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RESERVOIR INDUCED DESTABILIZATION OF REVERSE AND THRUST FAULTS

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ABSTRACT

A review of the literature reveals the following two facts about reservoir induced seismicity in reverse and thrust fault environments. First, induced earthquakes at Monticello, Manic 3 and Nurek reservoir sites yielded reverse and thrust fault type composite fault plane solutions. Second, theoretically also, numerical simulations of the response of a porous elastic earth to reservoir loads by Bell and Nur for reverse fault environment and by Roeloffs for reverse and thrust environments show that destablization of such faults can occur if they are located suitably with respect to the reservoir. The motivation for this review is that several large reservoirs are planned for the Garhwal Himalaya where geological mapping and earthquake fault plane solutions suggest that reactivation of reverse and faults has been and continues to be an important element of the tectonics of the region.

INTRODUCTION

Reservoir induced seismicity (RIS) is frequently observed when the reservoir is deeper than 100 m or has a storage capacity of more than 1 km^3 (e.g., Gupta and Rajendran, 1986). Gupta and Rajendran (1986) reviewed data for six similarly large reservoirs in the Himalaya and did not find evidence of RIS at any of the sites. They argued that the sites were located in the Himalayan Foothills, where a thrust environment prevails. They cited Snow's (1972) theoretical result that reservoir impoundment promoted stability if ambient stresses were conducive to thrust faulting. However, RIS observations at Manic 3 (Leblanc and Anglin, 1978) and Nurek (Keith et al., 1982) reservoir sites as well as theoretical analyses by Roeloffs (1988) indicate that even a thrust fault can be destabilized on reservoir impoundment under suitable circumstances. Thus, the explanation for apparent lack of RIS at reservoir sites already impounded in the Himalaya needs to be sought again site by site taking into account local factors, and the question of whether RIS can occur elsewhere in the Himalaya is open again. Since the hydroelectric potential of the Garhwal Himalaya (Fig. 1) is to be developed partly through impoundment of several large reservoirs, and since there is no direct experience so far regarding RIS in this region of predominantly reverse and thrust fault tectonics (Fig. 1), we review here the evidence which has a bearing on the problem.

We note at the outset that the largest induced earthquake in reverse and thrust fault environments had a magnitude of 4.6. Normally no damage is anticipated from such an earthquake to a dam designed to withstand an earthquake of magnitude 8 or greater.

TERMINOLOGY

The use of terms 'reverse' and 'thrust' faults interchangeably in the literature has led to some confusion. We shall use 'reverse fault' here as an abbreviation for high angle reverse fault, i.e., a fault which dips at between 45° and 90° and along which the hanging wall moves in the up dip direction only relative to the footwall. 'Thrust fault' will imply a low angle reverse fault, the fault dip being between 0° and 45°.

OBSERVATIONAL EXPERIENCE

The Monticello Reservoir situated in South Carolina, U.S.A is 52 m deep (Zoback and Hickman, 1982). Induced earthquake started almost immediately after impoundment commenced in early December, 1977 (Fig. 2). Maximum activity accompanied full impoundment in January and February, 1978. The magnitude of the largest induced earthquake was 2.8. The induced earthquakes occurred in three clusters under different parts of the reservoir. Most of the earthquakes occurred within 1.5 km of the earth's surface. Composite fault plane solutions for induced earthquakes indicated reverse faulting (Fig. 3). Many of the fractures observed in two wells drilled at the site had the same orientations as the nodal planes inferred from the fault plane solutions (Zoback and Hickman, 1982). In short, impoundment of the Monticello Reservoir led to reactivation of reverse faults already present beneath the reservoir.

The Manic 3 Reservoir in Quebec, Canada, had a depth of 108 m and storage capacity of 10.5 km^3 (Lablanc and Anglin, 1978). The induced earthquakes occurred in a small volume having an areal extent of 4 x 4 km^2 and depth of 1.5 km beneath the reservoir. The largest of the induced earthquakes had a magnitude of 4.1. The fault plane solution indicated that thrust faults beneath the reservoir had been destabilised. (Leblanc and Anglin, 1978).

