The representability of attenuation characteristics of strong ground motions observed in the 1986 Dharmsala and 1991 Uttarkashi earthquakes by available empirical relations

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The attenuation characteristics of the observed peak accelerations as a function of distance and magnitude for the 1986 Dharmsala (m_b 5.5) and the 1991 Uttarkashi (m_b 6.5) earthquakes have been compared with the empirical relations for various regions of the world. The relation of Abrahamson and Litehiser, obtained using a world-wide data set, is found to be capable of predicting the Uttarkashi acceleration data and that of Peng *et al.* for China describes the Dharmsala data set quite well up to a distance of 24 km. Thus, the above two adjacent regions in Himalaya are characterized by different attenuation properties which are a reflection of the nature of the upper crustal rocks present in the respective regions.

THE prediction of the peak ground accelerations due to a severe earthquake is necessary for the assessment of seismic effects on structures and their mitigation. The peak value of horizontal acceleration is one of the important parameters that is considered in the earthquake safe seismic design of engineered structures. Accordingly, several studies have been done to obtain attenuation relations of peak ground accelerations for various regions of the world[1–12]. Most of these studies are based on regression or multiple regression analysis of large data sets of strong motion acceleration records. In India, strong motion seismology started to develop only recently in the 1980s with the deployment of strong ground motion instruments in the Himalaya. The first strong motion records were obtained in Himalaya in 1986 (ref. 13). Subsequently, the Uttarkashi earthquake of magnitude m_b 6.5 in Garhwal Himalaya was also recorded. Other data sets are available for a few earthquakes in the eastern Himalaya which have different seismo-tectonic characters. However, the data sets obtained thus far for a specific region are not adequate to allow multiple regression analysis for obtaining distance attenuation laws. In this study, we investigate whether any of the available regressions are able to predict observed peak accelerations as a function of distance and magnitude for the 1986 Dharmsala (m_b 5.5) and the 1991 Uttarkashi (m_b 6.5) earthquakes. The utility of this study is twofold:

(i) The attenuation relation which gives a good fit with the observed strong ground motions in Himalaya can be used in estimating the acceleration due to future large earthquakes to estimate seismic hazard of the region.

(ii) Some semi-empirical techniques for the estimation of peak ground accelerations and envelopes of the accelerograms (e.g. Midorikawa[14]) are very sensitive to the attenuation relation used and therefore to apply such techniques in Himalaya, an appropriate attenuation relation is required.

A model based on the attenuation of body waves in an inelastic medium from a point source is given by[6,15]

$$\log(Y) = a_0 + a_1M + a_2r + a_3 \log(r),$$

where Y is the response variable under consideration, M is the magnitude, r is distance between the source and the recording station and a_i's are the coefficients to be determined. The term a_2r represents the inelastic attenuation, and the term $a_3 \log(r)$ represents the geometrical spreading.

The above model does not consider the depth of the crustal source. Ground motion of deeper earthquakes (within the crust) is generally stronger than that of shallower earthquakes with the same magnitude and the source distance[11]. The effect of the local ground condition is another important factor influencing the ground motion amplitudes. A regression model which takes care of depth as well as local ground condition along with other parameters is given by

$$\log(Y) = a_0 + a_1M + a_2r + a_3 \log(r) + a_4H + c,$$

where H is the depth in kilometers of the point in fault plane that is closest to the recording site and c is a coefficient representing the local site effect at the recording site.

In addition to the magnitude, distance, and site conditions, there are two other independent parameters which affect the attenuation relation. These are fault type (i.e. strike slip, normal, normal oblique, reverse or reverse oblique) and tectonic environment (interplate or intraplate).

