Modelling of strong ground motions from Dharmsala earthquake of 1986 (mb 5.7)

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We have modelled a suite of accelerograms recorded at nine stations during the 26 April 1986 Dharmsala earthquake using the composite source model. The synthetic accelerograms were generated by convolving a source pulse radiated from the composite source with the synthetic Green's function that was computed for a layered velocity structure representing the site and an appropriate fault plane solution. The velocity-*Q* structure was obtained on the basis of oil exploration information on velocities, using the model obtained for the 1991 Uttarkashi earthquake and its trial and error modification to match the observed and the synthetic accelerograms in terms of peak ground acceleration, duration of strong shaking and frequency content. The match is found to be satisfactory for stations having smaller epicentral distances. The observed and the synthetic accelerograms for the stations at Dharmsala, Kangra, Shahpur and Nagrota Bagwan show a satisfactory match in terms of appearance and in their spectrum. The information developed in the above analysis was used to estimate earthquake hazard at Dharmsala and Kangra for an earthquake of body wave magnitude 6.2 and having a similar focal mechanism as the Dharmsala event by simulating the ground motions. The expected peak ground accelerations for Dharmsala and Kangra for this hypothetical event are 0.7 g and 0.5 g respectively compared to 0.2 g and 0.15 g recorded for the mb 5.7 Dharmsala earthquake.

THE Himalaya plays host to considerable seismicity and hence any developmental programme in the region requires to have earthquake-safe structures. This needs characterizing the expected strong ground motions from future damaging earthquakes. The estimation of strong ground motion specific to a location can be done either by empirical methods or by numerical modelling. In order to make reliable prediction, using empirical methods, a large database of strong ground motion information is required. In a region like the Himalaya such information is sparse, hence one has to resort to theoretical modelling techniques to predict strong ground motion. In the present paper we use a technique where the available strong ground motion data is numerically modelled by describing the earthquake source in terms of its rupture geometry, fault plane solution, stress drop, seismic moment, the earth structure and applying analytically the earthquake source and wave propagation theory.

An opportunity to conduct such an exercise has been provided by the damaging earthquake of magnitude mb 5.7 in the Dharmsala region of Himachal Pradesh on the 26 April 1986. This event was recorded by three component accelerographs at 9 stations at epicentral distances in the range of 5 to 30 km (ref. 1). We have modelled the observed accelerograms using the complex source model[2] and wave propagation theory in a plane layered earth. A modified form of the fault plane solution given by Dziewonski *et al.*[3] is used as the earthquake source mechanism. In the process we have identified the appropriate velocity and *Q* models for the sites for obtaining the best visual matches of the observed and the synthetic accelerograms. Using multiple realizations of the earthquake source, we have examined the average predicted strong ground motion parameters in terms of peak ground motion parameters, Fourier and response spectra and compared the same with the empirical data. We have next simulated the expected ground motions

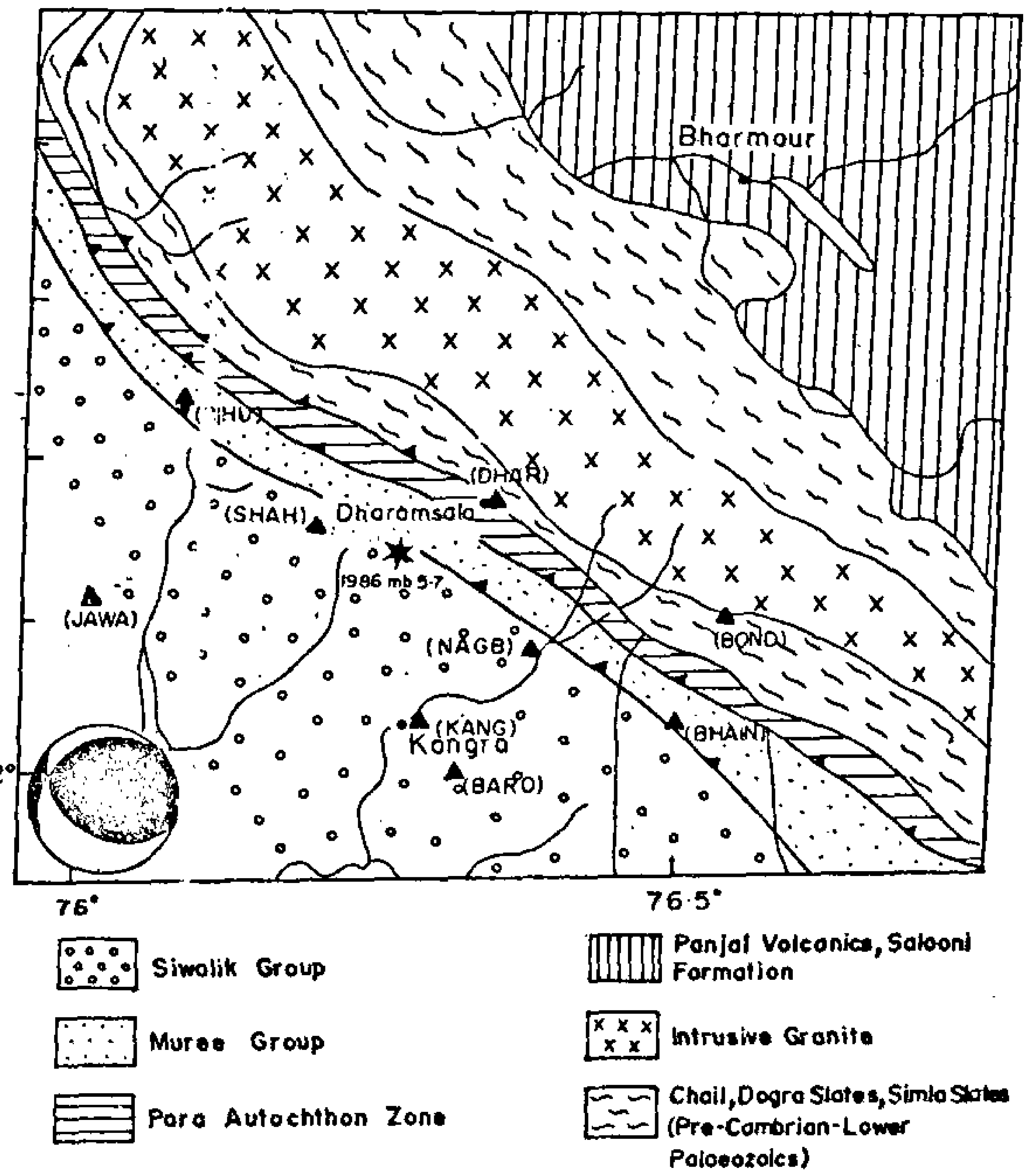

Figure 1. Map showing the location of the Dharmsala earthquake of 26 April 1986 and strong motion recording sites. The various geological units in the Kangra region of Himachal Pradesh are also shown. In the inset, the fault plane solution for the earthquake is shown.

