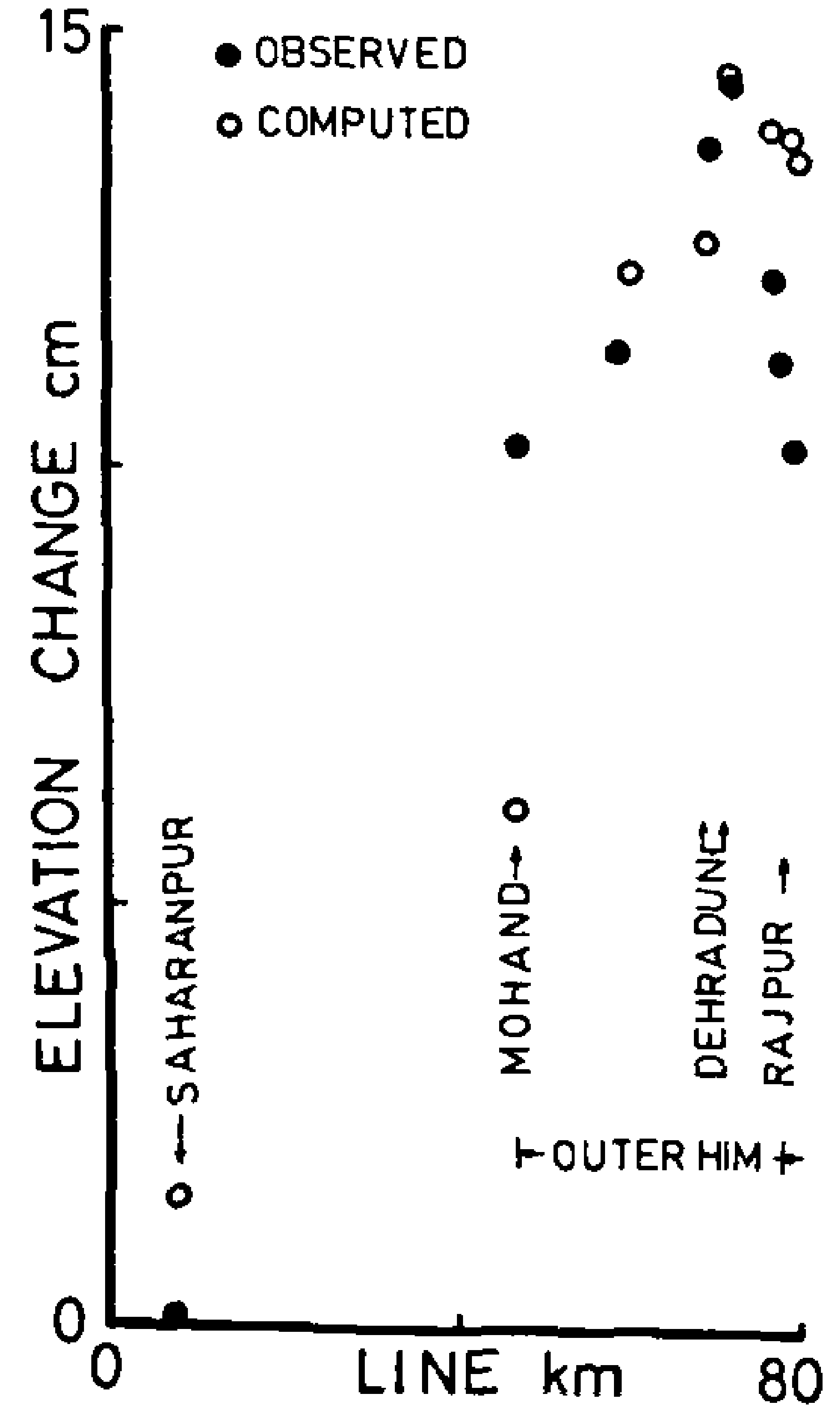

Figure 3. Observed and computed ground elevation changes along the Saharanpur–Mussoorie road up to Rajpur[7]