The largest induced earthquake at the Nurek Reservoir site in Tadjik Republic, U.S.S.R., had a magnitude of 4.6 (Keith et al., 1982). The induced earthquakes associated with the impoundment of the second stage of the reservoir were investigated in detail (Keith et al., 1982). The induced earthquakes had estimated focal depths between 1 and 8 km. They could be divided into five clusters on the basis of proximity of epicentres and similarity in fault plane solutions. Reverse and thrust fault solutions were observed for two of the clusters (Keith et al., 1982). Keith et al. (1982) pointed out that the induced earthquakes occurred in the hanging wall of a known thrust fault but they were not associated specifically with this or any other major fault mapped in the area and spatial distribution of induced seismicity would have been difficult to predict on the basis of geologic studies prior to impoundment.

AMBIENT STRESSES FOR REACTIVATION OF REVERSE AND THRUST FAULTS

Snow (1972), Simpson (1976), Bell and Nur (1978), Zoback and Hickman (1982) and Roeloffs (1988) estimated the stresses and pore pressures induced by a reservoir to be relatively small as they were found to be fractions of the pressure (Δp) exerted by the water at the base of the reservoir; Δp is about 1 MPa when the reservoir depth is 100 m. Thus reservoir induced stresses act only as trigger if ambient stresses in the rocks beneath the reservoir are already near critical levels for failure on suitably oriented faults. We review here briefly the magnitudes of stresses required for reactivation of reverse and thrust faults. Attention is restricted to the case when the maximum and minimum principal stresses are horizontal and vertical respectively. This is in view of the general observation

(Zoback et al., 1989) that one of the principal stresses in the earth's crust is usually subvertical.

Zoback and Hickman (1982) suggested that, for reactivation of a reverse fault, the vertical normal stresse (σ_v) and the maximum horizontal normal stress (σ_{Hmax}) should satisfy the following relation,

$$\sigma_{Hmax} = [\sqrt{1+\mu^2} + \mu]^2 \ (\sigma_v - p) + p \tag{1}$$

Here μ is the coefficient of friction on the fault plane and p is pore pressure. A value of p equal to the hydrostatic pressure at the point of observation in rock was considered adequate by Zoback and Hickman (1982).

Sibson (1989) presented the following more detailed formula.

$$\sigma_{Hmax} > [(\tan\theta_R + \mu) / (\tan\theta_R - \mu \tan^2\theta_R)] \, (\sigma_v - p) + p \tag{2}$$

Here θ_R is the dip of the reactivated fault. Both reverse and thrust faults are covered. The formula suggested by Zoback and Hickman (1982) is seen to apply strictly to reactivation of a fault dipping at $\tan^{-1}\mu$. Further, analysis of Eqn. (2) reveals that, under the above assumption about the orientations of principal stresses, reactivation of a reverse fault dipping at an angle greater than $\pi/2 - \tan^{-1}\mu$ requires supralithostatic pore pressures (Sibson, 1989). But p is constrained to then lie between σ_v and $\sigma_v + T$, where T is the tensile strength of rock.

RESERVOIR INDUCED STRESSES

The Infinite Reservoir Model

Snow (1972) considered an infinite reservoir of depth h over an elastic solid half space affected by a water filled system of axisymmetric fractures. Snow visualized that the elastic response of the half space would be instantaneous while the effect of the pore pressure would develop with time. The principal axes of the reservoir induced stresses were derived to be vertical and horizontal. For nominal values of rock properties (see Snow, 1972), the magnitudes of the induced stresses when pore pressures are fully developed were given as

$$\Delta\sigma_v = 0$$

$$\Delta\sigma_{Hmax} = \Delta\sigma_{Hmin} = -0.57\,\Delta p \tag{3}$$

Here Δp is the pressure of water at the base of the reservoir.

The net effect of these reservoir induced stresses on the above reverse and thrust fault producing ambient stresses is to promote stability because the difference between σ_{Hmax} and σ_v, the maximum and minimum principal stresses under the circumstances, is reduced (Fig. 4). This in turn leads to reduction in the range of dips of faults that can be reactivated (Fig. 4).

