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Attenuation of P- and S-waves in the Chamoli Region, Himalaya, India

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Abstract—The attenuation properties of the crust in the Chamoli region of Himalaya have been examined by estimating the frequency-dependent relationships of quality factors for P waves (Q_α) and for S waves (Q_β) in the frequency range 1.5–24 Hz. The extended coda normalization method has been applied on the waveforms of 25 aftershocks of the 1999 Chamoli earthquake (M 6.4) recorded at five stations. The average value of Q_α is found to be varied from 68 at 1.5 Hz to 588 at 24 Hz while it varies from 126 at 1.5 Hz to 868 at 24 Hz for Q_β. The estimated frequency-dependent relations for quality factors are $Q_\alpha = (44 \pm 1)f^{(0.82\pm.04)}$ and $Q_\beta = (87 \pm 3)f^{(0.71\pm.03)}$. The rate of increase of Q(f) for P and S waves in the Chamoli region is comparable with the other regions of the world. The ratio Q_β/Q_α is greater than one in the region which along with the frequency dependence of quality factors indicates that scattering is an important factor contributing to the attenuation of body waves in the region. A comparison of attenuation relation for S wave estimated here ($Q_\beta = 87f^{0.71}$) with that of coda waves ($Q_c = 30f^{1.21}$) obtained by Mandal *et al.* (2001) for the same region shows that $Q_c > Q_\beta$ for higher frequencies (>8 Hz) in the region. This indicates a possible high frequency coda enrichment which suggests that the scattering attenuation significantly influences the attenuation of S waves at frequencies >8 Hz. This observation may be further investigated using multiple scattering models. The attenuation relations for quality factors obtained here may be used for the estimation of source parameters and near-source simulation of earthquake ground motion of the earthquakes, which in turn are required for the assessment of seismic hazard in the region.

Key words: Attenuation, P waves, S waves, Q_α, Q_β, Chamoli.

1. *Introduction*

The amplitudes of earthquake ground motion at observing sites are influenced by the source characteristics, travel path and local site conditions. The effects of travel path on earthquake ground motion are linked to the attenuation of propagating seismic waves. The study of the attenuation of seismic waves is essential for determining the earthquake source parameters, to predict the strong ground motions due to earthquakes and thus useful in estimating the seismic hazard of a region. The attenuation properties of the media are inherent elements governing the amplitude of seismic waves at various distances from an earthquake source. The amplitudes of seismic waves decay faster than predicted by

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geometrical spreading of wave fronts. This additional attenuation of seismic waves is caused by scattering due to inhomogeneities in the media, inelasticity and multipathing. The attenuation of seismic waves when they traverse through an imperfectly elastic medium is characterized by the inverse of quality factor (Q^{-1}) given by (Knopoff, 1964):

$$Q^{-1} = -\Delta E/2\pi E,$$

where ΔE is the energy lost in one cycle and E is the total energy available in a harmonic wave. The attenuation parameter describes an essential property of the earth reflecting on its composition and thermal state. The techniques have been developed to study the attenuation of seismic waves in a region using different parts of the seismogram (e.g., Aki, 1969; Aki and Chouet, 1975; Hermann, 1980; Mitchell, 1995). It has been found that the attenuation (Q^{-1}) for P wave (Q_α^{-1}) is different from that of S waves (Q_β^{-1}). The ratio Q_β/Q_α also varies from one region to another (Rautian *et al.*, 1978). A number of studies have reported the attenuation of S waves in various regions of the world but there are few studies for the attenuation of P waves (Sekiguchi, 1991; Fedotov and Boldyrev, 1969; Masuda, 1988). Der (1998) has summarized the attenuation of high frequency P and S waves in the Earth. A very few studies have been done for the simultaneous estimation of Q_α and Q_β for the same region (Hough and Anderson, 1988; Masuda, 1988; Campillo and Planet, 1991; Yoshimoto *et al.*, 1993; Sharma *et al.*, 2007, 2008). Aki (1980) proposed the coda-normalization method to estimate the frequency-dependent relation for Q_β. Yoshimoto *et al.* (1993) extended this method for simultaneous measurement of Q_α and Q_β.

In the present study, the attenuation of P and S waves in the Chamoli region of Himalaya, India has been investigated. The extended coda normalization method (Yoshimoto *et al.*, 1993) has been used to estimate the frequency-dependent relationships for Q_α and Q_β in this region. The waveforms of 25 events recorded at five stations (four short periods and one broadband) in the region have been used for this purpose. These events are the aftershocks of the 1999 Chamoli earthquake (M_w 6.4) which occurred in the region. This is the initial study reporting the simultaneous estimation of frequency-dependent relationships for Q_α and Q_β in this region. Gupta *et al.* (1995) and Mandal *et al.* (2001) have earlier obtained the coda-Q estimates of the region using single backscattering model (Aki and Chouet, 1975). The estimates of Q_β based on strong motion data of the 1991 Uttarkashi and 1999 Chamoli earthquakes in the region are available (Singh *et al.*, 2004; Dinesh *et al.*, 2005; Sriram *et al.*, 2005). However, the waveforms of strong motion data are affected more by source characteristics as compared to the weak motion data considered here. The frequency-dependent relationships for Q_α and Q_β obtained here have been compared with those of other parts of the world.

2. *Tectonic Setup of the Region*

The Himalaya is the product of continent-continent collision between India and Tibet along the Indus-Tsangpo suture (Ni and Barazangi, 1984; Molnar, 1990). The region is characterized by the presence of many tectonic features that includes Main Central Thrust (MCT) and Main Boundary Thrust (MBT). These two thrusts exist through the entire length of the Himalaya. The MBT separates the lesser Himalaya from the sub-Himalaya belt while MCT separates the high Himalaya from the lesser Himalaya. The Himalayan seismotectonic zone has experienced four great earthquakes of magnitude greater than 8 spanning 53 years. From the analysis of space-time patterns of seismicity of the region, KHATTRI and TYAGI (1983) and KHATTRI (1987) established the existence of three seismic gaps in the Himalaya plate boundary. The 1991 Uttarkashi (Ms 7) and 1999 Chamoli (Ms 6.4) earthquakes occurred in the central seismic gap of the Himalayan plate boundary. Thus a serious seismic hazard scenario exists in the region. Figure 1 shows the epicenters of the earthquakes used in this study.