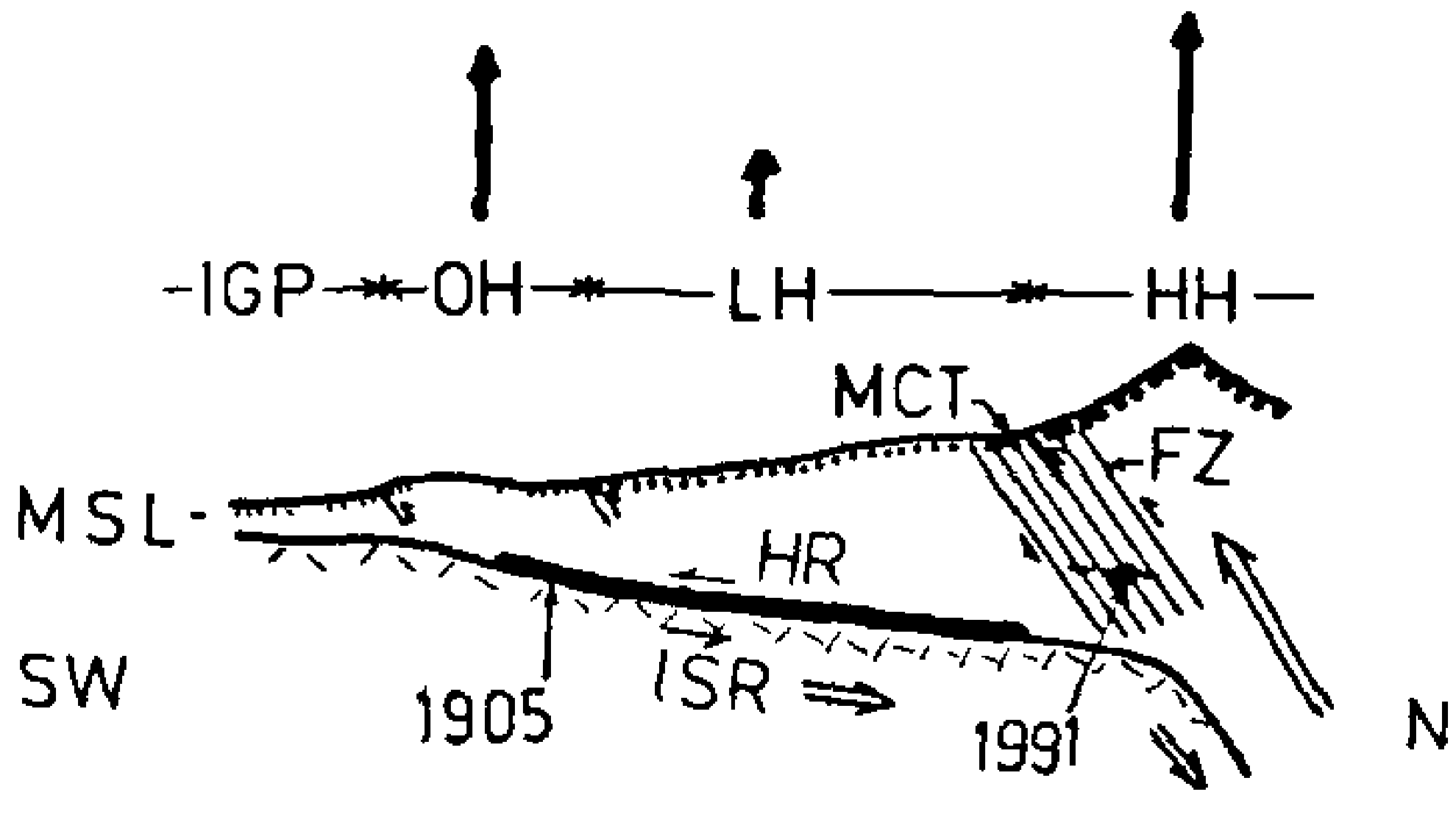

Figure 4. A schematic vertical section through the Garhwal Himalaya along a NE-SW line to put the ideas of uplift of the Outer and Higher Himalaya in a perspective. The figure is not to scale. This holds especially for depictions above mean sea level (MSL) The sizes of thick arrows at the top suggest that these relative uplifts may take place when the Outer (OH), Lesser (LH) and Higher (HH) Himalaya may be all rising relative to the centre of the earth HR and ISR denote Himalayan and Indian shield rocks The fault zone (FZ) represented schematically is from Figure 8 The thick line indicates the portion of the HR–ISR boundary which behaving as an active thrust fault slipped during the 1905 Kangra earthquake The inferred fault of the 1991 Uttarkashi earthquake is also shown schematically IGP represents the Indo-Gangetic plains