Table 1. Parameters for the modified fault plane solution

	Strike	Dip	Direction
NP1	232°	19°	325°
NP2	131°	69°	223°

Table 2. Station locations and the peak ground accelerations recorded during Dharmsala earthquake of 1986

Station	Station code	Station location Lat. (°N)	Long. (°E)	Epicentral distance (km)	Peak ground acceleration cm/s*s L	T	V
Dharmsala	Dhar	32.21	76.32	5.4	172.2	182.8	81.0
Kangra	Kang	32.10	76.38	8.8	144.9	109.4	70.8
Shahpur	Shah	32.21	76.19	10.2	200.1	243.2	64.4
Nagrota Bagwan	Nagb	32.11	76.38	11.4	145.5	78.5	50.0
Baroh	Baro	32.00	76.31	19.4	57.6	56.2	22.4
Bhawarna	Bhaw	32.05	76.50	21.1	36.5	34.7	35.4
Sihunta	Sihu	32.30	76.09	23.3	50.4	35.3	38.3
Bandlakhas	Band	32.13	76.54	24.5	142.5	122.4	22.1
Jawali	Jawa	32.14	76.01	30.3	14.8	16.6	10.9

Table 3. Velocity-Q structure used for the stations Dharmsala, Bhawarna, Sihunta and Bandlakhas

Thickness (km)	0.5	5.5	15.0	18.0	Half-space
V_p km/s	1.75	4.70	5.20	6.60	8.33
Q_p	200	1000	4000	4000	1000
V_s km/s	1.00	2.88	3.00	3.81	4.81
Q_s	100	500	2000	2000	500
Density (g/cc)	1.8	2.0	2.2	2.6	3.3

Table 4. Velocity-Q structure used for the stations Kangra, Nagrota, Shahpur, Baroh and Jawali

Thickness (km)	0.15	0.5	6.5	15.0	18.0	Half-space
V_p km/s	0.34	1.75	4.70	5.20	6.60	8.33
Q_p	30	200	1000	4000	4000	1000
V_s km/s	0.20	1.00	2.88	3.00	3.81	4.81
Q_s	25	100	500	2000	2000	500
Density (g/cc)	1.6	1.8	2.0	2.2	2.6	3.3

for a larger earthquake (mb 6.2) at two sites which serve to quantitatively demonstrate the increase in potential seismic hazard with an increase of 0.5 units in magnitude.

We note that Sinvhal *et al.*[4] have modelled one component of the accelerogram and the velocity time-histories recorded at the Kangra station due to this earthquake. However, both the simulated acceleration and the corresponding velocity time-histories have similar frequency content which is inconsistent, as the velocity time-history being the time integral of the acceleration time-history, should have a significantly lower frequency content. Their simplistic procedure does not take into account the velocity structure, free surface effect, geometrical divergence, attenuation and fault plane solution of the earthquake. The spectrum of the Ricker wavelet used to represent the radiation from the fault is also not consistent with the empirically determined. $\bar{\omega}$-squared model of the earthquake source spectrum.

The epicenter of this event lies in the Kangra region of Himachal Pradesh, very close to the thickly populated city of Dharmsala. This region is also the rupture zone of the great Kangra earthquake of 1905. Geologically Kangra region occupies a characteristic tectonic set-up in the north-west Himalaya. Two principle intra-crustal thrusts, the Pir Panjal thrust and the Main Boundary thrust (MBT) run in close proximity of each other. Pir Panjal thrust forms the north-west (NW) extension of the Main Central thrust (MCT) and brings the Chamba nappe to override the Panjal imbricate zone of the Lesser Himalaya. The epicenter lies south of MBT in the contact zone between the Lesser Himalaya and the Neogene Siwalik formations (Figure 1). The hypocentral parameters were determined by the United States Geological Survey (USGS), Harvard University, and India Meteorological Department (IMD). In this work, we adopted the hypocentral location given by IMD as being more precise as they used travel-times from the local stations as well. The earthquake parameters are as follows. Latitude = 32.19°N; longitude = 76.29°E; depth = 9.0 km; magnitude mb = 5.7; moment = 0.65e24 dyne-cm; stress-drop = 60 bars.

The focal mechanism solution determined by Dziewonski *et al.*[3], was modified using locally recorded first motion data. The parameters of the modified fault plane solutions are shown in Table 1.

The observed near source strong ground motion time-histories display a considerable randomness. This characteristic is mostly attributable to the radiation from the heterogeneous earthquake faulting process. The various patches on such a fault rupture in a quasi-random manner giving rise to the observed nature of the ground motion. The composite source model[2,5] constructs such a process of faulting by randomly distributing circular sub-faults over the earthquake fault plane. The number of sub-faults having a radius R is proportional to R^{-D}, where D is a model parameter. The sum of the moments of the all the sub-events is equal to the seismic moment of the main earthquake. The largest permitted radius is equal to the smaller dimension of the fault plane, so