3. Methodology

The coda normalization method (AKI, 1980) is based on the empirical observation that the coda spectral amplitude at lapse times greater than twice the S wave travel time is proportional to the source spectral amplitude of the S waves at distances of less than 100 km (YOSHIMOTO *et al.*, 1993; KIM *et al.*, 2004). Therefore, the source effects, common instrument and site responses are removed by normalizing S spectra to those of coda. The spectral amplitude of the coda, $A_c(f, t_c)$, can be written as (AKI, 1980):

$$A_c(f,t_c) = S_s(f)P(f,t_c)G(f)I(f), \tag{1}$$

where f is the frequency, t_c is the lapse time, $S_s(f)$ is the source spectral amplitude of S waves, $P(f, t_c)$ is the coda excitation factor, G(f) is the site amplification factor and I(f) is the instrumental response.

The spectral amplitude of the direct S wave, A_s (f, r) can be expressed as (YOSHIMOTO *et al.*, 1993):

$$A_s(f,r) = R_{\theta\phi}S_s(f)r^{-\gamma}\exp\left(-\pi fr/Q_\beta(f)Vs\right)G(f,\psi)I(f), \tag{2}$$

where $R_{\theta\phi}$ is the source radiation pattern and γ denotes the geometrical exponent. $Q_\beta(f)$ is the quality factor of S waves, V_s is the average S-wave velocity and ψ is the incident angle of S waves. On dividing equation (2) by equation (1), taking logarithm and simplifying, we obtain (YOSHIMOTO *et al.*, 1993):

$$\ln\left[R_{\theta\phi}^{-1}A_s(f,r)r^{\gamma}/A_c(f,t_c)\right] = -\pi fr/\left(Q_\beta(f)V_s\right) + \ln[G(f,\psi)/G(f)] + \mathrm{const}(f). \tag{3}$$

The contribution of $R_{\theta\phi}$ disappears by averaging over many different focal plane solutions and the ratio G(f, ψ)/G(f) becomes independent of ψ by averaging over many earthquakes which have a wide epicentral distribution. We note that this assumption may be a crude approximation that has somewhat blunted our inference. We get the following equation:

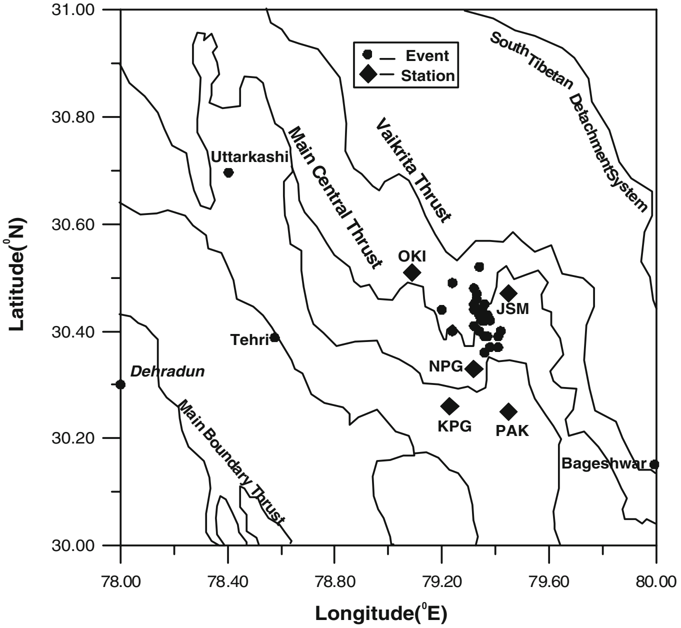

Figure 1
The location of the epicenters along with the recording stations used in the present study. The major tectonic features are also shown.

$$\langle \ln[A_s(f,r)r^{\gamma}/A_c(f,t_c)]\rangle_{r\pm\Delta r} = -\pi fr/\left(Q_{\beta}(f)V_s\right) + \mathrm{const}(f), \tag{4}$$

where $\langle \ln[A_s(f,r)r^{\gamma}/A_c(f,t_c)]\rangle_{r\pm\Delta r}$ represents the average for a hypocentral distance range $r \pm \Delta r$. The quality factor for S waves can be obtained from the linear regression of $\langle \ln[A_s(f,r)r^{\gamma}/A_c(f,t_c)]\rangle_{r\pm\Delta r}$ versus r by means of a least-squares method.

Yoshimoto *et al.* (1993) extended the above method for the estimation of Q under the assumption that the earthquakes within a magnitude range have the same spectral ratio of P- to S-wave radiation within a narrow frequency range. This assumption holds good even if the spectral shapes of P and S waves are different (e.g., Molnar *et al.*, 1973; Rautian *et al.*, 1978). Therefore we can write:

$$A_c(f,t_c) \propto S_s(f) \propto S_p(f), \tag{5}$$

where $S_p(f)$ is the source spectral amplitude of P waves. Using the above assumption an equation for estimating Q_{α} can be written as (Yoshimoto *et al.*, 1993):

$$\left\langle \ln\left[A_p(f,r)r^{\gamma}/A_c(f,t_c)\right]\right\rangle_{r\pm\Delta r} = -\pi fr/\left(Q_{\alpha}(f)V_p\right) + \mathrm{const}(f), \tag{6}$$

where $A_p(f, r)$ is the spectral amplitude of the direct P wave, V_p is the average P-wave velocity. The quality factor for P waves can be obtained from the linear regression of

Table 1

Names, codes and locations of the five recording stations

Station Code (Name)	Latitude (°N)	Longitude (°E)
NPG (Nandprayag)	30.33	79.32
KPG (Karanpryag)	30.25	79.22
PAK (Pakhi)	30.46	79.44
OKI (Okhimath)	30.52	79.09
JSM (Joshimath)	30.54	79.52

$\left\langle \ln\left[A_p(f,r)r^{\gamma}/A_c(f,t_c)\right]\right\rangle_{r\pm\Delta r}$ versus r by means of the least-squares method as done for S waves.

