1. Reddi, A. G. B., Mathew, M. P., Baldau Singh and Naidu, P. S., Aeromagnetic evidence of crustal structure in the Granulite Terrane of Tamil Nadu–Kerala. *J. Geol. Soc. India*, 1998, **32**, 368–381.
2. Magnetic anomaly maps of the Continental Shelf areas of India. Tech. Rep. no. NIO/TR-6/93, prep. NIO, Goa.
3. Subrahmanyam, A. S., Lakshminarayana, S., Chandrasekhar, D. V., Murthy, K. S. R. and Rao, T. C. S., Offshore structural trends from magnetic data over Cauvery Basin, East Coast of India. *J. Geol. Soc. India*, 1995, **46**, 269–273.
4. Sastri, V. V., Sinha, R. N., Gurucharan Singh and Murti, K. V. S., Stratigraphy and tectonics of sedimentary basins on East Coast of peninsular India. *Am. Assoc. Petrol. Geol. Bull.*, 1973, **57**, 655–678.
5. Chetty, T. R. K., Proterozoic shear zones in southern granulite terrain, India. The Achaean and Proterozoic terrains of southern India within East Gondwana, Gondwana Research Group, Mem., 1996, no. 3, pp. 77–89.
6. Subramanian, K. S. and Selvan, T. A., *Geology of Tamil Nadu and Pondicherry*, Geol. Soc. India, Bangalore, 2001, pp. 61–108.
7. Gopalakrishnan, K., Venkat Rao, V. and Viswanathan, P. T. V., Role of palaeosutures in the evolution of Southern Indian granulite terrain, Group Discussion on Sutures Zones – Young and Old. Wadia Inst. Him. Geol. and Geol. Soc. India, extended abstracts, Geol. Surv. India, 1990, pp. 55–60.
8. Rajaram, M. and Anand, Crustal structure of South India from Aeromagnetic Data. *J. Virtual Explorer*, 2003, **12**, 72–82.
9. Eremenko, N. A. and Datta, A. K., Regional geological framework and evolution of the petroleum prospects of the Laccadive – Archipelago and the adjoining offshore territory southwest of India. *Bull. Oil Natl. Gas. Comm. India*, 1968, **5**, 29–40.

ACKNOWLEDGEMENTS. We thank the Director, National Institute of Oceanography, Goa, India for permission to publish this paper. We thank the anonymous reviewers for their critical reviews on the manuscript. This research communication is National Institute of Oceanography (NIO) contribution no. 3899.

Received 1 August 2005; revised accepted 25 November 2005

Three dimensional attenuation structure of the central seismic gap region of Himalaya obtained from inversion of seismic intensity data

A. Joshi

Department of Earth Sciences, Kurukshetra University, Kurukshetra 136 119, India

The central gap region of the Himalaya, which lies in the northern part of the Indian subcontinent, is exposed to a great seismic hazard. Due to paucity of existing seismic instrumentation we have less digital data of past earthquakes in this region. With isoseismal data we have used damped least square inversion scheme to get three-dimensional attenuation structure of the region based on *Q* value. The obtained *Q* structure explains the aerial distribution of isoseismals of major earthquakes in the recent past. The studied area covers the Tehri town, which is the locale of one of the biggest earth-fill dams of height 260 m. The surface distribution of *Q* value suggests that the region around Tehri is surrounded by comparatively less attenuating medium and hence is a region of potential seismic hazard. The obtained *Q* structure explains the surface distribution of isoseismals of major earthquakes and provides important inputs for the purpose of seismic hazard zonation.

Keywords: Central seismic gap, Himalaya, isoseismal, *Q* value, seismic hazard, intensity.