Theoretical calculations for this fault model of the Kangra earthquake suggest that elevation changes were probably greater for other points between Kangra and Dehra Dun. The same calculations indicate that heights of points in the Lesser Himalaya decreased and thus subsidence occurred. But there are no measurements to check these predictions.

Post-seismic changes

Precision geodetic levelling was carried out between Saharanpur and Mussoorie in 1925–28 and 1973–74 also[10]. Our preliminary calculations based on the elevation changes suggest that permanent ground deformations as well as earthquake-generating stresses have started accumulating again in the Dehra Dun region.

Uplift of the Higher Himalaya and small earthquakes

Earthquakes in the Garhwal Himalaya

Earthquakes of a wide range of magnitudes have been investigated in the Garhwal Himalaya (Figures 2 and 5). All moderate and some small magnitude earthquakes of the Garhwal Himalaya since ca. 1964 have been located by international agencies using data recorded by seismographs situated outside the region. The 1991 Uttarkashi earthquake belongs to this category. The epicentres of such earthquakes lie in a belt near the Main Central Thrust[11] (Figure 5).

Smaller earthquakes of the region have to be investigated by local recording with sensitive seismographs. A systematic study of small and micro-earthquakes has been carried out in the region between the Tons and Alaknanda valleys of the Garhwal Himalaya during the period 1979 to 1990 (refs. 12–14). Five to seven portable seismographs were deployed at a time in an array whose size varied between 45 and 70 km, and whose position was shifted along the Main Central Thrust from time to time. The belt of small and micro-earthquakes traced in this way coincides with the belt mentioned in the preceding paragraph[13, 14] (Figure 5). The estimated focal depths of the locally recorded earthquakes ranged between 0 and 23 km, the vast majority occurring at depths less than 13 km (refs. 13, 14).

Fault plane solutions

An earthquake fault plane solution is a simulation of the causative fault at the earthquake focus. It also reveals the relative motion of rocks across the fault at the beginning of the earthquake. Computation of the fault plane solution by the US Geological Survey for the 1991 Uttarkashi earthquake indicates nodal planes dipping at 5° due N26° and 85° due N206°. On either plane the rocks above moved up relative to those below. In conformity with the general practice for moderate earthquakes of the Himalaya as a whole[15], the plane dipping in N26° direction is picked as the fault plane. This choice makes it plausible to assume that the earthquake is related to the underthrusting of Himalayan rocks by the Indian shield material (Figure 4).

A composite fault plane solution

An individual fault plane solution of the above type cannot be constructed reliably when the earthquake is of relatively smaller magnitude and the number of recording stations is small. A composited fault plane solution for 18 small earthquakes between the Bhagirathi and Alaknanda valleys (Figures 6 and 7) indicates nodal