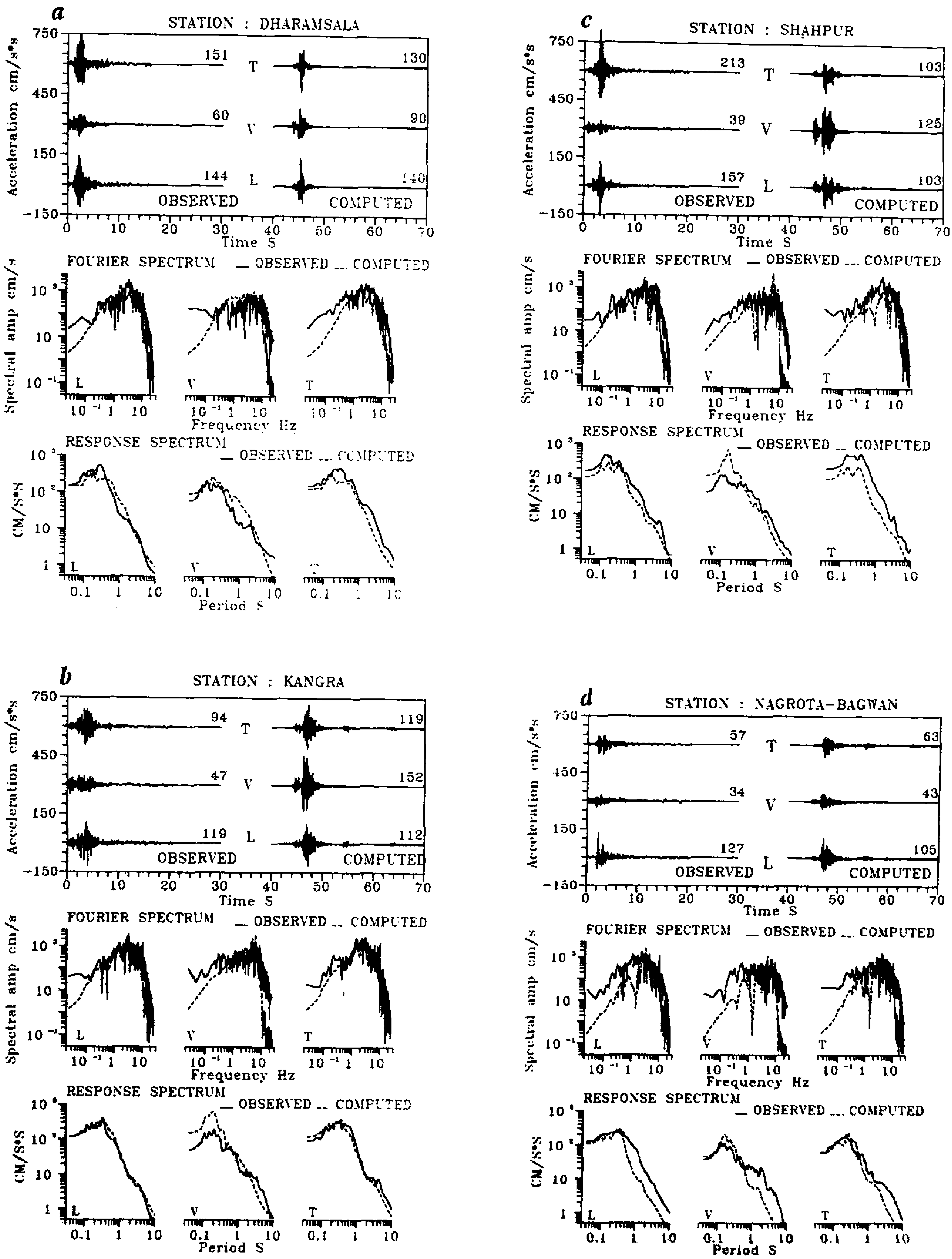

Figure 2 a–d. Comparison of observed and synthetic ground acceleration wave forms, Fourier amplitude spectra and response spectra (5% damping). The observations are low-pass filtered at 10 Hz.

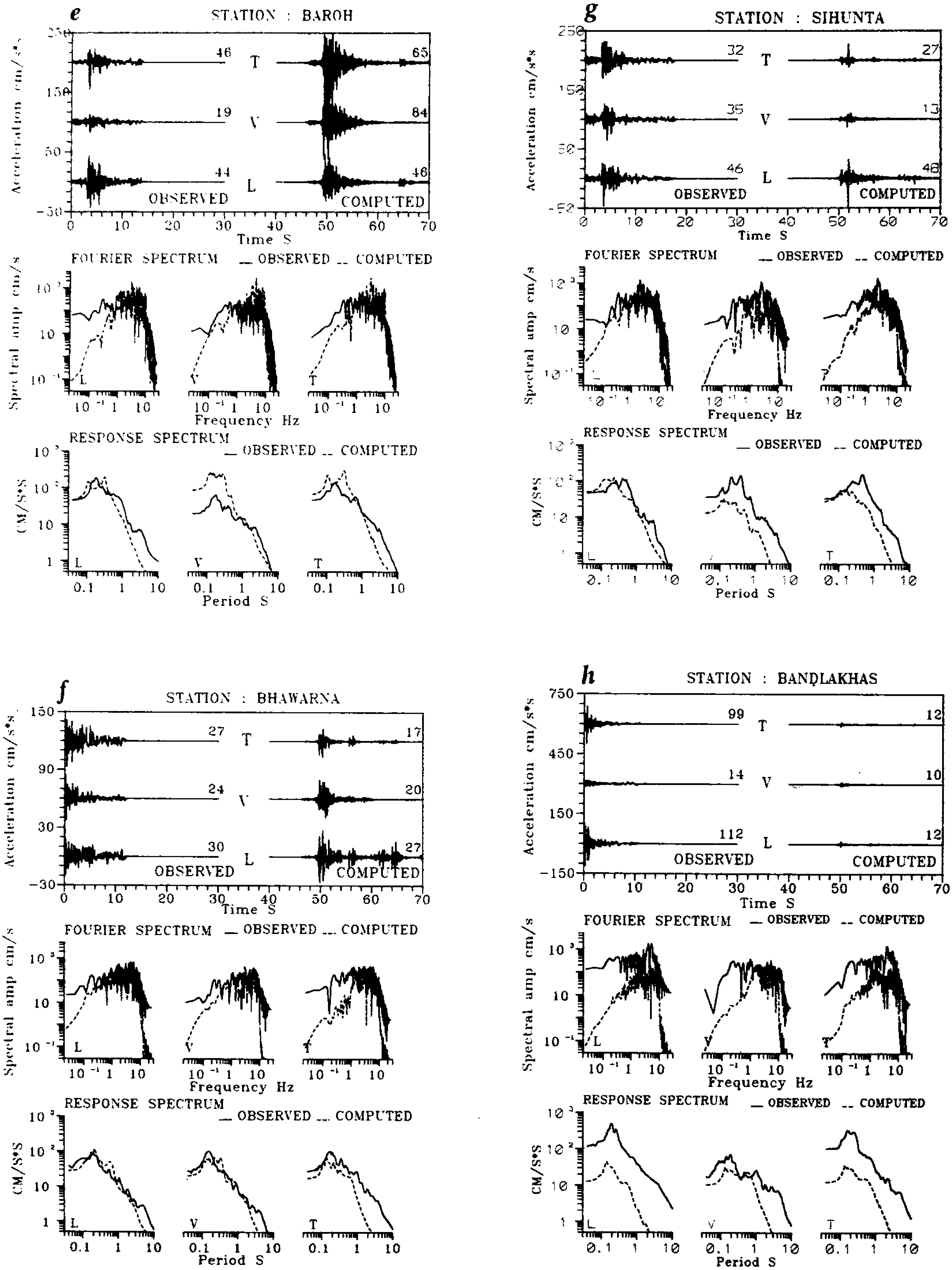

Figure 2 ***e–h***. Comparison of observed and synthetic ground acceleration wave forms, Fourier amplitude spectra and response spectra (5% damping). The observations are low-pass filtered at 10 Hz.

that all the sub-faults fit within the fault plane. The smallest radius is such that it does not have an effect on the numerical simulation of the strong motions. The sub-faults can overlap each other. The stress-drop parameter is the same for all the sub-faults. The rupture spreads from the hypocentre which can be assigned any place in the fault plane, at a constant rupture velocity and the sub-faults start to radiate a Brune pulse[6,7], when the rupture front reaches the center. The duration of the rupture is controlled by the radius of the sub-fault and the stress-drop. A composite source time function is formed by summing up the individual source time functions with the appropriate time delays. This is convolved with the Green's function calculated for the velocity structure of the region and the fault plane solution to obtain the final accelerograms.