THE Himalayan orogen, which extends over 2500 km from Kashmir in the northwest to Arunachal in northeast India, is believed to be the result of a collision of the Indian and Eurasian plates[1–4]. Four great earthquakes have occurred in this Himalayan belt; however the major intervening part of the plate boundary has not broken in this time interval. Three areas of seismicity gaps have been identified in this Himalayan plate boundary[5]. Among these, the extent of central gap is long and has the potential for sustaining two future great earthquakes[5]. The central gap region of the Himalayas lies in the northern part of the Indian subcontinent and falls under the highest zone V of seismic zoning map of India. This region lies in a seismically hazardous zone and has witnessed two major earthquakes in the last decade, which had killed nearly 2100 people. The seismic hazard in any region can be correlated with the attenuation property of the medium, which is inversely proportional to the quality factor (Q) of the medium. Based on the principle that the ground vibration generated due to an earthquake controls the surface damage, inversion is performed to correlate the intensity data with the subsurface Q structure of the region. The final Q structure shows that this region contains both low as well as high Q localities and the site of the Tehri dam lies in comparatively high Q zone, which indicates its high seismic hazard potential.

For homogeneous earth the intensity contours usually show co-circular pattern with their centre at the epicentre. Irregular patterns of isoseismals are explained by attenuation structures[6,7]. The basic assumption which is used in the inversion scheme is that the seismic intensity is a measure of the peak ground acceleration A, which is associated with the arrival of S-waves released from point source buried in the earth medium, where velocity is constant in the horizontal direction and varies in a vertical direction[8,9]. In the present work the relation applicable for Himalayan earthquakes has been used to convert observed intensity data into peak ground acceleration after carefully testing their applicability for the Himalayan earthquakes[10,11]. It has been seen by several numerical experiments that a quantitatively reliable Q structure and earthquake source strength can be obtained in a region using intensity data[8]. The procedure of inversion is based on the method of Aki and Lee,

