sent a synchronously rotating mmf vector corresponding to the stator currents. The components of this vector, at a particular instant are OB along the axis of the pole (d-axis) and OA along the quadrature or the q-axis. During oscillation, let the vector OP still rotating synchronously, be increased by PP′ and let the rotor occupy the dotted position displaced from the original position by an angle $\Delta\theta$. The component of OP′ along the d-axis is now OB_2 and OA_2 along the q-axis. According to the observer, the change in vector OP is B_1B_2 along its d-axis and A_1A_2 along the q-axis and the total change is therefore, $(B_1B_2^2 + A_1A_2^2)^{1/2}$, which is incorrect. If the observer did not move with the rotor (Kron's axis) and rotated synchronously, he would have measured BB′ and AA′ as the respective changes and would estimate the total change as $(BB'^2 + AA'^2)^{1/2}$ which is the actual change. It may be seen that neglecting the second order effects,

$$AA' = A_1A_2 - PA \cdot \Delta\theta,$$

or $$\delta i_q = \Delta i_q - i_d \cdot \Delta\theta$$

and $$\delta i_d = \Delta i_d - i_q \cdot \Delta\theta,$$

or $$\begin{bmatrix} \delta i_d \\ \delta i_q \end{bmatrix} = \begin{bmatrix} \Delta i_d \\ \Delta i_d \end{bmatrix} + \begin{bmatrix} & 1 \\ -1 & \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} \cdot \Delta\theta$$

or $$\underline{\delta i} = \underline{\Delta i} + \underline{\rho i}\Delta\theta$$

where ρ is the rotation tensor.

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Probable influence of Tehri reservoir load on earthquakes of the Garhwal Himalaya

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Our mathematical simulation suggests that the Tehri reservoir load may produce relatively small changes in the stabilities of nearby seismogenic faults and lead to comparable small advancements or postponements in the times of occurrence of earthquakes of the Garhwal Himalaya.

THE nature and extent of the environmental impact of the proposed Tehri reservoir (Figure 1) is a matter of considerable concern. A major apprehension is that the reservoir may trigger earthquakes. We examine here the possibility of an adverse influence of the reservoir on local seismicity through numerical simulations.

We may clarify at the outset that a man-made reservoir may influence local seismicity through firstly, load-induced stresses and secondly, pore pressure effects. The present study is an examination of only the load effects of Tehri reservoir because virtually nothing is known about the subsurface hydraulic regime in the region of interest. A partial study of this type appears justified because we should assess at least those effects of Tehri reservoir that we can with some degree of confidence with the resources at our command. Further comments which tend to mitigate partially the consequences of ignoring the pore pressure effects are given below.

The basis for the simulation

We assume that the problem may be examined through the following two-step procedure. Firstly, we may use the available seismological information to identify the hypocentral regions as well as the causative faults of future earthquakes around the Tehri reservoir region. It is implicit here that the hypocentres will lie in the causative faults. Secondly, we may assess the time (t) dependent influence of the reservoir load at a future hy-

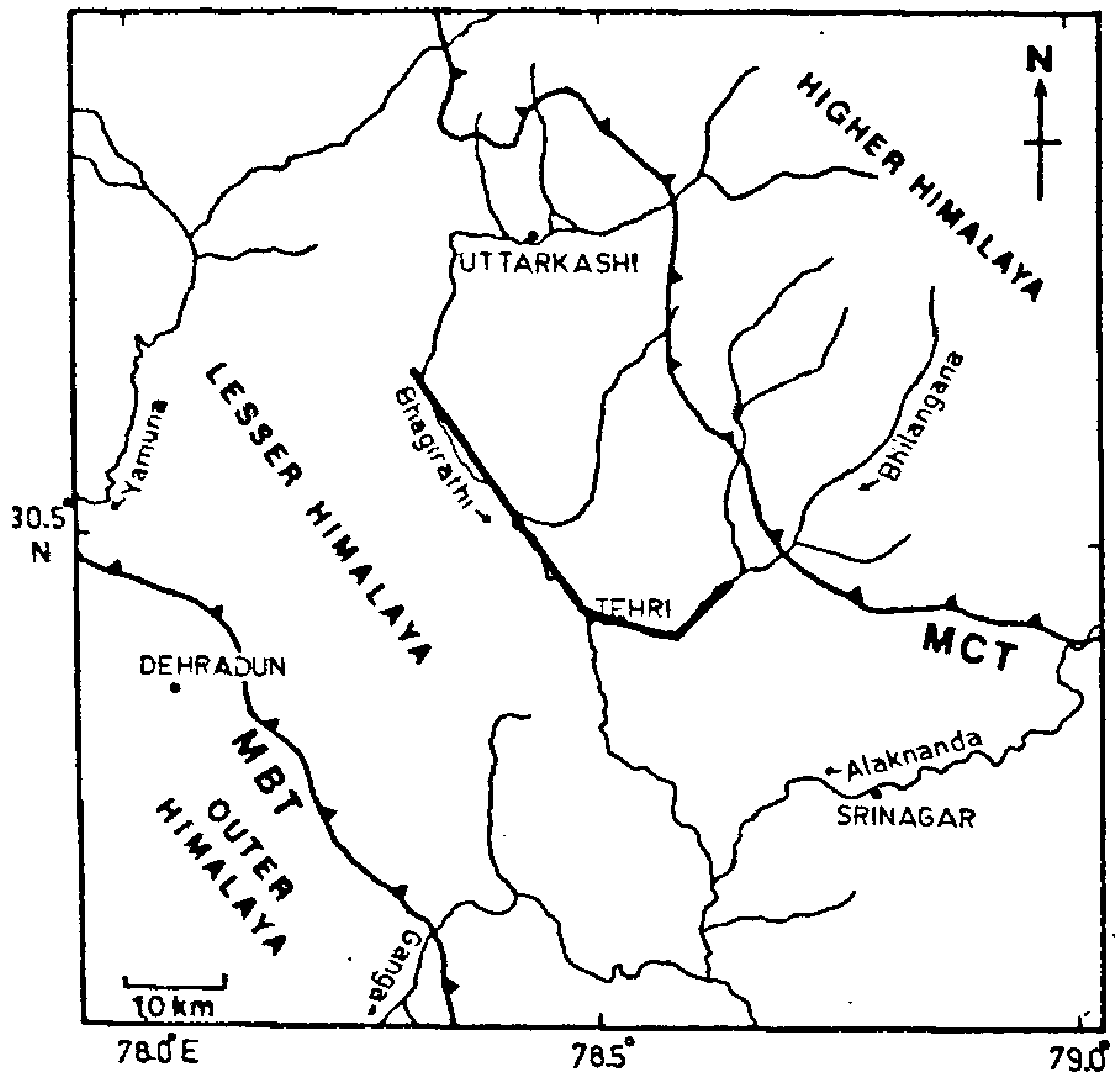

Figure 1. Tehri dam site is located a short distance downstream of the junction of Bhilangana river with Bhagirathi river. The thick straight lines represent the simulated axes of the proposed Tehri reservoir in the Bhilangana and Bhagirathi branches. The array of point loads mentioned in the text would be located along these lines at 1 km interval. The map and geological information are compiled from Valdiya[22]. MCT and MBT stand for Main Central and Main Boundary Thrusts.

pocentre by estimating whether the load induced normal ($\sigma_r(t)$) and shear ($\tau_r(t)$) stresses on the causative fault will enhance its stability or instability by opposing or promoting relative slip across it.