4. Data Used

On 28th March, 1999 a significant earthquake of $Ms = 6.4$ occurred in the Chamoli region of the Himalaya. National Geophysical Research Institute (NGRI), Hyderabad, deployed a network of nine digital stations, consisting of seven short-period (L4-3D sensors) and two broadband (CMG40T sensors) stations, in the region to monitor the aftershock activity. The waveforms of 25 aftershocks in the magnitude range 1.9–4.6 recorded at five stations have been used in the present study. These aftershocks occurred at the depth range 7–18 km. Out of five recording stations four (NPG, KPG, OKI and JSM) are equipped with short-period (L4-3D) sensors and one (PAK) with broadband (CMG-40T) sensor. The earthquakes were recorded at the sampling rate of 200 samples/sec at the station PAK and 100 samples/sec at the remaining four stations used here. The records of Z component have been used for P-wave analysis and of NS component for S-wave analysis, as significant differences were not observed between NS and EW components. Table 1 gives the locations of the five recording stations and the hypocentral parameters of the events are given in Table 2. The locations of the events and recording stations are shown in Figure 1.

5. Results and Discussions

The seismograms have been filtered using Butterworth bandpass filter with five frequency passbands of 1-2 (1.5 Hz), 2–4 (3 Hz), 4–8 (6 Hz), 8–16 (12 Hz) and 16–32 (24 Hz). On the filtered seismograms, amplitudes of direct P and S waves in a window length of 2.56 sec starting from the onset of P and S waves have been considered. We assumed $\gamma = 1$ for the geometrical spreading exponent. The coda spectral amplitude, $A_c(f, t_c)$, has been measured from more than twice the S-wave travel time for 2.56 sec lapse time window at $t_c = 30$ sec. The average velocities of 5 km/sec and 3 km/sec for P

Table 2

The hypocentral parameters of the events used in the present study

Sr. No.	Date	O.T.			Latitude (°N)	Longitude (°E)	Depth (km)	Magnitude M_w
	D M Y	H	M	S				
E1	06/04/99	19	37	27.04	30.44	79.32	8	4.62
E2	06/04/99	20	46	42.47	30.43	79.32	14	4.2
E3	06/04/99	22	52	15.53	30.43	79.33	15	3.2
E4	06/04/99	23	55	57.17	20.38	79.41	16	2.9
E5	07/04/99	15	49	14.07	30.47	79.32	17	4.3
E6	07/04/99	16	23	29.32	30.48	79.32	15	4.1
E7	07/04/99	17	18	20.11	30.42	79.36	12	2.8
E8	070/4/99	19	01	46.36	30.37	79.40	8	3.5
E9	09/04/99	07	29	51.73	30.39	79.36	15	3.2
E10	09/04/99	22	08	41.49	30.41	79.34	13	3.04
E11	11/04/99	09	31	08.09	30.49	79.23	12	3.04
E12	12/04/99	13	03	35.87	30.40	79.32	18	3
E13	12/04/99	14	11	28.35	30.43	79.20	7	3.5
E14	13/04/99	05	04	36.98	30.44	79.34	9	2.93
E15	14/04/99	15	54	13.27	30.44	79.35	12	2.8
E16	14/04/99	17	24	30.65	30.39	79.35	14	4.44
E17	22/04/99	00	57	42.11	30.42	79.34	10	2.8
E18	22/04/99	14	48	32.99	30.43	79.33	9	2.9
E19	25/04/99	09	52	15.78	30.41	79.36	11	3.5
E20	26/04/99	01	07	32.05	30.42	79.35	13	1.85
E21	01/05/99	02	04	38.85	30.42	79.37	10	2.98
E22	02/05/99	23	29	34.06	30.43	79.35	11	2.8
E23	07/05/99	17	12	04.34	30.36	79.38	17	3.7
E24	09/05/99	15	02	09.24	30.43	79.33	18	2.9
E25	14/05/99	08	31	03.23	30.51	79.32	8	3.6

and S waves, respectively, have been used in the present study (CHANDER *et al.*, 1986; KUMAR *et al.*, 1994).

The plots of the quantity $\ln((A_p/A_c)r)$ and $\ln((A_s/A_c)r)$ versus r along with the least-square fitted lines for the station KPG are shown in Figure 2a. The corresponding plots of the other four sites PAK, JSM, NPG and OKI are shown in Figures 2b–2e. The variation of the amplitude ratios with distance at all the stations validates the applicability of the coda normalization method for the distribution of the stations and events in this study. The slopes of the best fitted lines are used to estimate Q_β and Q_α (Eqs. (4) and (6)). The values of Q_α and Q_β coupled with their average values, thus obtained at different central frequencies for the five stations, are given in Table 3. We note that the estimated Q values increase with the increase in frequency. The average value of Q_α varies from 68 at 1.5 Hz to 588 at 24 Hz, while it varies from 126 at 1.5 Hz to 868 at 24 Hz for Q_β. The increase in Q values with the increase in frequency indicates the frequency-dependent nature of Q estimates in the region. In order to estimate the frequency-dependent relations for Q, the power law $Q = Q_0 f^n$ is fitted to the estimated Q values for each station.