e-mail: anushijos@yahoo.co.in

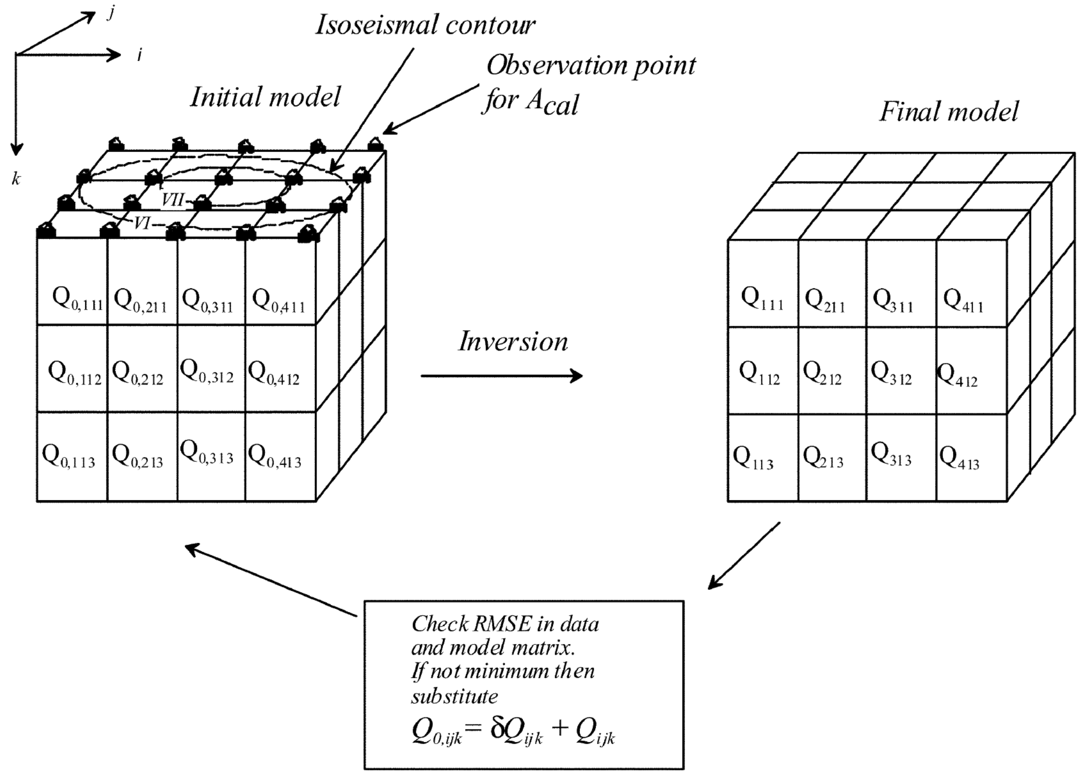

Figure 1. Division of area into several cubic blocks of same size with different Q values. Initial model of $Q_{0,ijk}$ is used for inversion in iterative manner to get final Q_{ijk} structure.

and has been successfully applied for obtaining Q structure of Japan[12,13]. For a model of the region defined by several blocks with constant but different Q_{ijk}, the relation between observed acceleration A_{obs} and calculated peak ground acceleration A_{cal} due to the S-wave can be given as[6]:

$$\ln(A_{obs}/A_{cal}) = \ln(S/S_0) - \sum(D_{ijk} - D_{0,ijk})T_{ijk} + e.$$

The parameter e in the above equation gives the estimate of error. In this equation the left hand side is known to us, S_0 is the calculated source strength from the assumed initial model $D_{0,ijk}$. S and D_{ijk} are the actual source strength and attenuation parameter of the real earth. T_{ijk} is the time spent in the ijkth block of attenuation coefficient D_{ijk} $(\pi f/Q_{ijk})$ and is calculated for different models using ray theory. For a particular earthquake, we have as many equations as there are observation points at the surface of the earth. Inversion in damped least square sense is performed in an iterative manner by first assuming an initial Q model. Inversion of all sets of equations gives an estimate of unknown quantities like $\ln(S/S_0)$, $\delta D_{ijk} = (D_{ijk} - D_{0,ijk})$ and e respectively. For the next iteration, a new Q model is prepared by adding δD_{ijk} in the initial mode (i.e. $\delta D_{ijk} + D_{0,ijk}$). Again, S_0 is computed at all observation points and average value is used to compute A_{cal} at all observation points. This again gives a new set of equations for inversion and again unknown parameters are estimated. This iteration is performed until δD_{ijk} and e are minimized (Figure 1).

In this central gap region of the Himalaya we have intensity data for only four earthquakes, namely the Chamoli earthquake of 23 January 1996 (lat. 30.48°, long. 79.41°, depth = 33 km, $m_b = 4.3$); the Garhwal earthquake of 26 March 1996 (lat. 30.65°, long. 79.10°, depth = 47 km, $m_b = 4.8$); the Uttarkashi earthquake of 20 October 1991 (lat. 30.78°, long. = 78.77°, depth = 10 km, $M_s = 7.0$) and the Chamoli earthquake of 28 March 1999 (lat. 30.51°, long. 79.4°, depth = 15 km, $M_s = 6.6$; Figure 2). Three-dimensional Q structure is determined in a selected rectangular block of length 150 km and width 250 km, which is divided into 36 small rectangular blocks of size 30 km × 43 km × 10 km. Three-dimensional division of this region is made by a total of 108 blocks. Using the intensity data at 36 observation points for four earthquakes, we obtained a set of 144 equations and 113 parameters. A known simple velocity Q model is assumed as the initial model[16]. This set is inverted in an iterative manner for several models and among these a final model is selected that minimizes δD_{ijk}. The final model gives the three-dimensional distribution of Q in the selected rectangular area.