The Finite Reservoir Model

Bell and Nur (1978) and Roeloffs (1988) considered the deformation of a porous elastic half space by reservoirs of finite width but infinite length. Among other cases, stability of a reverse fault dipping at 60° was considered. The concept of change in fault stability ΔS was introduced by Bell and Nur (1978) and defined as

$$\Delta S = \mu(\Delta\sigma - \Delta p) \pm \Delta\tau \qquad (4)$$

Here $\Delta\sigma$ and $\Delta\tau$ are incremental normal and shear stresses on the fault plane due to water load ΔP. Δp is the corresponding change in pore pressure. If the ambient shear stress favours reverse slip on the fault then the negative sign is considered in Eqn. (4). Negative values of ΔS imply destabilization of the fault. Time dependent solutions were obtained. It may be concluded from the results displayed by Bell and Nur (1978) and Roeloffs (1988) that compared to normal and strike-slip fault regimes, the reverse fault regime is more stable. Still definite zones of destabilization develop on impoundment of a finite reservoir in a reverse fault environment (Fig. 5). Depending upon permeability conditions, the decrease in stability may be 20 to 50% of Δp eventually.

Roeloffs (1988) also considered the stability of a 20° thrust fault under the same conditions and concluded that, in principle, destabilization can occur. Destabilization of a 20° thrust and 60° reverse fault at a particular depth beneath the reservoir is compared in Fig. 6 (after Roeloffs, 1988).

DISCUSSION

RIS Experience in Reverse and Thrust Fault Environments

Fault plane solutions of induced earthquakes at Monticello, Manic 3 and Nurek reservoir sites establish that RIS can occur in reverse and thrust fault environments. Thus, the apparent lack of RIS at sites of six large Himalayan reservoirs already impounded cannot be ascribed simply to a compressional tectonic environment. Local geohydrologic conditions and spatial relationships between faults and reservoirs may be contributory factors.

Theoretical Analyses

Theoretical analyses of Bell and Nur (1978) indicated that destabilization of a reverse fault should be facilitated if, among other things, the reservoir were located on the foot wall (Fig. 5). Zoback and Hickman (1982) pointed out that the Monticello Reservoir was probably situated on both the hanging and foot walls of the reactivated reverse faults because the induced earthquakes were mainly with in the reservoir area.

Zoback and Hickman (1982) suggested that reservoir induced pore pressures were responsible for RIS at the Monticello site and that the pore pressures were communicated through a permeable fracture system. Roeloffs (1988) opined that "...Complex geologic structure undoubtedly plays a role in the mechanics of induced seismicity and fluid flow in bedrock beneath a seismic reservoir may be channeled into a limited number of dominant fractures...However, before invoking complications of material heterogeneity and fracture flow, the uniform porous elastic model *should be proved an inadequate description of the phenomenon of induced* seismicity....."

Implications for RIS in the Garhwal Himalaya

Back-ground Large (M_S greater than 8), moderate and small (m_b less than 5) earthquakes occur in the Garhwal Himalaya. Khattri et al. (1989) summarized investigations of 252 small earthquakes which occurred in the Garhwal Himalaya and were located from locally recorded data. Epicentres and foci of these earthquakes are displayed in Figs. 7 and 8 respectively. 63%, 29% and 8% of the earthquakes had estimated focal depths in the ranges of 0-7, 7-14 and 14-23 km respectively. Two well constrained composite fault plane solutions (Fig. 9) indicated that some earthquakes were occurring by strike-slip motion on N-S or E-W striking vertical planes while others were occurring by either reverse fault motion on a plane dipping at 60° to the NE or by thrust fault motion on a plane dipping at 30° to the SE (Khattri et al., 1989).

Moderate (m_b between 5 and 6 mainly) earthquakes occur in the region a few times a year. Sarkar et al. (1987) estimated a focal depth of 15 km using local data for the moderate earthquake which occurred in the region on December 28, 1979. Molnar and Lyon-Caen (1989) estimated the focal depth of 13 km for the moderate earthquake of July 16, 1986 using synthetic wave form technique and teleseismic data. They obtained a fault plane solution for the earthquake and suggested on plate tectonic considerations that the nodal plane dipping at 8° to the NE was the fault plane. The estimated focal depth of these two Garhwal earthquakes are consistent with the view (Ni and Barazangi, 1984) that moderate earthquakes of the Himalayan seismic belt occur at depths of between 10 and 20 km along or near the boundary between the overlying wedge of Himalayan rocks and the underthrusting Indian lithospheric plate. The fault plane solution interpretation (Molnar and Lyon-Caen, 1989) is consistent with the interpretations of Fitch (1970), Chandra (1978), Ni and Barazangi (1984) and Baranowski et al. (1984) for moderate earthquakes in other sections of the Himalaya. The occurrence of moderate earthquakes in the Garhwal Himalaya is shown in Fig. 8 schematically through open circles.