Joint influence of ambient and reservoir-induced stresses on a nearby fault

Situation in the absence of a reservoir. Elastic stresses due to diverse causes will be acting at the hypocentre of a future earthquake even in the absence of the reservoir. We shall call these stresses collectively as the ambient stresses. Let $\sigma_a(t)$ and $\tau_a(t)$ be the cumulative, time varying, normal and shear components of ambient stresses on the identified fault at the hypocentre. If $\tan\phi$ is the coefficient of friction on the fault, then let a quantity $S_a(t)$, called fault stability[1,2] under ambient stresses, be defined through the relation

$$S_a(t) = \sigma_a(t)\tan\phi - \tau_a(t). \qquad (1)$$

Here, $\sigma_a(t)\tan\phi$ represents the frictional stress mobilized on the fault under the ambient stresses and it opposes slip on the fault. $\tau_a(t)$, on the other hand, is the motive shear stress promoting slip on the fault. $S_a(t)$ is a measure of the difference between the opposing frictional and motive shear stresses and it should be positive ordinarily. In the absence of the reservoir a natural earthquake will occur at a time t_{Hn} when $S_a(t_{Hn})$ equals zero numerically. It is acknowledged that it may be difficult to measure or estimate the ambient stresses. But the concepts hold so long as it is assumed that earthquakes occur by frictional failure on faults.

Situation after reservoir impoundment. Similarly, we may define $S_r(t)$, fault stability under the influence of the reservoir load, through the relation

$$S_r(t) = \sigma_r(t)\tan\phi - \tau_r(t)\cos\theta(t). \qquad (2)$$

Here, $\theta(t)$ is the angle between the directions of $\tau_a(t)$ and $\tau_r(t)$ measured in the plane of the fault at the hypocentre. The justification for introducing the factor $\theta(t)$ is provided in the following paragraph. $\sigma_r(t)$, $\tau_r(t)$ and $S_r(t)$ will vary due to changing water levels in the reservoir. A reservoir will be deemed to have a stabilizing or destabilizing influence on the fault at time t if $S_r(t)$ has a positive or negative value numerically.

Stresses due to the reservoir load and ambient causes operate jointly after impoundment. The resultant frictional stress is $(\sigma_a(t) + \sigma_r(t))\tan\phi$. The resultant shear stress promoting slip on the fault is the vector sum of $\tau_a(t)$ and $\tau_r(t)$. But we anticipate that the magnitude of $\tau_r(t)$ will be much smaller than that of $\tau_a(t)$. Thus the magnitude of the resultant shear stress, namely, $(\tau_a^2(t) + \tau_r^2(t) + 2\tau_a(t)\,\tau_r(t)\cos\theta(t))^{1/2}$, may be written, correct to first order of small quantities, as $\tau_a(t) + \tau_r(t)\cos\theta(t)$. The direction of the resultant shear stress may be defined by the direction of τ_a to the same approximation. Therefore, we may define total fault stability $S(t)$ approximately as

$$S(t) = S_a(t) + S_r(t), \qquad (3)$$

where the terms on the right are as defined in equations (1) and (2). Ordinarily $S(t)$ should have a positive value, but, at the time t_{Hr} of an earthquake after reservoir impoundment, $S(t_{Hr})$ will be numerically zero and

$$S_a(t_{Hr}) = -S_r(t_{Hr}). \qquad (4)$$

Even though $\sigma_a(t_{Hr})$ and $\tau_a(t_{Hr})$ may not be known, the numerical value of $S_a(t_{Hr})$ is known through simulations of $S_r(t_{Hr})$ via this equation.

In practice, in the absence of measurements, the direction of τ_a in the fault will be unknown also. But assuming that this direction would be constant on the time scales of decades or centuries that are of interest here, we may estimate it from fault plane solutions of recent pre-impoundment earthquakes.

The interplay of $S_a(t)$ and $S_r(t)$

Let t_{Hr} and t_{Hn} be the times of occurrence of the next earthquake at a given hypocentre in a given fault depending upon whether a reservoir has or has not been impounded nearby. Then three cases may be identified and analysed depending upon whether $S_r(t_{\rm Hr})$ is negative, positive or zero numerically.

Case I. Let $S_r(t_{\rm Hr})$ be negative so that the reservoir load has a destabilizing influence on the causative fault at the hypocentre at time $t_{\rm Hr}$ of the future earthquake. It follows from eq. (4) that $S_a(t_{\rm Hr})$ has to be just small enough positive to equal $-S_r(t_{\rm Hr})$ in magnitude at $t_{\rm Hr}$. In other words ambient stresses do not have to accumulate to the extent that $S_a(t)$ diminishes to zero exactly for the earthquake to occur. Therefore, $t_{\rm Hr}$ will be earlier than $t_{\rm Hn}$ and the time of occurrence of the earthquake will be changed under the destabilizing influence of the reservoir.

Case II. Let $S_r(t_{\rm Hr})$ be positive so that the reservoir load has a stabilizing influence on the causative fault at the hypocentre at the time $t_{\rm Hr}$. It now follows from eq. (4) that $S_a(t_{\rm Hr})$ will have to have a numerically negative value of $-S_r(t_{\rm Hr})$ at $t_{\rm Hr}$. In other words, ambient stresses will have to accumulate to the extent that $S_a(t)$ has to diminish beyond zero and become negative for the earthquake to occur. Therefore, $t_{\rm Hr}$ will be later than $t_{\rm Hn}$ and the time of occurrence of the earthquake will be delayed or postponed under the stabilizing influence of the reservoir.

Case III. Lastly, if $S_r(t_{\rm Hr})$ is zero then the hypocentre lies on the boundary between regions of stabilizing and destabilizing influences of the reservoir load on the causative fault. From eq. (4) $S_a(t_{\rm Hr})$ will be zero also in this case. Hence, $t_{\rm Hr}$ and $t_{\rm Hn}$ will be identical and the earthquake will occur at the original time $t_{\rm Hn}$ even in the presence of the reservoir.