The earthquake triggered 9 three-component strong motion instruments in the Kangra array operated by the Department of Earthquake Engineering, University of Roorkee. These stations were in the epicentral distance range of 5 to 30 km. The analog recordings were digitized at a sample rate of 0.02 s and bandpass filtered using Ormsby filter (0.17, 0.20; 25.0, 27.0 Hz)[1]. The digitized data were made available for analysis by the Department of Science and Technology. Table 2 lists the station locations and the observed peak ground accelerations. The locations of these stations are shown in Figure 1.

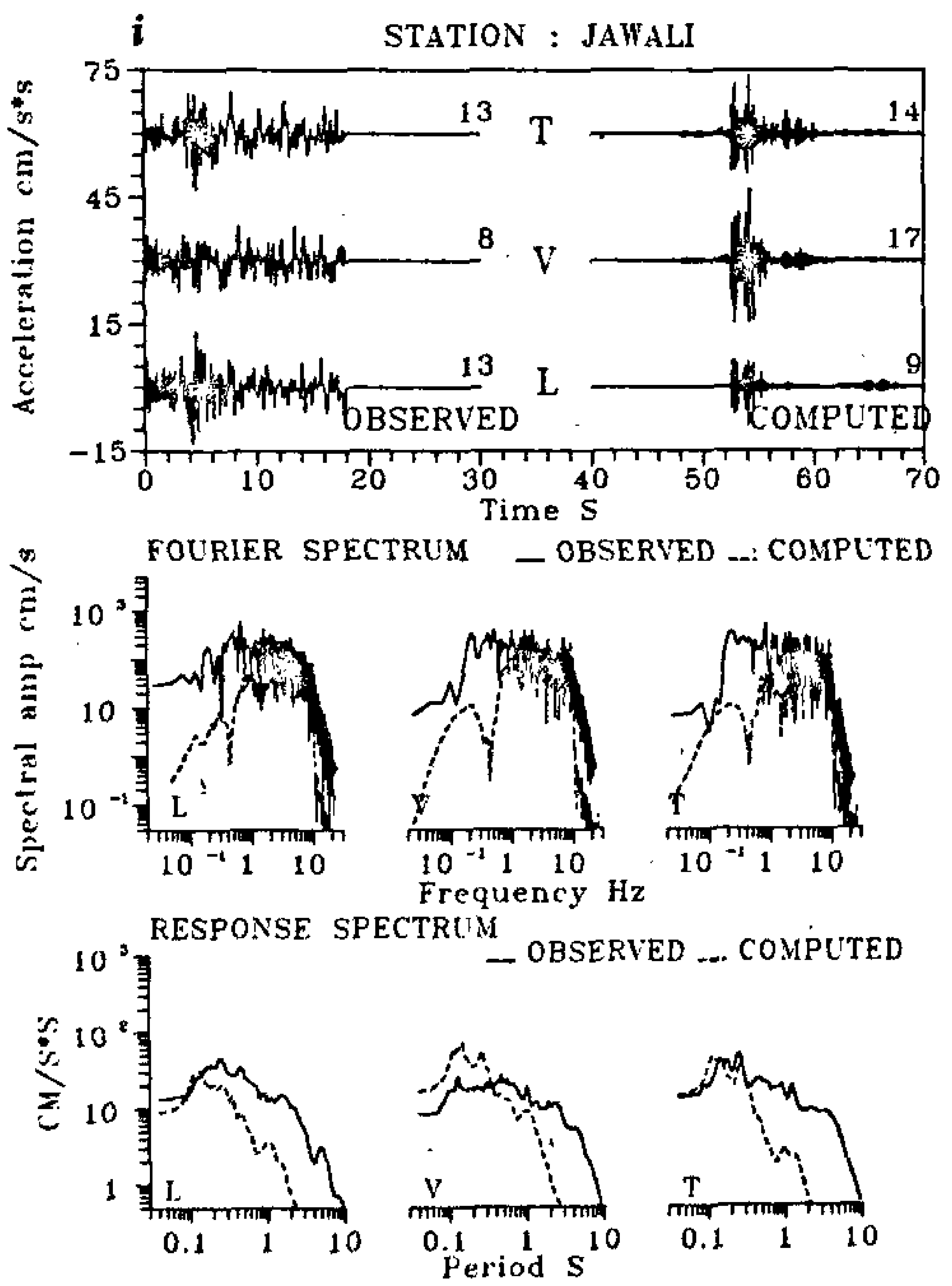

Figure 2 *i*. Comparison of observed and synthetic ground acceleration wave forms, Fourier amplitude spectra and response spectra (5% damping). The observations are low-pass filtered at 10 Hz.

The stations at Dharmsala, Kangra, Nagrota Bagwan, Baroh and Shahpur were triggered by the pre-*S* phases while the stations at Bandlakhas, Jawali, Bhawarna and Sihunta were triggered by the *S* phase group. The quality of data is good for all the stations except Jawali and Bhawarna.

For the computation of Green's functions, the velocity structure of the region is required. The strong motion recording stations are situated in mountainous terrain, and detailed knowledge of the local site geology is not available. Hence, as a starting point, we have taken the model obtained from a similar analysis done for the Uttarkashi earthquake of 1991, in the Garhwal Himalaya[5] and modified its shallow layers with the help of velocity information available from a nearby oil well data and other surface geological informations as well as by a trial and error procedure in which the starting model was modified for obtaining better match of the simulations with the empirical accelerograms. The velocity-Q structures obtained for various stations are given in Tables 3 and 4.

To model the strong ground motion using composite fault model, information about the earthquake source including the fault plane solution, seismic moment, stress drop parameter, rupture geometry and hypocentral parameters are required. Since no aftershock data are available for this event, the rupture area is estimated using empirical relation between magnitude and fault area as 48 sq km (ref. 8). Accordingly, the rupture zone is modelled by a 8 km long and 6 km wide plane. The orientation of the fault is given by the fault plane solution obtained for this event. The shallow north dipping nodal plane (NP1) seems to be a better choice to represent the local tectonic set-up. However, the fault dimensions and the depth of the earthquake focus are not consistent in this case. The rupture must break-out, but no surface rupture has been reported[9]. For these reasons we considered the alternative steep south dipping nodal plane (NP2) to represent the fault plane. The bottom of the fault plane coincides with the hypocentral depth and the rupture propagates up-dip at an angle of 69° to form the rupture zone. We have restricted the simulation up to a frequency of 10 Hz. The observed accelerograms are also low-pass filtered at cut-off frequency of 10 Hz for making a proper comparison.

As mentioned earlier a trial and error procedure was conducted to obtain an improved crustal model by adjusting the shallow layer thickness, velocity and Q until the synthetic accelerograms matched the observed accelerograms in terms of peak acceleration, duration of strong shaking, envelope and frequency content. The stress-drop parameter $\Delta\sigma = 60$ bar is found to explain the frequency content of the observations most satisfactorily.