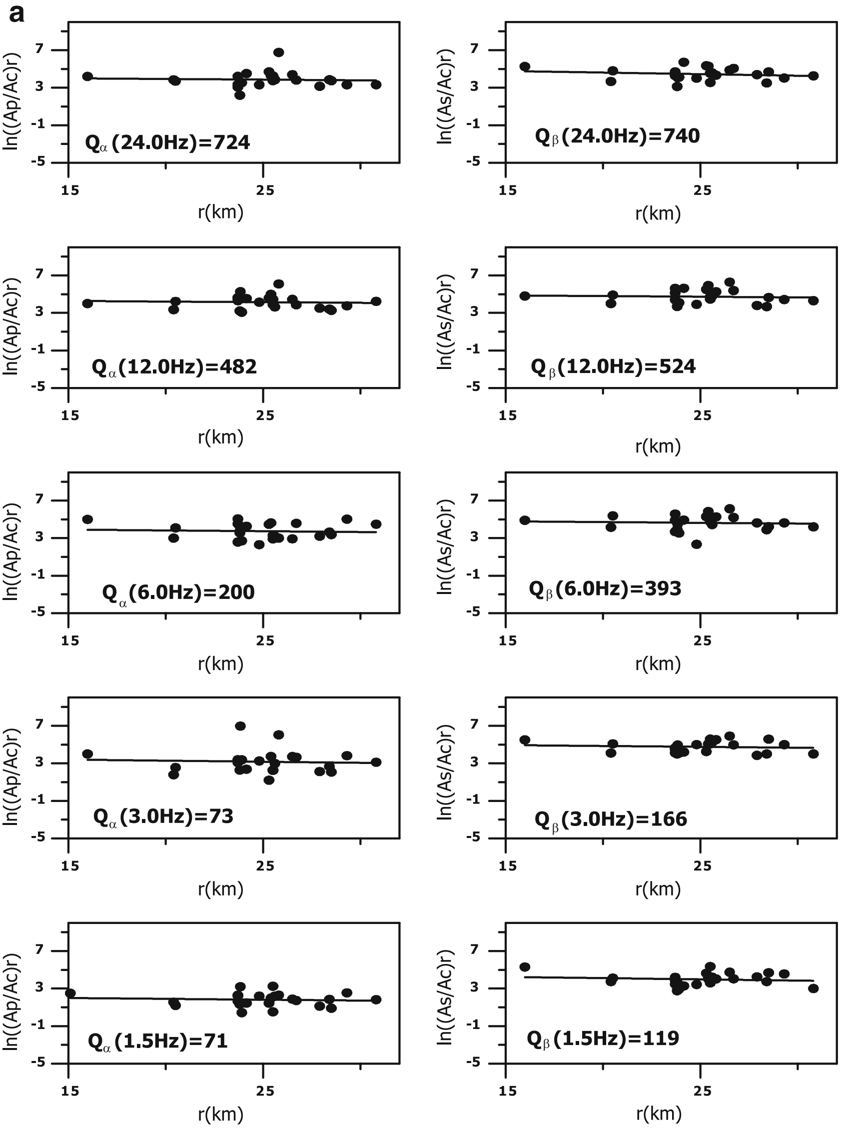

Figure 2
Coda normalized peak amplitude decay of P and S waves with hypocentral distance for five central frequencies at (a) KPG, (b) PAK, (c) JSM, (d) NPG, and (e) OKI. The least-squares best-fitted lines are also shown.

The frequency-dependent relations thus obtained are given in Table 4. Figures 3a and 3b show the comparison of the frequency-dependent relations for Q_α and Q_β estimated at five stations. The average frequency-dependent relations for the region are $Q_\alpha = (44 \pm 1)f^{(0.82\pm.04)}$ and $Q_\beta = (87 \pm 3)f^{(0.71\pm.03)}$. We find that the estimated Q