Active faults and fault sets near Tehri reservoir identified for analysis

We use the results of several seismological investigations[3–9] over the past fifteen years to identify the following three seismically active faults and fault sets of the Garhwal Himalaya near the proposed Tehri reservoir.

Intracrustal thrust fault responsible for the great Kangra earthquake of 1905

A series of articles in the literature[3,5–8] suggest that the 1905 Kangra earthquake ($M = 8.5$) occurred by an extended rupture in a major intracrustal low angle thrust fault dipping gently under the northwest Himalaya. There was damage at Tehri during the Kangra earthquake and it may be assumed that the earthquake rupture in the intracrustal thrust fault extended southeastward from Kangra up to the vicinity of Tehri (Figure 2).

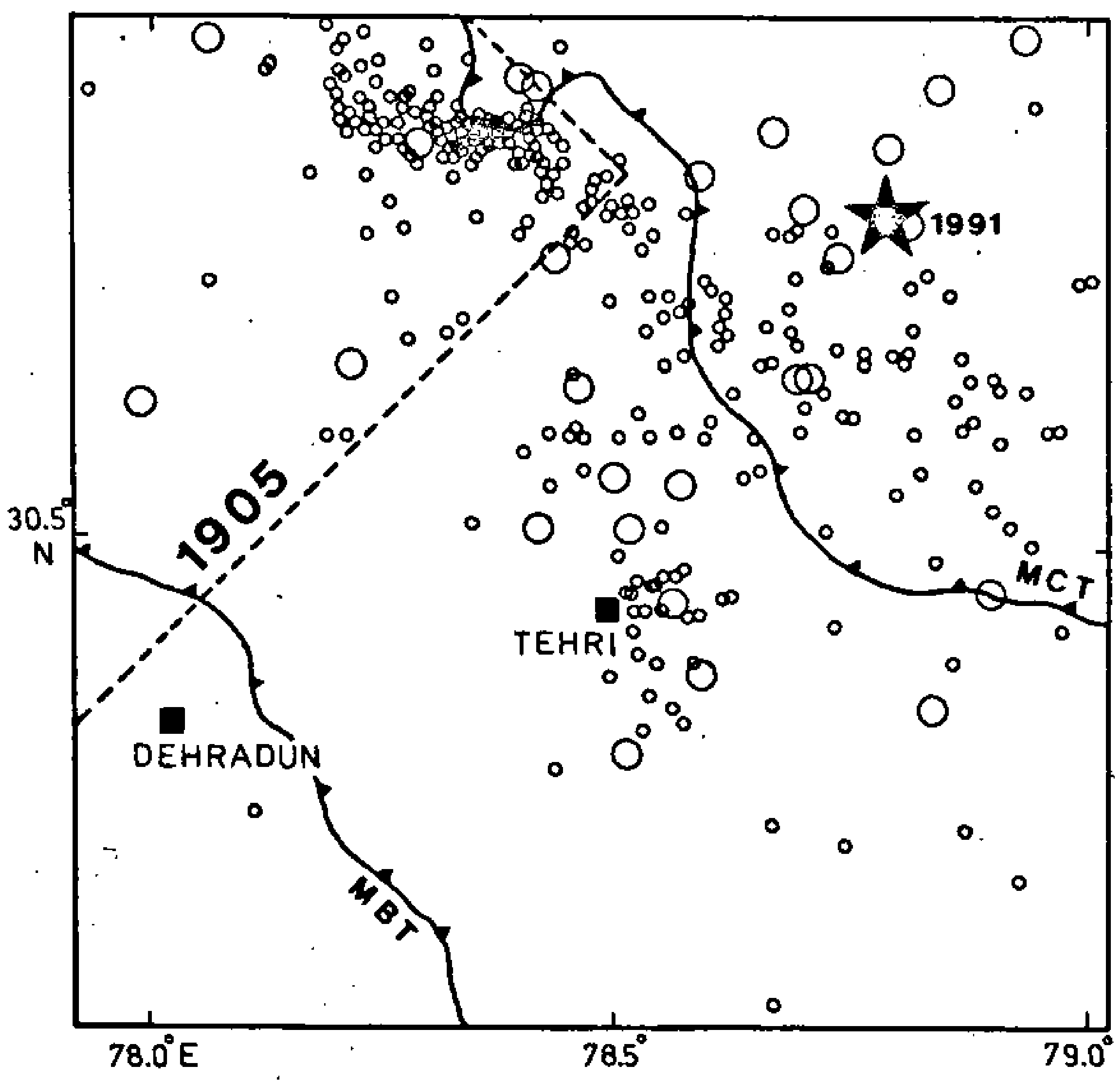

Figure 2. A seismicity map of the area around Tehri. The dashed straight lines marked by 1905 define the inferred[7] south-eastern limit of the 1905 Kangra earthquake ($M_s = 8.5$, ref. 16) in the intracrustal thrust fault. The region south-east of this limit is a seismic gap. Large open circles represent epicentres of moderate earthquakes since ca 1964 according to US Geological Survey. The star marks the epicentre of the 1991 Uttarkashi earthquake according to US Geological Survey. The small open circles mark epicentres of some of the locatable small and micro-earthquakes which have occurred in the region between December, 1979 and June, 1990 (refs. 11, 12).

There is speculation[3,5,9] that the next great earthquake of the Garhwal Himalaya may occur on the southeast extension of the same intracrustal fault. For the purpose of simulation we locate this dip slip thrust fault at a depth of 12 km below the dam with a dip of 5° to the northeast[6]. We examine the influence of the Tehri reservoir load on this fault for dip slip thrust motion during a future great earthquake. The probable hypocentre of such an earthquake should be located in this fault at the depth of brittle–ductile transition[10]. Taking clue from the models[6,7] of the Kangra earthquake, this should happen geographically near the surface trace of the Main Central Thrust (Figure 2).

Causative fault of the 1991 Uttarkashi earthquake

There has been considerable speculation about the possible impact of the 1991 Uttarkashi earthquake ($M_s = 7.0$) on the Tehri dam (Figure 2). We examine here the converse question of the probable influence of the Tehri reservoir load on the occurrence of this earthquake if it had been impounded shortly prior to 1991.