The simulations for some stations are carried out for 10 realizations of random sub-event distribution in order

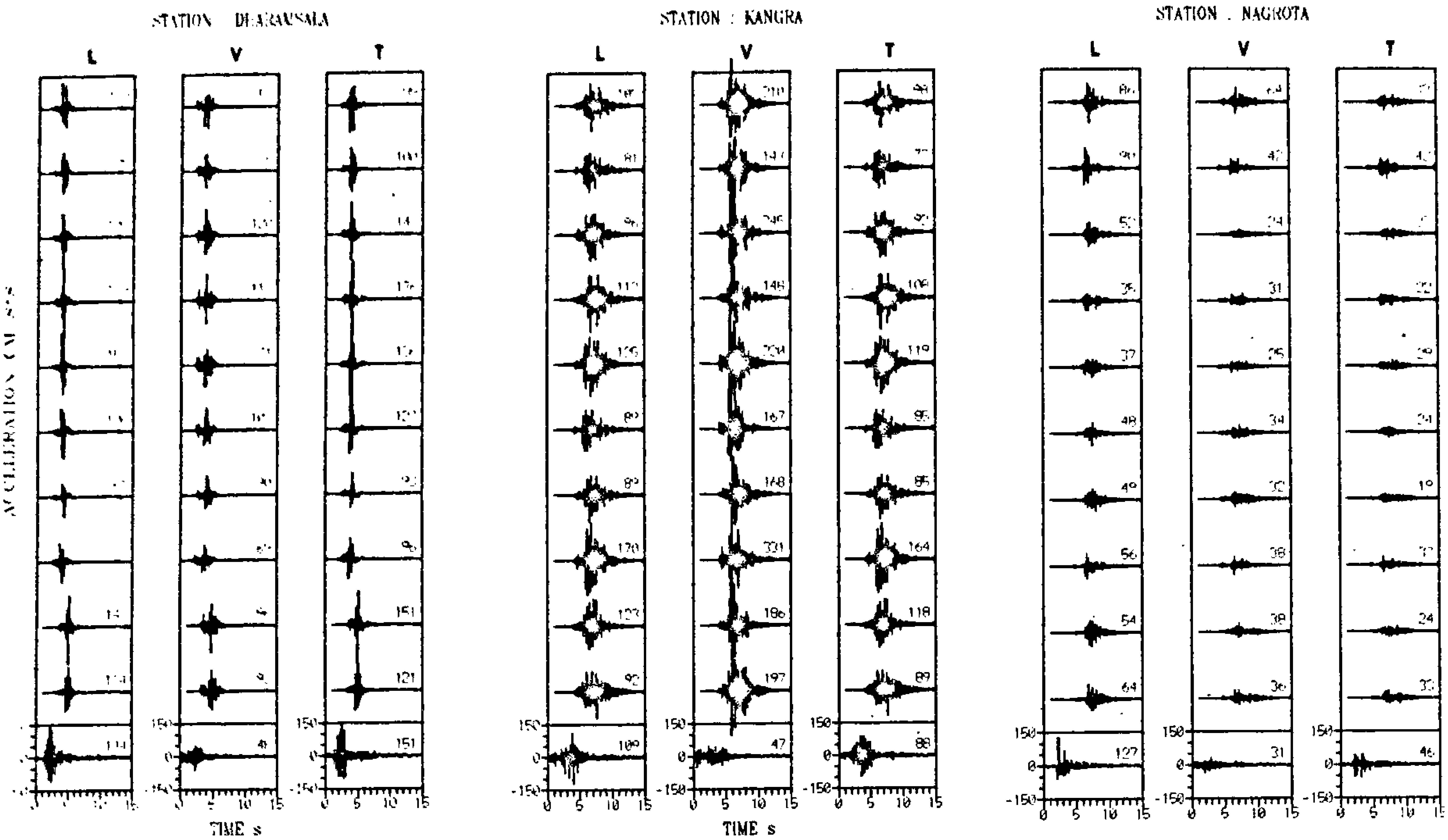

Figure 3. Ten realizations of synthetic acceleration wave forms for the stations Dharmsala, Kangra and Nagrota Bagwan. The bottom most panel shows the observed acceleration wave form.

to demonstrate the variability one may expect in a realization of earthquake faulting.

The simulations for a stress parameter value of 60 bars and the observed accelerograms are shown in Figure 2. The panel on the top shows the observed accelerograms and the synthetic accelerograms. The nearest station at Dharmsala, which is at an epicentral distance of approximately 5.4 km, displays a good match in terms of the peak amplitudes, durations, frequency spectra and envelopes. The peak acceleration for the vertical component shows the largest difference by a factor of about 1.5. The corresponding Fourier and response (5% damping) spectra are also shown in the same figure. The Fourier spectra are well matched in the frequency band of 0.2–10 Hz, except in the case of the *T* component where there is larger energy in the lower frequencies compared to that in the synthetics. The observed spectra in the frequencies below about 0.2 Hz are not reliable because of the instrumental limitations as well as manual digitization of the accelerograms. Hence the comparisons are confined for frequencies higher than this frequency. The response spectra are also reasonably well matched. The synthetics and the observed accelerograms, the Fourier and the response spectra for the next farther station at Kangra ($\Delta \sim 9$ km) are also well matched. In this case again the observed vertical component is having a peak acceleration value that is low compared to the synthetic by about a factor of 2. Thus, in these two cases, there is a little larger energy in the vertical component synthetics and lower energy in the 0.2 to 2 Hz band. The matches for Shahpur ($\Delta \sim 10$ km) are comparatively less satisfactory. The synthetic accelerations are low by a factor of 2.5 in the *T* component. A few large amplitude spikes seen in the observed accelerograms are not predicted in the synthetics. This could be due to the local site conditions not accounted for in the velocity model used.