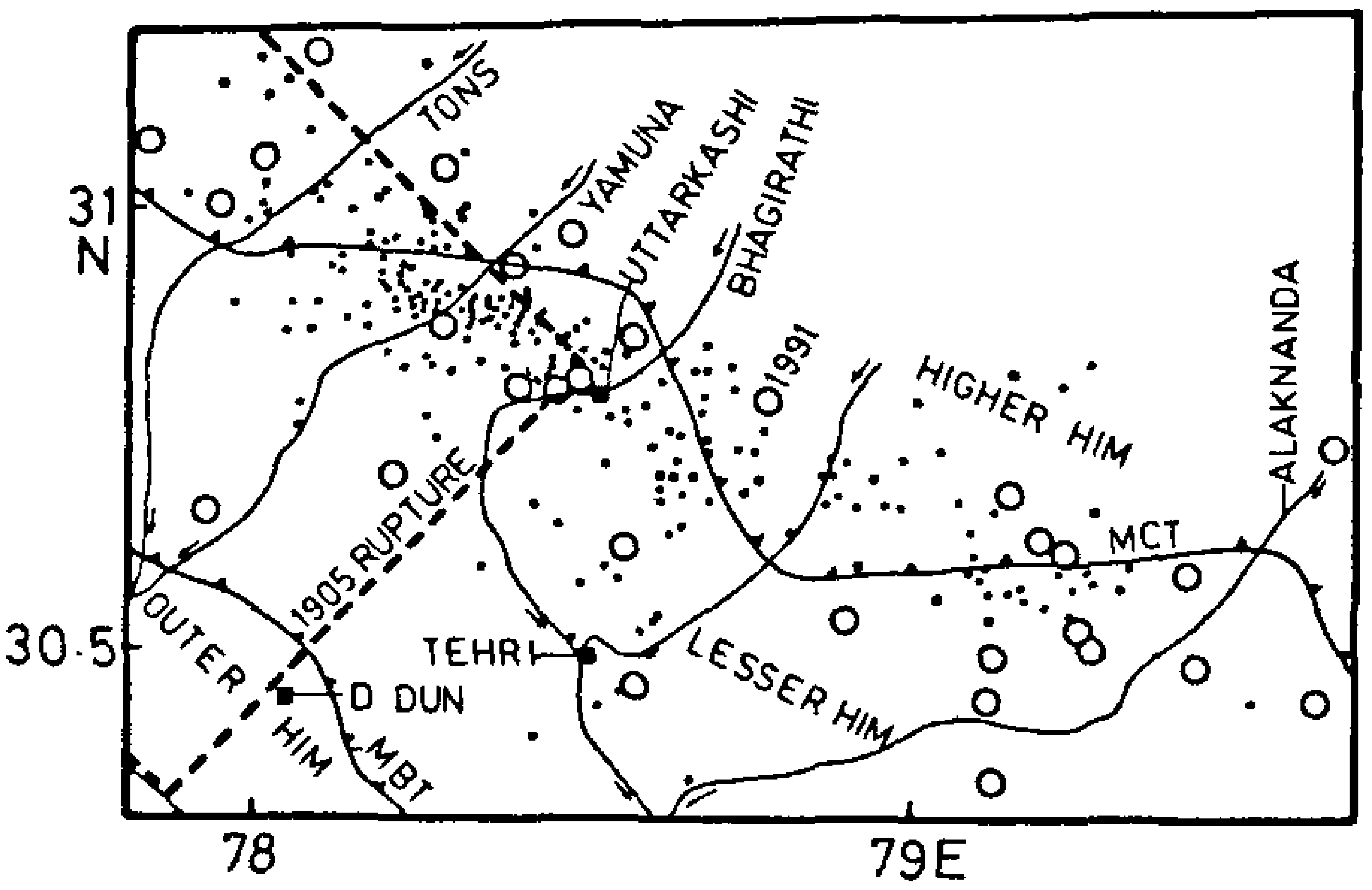

Figure 5. Seismicity of the Garhwal Himalaya The inferred rupture of the 1905 Kangra earthquake is after Chander[7]. Open circles represent epicentres of teleseismically located earthquakes The dots mark epicentres of locally recorded small and micro-earthquakes[12–14].