The estimated epicentre of the Uttarkashi earthquake was at a longitude 78.8°E and latitude 30.85°N according to the US Geological Survey. This point was about 50 km to the northeast of the dam (Figure 2). The estimated focal depth was about 10 km. The preferred nodal plane of the fault plane solution determined by the US Geological Survey using first P motion data has a strike of N296°, dip of 5° due to N26° and rake of 90°. In words, these data imply dip-slip thrust motion on a thrust fault dipping at 5° due N26° and passing through the hypocentre.

Imbricate faults near the Tehri reservoir

Kumar[11] and Khattri *et al.*[12] have located a number of small (magnitude between 3 and 4) and micro- (magnitude less than 3) earthquakes near the Tehri reservoir (Figure 2). Their estimated focal depths are between 0 and 16 km. The composite fault plane solution determined by Kumar[11] for these earthquakes reveals reverse dip slip motion on nodal planes striking NW–SE. The two nodal planes have dips of 60° to the NE and 30° to the SW respectively. The former nodal plane is preferred[13] as representative of the faults responsible for the small and micro-earthquakes of the region. The choice of this suite of faults is attractive also because it is consistent with the idea that these earthquakes occur due to uplift of the Higher Himalaya relative to Lesser Himalaya. These upper crustal reverse faults would be imbricate to the intracrustal thrust fault which is the potential seat of the next great earthquake in the region[4]. We analyse the stability of the imbricate reverse faults also.

Simulation of the Tehri reservoir load

The reservoir will be impounded in the long and narrow valleys of Bhagirathi and Bhilangana rivers. We simulate the reservoir as two long triangular pyramids, each with a very short, vertical, triangular base at the dam and three long triangular faces converging at the apex upstream in the respective valley. One of the long triangular faces is horizontal in each case and it represents the water surface. The other two long, symmetrical, triangular faces represent stylised smooth contact surfaces between the water in the reservoir and the valley walls. A nominal slope of 20° is assigned to each of these two faces. The centre line of the Bhagirathi branch of the reservoir is approximated by a straight line segment and that of the Bhilangana branch by two straight line segments (Figure 1). Thus the Bhilangana branch of the model reservoir actually becomes a lower frustum and an upper short pyramid. The maximum depth of water in the reservoir is taken as 260 m, the publicly known height of the dam.

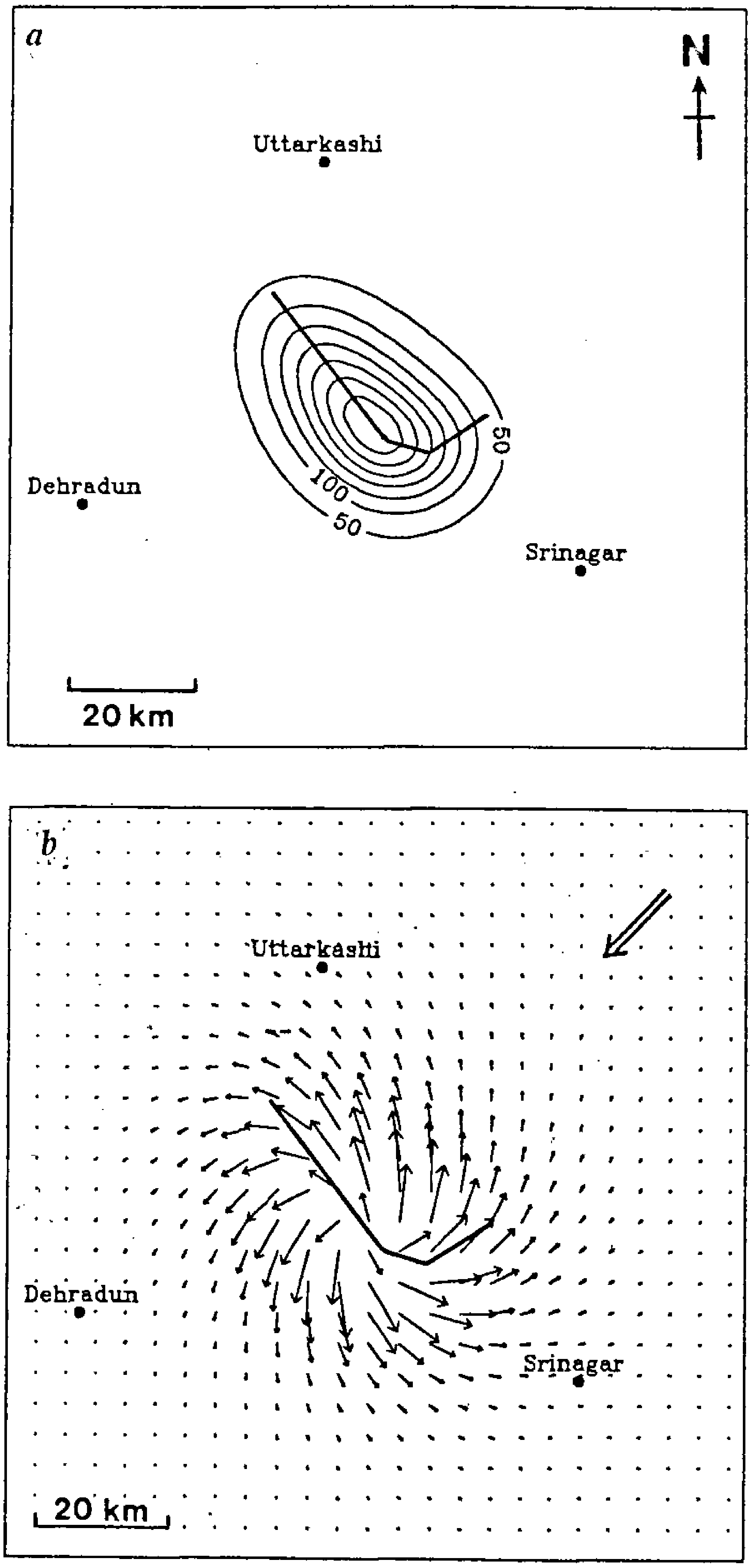

Figure 3. *a*, Contours of normal stress σ_r (in kPa) induced on the intracrustal thrust fault by the proposed Tehri reservoir; *b*, Shear stress τ_r induced on the intracrustal thrust fault. The tail of an arrow indicates the point where the stress acts. Direction of an arrow is the direction of likely slip induced by τ_r on rocks above the fault. The scale of magnitude of τ_r is indicated at the bottom. The large arrow indicates the inferred direction of ambient shear stress (τ_a) on the fault for likely slip of rocks above the fault.

The final simplification in simulating the reservoir load is that we consider 1 km wide vertical slices of these prone pyramids of water. The weight of water in each slice is regarded as a point load on a flat elastic earth. Needless to say, the loads decrease linearly away from the dam in each reservoir branch. This array of point loads visualized along the straight lines of Figure 1 simulates for us the proposed Tehri reservoir.