The southeastern part of the 1905 Kangra earthquake (M_s = 8.5) meizoseismal area extended into the NW half of the Garhwal Himalaya. Chander (1988) found the the geodetically observed ground level changes due to this earthquake consistent with the view that the causative rupture had an area of 280 x 80 km^2 in the upper surface of the Indian lithospheric plate underthrusting the Himalaya. The rupture dip was 5° to the NE, and the SW long edge of the rupture surface was estimated to be near Dehra Dun at a depth of 10 km. Thrusting motion occurred across the fault.

Geologically too, although faults of all types are to be found, the so called "thrusts" are especially numerous in the Himalaya, including the Garhwal Himalaya. Some of the more important "thrusts" mapped in the Garhwal Himalaya are shown in Fig. 1. Many of them can be traced over long distances along respective strikes. The word "thrust" is deeply entrenched in Indian geology (Mehdi et al., 1971) and has been used even when "reverse fault" would have been more appropriate (e.g., Mehdi et al., 1971 ; also see Gansser, 1964, p. 247, Valdiya, 1981, p. 103, 119, 134, etc.). Since precise measurements of dips of outcrops are not always possible in the rugged mountainous terrane (A.K. Jain, personal communication, 1990) views may differ as to whether a particular fault is of reverse or thrust type. Further, the concept of reverse listric fault (McClay, 1981) has gained acceptance in the last decade. It is a concave upward curved fault along which the hanging wall moves up relative to the foot wall. It may be a reverse fault in outcrop and a thrust fault at depth. Thus, Valdiya's (1986) statement that Himalayan "thrusts" flatten at depth implies that they are reverse listric faults (cf., Gansser, 1964, p. 247). We conclude that both reverse and thrust faults exist in the Garhwal Himalaya. This fact, combined with observations of reverse and thrust type fault plane solutions indicate that stresses conducive to formation and reactivation of these faults existed in geologic past and continue even today in the Garhwal Himalaya.

Implications Sibson (1982) postulated that crustal earthquakes occur by reactivation of pre-existing faults by a process of frictional failure. We assume that this holds for earthquakes of the Garhwal Himalaya also. Thus the occurrence of these earthquakes indicates that the currently prevailing stresses in the region are frequently at critical levels for reactivation strike-slip, reverse and thrust faults parallel to those inferred in the fault plane solutions mentioned above. It follows that one of the ways in which RIS could occur in the Garhwal Himalaya is through destabilization of pre-existing reverse and thrust faults in the upper crust. Assessment of whether RIS will occur at a specific site in the region in this way would require investigation of geohydrological conditions at the site as well as of the spatial relationship between the reservoir and the candidate reverse and or thrust faults. But as mentioned above, such investigations may not always be conclusive one way or the other (Keith et al., 1982). Also, other factors being equal, there is less likelihood of RIS in the reverse and thrust fault environment actually prevailing in the Garhwal Himalaya than would have been the case if normal or strike-slip environment was similarly pronounced.

CONCLUSION

Reservoir induced destabilization of reverse and thrust faults is possible in principle.