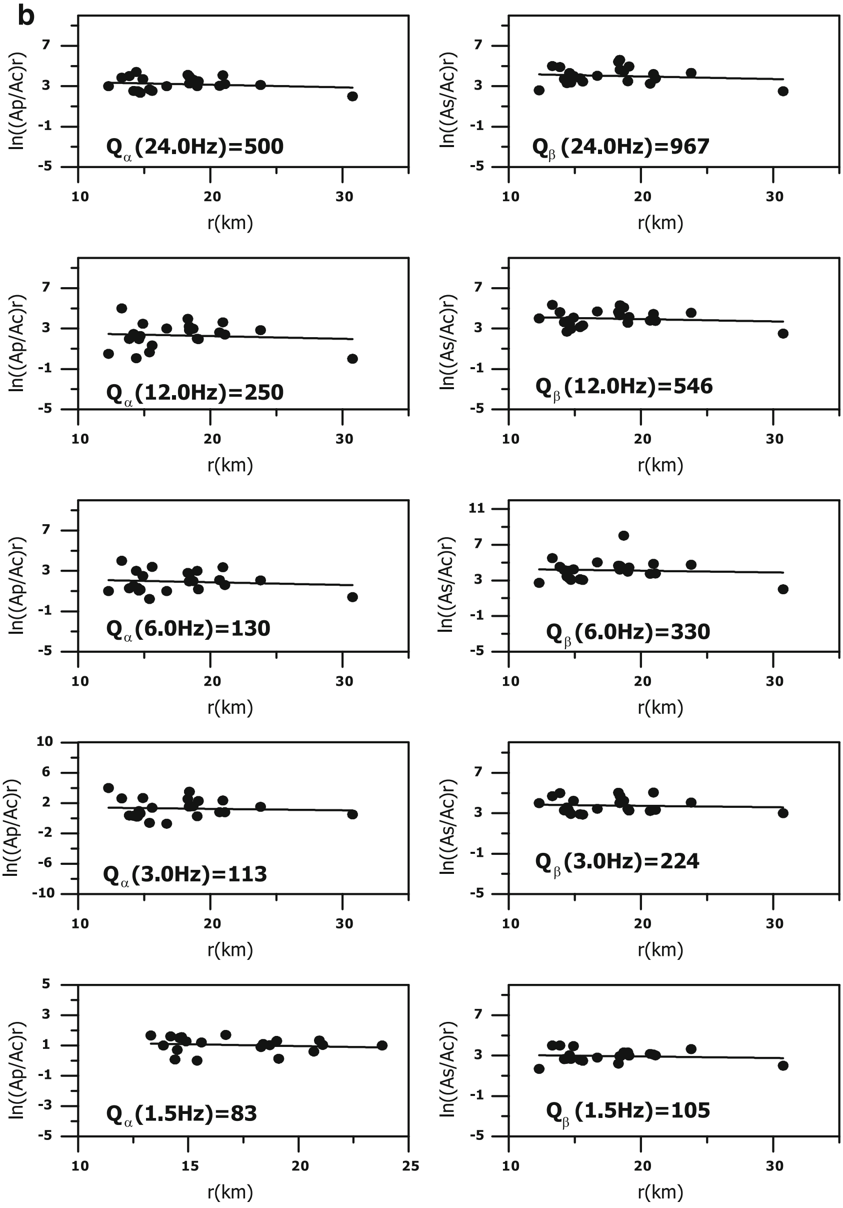

Figure 2
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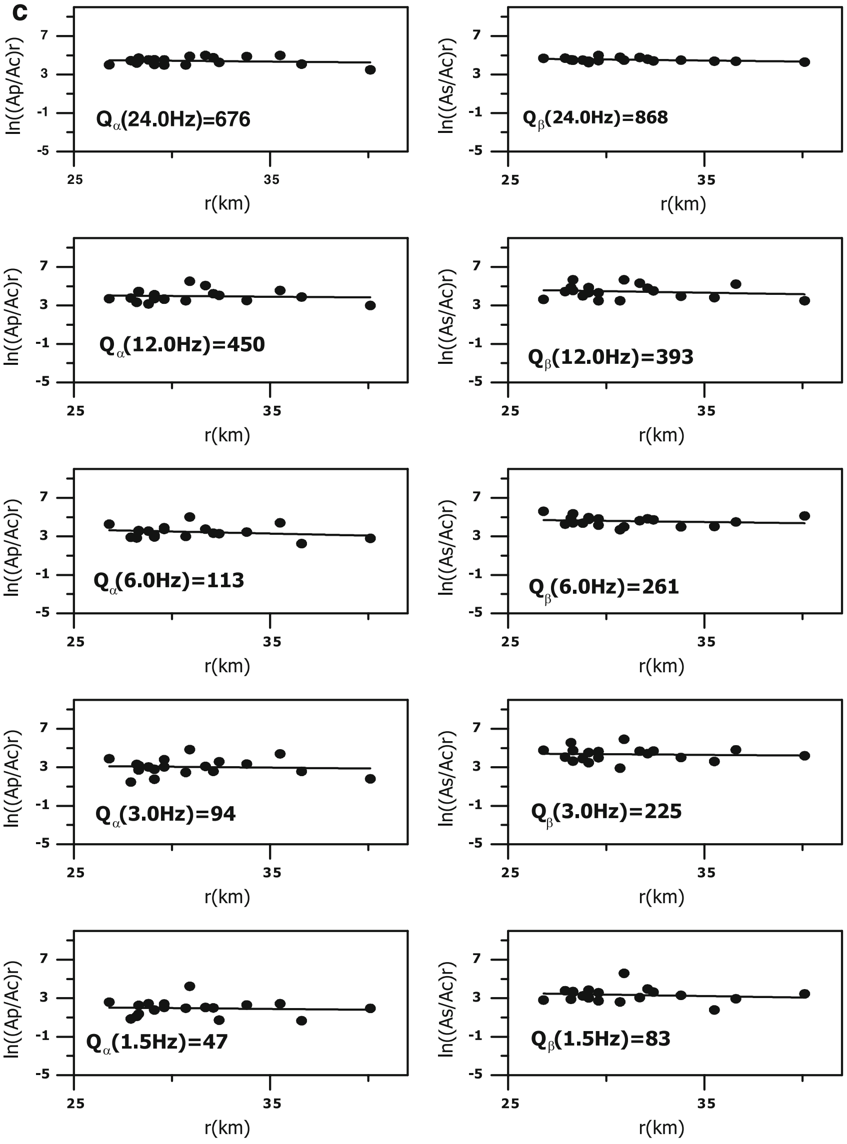
values show lateral variation in the region. This variation in Q values may be due to the heterogeneities present in the region and/or differences in the distances of the events from the recording stations.



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A comparison of the estimated Q relations for P and S waves in this study with those of other regions of the world has been shown in Figures 4a and 4b. We note that the rate of increase of Q(f) for P and S waves in the Chamoli region is comparable with the other regions and close to the Kanto region in absolute values. This shows the similarity between the Chamoli region of Himalaya and the Kanto region in terms of high

