Pure Appl. Geophys. 172 (2015), 1451–1469

DOI 10.1007/s00024-014-0966-9

Pure and Applied Geophysics

Body Wave Crustal Attenuation Characteristics in the Garhwal Himalaya, India

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Abstract—We estimate frequency-dependent attenuation of P and S waves in Garhwal Himalaya using the extended coda normalization method for the central frequencies 1.5, 2, 3, 4, 6, 8, 10, 12, and 16 Hz, with earthquake hypocentral distance ranging from 27 to 200 km. Forty well-located local earthquake waveforms were used to study the seismic attenuation characteristics of the Garhwal Himalaya, India, as recorded by eight stations operated by Wadia Institute of Himalayan Geology, Dehradun, India, from 2007 to 2012. We find frequency-dependent P and S wave quality factors as defined by the relations $Q_P = 56 \pm 8f^{0.91\pm0.002}$ and $Q_S = 151 \pm 8f^{0.84\pm0.002}$ by fitting a power-law frequency dependence model for the estimated values over the whole region. Both the Q_P and Q_S values indicate strong attenuation in the crust of Garhwal Himalaya. The ratio of $Q_S/Q_P > 1$ obtained for the entire analyzed frequency range suggests that the scattering loss is due to a random and high degree of heterogeneities in the earth medium, playing an important role in seismic wave attenuation in the Himalayan crust.

Key words: Body waves, coda normalization, lapse time, seismic attenuation, quality factor.

1. Introduction

The attenuation of seismic waves, expressed by the inverse of the quality factor (Q), is one of the important geophysical parameters characterizing the material through which seismic waves propagate. The two basic methodologies for measuring the attenuation of seismic waves are based on the use of (1) the direct waves, and (2) the coda waves. Aki (1969), Aki and Chouet (1975), and Sato (1977) interpreted the coda waves as single backscattered S-to-S waves from heterogeneities in the crust and upper mantle. Since then, the rate of time decay of coda-wave amplitude has been widely used for estimation of coda attenuation (Q_C^{-1}) (Herraiz 1987). Aki (1980) first introduced the coda normalization method to estimate the frequency-dependent Q_S^{-1}. Several authors, such as Rautian and Khalturin (1978a), Aki (1980), Herrmann (1980), Roecker *et al.* (1982), and Campillo *et al.* (1985), found that Q_C and the S-wave Q (Q_S) estimated from direct waves or L_g waves are approximately equal. This observational result suggests that the use of coda waves is the easiest way to estimate Q_S (Novelo-Casanova and Lee, 1991). On the other hand, the model of Zeng *et al.* (1991) predicts that the effects of intrinsic and scattering attenuation combine in a manner such that Q_C should be more than Q_S. However, there is still some uncertainty both about how the apparent attenuation inferred from coda waves is related to the attenuation of the direct S waves and about the relative contribution of scattering attenuation and intrinsic attenuation to the coda and S-wave attenuation (Frankel and Wennerberg, 1987; Sato, 1990; Frankel, 1991).

The tool originating from the study of coda waves is the coda normalization method, which is based on the assumption of a uniform spatial distribution of coda energy for long lapse times. The coda normalization method allows one to estimate the difference of site amplification factors as a function of frequency, to distinguish differences in source spectral characteristics, and to measure attenuation using data from only a single station (Aki, 1969, 1980; Phillips and Aki, 1986).

There are very few studies on frequency-dependent Q_P, e.g., those carried out by Fedotov and Boldyrev (1969), Hough *et al.* (1988), and Kohketsu and Shima (1985). Yoshimoto *et al.* (1993) proposed a new method for simultaneous measurement of Q_P and Q_S by extending the conventional coda

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normalization method, earlier developed by Aki (1980). This method has been successfully applied further to obtain both P and S wave attenuation for a few places globally, such as Kanto, Japan by Yoshimoto et al. (1993); Western Nagano, Japan by Yoshimoto et al. (1998); South-Eastern Korea by Chung and Sato (2001); central South Korea by Kim et al. (2004); Koyna, India by Sharma et al. (2007); Bhuj, India by Padhy (2009); Cairo metropolitan area by Abdel-Fattah (2009); East-Central Iran by Ma'hood et al. (2009); Kumaun Himalaya, India by Singh et al. (2011); Kinnaur Himalaya, India by Kumar et al. (2014); and Northeast India by Padhy and Subhadra (2010). We also adapt the method of extended coda normalization.