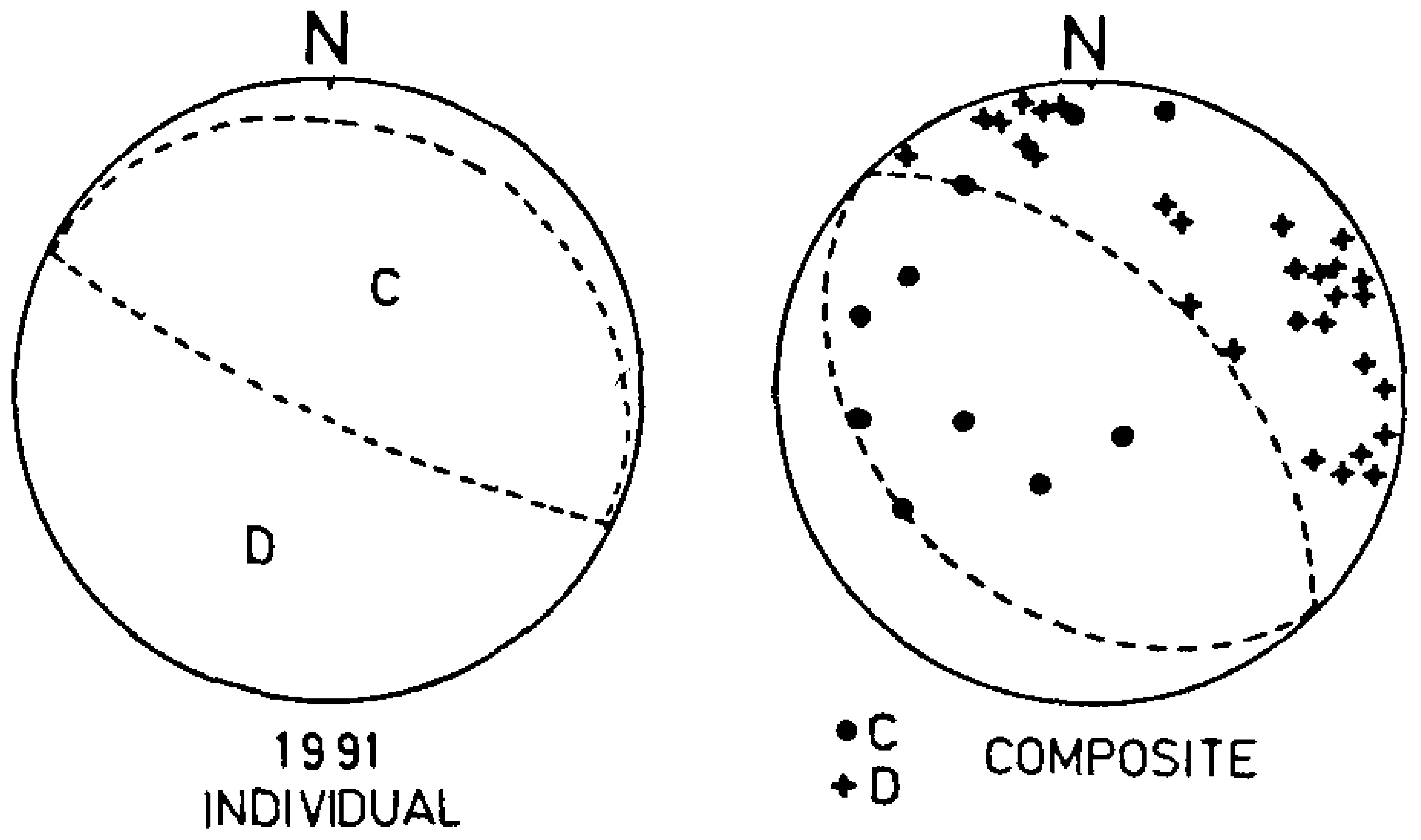

Figure 6. Fault plane solutions for earthquakes between Bhagirathi and Alaknanda valleys. The individual solution for the 1991 Uttarkashi earthquake is after US Geological Survey The composite solution is based on data for earthquakes with epicentres shown in Figure 7 (ref 13)