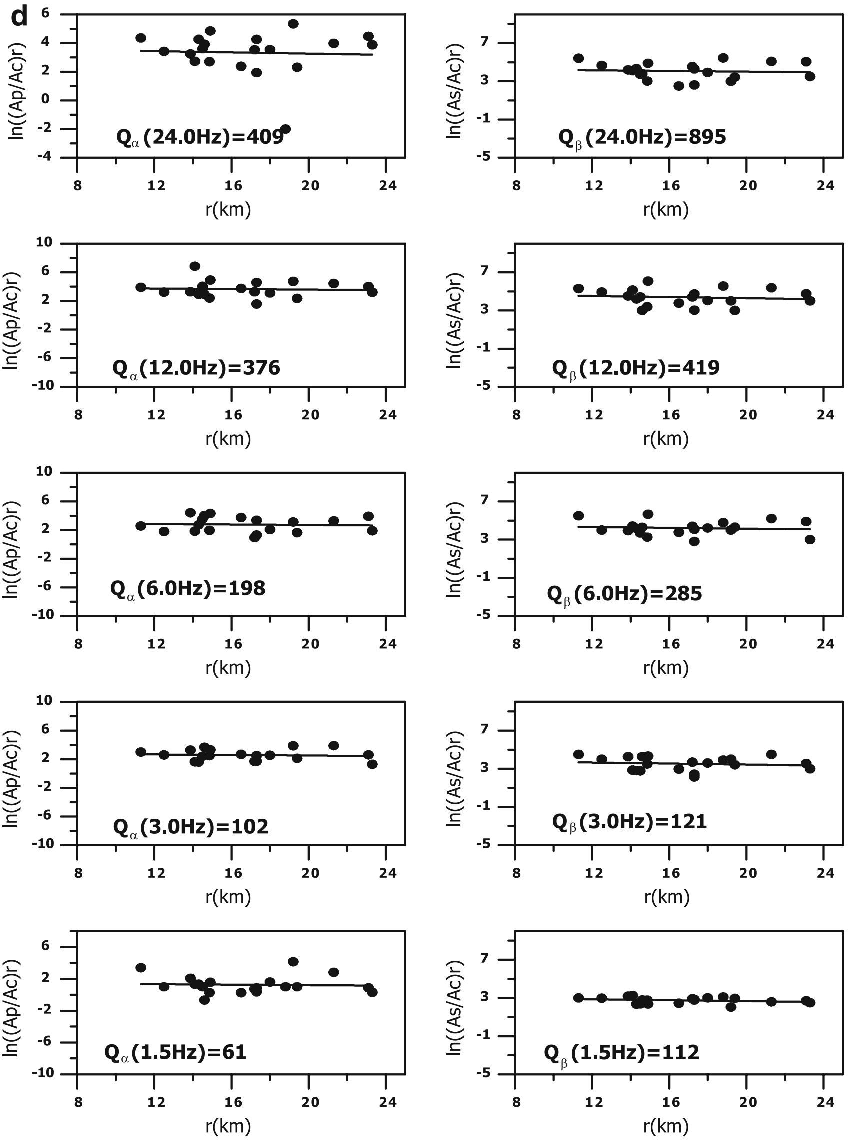

Figure 2
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seismicity and complex geology. Most of the earthquakes in these two regions are associated with plate boundaries. Using the strong motion data of the 1991 Uttarkashi earthquake which occurred in a region adjacent to Chamoli region, GUPTA and KUMAR (1998) estimated a relation $Q_\beta = 90f^{1.06}$. MUKHOPADHYAY *et al.* (2006) have obtained a relation $Q_\beta = 70f^{1.18}$ for the NW Himalaya. The relation for S waves estimated in the present study is in agreement with these relations.

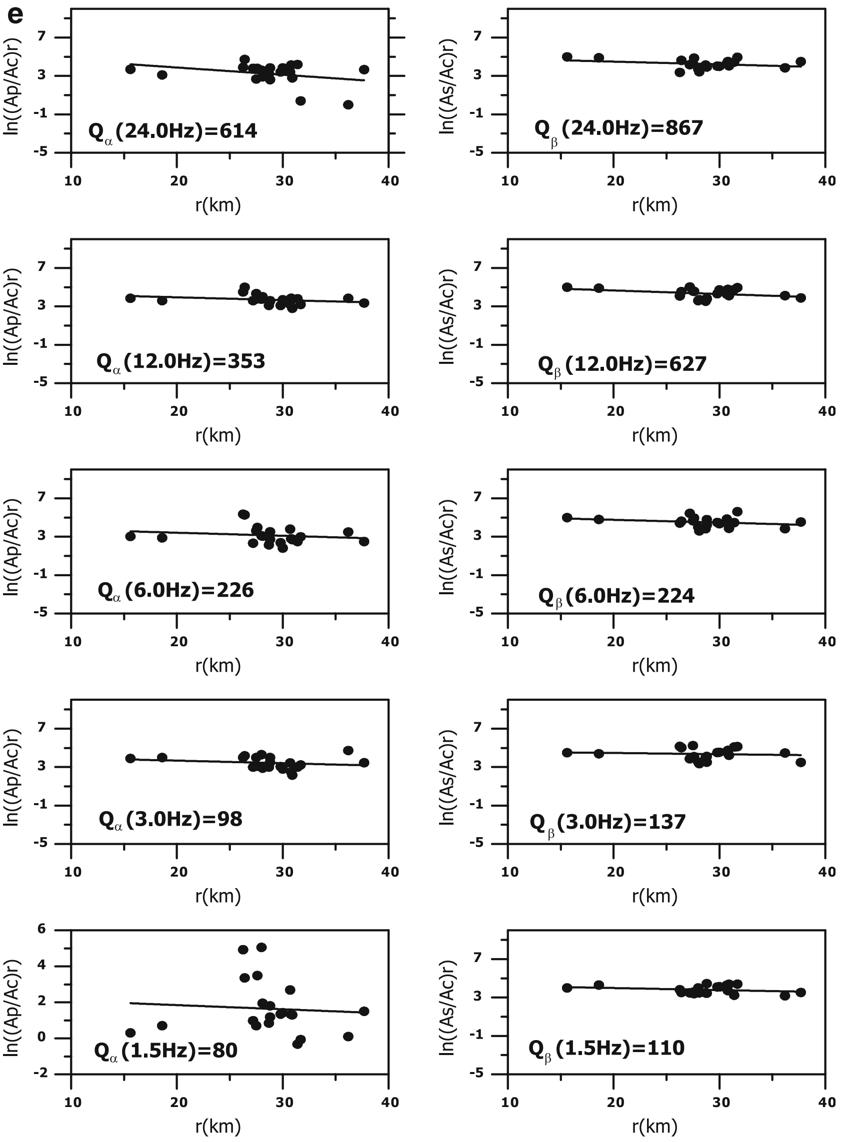

Figure 2
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We find from the values of Q for P and S waves estimated in the present analysis that the ratio Q_β/Q_α is greater than unity for the frequency range (1.5 Hz–24 Hz) considered here. This is different from the results of Q_β/Q_α ratio for frequencies lower than 1 Hz (e.g., TSAI and AKI, 1969). In a detailed analysis, YOSHIMOTO *et al.* (1993) have shown the

Table 3

Values of Q_α and Q_β at five stations at five central frequencies (C.F.) along with average values