A number of empirical relationships have been developed for various regions of the world. Some of the attenuation relations have incorporated the various parameters noted above (e.g. references 11, 16, 17). We have examined ten attenuation relationships, which are summarized in Table 1, for finding a suitable relation that may predict the observed data set of the earthquakes under consideration. We note that differing definitions of distance and response variable are used in these re-

Table 1. Comparison of attenuation relations for different regions of the world

Reference number	Attenuation relation	Region	Magnitude scale used	Distance used	Response variable
1	$\ln(a) = 3.40 + 0.89M - 1.17 \ln(R)$	Western USA	Richter	Hypocentral	Peak hor. acc.
3	$\log(a) = -0.474 + 0.613M_s - 0.873 \log(r) - 0.00206r$	N.E. China	Surface wave	Epicentral	Mean of peak hor. acc.
3	$\log(a) = 0.437 + 0.454M_s - 0.739 \log(r) - 0.00279r$	S.W. China	Surface wave	Epicentral	Mean of peak hor. acc.
4	$\log(a) = 2.3664 + 0.313M - 1.218 \log(r + 30)$	Japan	Japan Met. Agen. (JMA)	Epicentral	Resultant
2	$\log(a) = 1 + 0.56m_b - 1.5 \log(R)$	Western Canada	Body wave	Hypocentral	Peak hor. acc.
2	$\log(a) = 0.53 + 0.56m_b - 1.5 \log(R)$	Eastern Canada	Body wave	Hypocentral	Peak hor. acc.
9	$\ln(a^*) = -1.62 + 1.24m_b - 1.24 \ln(R + 25)$	Central USA	Body wave	Hypocentral	Peak hor. acc.
6	$\log(a^*) = -0.62 + 0.177M_s - 0.982 \log(R + \exp(0.284M_s)) + 0.132F - 0.0008ER$ $F = 1$ for reverse and 0 otherwise $E = 1$ for interplate and 0 for intraplate events	World wide	Surface wave	Hypocentral	Peak hor. acc.
7	$\log(a^*) = -1.06 + 0.245M_s - 0.00045R - 1.016 \log(R) + 0.25P$ $P = 0$ for 50 percentile and 1 for 84 percentile	Europe	Surface wave	Hypocentral	Peak hor. acc.
12	$\log(a) = 1.14 + 0.31m_b - 0.615\log(R)$	North India	Body wave	Hypocentral	Peak hor. acc.

a, Acceleration in cm/s*s; a^*, Acceleration in g; M, m_b, M_s: Magnitude; R & r, Distance (km).