Computation of elastic stresses due to the simulated reservoir load

Boussinesq's formulas[14] for elastic stresses induced by a vertical point load are the basis for our stress simulations. Assuming a cartesian coordinate system with axes pointing north, east and vertically down, stresses σ_N, σ_E, σ_Z, τ_{NZ}, τ_{EZ} and τ_{NE} due to a single point load on the surface of an elastic half space may be computed for an interior point of the medium using these formulas. Here σ and τ stand for normal and shear stresses respectively. Superposition of stresses due to the assumed array of point loads leads to stress components σ_{Nr}, σ_{Er}, σ_{Zr}, τ_{NZr}, τ_{EZr}, and τ_{NEr}, due to the proposed Tehri reservoir.

Finally, at a given point on a given fault plane, resolved normal and shear stresses σ_r and τ_r due to the reservoir can be computed from σ_{Nr}, σ_{Er}, σ_{Zr}, τ_{NZr}, τ_{EZr}, τ_{NEr} using the formulas[14] for transformation of the second rank stress tensor from one coordinate system to another.

Stability of the intracrustal thrust fault under the Tehri reservoir load

Figure 3 *a* is a contoured display of σ_r induced by the proposed Tehri reservoir load on the dipping plane representing the intracrustal thrust fault. On the other hand, Figure 3 *b* shows τ_r through directed arrows at an array of points on the same fault. The direction of an arrow is also the direction of the tendency to slip in shear of the rocks above the fault at the point corresponding to the tail of the arrow under the influence of the reservoir. Finally, Figure 4 displays contours of resultant S_r for the intracrustal thrust fault at an instant when the reservoir is full to the brim. The computations are on the assumption that the rocks have a Poisson's ratio of 0.25 and the friction coefficient $\tan\phi$ has a value of 0.65. Two main facts are noteworthy here. Firstly, the zero value contour of S_r encloses a broad area of positive values northeastward of a NW–SE line passing near the dam. This then is the region of reservoir-induced stabilization on the intracrustal thrust fault. Secondly, the maximum positive value of about 30 kPa only for S_r is attained close to the Tehri reservoir. Otherwise the stability mobilized is of the order of a few (less than 5) kPa or less over large areas. This holds particularly for negative values of S_r.

Seismic hazard implication

Since the stability of the intracrustal thrust fault is the most important from the standpoint of great earthquakes, we take it up for discussion first.

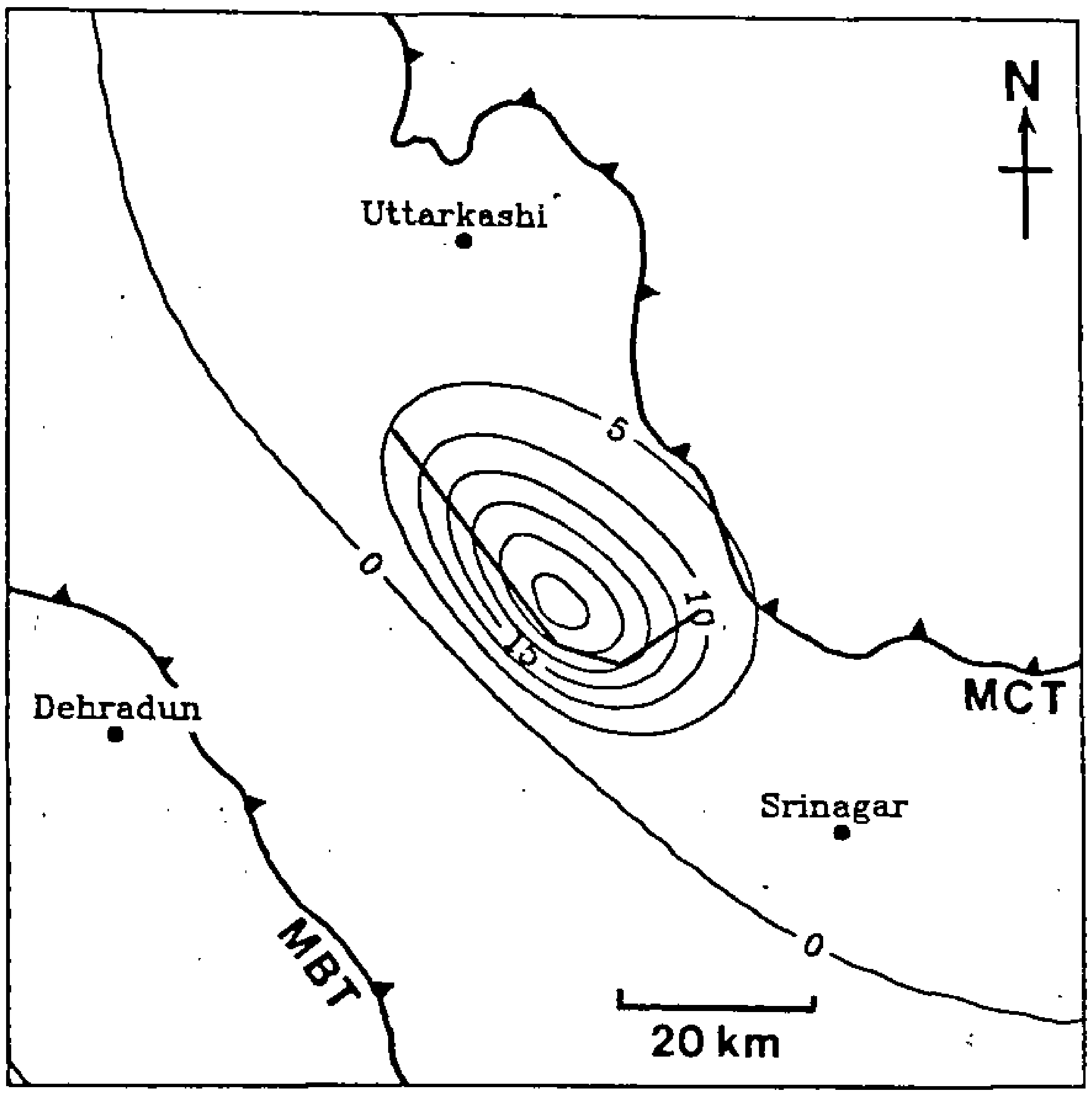

Figure 4. Map showing contours of stability S_r likely to be induced by the Tehri reservoir on the intracrustal thrust fault in the absence of any pore pressure. The contour values are in kPa. The absence of contours south-west of the zero value contour indicates that reservoir-induced instability is less than 5 kPa at all the investigated points on the intracrustal thrust fault in this region. The geographic positions of reservoir axes and MCT and MBT are from Figure 1. The next great earthquake of the region may nucleate on the intracrustal thrust fault at depth near the geographic position of the MCT. The Tehri reservoir would exert a stabilizing influence on the intracrustal thrust fault in the probable nucleation zone of the great earthquake.