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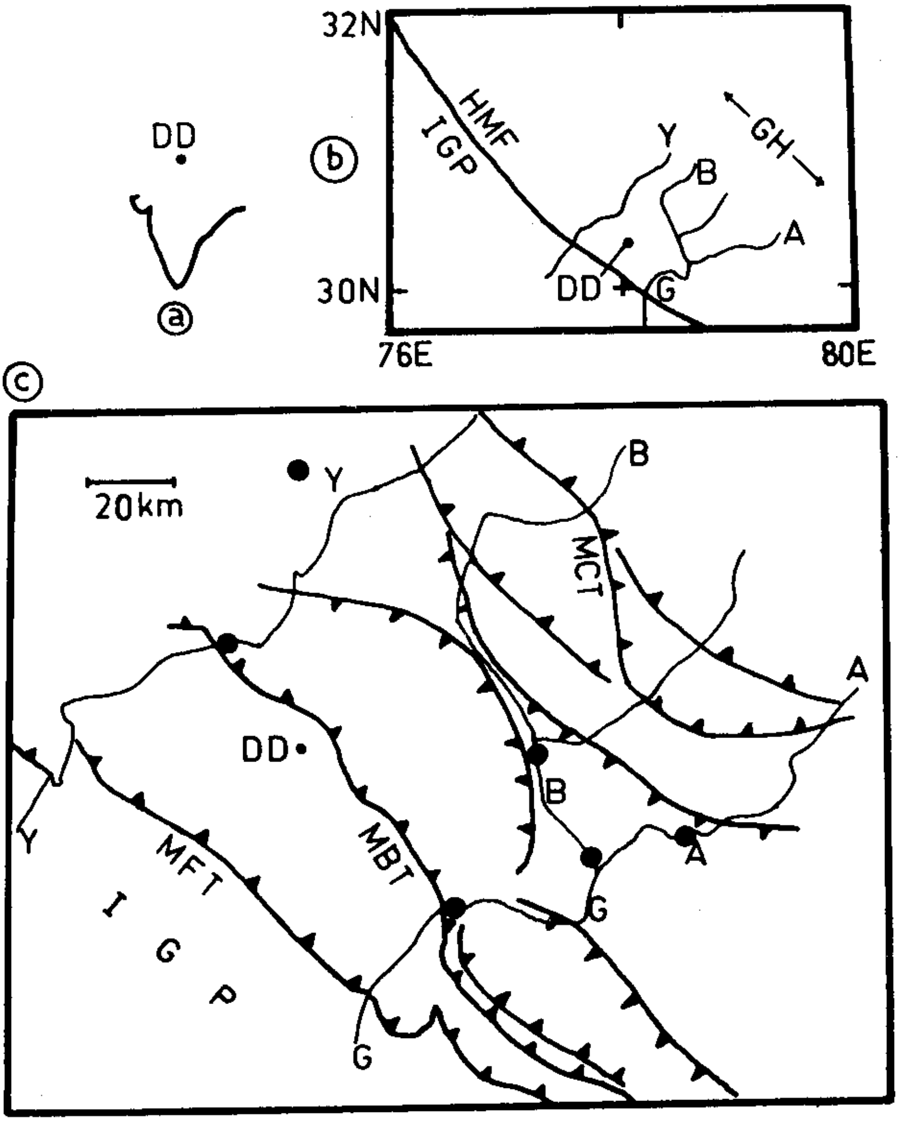

Fig. 1(a) and (b) are maps to identify the location of the Garhwal Himalaya (GH). (c) shows some of the important "thrusts" mapped in the Garhwal Himalaya (see text). DD-Dehra Dun; HMF-Himalayan Mountain Front; IGP-Indo-Gangetic Plains; Y,B, A and G-Yamuna, Bhagirathi, Alakhnanda, and Ganges rivers; MGT, MBT and MFT-Main Central, Main Boundary and Main Frontal Thrusts. Dark circles identify schematically locations of large reservoirs under construction or in the planning stage. (c) is partly after Jain (1987).