In India a few studies have been carried out to understand the attenuation characteristics of the medium in the central gap of the Himalaya. Some of these studies suggest

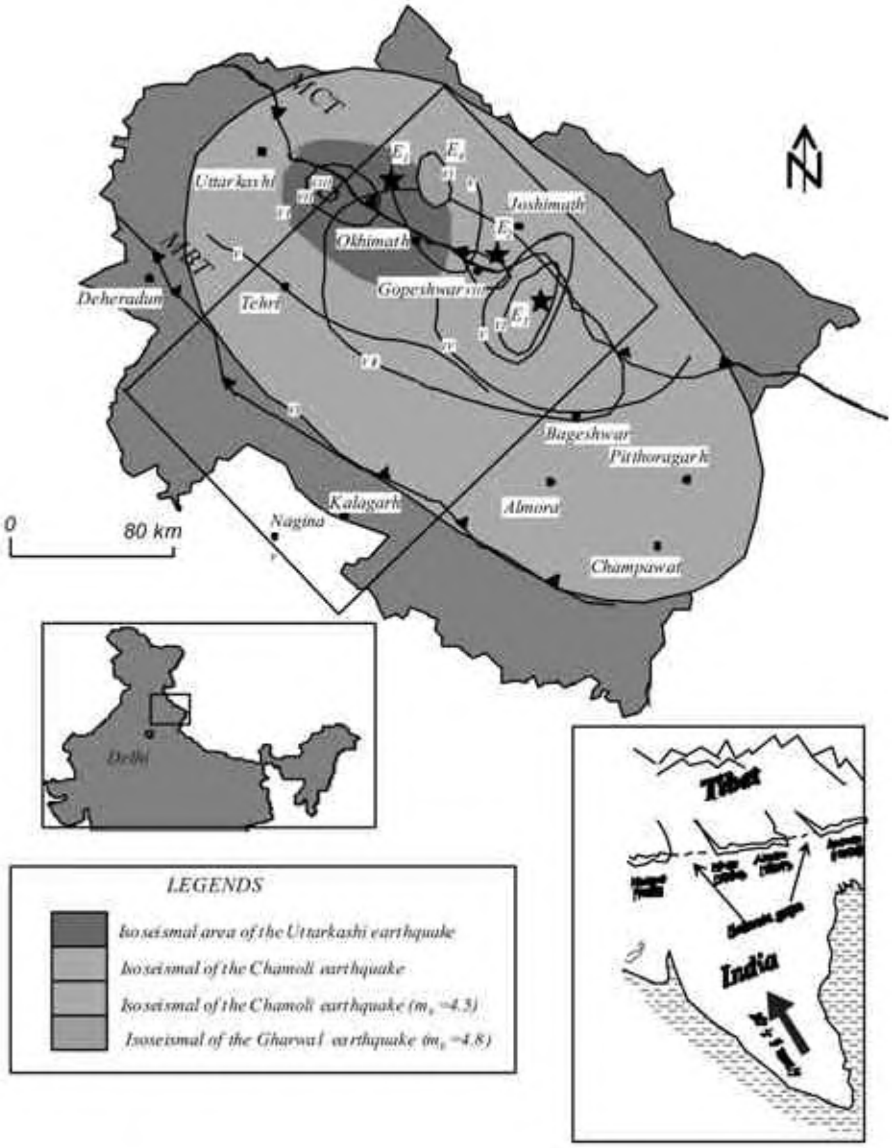

Figure 2. Isoseismals of the Uttarkashi, Garhwal and Chamoli earthquakes in MMI scale[14,15]. Shaded region shows area covered by isoseismal of VI value on MMI scale. E_1, E_2, E_3 and E_4 are epicentres of the Uttarkashi (M_s = 7.0), Chamoli (M_s = 6.5), Chamoli (m_b = 4.5) and Garhwal (m_b = 4.8) earthquakes. (Inset) Selected area lies in the central seismic gap between great Kangra and Assam earthquakes in the Indian lithoshperic plates moving at the rate of 5.5 cm/yr (after Gaur[24]). MBT, Main Boundary Thrust; MCT, Main Central Thrust.

low Q value, while others suggest high Q value[17–19]. These conflicting results may have arrived from the use of different datasets for estimating a single Q value representative of the large area. These findings are unable to explain why the area covered by similar intensity contours in the Uttarkashi earthquakes was smaller than that of the Chamoli earthquake, despite the higher energy released. Maximum mud, adobe and stone houses are in the Chamoli district[20]. This also fails to explain the cause of real destruction scenario during earthquakes in this region.