But a clarification is required. A great Himalayan earthquake may rupture an area of the order of 300 × 100 km^2 in the intracrustal thrust fault. The length of the ruptured zone should be parallel to the local strike of the fault, while widthwise the zone should extend updip from the geographic vicinity of the Main Central Thrust (MCT) (Figure 1). However, the earthquake would originate at a single point, the hypocentre, located within the ruptured segment of the intracrustal thrust fault. The Tehri reservoir load may influence the occurrence of only those future great earthquakes of the Himalaya whose epicentres may lie within Garhwal segment.

As mentioned above, a reasonable view[3,5,13] regarding great earthquakes of the Himalaya is that they should nucleate in the intracrustal thrust fault beneath the surface trace of the MCT. It is seen from Figure 4 that this probable source region of a great earthquake originating in the Garhwal Himalaya would lie in the zone of stabilization due to reservoir-induced elastic stresses.

Thus we conclude, as explained under case II above, that the influence of Tehri reservoir load will be to delay

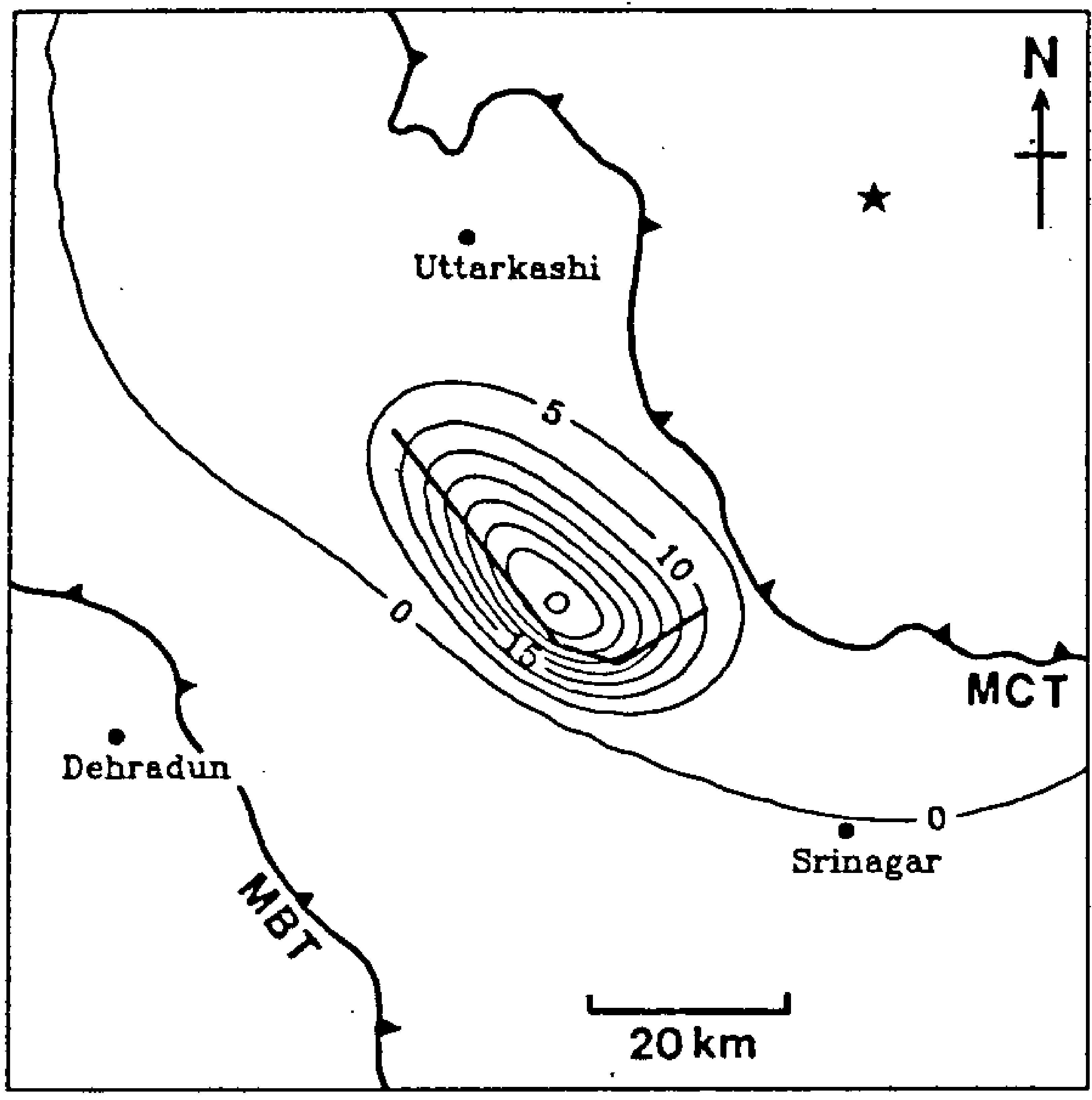

Figure 5. Comparable to Figure 4 but for the causative thrust fault of the 1991 Uttarkashi earthquake whose epicentral location is shown by the star. We infer that if the Tehri reservoir had been impounded a short time prior to the Uttarkashi earthquake then it would have exerted a stabilizing influence at the hypocentre located in the causative fault (see text).

or postpone the next such great earthquake of the region. See § on Discussion for further comments.

Moderate earthquakes on the intracrustal thrust fault

According to Ni and Barazangi[15] some moderate earthquakes may also occur on the above intracrustal thrust fault with epicentres near the surface trace of the MCT. The occurrence of these earthquakes also would be postponed duly under the stabilizing influence of the Tehri reservoir load.

Stability of the causative fault of the Uttarkashi earthquake

We omit the display of stresses σ_r and τ_r in view of their general similarity to those shown in Figure 3. Figure 5 is a display of fault stability S_r due to elastic stresses under the influence of the Tehri reservoir load. The hypocentral region falls in the stabilizing zone. Thus the impoundment of the reservoir prior to 1991 would have delayed the Uttarkashi earthquake but not prevented it altogether. See § on Discussion also.