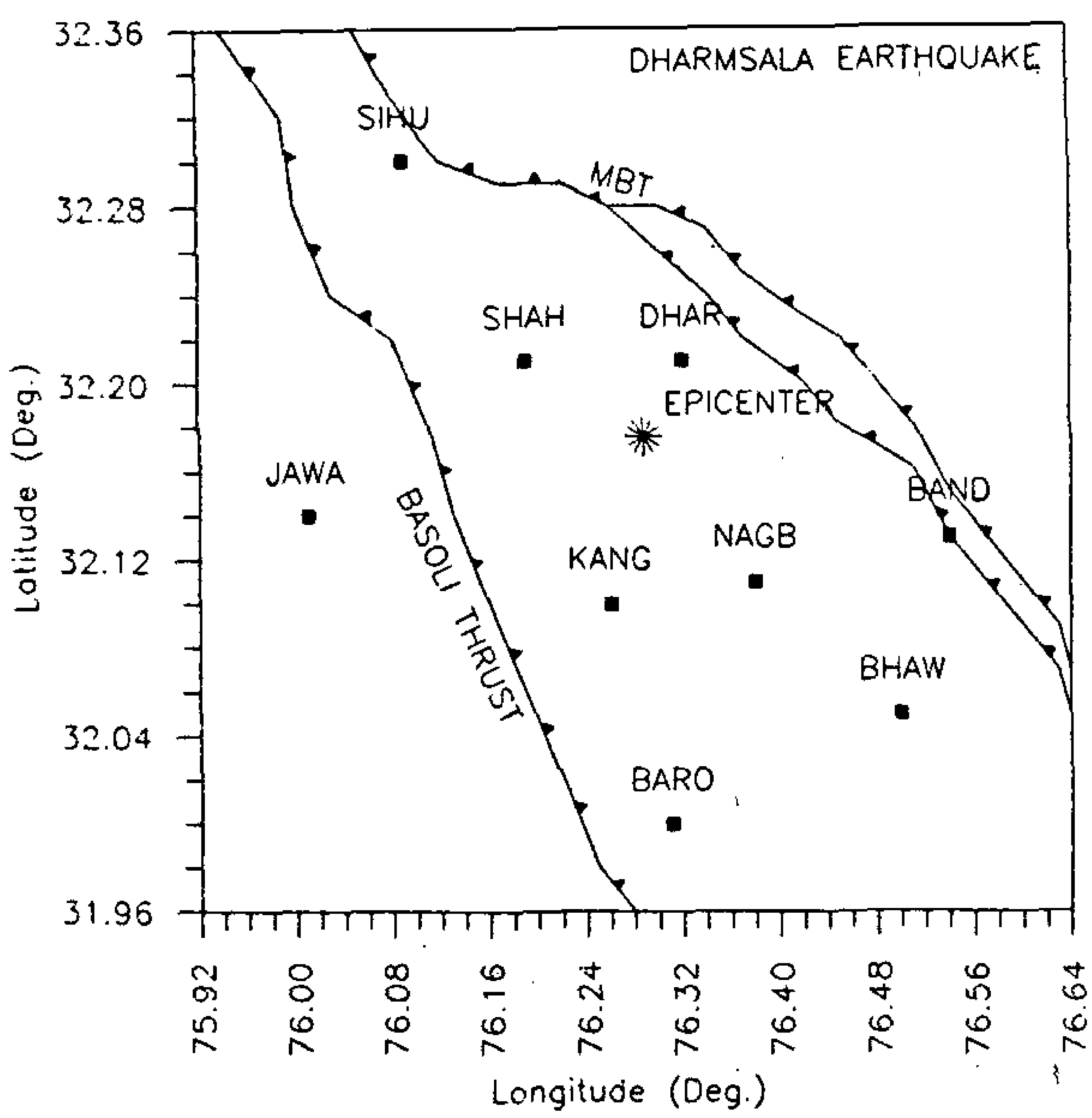

Figure 1. Locations of the epicenter of the 1986 Dharmsala earthquake and the recording stations.