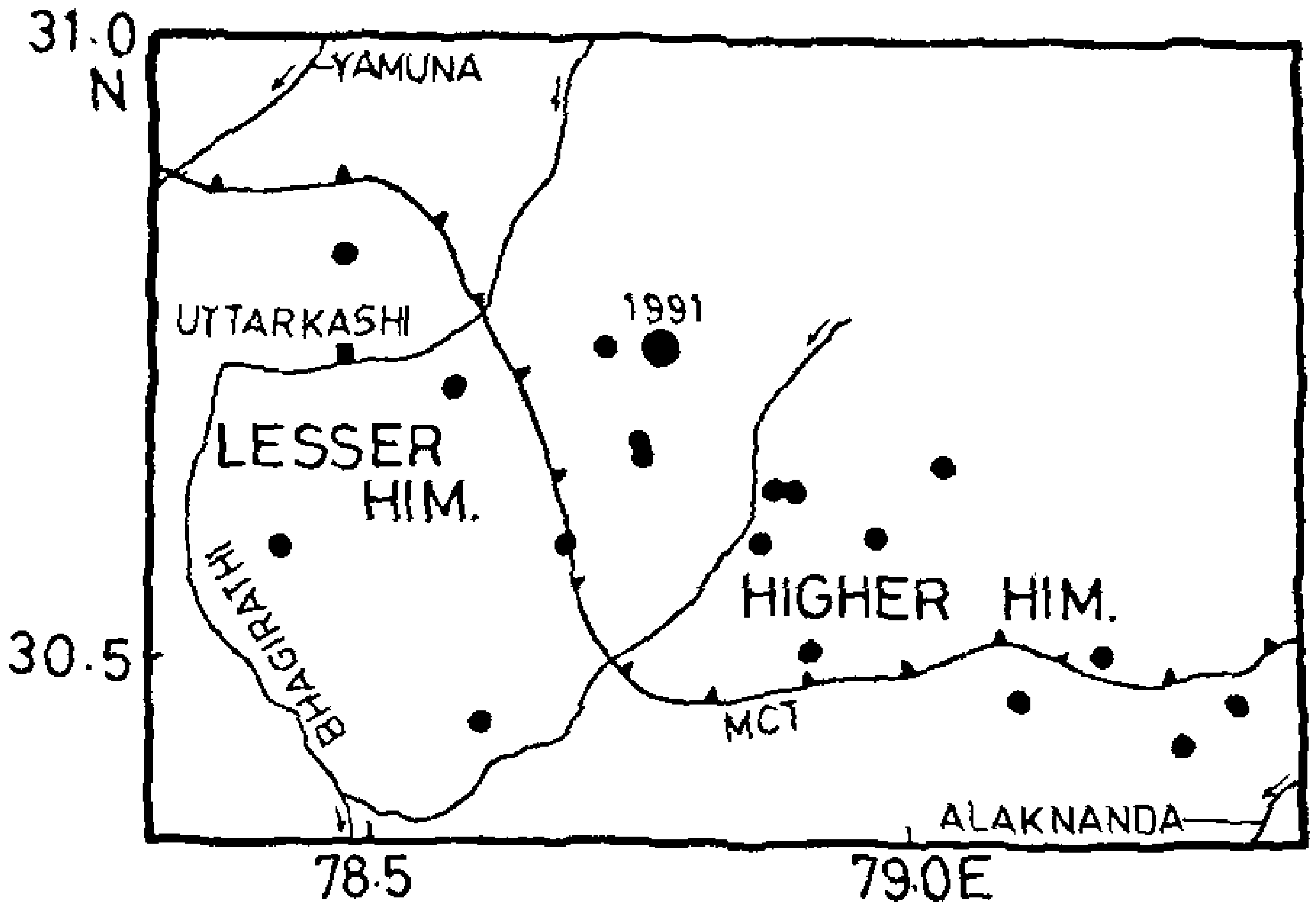

Figure 7. Epicentres of earthquakes whose data were used in the composite fault plane solution of Figure 6 The 1991 Uttarkashi earthquake epicentre is shown for completeness