Spatial distribution of Q value in the selected area shows low value at the epicentral region of the Uttarkashi earthquake and high value at the epicentral region of the Chamoli earthquake (Figure 3). This clearly explains that, though the amount of energy released during the Uttarkashi earthquake was high, it was attenuated at a faster rate than that of the Chamoli earthquake. Therefore, isoseismals for the Uttarkashi earthquake covered a smaller area than that of the Chamoli earthquake. The final Q structure coincides with the steady state model of the continental subduction in the central part of the Himalaya[3] (Figure 4). The studied area includes the Tehri region, which is the site of one of the largest rockfill dams of height of 260 m across the river Bhagirathi. Seismological research[16,21,22] reveals that this region can experience peak ground acceleration more than 1 g. Little information is available about the attenuating char-

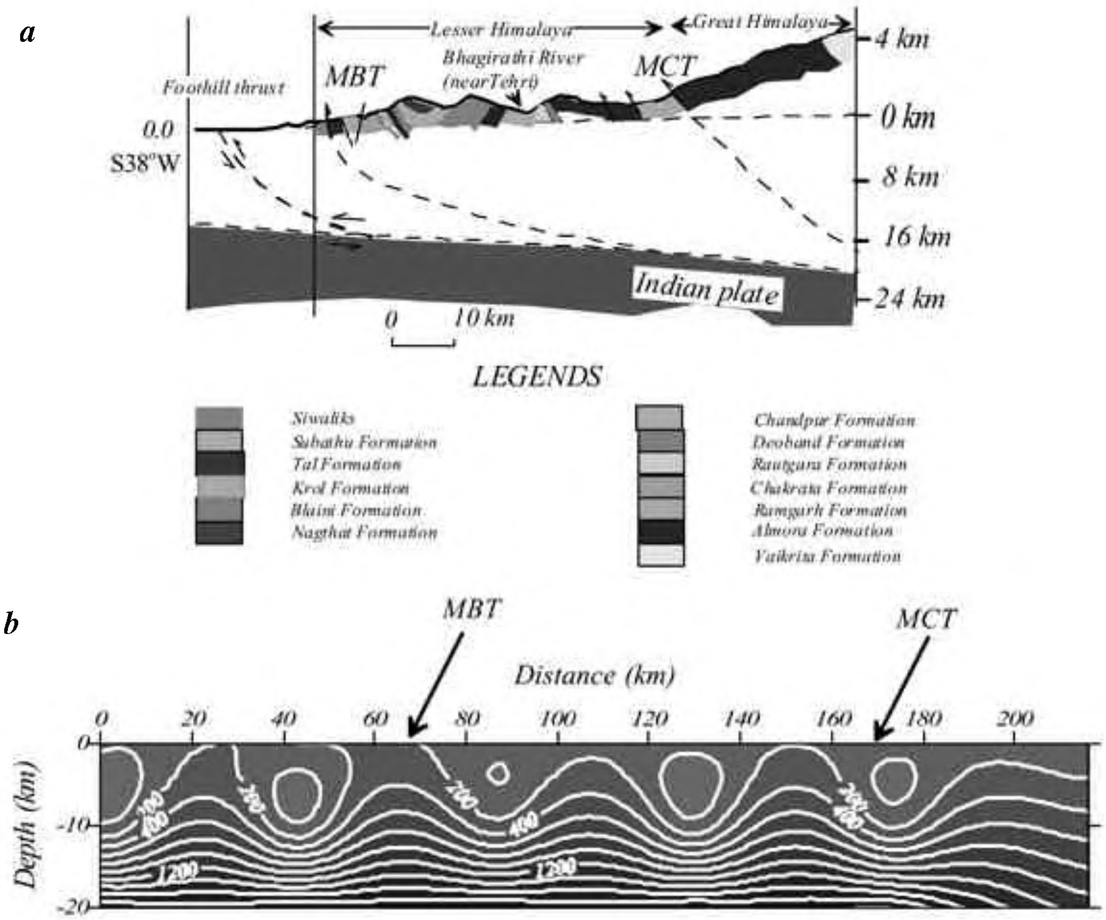

Figure 3. (***a***), Geological depth section along central Himalayan region transverse to the strike of MCT and MBT and (***b***) the obtained Q structure. The depth section is taken after Seeber *et al.*[3].

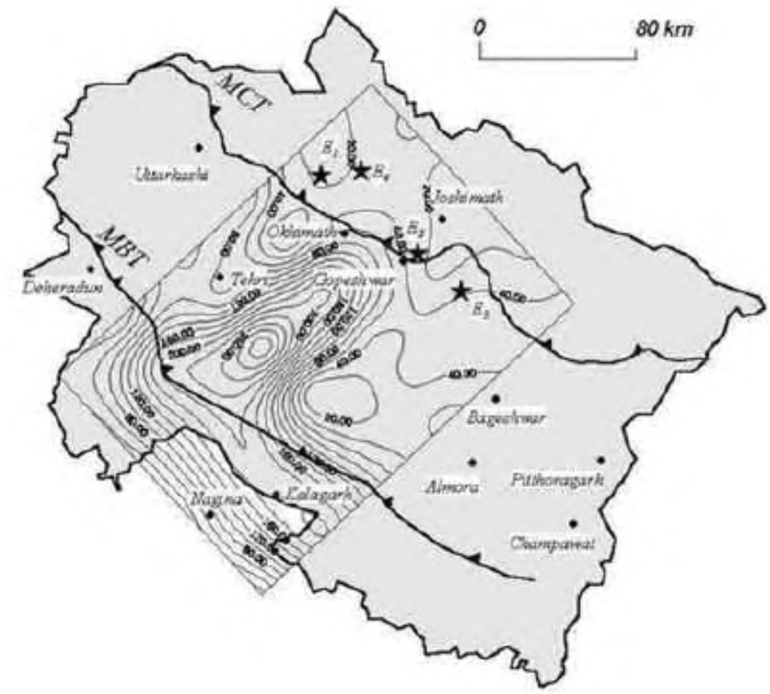

Figure 4. Q contours in the central gap region of the Himalaya.

acteristics of the medium beneath Tehri. Our study shows that the Tehri region is surrounded by comparatively high Q zone. Seismic energy released from source attenuates at a rate proportional to $e^{-\pi fR/Qc}$ where f is the frequency, R hypocentral distance and c the propagation velocity. Therefore, high Q value means low attenuation of seismic energy in the medium and hence high probability of seismic hazard in this region. As the region is identified to be in the central seismic gap of the Himalaya[5], a great magnitude earthquake is expected here. During the last great earthquake of 1905, 19,500 people were killed due to collapse of houses[23]; therefore any great earthquake in this region presents risk to 50 million people who live in towns and villages of the Himalayan mountain and the Ganges plains. Under such circumstances, demarcation of high and low attenuation zones proves to be useful for planners and engineers. The Q structure obtained from the present inversion can be used together with the site effects of the topmost soil for seismic hazard zonation of those regions where such data are available. Due to limited digital data available in this region, seismic intensity has been used as input for inversion and hence the results obtained here are mostly qualitative in nature. With the advancement of the digital network and increase in the database of large earthquakes in future, the present technique can be applied to obtain quantitative estimate of three-dimensional Q structure of the earth crust.