Taylor et al. (1986) briefly defined the limitations involved with the lack of broadband data and single phase data in studying body wave attenuation characteristics. Such studies may suffer from some fundamental problems because many attenuation mechanisms are thermally activated and vary with physical properties and/or composition and will thus show variations with depth. Furthermore, some attenuation mechanisms are activated by either shear or compressional motion and therefore exhibit different frequency dependence and magnitude for P and S waves. The different frequency dependence of P and S waves therefore obliges one to study both primary and shear waves simultaneously. Here, we utilize broadband data to estimate the frequencies, where the effects due to scattering become dominant over intrinsic effects at higher frequencies (Taylor et al., 1986).

Also, regional attenuation properties are very important when comparing seismic travel-time differences (Liu et al., 1976). The importance of phase velocity dispersion arising from anelasticity has been discussed by various researchers (e.g., Lomnitz 1957; Jeffreys, 1965; Randall, 1976). Thus, the frequency dependence of seismic attenuation in the earth's crust is crucial for correcting the velocity dispersion due to anelasticity. The attenuation properties as discussed by Karato (1993) are also very important in the interpretation of seismic tomography.

We have applied the single-station method based on the rate of decay of the P and S wave to the coda-wave amplitude ratio over distance for different frequencies. This method has been applied by Rautian and Khalturin (1978b), Aki (1980), and Roecker et al. (1982) to determine the attenuation of S waves for the Garm region, Tajikistan, the Kanto region, Japan, and Central Asia, respectively. Earlier studies in the Garhwal region mainly focused on attenuation of coda waves (Gupta and Kumar, 2002; Gupta et al., 1995; Mukhopadhyay et al., 2010). Here, we make an attempt to study and constrain the frequency dependence of body wave characteristics (Q_P and Q_S) in the Garhwal region of Northwest Himalaya.

2. Seismotectonic Settings of the Study Region

The emergence of Himalaya due to the ongoing convergence of the Indian and Eurasian Plates since 50 Myrs has accommodated nearly 2,000 km of crustal shortening in its postcollisional phase (Molnar and Tapponier, 1975). This resulted in a high level of tectonic activity developing the major tectonic boundaries striking northwest-southeast, viz. the Indus–Tsangpo suture zone (ITSZ), South Tibetan Detachment (STD), and prominent intracontinental thrust boundaries such as the Main Central Thrust (MCT), Main Boundary Thrust (MBT), and Himalayan Frontal Thrust (HFT) (Fig. 1c). All these tectonic boundaries are suggested to root into a low-angle detachment, the Main Himalayan Thrust (MHT) (Schelling and Arita, 1991; Fig. 1c). The tectonic zones characterized between these major tectonic boundaries in continuation from north to south descend from the Tethys Himalaya, Higher Himalaya, Lesser Himalaya to the Siwalik or Sub-Himalaya. The present study area, the Garhwal region, lies in the northwestern part of the Himalaya and shows development of all four tectonic zones (Fig. 1a, b). The presence of transverse tear faults along the entire Himalayan arc splits the area into different blocks along which neotectonic movement and related seismicity take place (Paul, et al., 2004). Nath et al. (2008) divided the northwest Himalaya into different active tectonic zones, where the Garhwal zone is delimited in the east and west by the Kumaun and Kinnaur active tectonic zones (Fig. 1b). These zones have experienced a number of damaging earthquakes in the past, as is evident from the recorded seismic history of this region. The Garhwal and the adjacent Kumaun region have experienced a total of 13 earthquakes with magnitude ≥6.0 recorded in the last 100 years (Rastogi, 2000). Ni and Barazangi (1984) suggested that the majority of earthquake epicenters lie just south of the surface trace of the MCT. In Garhwal Himalaya, the MCT is present at the base of the crystalline zone, inclining at a varying dip from 30° to 45° northward forming a large-scale zone of intense shearing (Gansser, 1964; Valdiya, 1980). It divides the predominantly high-grade metamorphic crystalline rocks of Higher Himalaya in the north from the low- to medium-grade unfossiliferous metasedimentary rocks of Lesser Himalaya to its south (Searle 1986). In the present study, more than 80 % of the seismic activity is observed around the surface of detachment, i.e., the MHT, which lies at about 12–15 km depth beneath Lesser and Higher Himalaya. This indicates that the MHT in most cases has been responsible for generating the Himalayan earthquakes (Pandey *et al.* 1999; Monsalve *et al.* 2006; Mahesh *et al.* 2013). Studying the attenuation properties of seismic waves in such a complex tectonic setting therefore provides an opportunity to augment our understanding of the medium properties.