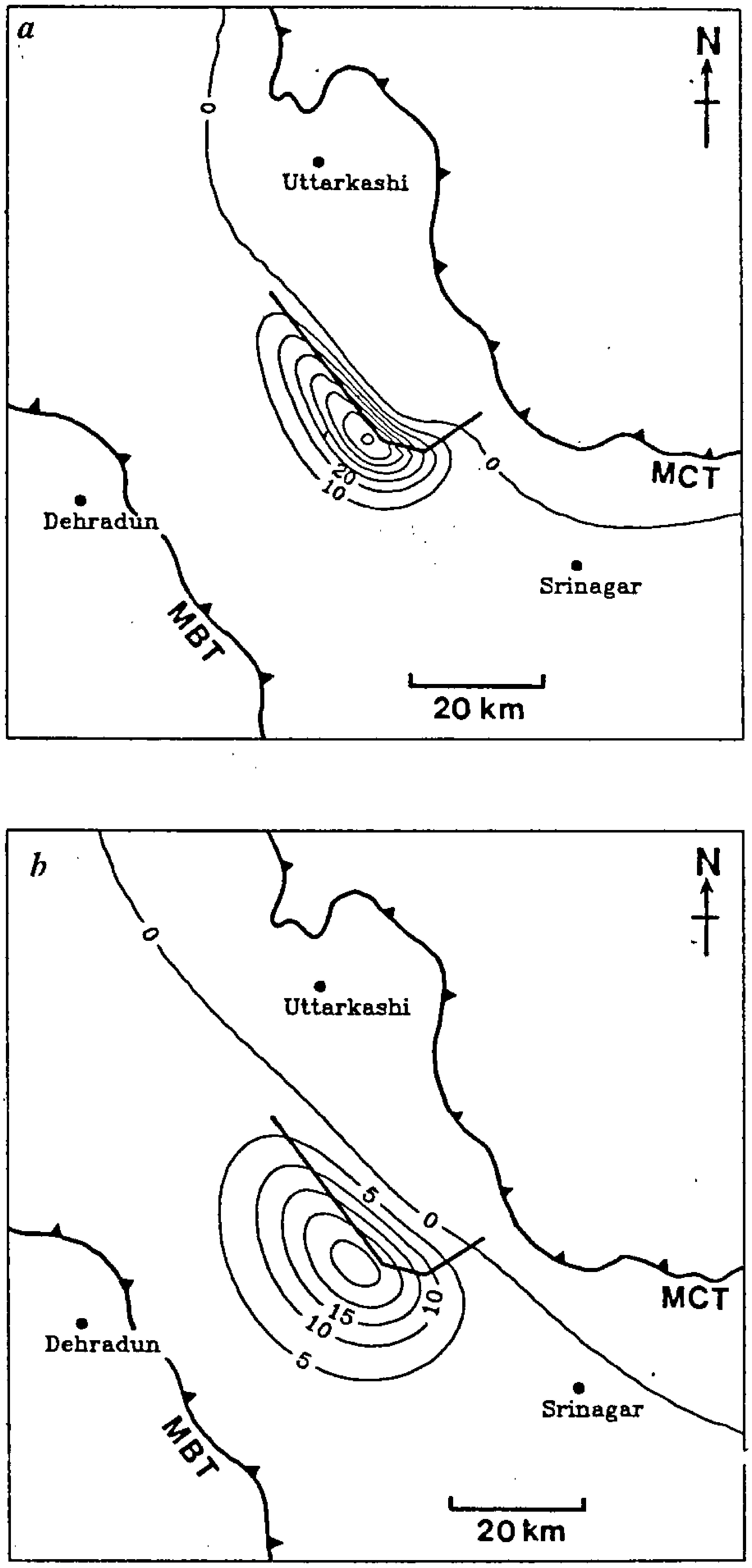

Figure 6 *a*, *b*. Contour maps for stability of imbricate reverse faults responsible for many small and micro-earthquakes of the region. Whereas Figures 4 and 5 were for two specific faults, the Figures 6 *a* and *b* are for depths of 6 and 13 km within the ground (see text). We ignore the mountainous topography of the region in defining these depths. The destabilizing zones at both depths lie north-east of the zero value contours in these cases.

Stability of imbricate faults

Figures 6 *a* and *b* show contours of S_r along horizontal planes at two different depths of 6 and 13 km. These figures differ from Figures 4 and 5, which pertain to stability of individual faults. Rather Figures 6 *a* and *b* show stability of similarly oriented faults at the same depth in the ground at different geographical locations. The zone of destabilization of the imbricate faults starts some kilometres north-east of the reservoir. The distance is comparatively greater for greater depths in the crust. The topography of the region is ignored for these remarks.

We conclude from case I above that the impoundment of Tehri reservoir will hasten or advance the occurrence of some small and micro-earthquakes associated with these imbricate faults lying in the destabilization zone of the reservoir. But in the immediate vicinity of the reservoir even small and micro-earthquakes will be delayed because the associated imbricate faults lie in the zone of stabilization and case II above is applicable.

Discussion

Choice of faults for analysis

We have not considered the stability of geologically mapped faults of the region around Tehri reservoir for two reasons. Firstly, surface measurements of dips and strikes of these faults provide no clues about their dispositions at depths. Linear extrapolation to estimated seismogenic depths of up to 15 to 20 km in the Himalaya are unwarranted. Secondly, there are no specific geological measurements to determine current movements on these faults. The current here means a time scale of decades, or centuries at the most.

On the other hand, use of geophysically, mostly seismologically, modelled faults for stability analysis has the disadvantage that there is no visible proof of the existence of these faults. But once we adopt the current seismological view[16] that tectonic earthquakes occur due to slips on buried faults then this objection loses validity. Of course the precise locations and attitudes of these faults have to be inferred from seismological observations. The estimate will have uncertainties due to errors of observation and limitations of data interpretation. But, in our opinion, these constraints are not as severe as those of geological extrapolation. At the same time the geological and seismological models should be complementary as far as possible. The faults identified on geophysical grounds for stability analysis here are not in any obvious contradiction with geological opinion as far as we are aware.

Extent of simplification and its impact on the utility of the simulation

The extent of simplification made for the simulation of the Tehri reservoir load has been already indicated. Still we believe that the conclusion about the domains of stabilization and destabilization of different faults and fault sets will not change significantly enough in an improved simulation of the Tehri reservoir load. Some differences in magnitudes of stabilization S_r at different points may arise. But it is our considered opinion that they too will not be important enough to matter. These remarks hold strictly for S_r due to the simulated elastic stresses.

A different set of simplifying assumptions are related to the fact that Boussinesq theory is for a homogeneous earth while the crust in the vicinity of the Tehri reservoir is quite heterogeneous. The simplicity of the Boussinesq theory is such a great advantage that errors due to heterogeneity of the medium have to be tolerated especially in a first analysis of this type. The expectation remains that, barring the possibility of local stress concentrations in a heterogeneous medium, a good average approximation of reservoir-induced stresses may be obtained with the formulas used.