1. Gansser, A., *Geology of Himalaya*, Interscience, New York, 1964, p. 298.
2. Holmes, A., *Principles of Physical Geology*, Ronald Press, New York, 1965, p. 1288.
3. Seeber, L., Armbruster, J. G. and Quittmeyer, R. C., Seismicity and continental subduction in Himalayan arc, Hindu Kush. In *Himalay, Geodynamic Evolution* (eds Gupta, H. K. and Delany, F. M.), Geodyn. Sep. vol. 3, AGU Washington DC, 1981, pp. 215–242.
4. Lyon Caen, H. and Molnar, P., *J. Geophys. Res.*, 1983, **88**, 8171–8191.
5. Khattri, K. N., *Tectonophysics*, 1987, **138**, 79–92.
6. Nakanishi, I. and Horie, A., *J. Phys. Earth*, 1980, **28**, 336–360.
7. Utsu, T., *J. Fac. Sci., Hakkaido Univ*., 1966, **2**, 359–374.
8. Hisada, T. and Shimazaki, K., *J. Phys. Earth*, 1984, **32**, 299–316.
9. Hadley, D. M., Helemberger, D. V. and Orcutt, J. A., *Bull. Seismol. Soc. Am*., 1982, **32**, 163–191.
10. Ramalingeshwar, Rao, Prakasa Rao, T. K. S. and Sitapathi Rao, P., *Geophys. Res. Bull*., 1982, **20**, 191–204.
11. Joshi, A., *J. Seismol*., 2000, **4**, 143–160.
12. Aki, K. and Lee, W. H. K., *J. Geophys. Res*., 1976, **81**, 4381–4399.
13. Hasida, T., *Bull. Earthquake Res. Inst., Univ. Tokyo*, 1987, **62**, 247–287.
14. Dasgupta, S. *et al.*, *Seismotectonic Atlas of India and its Environs*, Geol. Soc. India, Bangalore, 2000, vol. 43.
15. Rastogi, B. K., *J. Geol. Soc. India*, 2000, **55**, 505–514.
16. Yu, G., Khattri, K. N., Anderson, J. G., Brune, J. N. and Zeng, Y., *Bull. Seismol. Soc. Am*., 1995, **85**, 31–59.
17. Mandal, P., Padhy, S. Rastogi, B. K., Satyanarayana, V. S., Kousalya, M., Vijayragvan, R. and Srinivasan, A., *PAGEOPH*, 2001, **158**, 1719–1735.
18. Chandrasekaran A. R. and Das, J. S., *Bull. Indian Soc. Earthq. Technol*., 1992, **29**, 35–55.
19. Gupta, S. C., Singh, V. N. and Kumar, A., *Phys. Earth Planet. Inter*., 1995, **87**, 247–253.
20. Arya, A. S., Long-term measures for earthquake protection in Uttaranchal area of Uttar Pradesh, India. *Mem. Geol. Soc. India*, 1995, 30, 191–201.
21. Brune, J. N., *Tectonophysics*, 1993, **218**, 281–286.
22. Joshi, A. and Patel, R. C., *Tectonophysics*, 1997, **283**, 289–310.
23. Bilham, Gaur, V. K. and Molnar, P., *Science*, 1995, **293**, 1442–1444.
24. Gaur, V. K., *Earthquake Hazard and Large Dams in the Himalaya*, INTACH, New Delhi, 1993, pp. 63–74.

ACKNOWLEDGEMENTS. The genesis of this work goes back to 2001 in Japan during my BOYSCAST fellowship sponsored by DST, New Delhi. Thanks are due to the anonymous referee of my earlier paper, who suggested the reference of Hisada to me. I thank Prof. Midorikawa and his laboratory for providing me the literature for this work. Thanks are also due to my geophysicist colleagues at the Department of Earth Sciences, Kurukshetra University for encouragement. Financial aid was received for this work from DST.

Received 20 December 2004; revised accepted 25 November 2005