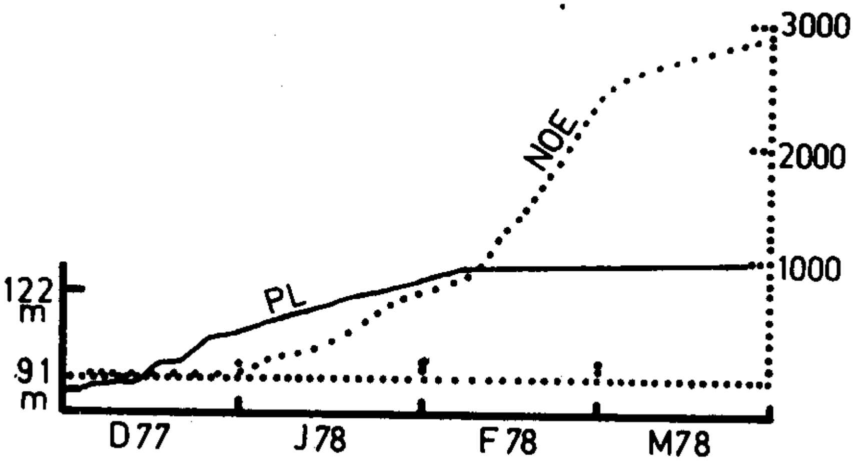

Fig. 2. Data for the Monticello reservoir site. Curves show history of reservoir filling (PL) and total number of induced earthquakes (NOE). D77-December, 1977; M78-March, 1978, (After Zoback and Hickman, 1982).

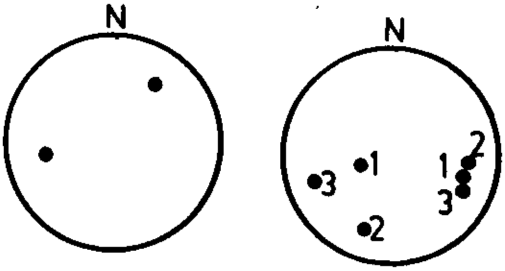

Fig. 3. Lower hemishere stereographic plots showing poles of nodal planes obtained from composite fault plane solutions of induced earthquakes at Monticello reservoir site. Motion on the planes was of shallow reverse type. (After Zoback and Hickman, 1982).

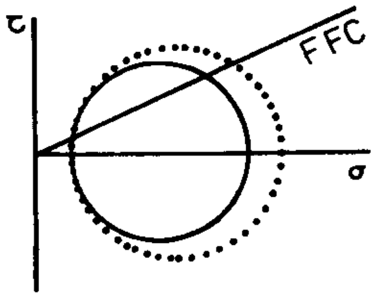

Fig. 4. Schematic comparison of pre- (dotted) and post- (solid line) impoundment Mohr circles according to Snow's (1972) model for reservoir induced stresses when minimum principal stress is vertical. FFC indicates frictional failure criterion. The range of dips for which reverse and thrust fault planes are dangerously oriented under prevailing stresses is reduced on impoundment.

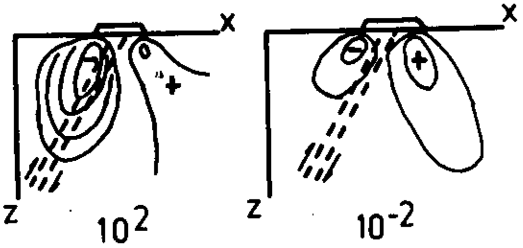

Fig. 5. Contours of change in fault stability (Δ S) due to impoundment of a finite reservoir in a reverse fault environment (after Bell and Nur, 1978). Trapeziums represent reservoir load. The dashed lines represent fault zone with 100 time higher (left) and lower (right) permeability relative to surrounding rock. Negative values imply fault destabilization. Innermost negative region contour indicates stability decrease of 40% (left) and 20% (right) relative to maximum reservoir load.

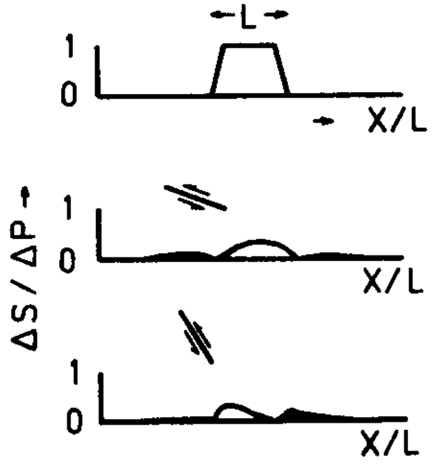

Fig. 6. Comparison of stability changes ΔS in thrust (middle) and reverse (lower) fault environment due to reservoir load (ΔP) at (top), after Roeloffs (1988). Lower two curves are for a depth L/2 below the reservoir, L being reservoir width. Darkened segments of curves correspond to decrease in stability.