The match for Nagrota-Bhagwan which lies at an epicentral distance of about 11 km is again quite satisfactory in terms of peak accelerations, duration, and envelope. However, the observed accelerograms are comparatively richer in lower frequencies than their synthetic counterparts, which is brought out in the spectrum. The synthetics for Baroh ($\Delta \sim 19$ km) are well matched for the horizontal components, whereas the vertical component in the synthetics is higher by a factor of 2. This comparison is with respect to higher frequencies. There is deficiency of energy in the synthetics in the lower frequencies. This is well reflected in the response spectrum as well. At Bhawarna ($\Delta \sim 21$ km) the synthetic *T* component is lower in the band of frequencies less than 2 Hz. The Jawali station ($\Delta \sim 30$ km) is very noisy, probably due to instrumental resonance. The stations at Sihunta ($\Delta \sim 23$ km) and Bandalkhas ($\Delta \sim 25$ km) show

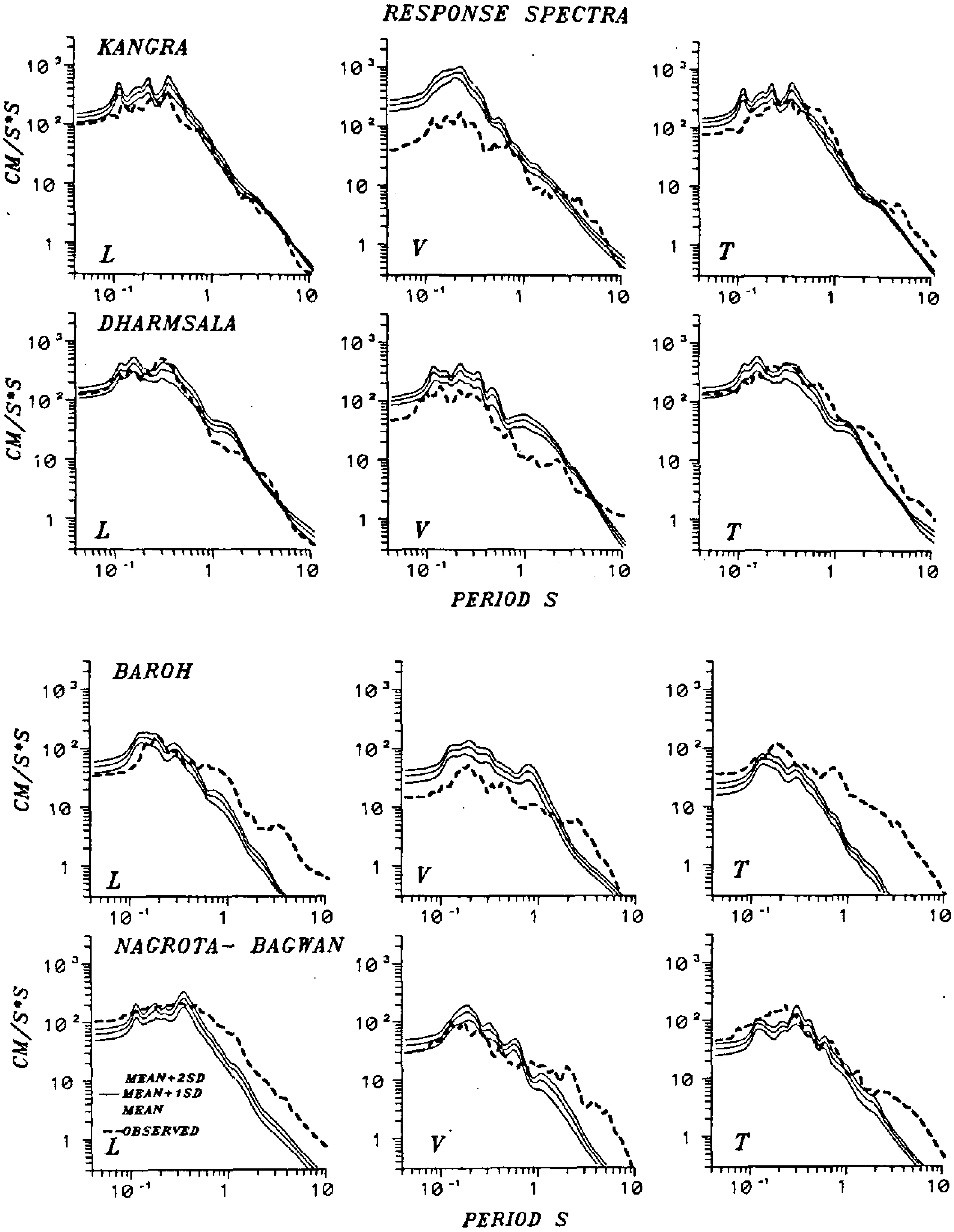

Figure 4. Comparison of response spectra obtained for ten realizations with the observed response spectrum. The mean, mean ± 1 S.D. and mean ± 2 S.D. response spectra for the synthetics are also shown.

a remarkably consistent Fourier and response spectra but having a lower value in the entire frequency band of the computed spectra in all the components. The computed peak accelerations are lower by a factor of 2 to 6 compared to the observed values. Thus, this effect is not explained by velocity model or due to topographic effects or basin effects as these would be expected to show some spectral characteristics like resonance.

In general, the synthetics consistently show a lower value in the horizontal components for the distant stations. This could result either due to an inappropriate radiation pattern or errors in instrument calibration. As we have good matches for several stations the fault plane choice seems to be adequate. One does not expect the possibility of error in instrument calibration as the source of the anomalies either. The region is structurally complicated with folds and imbricate thrusts. At increasing distances, the flat layer model will depart significantly from reality and will not be able to predict possible focussing and other wave-guide effects that may have led to the stronger observed accelerations at these stations.

In general the fidelity of the synthetics improves for lower frequencies. Therefore, the divergence observed here at lower frequencies, which consistently show higher values for the observed accelerograms compared to the synthetics, are indeed curious. This could also result