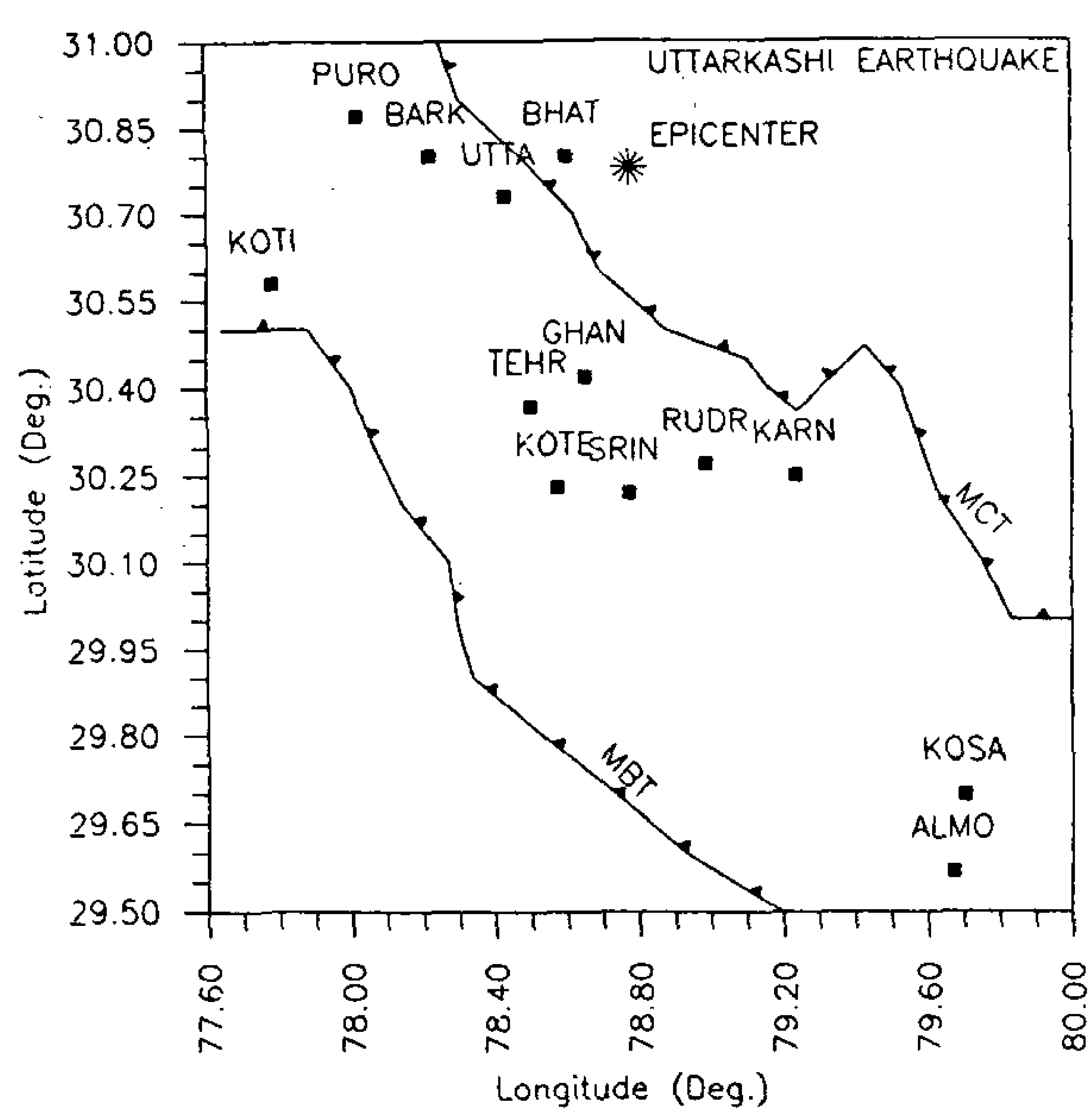

Figure 2. Location of the epicenter of the 1991 Uttarkashi earthquake and the recording stations.

gression relations. Similarly, alternative magnitude scales are used in some of them. Accordingly appropriate values for these parameters were obtained from the observed data sets for analysis in the present study.

The 1986 Dharmsala and the 1991 Uttarkashi earthquakes provide us with an opportunity to see if any of the available attenuation relationships are able to predict the observations in Himachal and Garhwal Himalaya satisfactorily. The Dharmsala earthquake (m_b 5.5, M_s 5.3; U.S.G.S.) was recorded at nine sites[18]. The epicenters reported for this earthquake by three agencies namely DEQ, IMD and USGS are not coincident. In the present study, we have adopted the following hypocentral parameters as reported by DEQ since it best fits the observed data:

Origin time: 7 h 35 m 16.42 s
Latitude: 32.175°N; Longitude: 76.287°E
Depth: 7 km

Figure 1 shows the location of the epicenter of the earthquake along with the recording stations. Table 2 lists the peak accelerations of the horizontal components, their resultant as well as their mean[18].

The Uttarkashi earthquake having a magnitude m_b 6.5 (M_s 7.0; U.S.G.S.) was recorded at thirteen stations[19]. In

Table 2. Peak accelerations of the horizontal components recorded in the 1986 Dharmsala earthquake

Station	Epicentral distance (km)	Hypocentral distance (km)	$a_{max} - L$ $a_{max} - T$ (cm/s²)	Mean (cm/s²)	Resultant (cm/s²)
Bandlakhas	24.40	25.38	142.49 122.36	132.4	144.0
Baroh	19.55	20.77	57.56 56.17	56.9	60.4
Bhawarna	24.40	25.38	36.49 34.72	35.6	38.0
Dharmsala	5.39	8.83	172.21 182.89	177.6	237.6
Jawali	26.40	27.31	14.87 16.55	15.7	18.7
Kangra	8.80	11.24	144.97 109.43	127.2	157.4
Nagrota-Bagwan	11.43	13.40	145.54 78.59	112.1	145.6
Shahpur	10.08	12.27	200.17 243.20	221.7	263.9
Sihunta	23.28	24.31	50.41 35.32	42.9	57.0