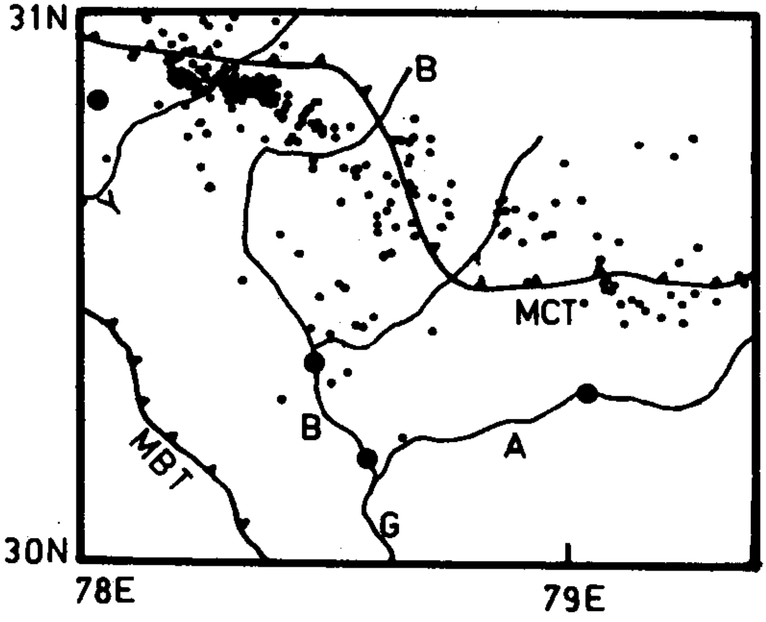

Fig. 7. Epicentres of small earthquakes (m_b less than 5) in the Garhwal Himalaya (after Khattri et al., 1989). Symbols are same as in Fig. 1.

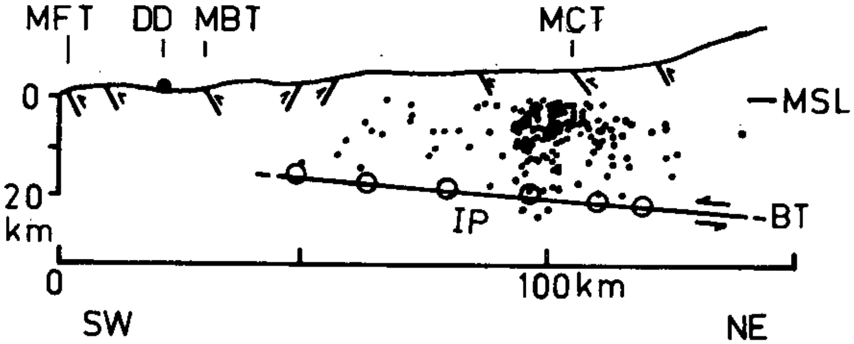

Fig. 8. Focal depths of small earthquakes in the Garhwal Himalaya (after Khattri et al., 1989). Topography and faults are schematic except that horizontal locations of MFT, MBT and MCT are to scale. Open circles indicates range of focal depths of moderate (m_b between 5 and 6 mainly) earthquakes (see text). BT is the thrust boundary between the Indian lithospheric plate (IP) and overlying wedge of Himalayan rocks. It would have been the seat of the 1905 Kangra earthquake rupture according to Chander (1988).

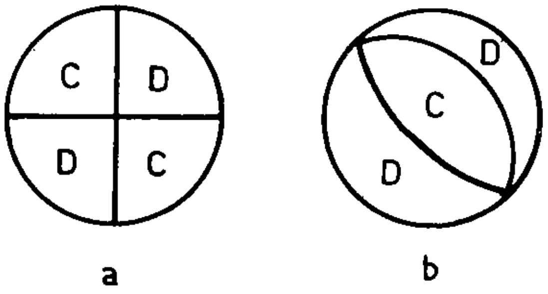

Fig. 9. Upper hemisphere equal area projections of nodal planes of two composite fault plane solutions of small earthquakes in the Garhwal Himalaya (after Khattri et al., 1989). C-compression and D-dilatational quadrants. Strike-slip solution is at left. In the solution at right, NE and SW dipping nodal planes have reverse and thrust type motion respectively.