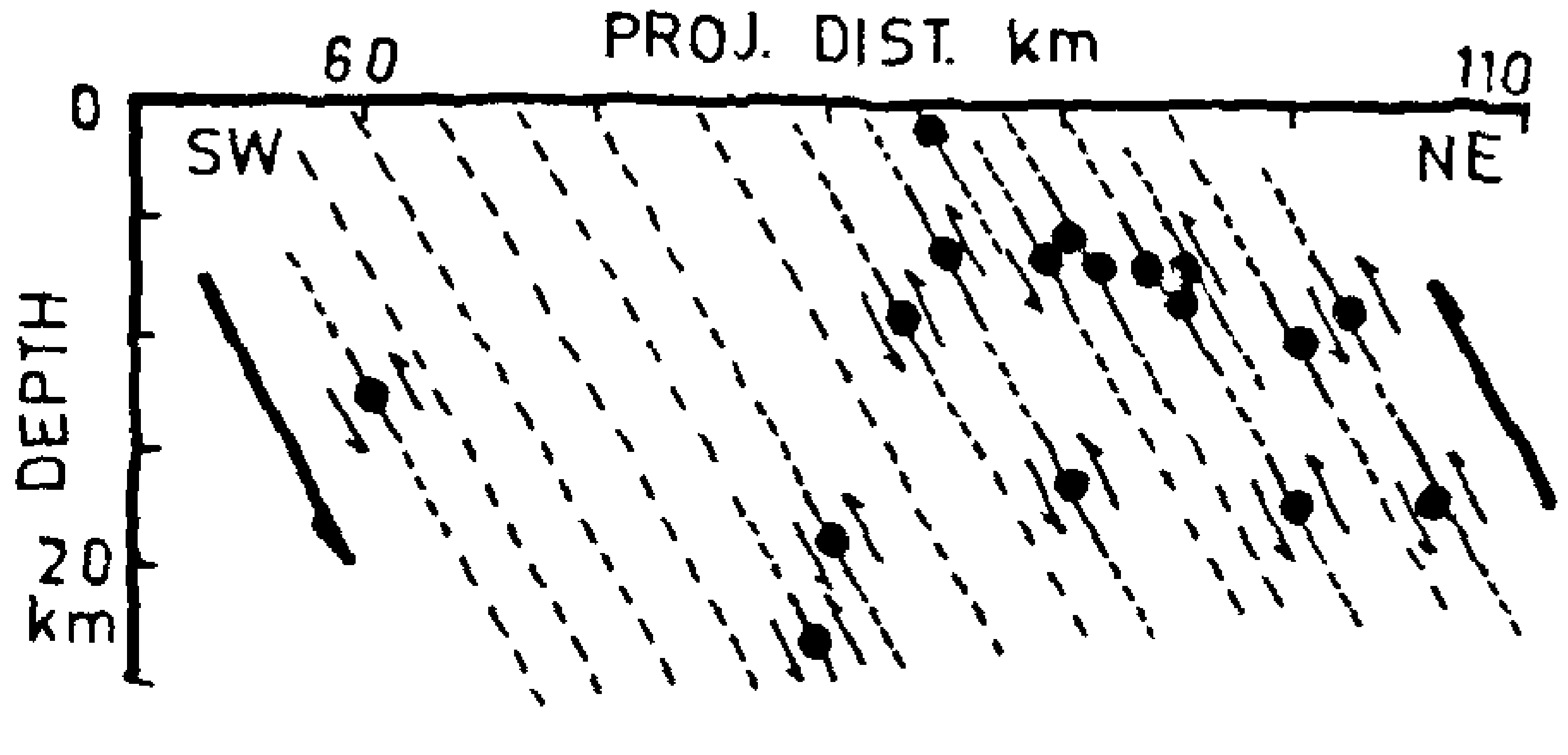

Figure 8. A partly schematic, NE-SW oriented, vertical cross-section across the conjectured fault zone Solid dots represent hypocentres of small and micro-earthquakes pertaining to Figures 6 and 7. The causative faults of these earthquakes are shown as solid line segments in accord with the composite fault plane solution of Figure 6 These are the ruptured segments of more extensive faults of the zone See text under Interpretation for further details Horizontal distances are from an origin at 30°N and 78°E after projection onto the plane of the figure

planes dipping northeastward at 60° and southwestward at 30° (ref. 13). The former nodal plane having reverse fault motion is chosen as the fault plane as it simulates numerous northeast dipping reverse and thrust faults mapped geologically in the region.