Finally, the value of the coefficient of friction adopted here is conservative and favours higher estimates of stability. Lowering the value of this coefficient would increase the area of the region of destabilization.

Effect of reservoir operation

The above calculations are for a maximum reservoir depth of 260 m. But it is acknowledged that the reservoir level will not be uniform throughout the year and from year to year due to meteorological and other causes. Our calculations above, in conjunction with others not shown here, indicate that the size of the zones of stabilization and destabilization on identified faults may fluctuate to some extent with fluctuating reservoir levels. But major areas of a given fault will continue to be in the same respective zones at all reservoir levels, even though the magnitude of S_r will increase or decrease with rising or falling levels. The influence of the reservoir level on the occurrence of nearby earthquakes will be as follows. The chances of occurrence of earthquakes in zones of reservoir-induced stabilization on the causative faults will be greater at lower reservoir levels. On the other hand, chances of occurrence of earthquakes in zones of destabilization will be greater at higher reservoir levels.

Impact of ignoring pore pressure

As noted earlier, simulation of pore pressure has not been undertaken here because little is known about the subsurface hydraulic regime and hydraulic properties in the region of interest.

The effect on the results due to neglect of pore pressure could be significant in principle. Still, it can be predicted even without any calculations that the effect will be to reduce stability and increase instability of all the seismogenic faults around Tehri reservoir. This is because pore pressure tends to reduce the frictional stresses opposing slip on the faults.

We may add that we would find it hard to conceive a direct hydraulic connection between the Tehri reservoir and any significant part of the intracrustal thrust fault. But the possibility mentioned by Simpson and Narasimhan[17] is more potent, easier to accept and more difficult to assess quantitatively. This is the concept of fluid migration over short distances into and along the fault zone as a result of compression of pore spaces under the reservoir-induced elastic stresses. In this connection, Chander and Gahalaut[4] have argued that substantial ambient pore pressure is required for nucleation in the hypocentral regions of great and moderate earthquakes on the intracrustal thrust fault under the Himalaya. Similar remarks apply for the causative fault of the 1991 Uttarkashi earthquake and the imbricate faults which are the seats of small and micro-earthquakes at some distance from the Tehri reservoir.

Delays or advances in times of earthquakes should be small

Our statements above in this regard are more conceptual than quantitative. This is because we disregard pore pressure in our simplified analysis. Also we are ignorant about rates of accumulation of earthquake-generating stresses in the Garhwal Himalaya. But our guess is that these rates are significantly high. Moreover, the reservoir-induced stress changes are small in magnitude generally. The changes in pore pressure should be comparable to normal stresses. Thus, changes in the times of occurrence of earthquakes due to the influence of the Tehri reservoir should be small in general.

The influence of pore pressure should be asymmetric in that the extent of reservoir-induced advancement of earthquakes will be enhanced but the extent of delay in their occurrence will be curtailed with increase in pore pressure assuming a uniform rate of stress accumulation.

Comparison of our conclusions with those of earlier investigators

Gupta and Rajendran[18] inferred systematic stabilization of thrust faults in the Himalaya. They were using the arguments of Snow[19] who carried out the analysis for an infinite reservoir which affects all parts of the same thrust fault uniformly. Our 3D analyses show clearly that the same intracrustal thrust fault is stabilized downdip of Tehri reservoir but destabilized updip from it. The relative position of the hypocentre in the thrust fault and the reservoir on the ground is a critical factor.

Chander and Sarkar[20] attached importance to the fact that the stabilization of a thrust fault would be reduced by the process of draining of a reservoir. But, as pointed out above, the remaining water in the reservoir may still exert a stabilizing influence on most of that section of a fault which was stabilized at higher water levels also. It is our opinion that the view of the present article is not entirely contradictory to Chander and Sarkar's[20] view. But at the same time, whereas an earthquake on the intracrustal thrust fault north-east of the reservoir during a low water stand would be reservoir-induced according to Chander and Sarkar[20], it would still be a reservoir delayed natural earthquake in terms of the present analysis.

Implications of the analysis on the Tehri dam controversy

We venture to put down here our own views of how the above analysis bears on the Tehri dam controversy. The simulations indicate that the chances of earthquakes being triggered by Tehri reservoir are less than has been suggested by some in the literature[20,21]. The assessment of seismic hazard to the dam and reservoir may be lowered accordingly.

On the other hand, reservoir-induced stability of seismogenic low angle thrust faults northeast of a NW–SE line passing near the dam should not be a great consolation to those who support its construction. This is because the inexorable accumulation of ambient stresses due to plate tectonic causes will wipe out the reservoir load-induced stabilization with time. Natural earthquakes will occur again on these faults when $S(t)$ of eq. (3) tends to zero. The only consolation to these people would be if the accumulation of these stresses is at a relatively slow rate because then the postponement of natural earthquakes may be for a longer period than the useful life of the dam and reservoir. This consideration is beyond the scope of the present simulation. Still our guess is that the rates of stress accumulation in the Himalaya are not that slow. Also the reservoir-induced stresses are of small magnitudes and their stabilizing effect may be overcome through plate tectonic processes rapidly.

Conclusions

Our simulations for the elastic stresses due to the proposed Tehri reservoir load are grossly simplified. But it appears that the reservoir should have a stabilizing influence on those parts of the intracrustal thrust fault where the next great earthquake of the Garhwal Himalaya may nucleate on it. Had the Tehri reservoir been impounded shortly before 1991, it would have exerted a stabilizing influence on the causative fault of the Uttarkashi earthquake. The reservoir should have a destabilizing influence on some nearby shallow reverse faults on which small and micro-earthquakes have been observed in the past fifteen years.

The Tehri reservoir load should lead to postponement of the next great earthquake of the region by an unspecified time. It is our conjecture that the reservoir load would have delayed the Uttarkashi earthquake also by an undetermined time. But the times of some nearby small and micro-earthquakes of the future may be advanced to some extent. Quantification of postponements and advancements of earthquakes has been eschewed because it is not feasible at this time. But we have argued above that these changes in times of occurrence of earthquakes near the Tehri reservoir would be small.

Thus it is our sense from the simulation that the impact of Tehri reservoir on nearby future earthquakes may be small on the whole. Accordingly, the adverse influence of the reservoir in this regard may not be as severe as anticipated and estimates of seismic hazards to the Tehri project may be lowered to that extent. But the estimates of seismic hazards to the Tehri dam and reservoir due to the natural earthquakes of plate tectonic origin in the Garhwal Himalaya may not be lowered on the basis of this analysis.

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