S.N.	C.F.	NPG		KPG		PAK		OKI		JSM		Average	
		Q_α	Q_β	Q_α	Q_β	Q_α	Q_β	Q_α	Q_β	Q_α	Q_β	Q_α	Q_β
1.	1.5	61 ± 7	112 ± 11	71 ± 6	119 ± 10	83 ± 8	105 ± 10	80 ± 5	110 ± 9	47 ± 3	83 ± 7	68 ± 6	126 ± 9
2.	3	102 ± 8	121 ± 9	73 ± 8	166 ± 12	113 ± 11	224 ± 22	98 ± 8	137 ± 12	94 ± 8	225 ± 18	96 ± 9	175 ± 15
3.	6	198 ± 14	285 ± 25	200 ± 14	393 ± 24	130 ± 13	330 ± 27	226 ± 15	224 ± 18	113 ± 10	261 ± 19	173 ± 12	299 ± 23
4.	12	376 ± 31	419 ± 29	482 ± 32	524 ± 36	250 ± 21	546 ± 34	353 ± 19	627 ± 27	450 ± 34	393 ± 27	382 ± 27	502 ± 31
5.	24	409 ± 33	895 ± 54	724 ± 45	740 ± 39	500 ± 29	967 ± 49	614 ± 21	867 ± 38	676 ± 36	868 ± 45	588 ± 33	868 ± 38

Table 4

Frequency dependent relationships for five stations

Station code	Relation for P wave	Relation for S wave
NPG	$Q_\alpha = (48 \pm 1)f^{(0.73 \pm .02)}$	$Q_\beta = (66 \pm 2)f^{(0.77 \pm .03)}$
KPG	$Q_\alpha = (38 \pm 1)f^{(0.94 \pm .03)}$	$Q_\beta = (89 \pm 3)f^{(0.69 \pm .05)}$
PAK	$Q_\alpha = (55 \pm 2)f^{(0.64 \pm .01)}$	$Q_\beta = (83 \pm 3)f^{(0.77 \pm .08)}$
OKI	$Q_\alpha = (51 \pm 2)f^{(0.77 \pm .04)}$	$Q_\beta = (66 \pm 2)f^{(0.81 \pm .02)}$
JSM	$Q_\alpha = (29 \pm 0.5)f^{(0.99 \pm .07)}$	$Q_\beta = (71 \pm 3)f^{(0.76 \pm .05)}$

reversal of Q_β/Q_α ratio at low frequencies (<1 Hz) to high frequencies (>1 Hz). It has been revealed in laboratory measurements that Q_β/Q_α ratio is less than unity in fluid-saturated rock matrices and larger than unity in dry rocks (e.g., Toksöz *et al.*, 1979; Mochizuki, 1982; Winkler and Nur, 1982). The study of Johnston *et al.* (1979) also indicates that at surface pressure most dry rocks have $Q_\beta/Q_\alpha > 1$. Yoshimoto *et al.* (1993) have estimated Q_β/Q_α ratio larger than unity at frequencies higher than 1 Hz for the Kanto area, Japan. Rautian *et al.* (1978) also reported that the ratio Q_β/Q_α for crustal rocks takes the value larger than one in the Garm region, central Asia. For South Eastern Korea, the ratio is found to be greater than 1 for the frequency range 1.5–10 Hz (Chung and Sato, 2001). The value of ratio Q_β/Q_α found in the present analysis is in agreement with the results of the laboratory measurements and other studies mentioned above. It is expected that $Q_\beta/Q_\alpha > 1$ for most kinds of scattering (Hough and Anderson, 1988). The ratio Q_β/Q_α as well as the frequency dependence of quality factors estimated in this study indicate that scattering is an important factor contributing to the attenuation of body waves in the region.

Using the single back scattering model of Aki and Chouet (1975), Gupta *et al.* (1995) have estimated a coda-Q relation $Q_c = 126f^{0.95}$ for the adjoining area of the Chamoli region. Using the same model, Mandal *et al.* (2001) have obtained a relation $Q_c = 30f^{1.21}$ for the Chamoli region from the analysis of aftershocks of the 1999 Chamoli earthquake. It has been found by Aki (1969) and Aki and Chouet (1975) that the coda waves are dominated by S to S-backscattered waves and have a common amplitude decay (e.g., Rautian *et al.*, 1978). On the other hand, Zeng *et al.*'s (1991) model predicts that the effects of intrinsic and scattering attenuation combine in a manner such that Q_c should be more than Q_β. A comparison of Q_β estimated in the present analysis $(= 87f^{0.71})$ with that of Q_c $(=30f^{1.21})$ obtained by Mandal *et al.* (2001) shows that $Q_c > Q_\beta$ for higher frequencies (>8 Hz) in this region. This indicates a possible high frequency coda enrichment which suggests that the scattering attenuation important by contributes to the attenuation of S waves at frequencies >8 Hz. This observation may be further investigated using the multiple scattering model (Hoshiba, 1991). The high frequency coda enrichment has been reported from other regions also (e.g., Frankel, 1991; Sarkar and Abers, 1998).