Table 3. Peak accelerations of the horizontal components recorded in the 1991 Uttarkashi earthquake

Station	Epicentral distance (km)	Hypocentral distance (km)	$a_{max} - L$ $a_{max} - T$ (cm/s²)	Mean (cm/s²)	Resultant (cm/s²)
Almora	159.46	159.77	17.41 21.02	19.22	22.27
Barkot	53.07	54.00	93.18 80.47	86.83	103.88
Bhatwari	16.75	19.51	248.37 241.89	245.13	271.63
Ghansiali	41.68	42.86	115.59 114.89	115.24	141.98
Karnprayag	73.26	73.94	60.99 77.35	69.17	84.74
Kosani	149.22	149.56	28.34 31.50	29.92	31.58
Koteshwar	64.06	64.84	98.85 65.23	82.04	99.08
Koti	97.79	98.30	20.64 40.95	30.80	41.09
Purola	72.83	73.51	73.95 91.68	82.82	96.13
Rudraprayag	59.88	60.71	52.29 50.76	51.53	65.27
Srinagar	62.06	62.86	65.44 49.45	57.45	65.77
Tehri	52.47	53.41	71.41 61.13	66.27	73.63
Uttarkashi	33.36	34.83	237.27 303.99	270.63	313.09

this study, we have used the following hypocentral parameters as reported by PDE (October 1991):

Origin time: 21 h 23 m 14.3 s
Latitude: 30.780°N; Longitude: 78.774°E
Depth: 10 km

Figure 2 shows the epicenter of the Uttarkashi earthquake along with the recording stations. The peak accelerations of the horizontal components, their vector resultant and their arithmetic mean are given in Table 3 (ref. 19).

The observed horizontal peak accelerations for the Dharmsala earthquake and the ten regressions examined here are shown in Figure 3. We note that the regressions use a variety of magnitude scales and distances. An appropriate conversion was made while preparing these graphs for proper comparisons. A cursory examination shows that none of the regressions is adequate to satisfactorily predict the observed acceleration values at all the distances. The regression for western United States[1], Europe[7], world-wide data set[6], Indian data set[12], central United States[9], eastern Canada[2] and Japan[4] shown in Figures 3 *a–d*, *f*, *g* and *j* all show a much slower attenuation rate and over-predict the accelerations at larger distances of 20–30 km. Moreover the regressions for Europe and western and eastern Canada over-predict the accelerations even at shorter distances as well. This suggests that the geological composition of rocks comprising of Neogene thick Siwalik sediments are comparatively more attenuating than the rocks of other regions which are comprised of considerably older formations. The attenuation rate in the western United States (Figure 3 *a*) is similar although a little lower than in Dharmsala region. The regression for China[3] shown in Figures 3 *h* and *i* is closest to the empirical data of Dharmsala earthquake in terms of the rate of decay. Of these two, the one for south-west China predicts the observations satisfactorily up to a distance of about 24 km although we note some scatter in the observed values.

The observed acceleration values for the Uttarkashi earthquake are compared with the regressions in Figure 4. In this case the regressions for eastern Canada (Figure 4 *f*), central United States (Figure 4 *g*), north-east as well as south-west China (Figures 4 *h* and *i*) and Japan (Figure 4 *j*) predict much higher accelerations at all the distances as well as show weaker attenuation with distance. The relation for India shows a much weaker attenuation rate, though it better predicts the accelerations at shorter distances (Figure 4 *d*). For obtaining the regression for Indian data set, distinction has not been made between the crustal earthquakes of Himachal and Garhwal Himalaya and the deeper earthquakes of eastern Himalaya which seems to be the cause for the observed misfits. The regressions for western United States and Europe have comparable attenuation rates to