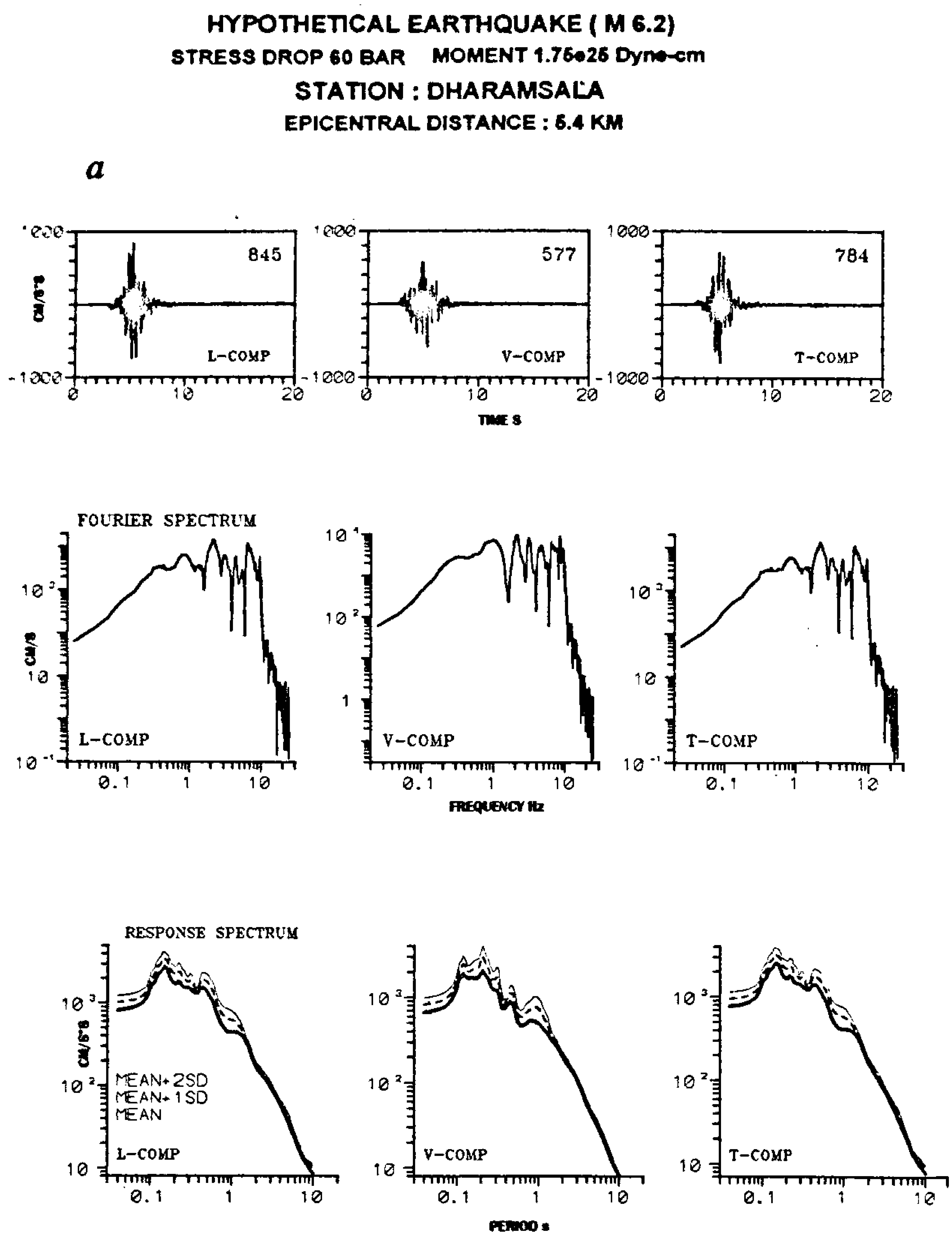

Figure 5 *a*. Simulation of strong ground acceleration wave forms for the hypothetical earthquake of body wave magnitude 6.2. The Fourier amplitude spectra and the response spectra (5% damping) are also shown.

from aliasing. Hence, one needs to examine the possibility of introduction of low frequency noise by aliasing in the manual digitization procedures used in the present case as also the instrumental limitations at low frequencies.

In order to examine the variability of the ground motion characteristics in random realizations of the faulting process, which may represent variability expected in the actual earthquake rupturing process, ten realizations for each station at Dharmsala, Kangra, and Nagrota were calculated and are shown in Figure 3. The corresponding response spectra are shown in Figure 4. One observes the consistency of peak accelerations, envelope and frequency content of the realizations in all the cases.

The coda present in the observed accelerograms representing the scattering of energy due to heterogeneities in the shallower section of the crust is not modelled and is therefore missing in the simulations. The coda does not have a significant role in earthquake damage.

Having assured that the velocity and source models are appropriate for synthesizing strong ground motions at Dharmsala and Kangra, we have synthesized the strong ground motions for a higher magnitude earthquake (mb 6.2) to assess the corresponding increase in the earthquake damage potential. The fault dimension adopted for this hypothetical event is 12×8 km and the

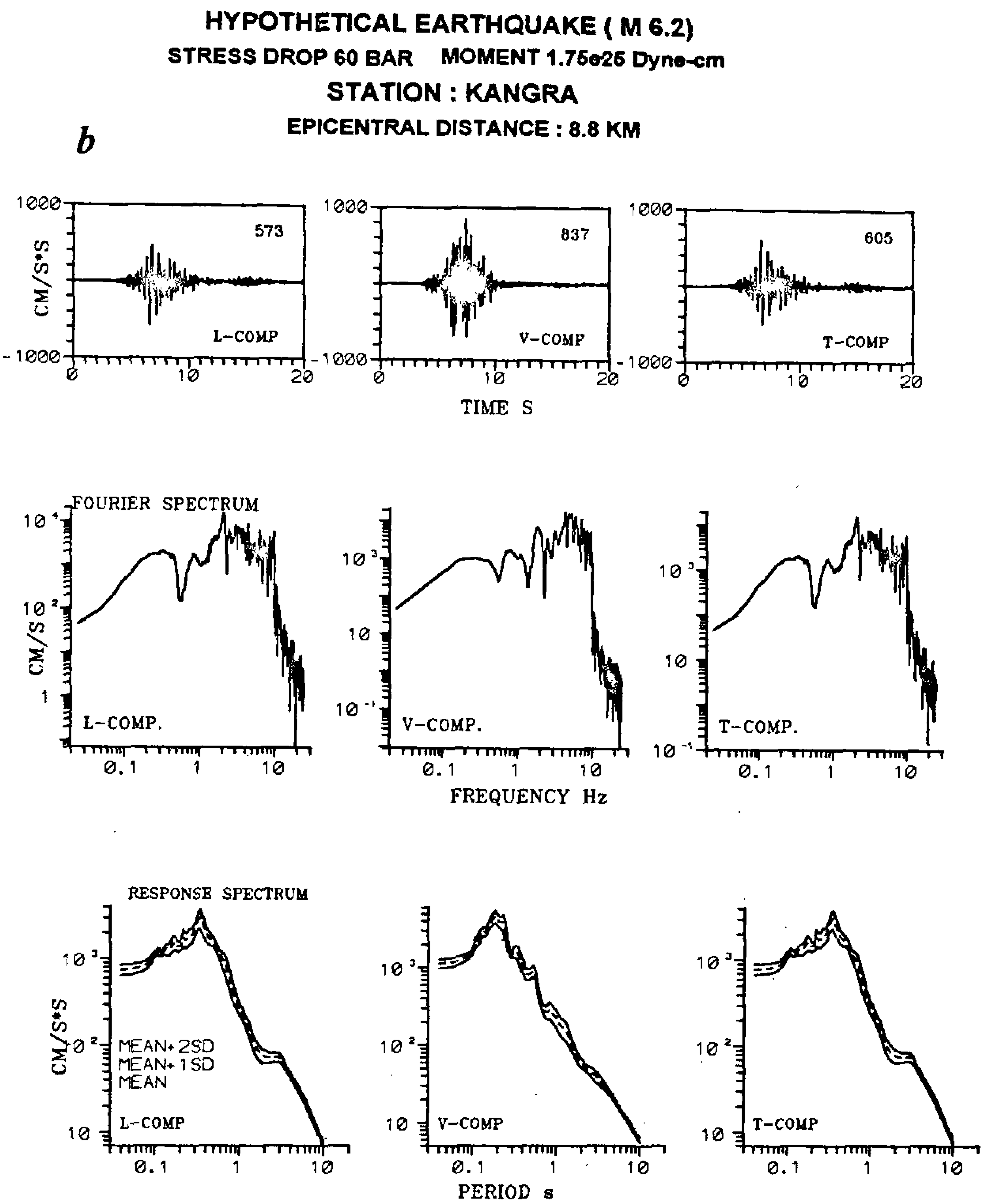

Figure 5 *b*. Simulation of strong ground acceleration wave forms for the hypothetical earthquake of body wave magnitude 6.2. The Fourier amplitude spectra and the response spectra (5% damping) are also shown.

seismic moment is 1.75e25 dyne-cm (ref. 8). The other fault parameters are assumed to be the same as that of the Dharmsala event. The simulations show the expected peak ground acceleration at Dharmsala to be 0.7 g and at Kangra 0.5 g. The simulated accelerograms along with their Fourier and response spectra (5% damping) are given in Figure 5.