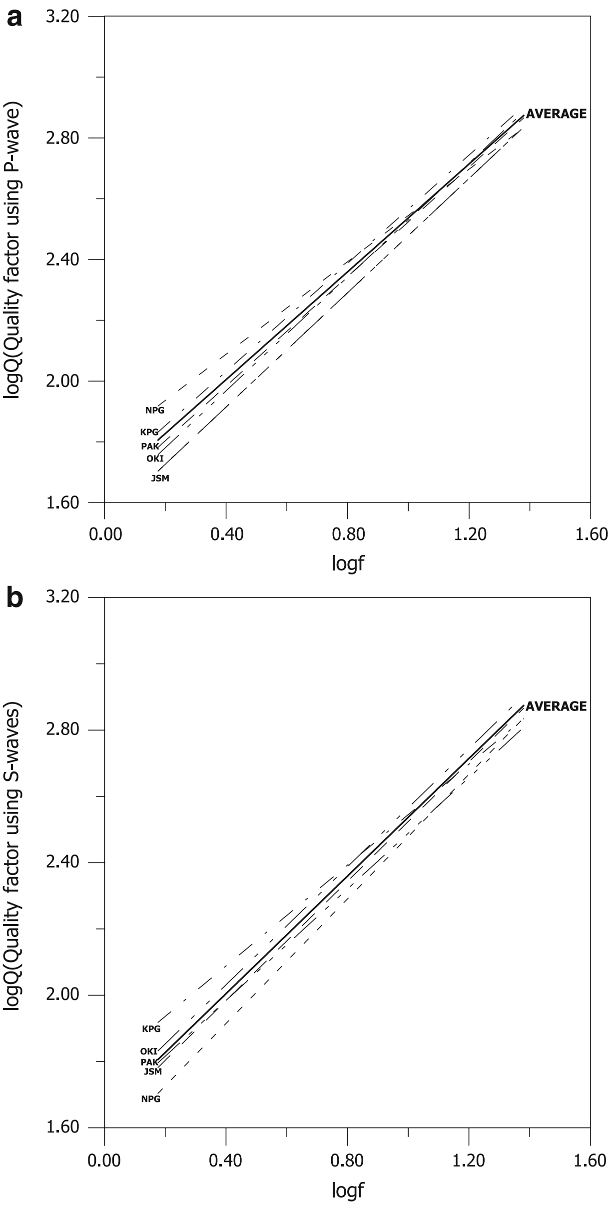

Figure 3
Comparison of frequency dependent relations estimated at five stations for (a) P waves (Q_α), (b) S waves (Q_β). The solid line corresponds to the average relation.

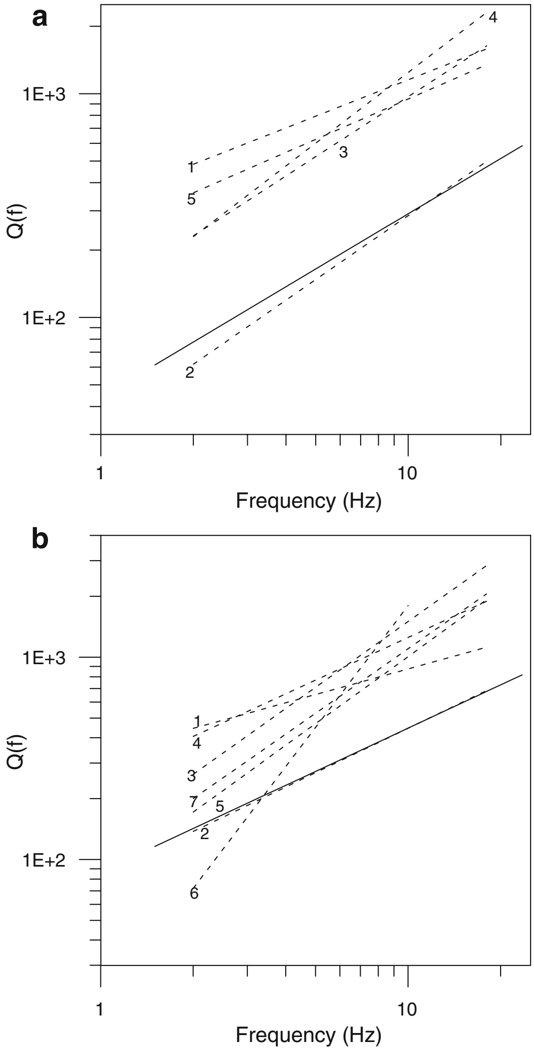

Figure 4

a Comparison of Q(f) for P waves of the Chamoli region obtained in this study (solid line, Q_α (f) = $44f^{(0.82)}$) with those of other regions of the world (dashed lines). line 1: Central South Korea, Q(f) = $333f^{0.54}$, Kim *et al.*, (2004); line 2: Kanto, Japan, Q(f) = $32f^{0.95}$, Yoshimoto *et al.* (1993); line 3: Baltic Shield, Q(f) = $125f^{0.89}$, Kvamme and Havskov (1989), line 4: South Eastern Korea, Q(f) = $111f^{1.05}$, Chung and Sato (2001); line 5: France, Q(f) = $238f^{0.6}$, Campillo and Planet (1991). Figure 4b: Comparison of Q(f) for S waves of the Chamoli region obtained in this study (solid line, Q_β (f) = $87f^{(0.71)}$) with those of other regions of the world (dashed lines). line 1: Central South Korea, Q(f) = $333f^{0.42}$, Kim *et al.* (2004); line 2: Kanto, Japan, Q(f) = $83f^{0.73}$, Yoshimoto *et al.* (1993); line 3: Baltic Shield, Q(f) = $125f^{1.08}$, Kvamme and Havskov (1989), line 4: South Eastern Korea, Q(f) = $250f^{0.70}$, Chung and Sato (2001); line 5: Northern Italy, Q(f) = $80f^{1.1}$, Console and Rovelli (1981); line 6: Central Italy, Q(f) = $18f^{2.0}$, Castro *et al.* (2002); line 7: South Central Alaska, Q(f) = $96f^{1.06}$, Dutta *et al.* (2004).

The frequency-dependent attenuation relations for P and S waves obtained here may be used for the estimation of source parameters and near-source simulation of earthquake ground motion of the earthquakes in the Chamoli region. This becomes an input for the seismic hazard assessment of the region.

6. Conclusion

The most significant contribution of this study is that it is reporting for the first time the simultaneous estimation of P- and S-wave attenuation for the Chamoli region of the Himalaya. In order to investigate the attenuation characteristics of the body waves in the region, the frequency-dependent relationships $Q_\alpha = (44 \pm 1)f^{(0.82\pm.04)}$ and $Q_\beta = (87 \pm 3)f^{(0.71\pm.03)}$ are obtained using the extended coda normalization method. The estimated relation for Q_β is found to be in agreement with those obtained for the adjacent regions using different data sets and methods. The rate of increase of Q(f) for P and S waves in the Chamoli region has been found to be comparable with the other regions of the world. The frequency dependence of quality factors and the ratio Q_β/Q_α (>1) obtained here suggests the importance of scattering loss in seismic wave attenuation in the region. This is further validated by comparing the attenuation relation for S waves obtained in the present analysis with that of coda waves obtained by MANDAL *et al.* (2001) showing $Q_c > Q_\beta$ for higher frequencies. The scattering in the region is caused by faults and fractures present there. The study can be further extended using multiple scattering models. The frequency-dependent attenuation relations obtained here may be used for the estimation of source parameters and near-source simulation of earthquake ground motion of the earthquakes, which in turn are required for the assessment of seismic hazard in the region.

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