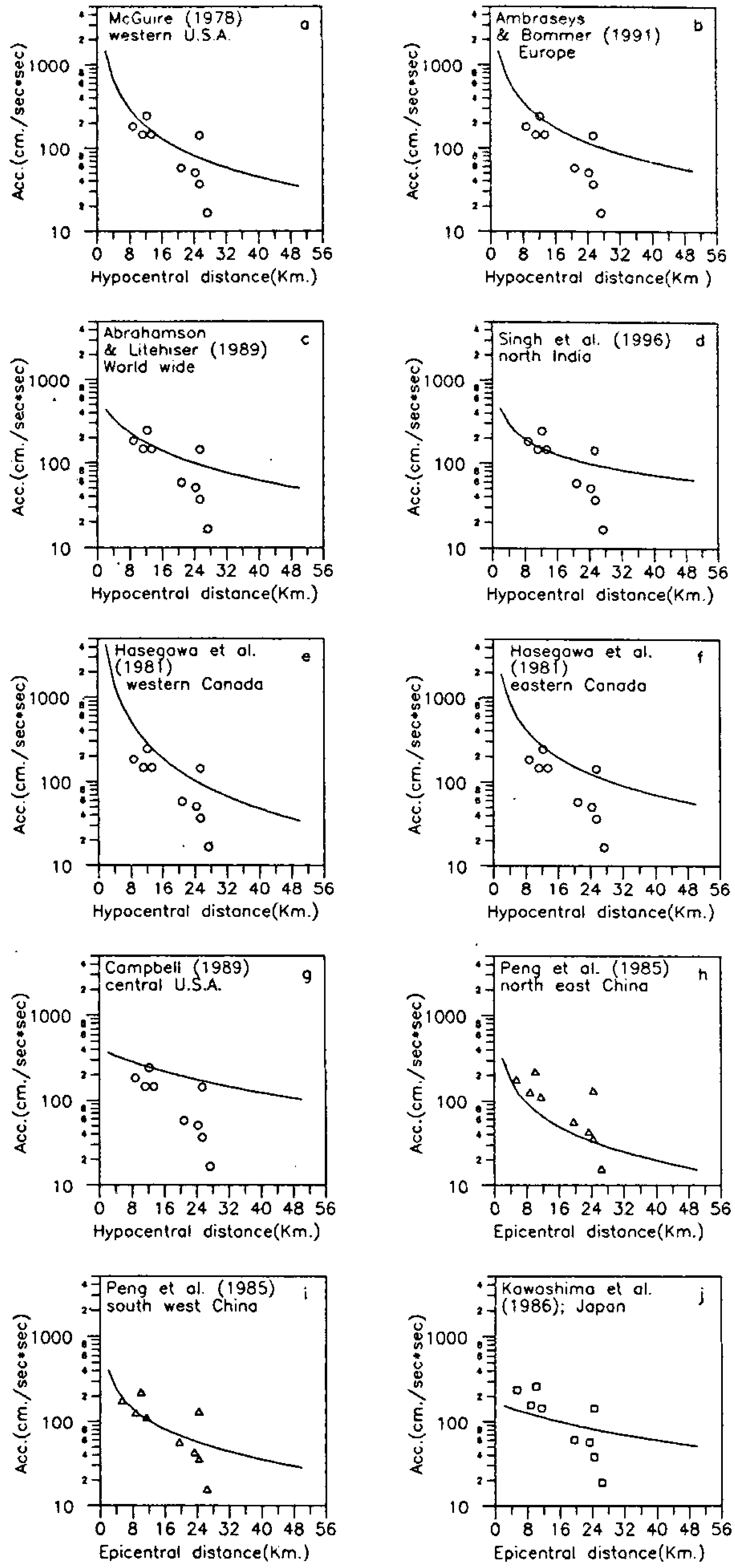

Figure 3. Plot of the observed accelerations with distance for Dharmasala earthquake and the values predicted by the empirical regressions. O, largest peak horizontal accelerations; Δ, mean of the horizontal components for the peak acceleration; □, resultant horizontal acceleration.

the observed ones but both predict higher values at all the distances (Figures 4 *a* and *b*). The regressions for world-wide data set and western Canada (Figures 4 *c* and *e*) are fairly close to the Uttarkashi data. However, since the regression for world-wide data set is considered better at shorter distances where the predictions are more important, it is preferred over the other one. The