Interpretation

It may be concluded that the region of the upper crust demarcated by the foci of small and micro-earthquakes in the Garhwal region is a fault zone separating the Higher and Lesser Himalaya. A system of closely spaced faults dipping 60° to the northeast, consistent with the orientation of the chosen nodal plane in the composite solution, exists within the fault zone (Figure 8). As each new earthquake occurs in the fault zone, the rocks immediately above and to the northeast of the causative fault move up relative to the rocks below and to the southwest (Figure 8). The amount of slip in such small earthquakes would be small also, say in the range of centimetres or less, compared with the estimated 5 m for the Kangra earthquake[7].

Each small and even micro-earthquake is the cause of appropriately small elevation changes of the ground. The cumulative effect of a large number of such earthquakes on different faults of the above fault zone will be a quantum of over all uplift of the Higher Himalayan rocks relative to the Lesser Himalayan rocks. In this view, the earthquakes are the cause of the uplift.

Alternatively, the uplift of the Higher Himalaya relative to the Lesser Himalaya may be accommodated through distributed small slips on various faults of the above zone. The slip on each fault in turn would be responsible for the small and micro-earthquakes associated with it. Such a view is entirely consistent in seismology because it is the application of elastic rebound theory[1] to these earthquakes. The cause of the relative uplift is the underthrusting of Indian shield rocks beneath the Himalayan rocks in response to the continuing convergence of Indian and Eurasian plates. The underthrusting rocks experience a change from brittle to ductile rheology as they penetrate deeper while moving northward. In the geographic vicinity of the Main Central Thrust, the transition has progressed to such an extent that a steepening of the angle of underthrusting occurs[9, 16]. This imparts a corresponding steeper uplift to the overlying Main Central Thrust sheet (Figure 4). Thus the Higher Himalaya appears to rise relative to the Lesser Himalaya.

A similar interpretation can be made from a composite fault plane solution for small and micro-earthquakes of the Tons–Yamuna valley region[14] (Figures 2 and 5). However, several small and micro-earthquakes in the Yamuna–Bhagirathi valley region yield a strike–slip type composite fault plane solution[12, 13]. This indicates concurrent horizontal relative movements between different segments of the Himalaya.

Geomorphic evidence

Support for the view that the Higher Himalaya is rising relative to the Lesser Himalaya comes from studies of river bed gradients. Seeber and Gornitz[17] observed that trans-Himalayan rivers have steeper bed gradients in their courses through the Higher Himalaya than in the courses above and downstream. They attributed it to the continuing rise of the Higher Himalaya relative to the Lesser Himalaya in response to plate tectonic forces. Gupta[18] found in the case of six major rivers of the Garhwal Himalaya that their beds too were steeper in the Higher Himalaya than in the Lesser Himalaya. The regions of changes in bed gradients coincide with the belt of small and micro-earthquakes in the Garhwal Himalaya.

An implication

More than one set of faults may be active at any time in the fault zone under consideration. Conceivably, slip on a steep fault of the fault zone could produce chattering or grating action on rocks separated by the gentler dipping faults (Figure 4). This could trigger a moderate or great earthquake on a gently dipping fault by facilitating slip due to reduction of effective normal stress and attendant lowering of frictional stress. In other words, small pulses of uplift of the Higher Himalaya relative to the Lesser Himalaya could act as triggers for moderate and great Himalayan earthquakes.

Concluding remarks

Uplift of both the Outer and Higher Himalaya relative to the Lesser Himalaya is attributable ultimately to the underthrusting of the Himalayan rocks by the Indian shield rocks in response to plate tectonic forces (Figure 4). While the geodetically observed uplift of the Outer Himalaya is interpreted as an effect of the Kangra earthquake, the small and micro-earthquakes of the Garhwal region near the Main Central Thrust are regarded as effects of the relative uplift of the Higher Himalaya.

The observations discussed here cover a time span of about 130 years only. This is but an instant in geologic terms. Still we may extrapolate and assert that the uplift of the Higher Himalaya is a steady trend for the time being. It began some time in the past and will persist for some more time at least. Geological evidence[19] suggests that relative uplift of the Outer Himalaya too has been occurring for some time. But more geodetic observations are needed to decipher shorter term trends.

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