The decay of peak ground acceleration as a function of distance for the observed as well as the synthesized motions is shown in Figure 6. Several empirical relations for the decay of the peak acceleration with epicentral or hypocentral distance are available for various regions of the world. Dinesh Kumar *et al.*[10] have compared the data set for the Dharmsala earthquake with these relations and found that while the observations are well predicted in the distance range up to 12 km by Peng *et al.*[11] regression relation for the data set from the south-west China region, those at larger distances (~ 24 km) are smaller compared to the regression. As attenuation does not play a significant role at short distances, the good match at such distances is indicative of the similarity of stress-drop in the respective areas. The peak ground accelerations from the synthesized wave forms follow the observed values closely, although having somewhat smaller values. The pluses show the observed values when the filtering was not applied and the other two symbols are for the case with the upper frequency cut-off of 10 Hz.

In this article we have modelled the strong ground motions recorded in the 1986 Dharmsala earthquake, using the composite source model and synthetic Green's functions. The recording sites are in an undulating terrain

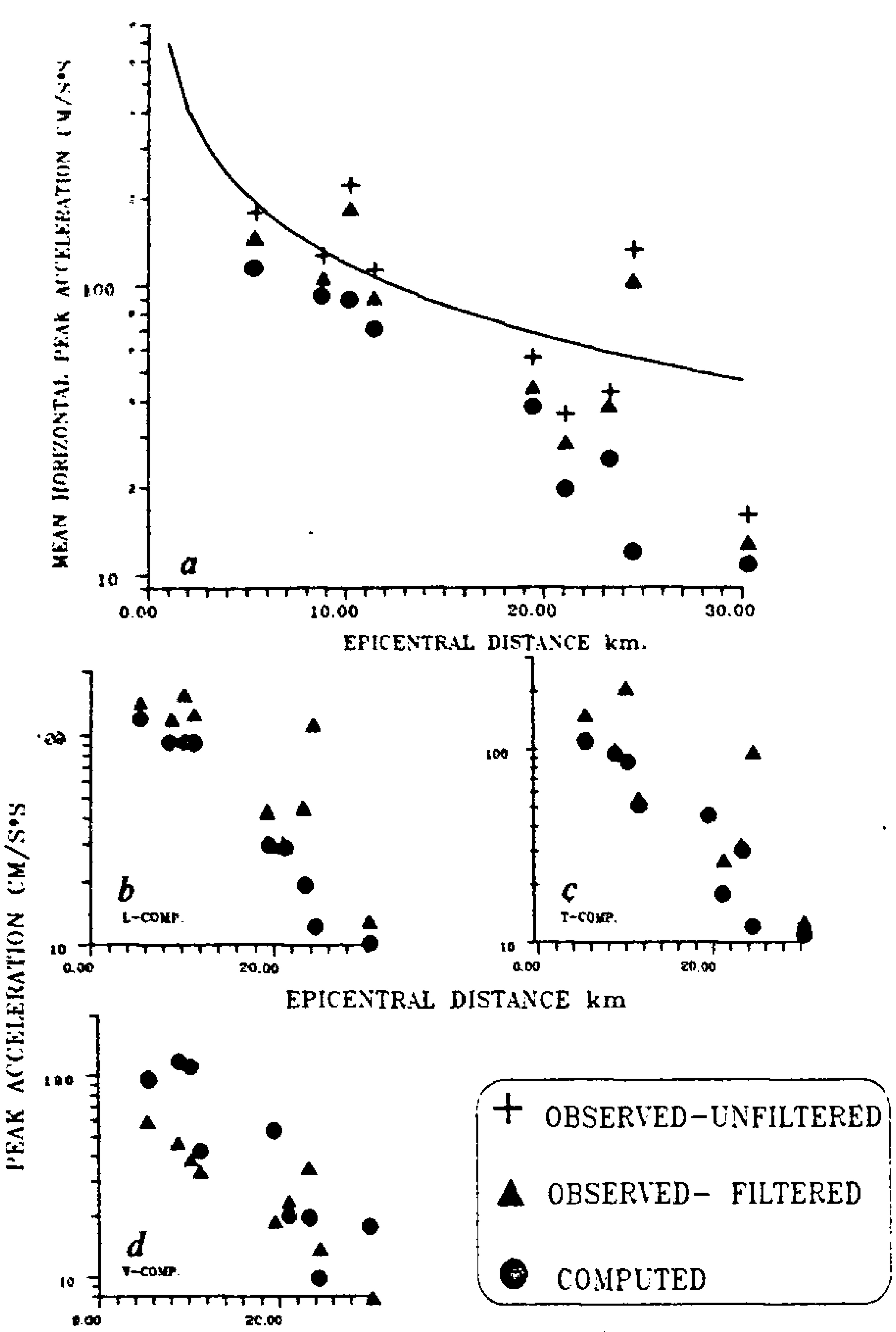

Figure 6. *a*, Distribution of mean horizontal peak ground acceleration with epicentral distance for the unfiltered, filtered and the computed data. Peng *et al.*'s regressions relation for the south-west China region is also shown for comparison. The filtered data falls below the unfiltered data because of removing energy in the frequency above 10 Hz. *b*, *c* and *d* show the distribution for the individual components *L*, *T* and *V* respectively.

with complex geological set-up. A prior knowledge of the local site conditions and velocity-Q models are not available. A trial and error modification of a starting velocity-Q structure which was obtained from the studies in Garhwal Himalaya and oil well velocity data, were done to bring out a match between the observed and the synthetic accelerograms in terms of the peak ground acceleration, envelope of strong shaking and its frequency content. The overall match for four of the stations ($\Delta < \sim 22$ km) is found to be satisfactory. However, four stations ($\Delta > \sim 22$ km) could not be well matched, the synthetics having a significantly weaker motion than the observed. This is interpreted to be possibly due to the complex geology of the region. The better match obtained for nearer stations which are situated in the domain of Siwalik sediments suggests that the velocity-Q model selected for the region is a good representation of the overall characteristics of the medium. Using this velocity-Q model we have estimated the expected strong ground motion for a hypothetical future earthquake (mb 6.2) for the purpose of seismic hazard evaluation.

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