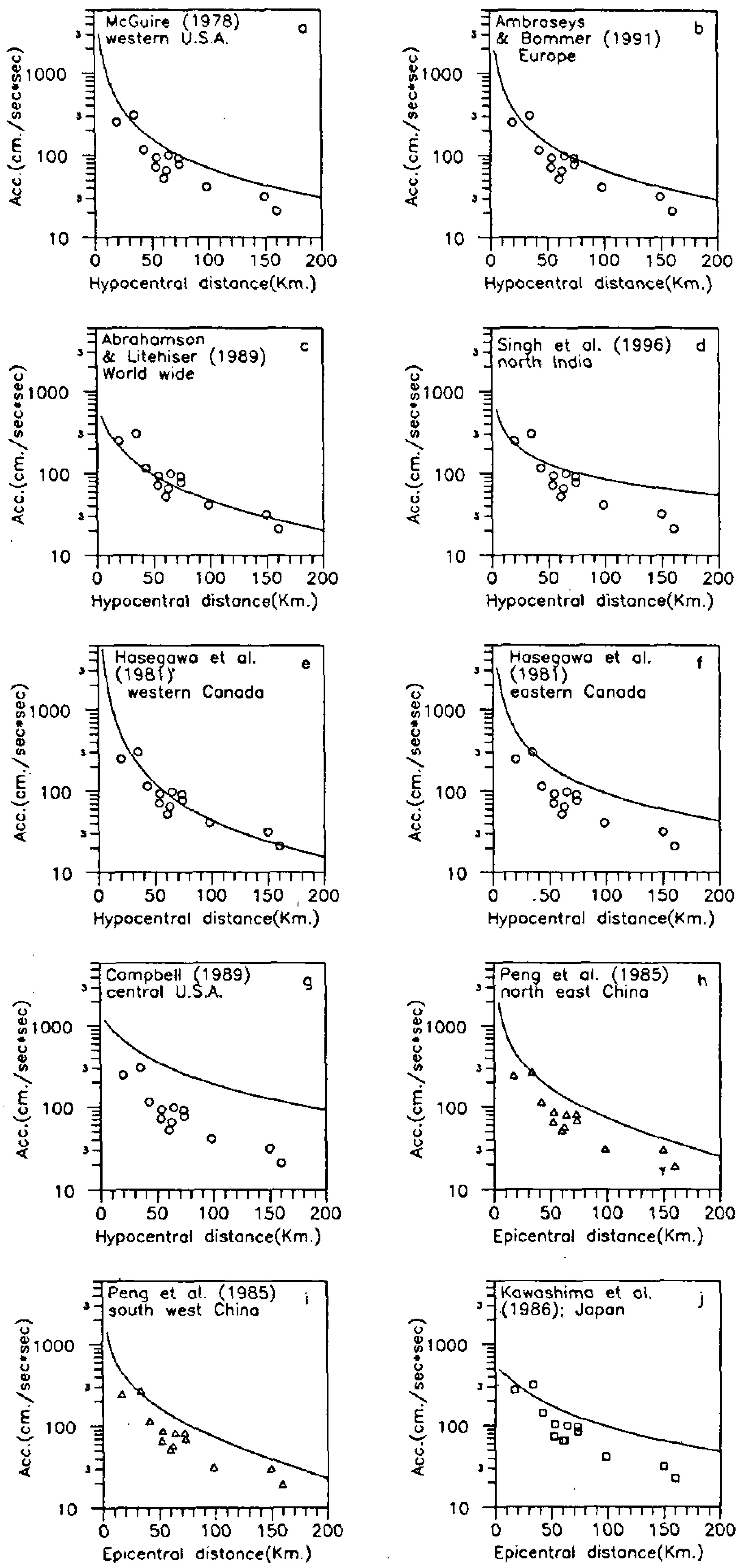

Figure 4. Plot of the observed accelerations with distance for Uttarkashi earthquake and the values predicted by the empirical regressions. O, largest peak horizontal accelerations; Δ, mean of the horizontal components for the peak acceleration; □, resultant horizontal acceleration.

scatter of the observed values with respect to this regression is small in most of the cases.

We find that in general the seismo-tectonic regions are characterized by their specific attenuation relation governed by the respective geology and seismic regime. In the absence of observations of accelerations for a number of earthquakes in the same region, it is not possible to develop region-specific predictive regressions. However, the comparisons for the Uttarkashi earthquake data with the regressions from other regions of the world show that the regression for the world-wide data set[6] is satisfactory for predicting the same. On the other hand for the Dharmsala data set the regression for south China[3] is satisfactory up to a distance of about 24 km. Thus the Dharmsala and Uttarkashi areas which lie in adjacent sectors of Himalaya have different attenuation characteristics. This is a reflection of the geological differences between the two regions. In the Dharmsala area which shows a higher attenuation rate, a thick Neogene Siwalik sedimentary lid forms the upper crustal layers. These layers are comparatively less consolidated and also contain gravel and boulder beds which promote attenuation of waves by scattering. Uttarkashi lies in the Lesser Himalaya where the upper layers are composed of the Paleozoic metasedimentary rocks. The attenuation rate here is lower, which is in keeping with the consolidated and hard nature of the rocks. Thus the observations are consistent with the geological compositions of the two regions.

This investigation has focussed on the need to use region-specific attenuation relations for assessment of expected peak accelerations for proper seismic hazard assessment. In order to develop such relations, it is required to instrument Himalaya intensively so as to collect the needed data sets.

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MEETINGS/SYMPOSIA/SEMINARS

School on Cosmic Ray Astrophysics

Date: 3–14 November 1997
Place: Ooty

This school sponsored by TIFR and IUCAA is open mainly to research scholars and research workers actively interested in the area of Cosmic Ray Astronomy and related fields. Topics include: General Astronomy; Optical Astronomy; Theoretical and Observational X-ray Astronomy; Theoretical and Observational Gamma Ray Astronomy; Gamma Ray Bursts; Theoretical and Observational Cosmic Ray Physics; Neutrino Astronomy; Radio Astronomy; Statistics and Simulation Studies; Basic Electronics and Data Acquisition Systems.

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National Seminar on Sustainable Environment

Date: 4–6 November 1997
Place: Alwakurichi

Topics include: Current environmental status (terrestrial and aquatic); Industrial toxicology; Industrial wastewater treatment; Biological waste utilization and recycling; Impact of agriculture and aquaculture on environment and Environmental sustainability.

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National Workshop on Electron Microscopy: Its Application in Biological and Materials Sciences

Date: 10–13 November 1997
Place: Calcutta

Course content: Introduction to electron microscopy; Fundamentals of electron optics and instrumentation; Principle of working of electron microscope image formation; Scanning electron microscope – the instrument; Transmission electron microscope – the instrument; Specimen (biological) preparation techniques in electron microscopy; Electron microscopy for materials characterization; Thin film studies with electron microscope; Application of EM for studying biological specimen; Application of electron microscope for studying geological samples; Other topics of current interest.

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National Symposium on Microbes in Plant Improvement and Environmental Protection

Date: 23–24 December 1997
Place: Delhi

Focal themes include: Microbial transformations in biomass production; Biological control of plant diseases; Rhizosphere microbiology for enhanced plant productivity; Plant surface microbiology in relation to plant metabolism; Microbial transformations of hazardous compounds.

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DAE Solid State Physics Symposium

Date: 27–31 December 1997
Place: Kochi

Subjects include: Phonon physics; Electron states and electronic properties; Magnetism and magnetic properties; Semiconductor physics; Physics of defects and disordered materials; Transport properties; Superconductivity and superfluidity; Liquids, liquid crystals and plastic crystals; Phase transitions and critical phenomena; Surface and interface physics; Non-equilibrium phenomena in solids; Physics of complex systems; Resonance studies and relaxation phenomena; Neutron scattering techniques; Computational condensed matter physics; Solid state devices, techniques and instrumentation.

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