3. Data

A seismic network of 10 broadband stations has been operated by Wadia Institute of Himalayan Geology (WIHG), in the Garhwal Himalaya, India, since 2007. We use waveform data from only eight stations installed in the mountainous terrain of Himalaya (Fig. 2). The other two stations, DBN and DDN, are located on thick alluvium sediments of Gangetic Plains, resulting in very high noise in the data. Therefore, we decided not to use the data from these stations in this study. The broadband stations are equipped with a Trillium 240 seismometer with high dynamic range (>138 dB) with a Taurus data acquisition system. The standard frequency bandwidth is 0.05–50 Hz, and three-component data are acquired in continuous mode at 100 samples per second for three components at each station. The data are recorded and monitored at the Central Recording Station (CRS) operating at the earthquake processing center of the Wadia Institute of Himalayan Geology (WIHG), Dehradun, India. We used 40 well-distributed local earthquakes recorded during 2007–2012 in the study region, with $2.5 \leq M_L \leq 5$ (Fig. 2). The hypocentral parameters were determined using the HYPOCENTER location program of Lienert *et al.* (1986) based on the crustal velocity model by Mahesh *et al.* (2013) and Kumar *et al.* (2009). The uncertainties involved in the estimation of epicenter, depth, and origin time are on the order of 0–5 km and 0–0.5 s, respectively. Here, we constrain our study to the crustal level, taking earthquakes with focal depth ≤45 km above Moho, which is nearly horizontal at 35–45 km depth beneath the Sub- and Lesser Himalaya (Caldwell *et al.*, 2013). As mentioned in Sect. 2, the majority of the earthquakes considered in this study lie within depth of 15 km, whereas the hypocentral distance varies from 27 to 200 km.

The seismograms of all well-located events were visually examined for any recording problems such as high noise, missed recordings, overlapping, or early cutoff. We analyzed the local earthquake spectra of S, P, and coda-wave windows of 5-s duration where, for each event, the signal-to-noise ratio was >2 over the frequency range of 1.5–16 Hz for both P and S waves.

4. Method

The coda normalization method was first obtained by Aki (1980) to estimate frequency-dependent Q_S^{-1}. The coda normalization method was further extended by Yoshimoto *et al.* (1993) to estimate Q_P^{-1}. This method is termed the extended coda normalization method. In the present study, Q_P and Q_S values for Garhwal Himalaya region were estimated by applying the extended coda normalization method (Yoshimoto *et al.*, 1993).

The method is based on the idea that coda waves consist of scattered S waves from random heterogeneities in the earth (Aki, 1969; Aki and Chouet, 1975; Sato, 1977). The lapse time (t_C) is chosen to be >2 times the S-wave travel time (Fig. 3). For lapse times greater than twice the direct S-wave travel time, the spectral amplitude of the coda $A_C(f, t_C)$ is independent of the hypocentral distance r in the regional distance range (Aki, 1980) and is given by

$$A_C(f, t_C) = S_S(f)P(f, t_C)G(f)I(f), \quad (1)$$

where f is the frequency, $S_S(f)$ 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 $I(f)$ denotes the instrumental response. The coda excitation factor $P(f, t_C)$ represents how the spectral amplitude of coda waves decays with lapse time.

Similarly, the direct body wave (P or S) spectral amplitude $A_i(f, r)$ (Yoshimoto *et al.*, 1993) for the ith event may be written as

$$A_i(f, r) = R_{\theta\phi}S(f)r^{-\gamma}\exp\left(-\frac{\pi f}{Q(f)V}r\right)G(f, \psi)I(f), \quad (2)$$

where $R_{\theta\ \phi}$ is the source radiation pattern and γ denotes the geometrical spreading exponent. The symbol $Q(f)$ is the quality factor of the body wave, V is the average body wave velocity, and ψ represents the incidence angle of the body wave.

The effects of source, site, and instrument can be eliminated, and data from many earthquakes can be combined to obtain a stable estimate of attenuation (Kumar *et al.*, 2014). Due to the wide epicentral distribution of the studied earthquakes, we assume the following:

1. The contribution of source radiation pattern ($R_{\theta\ \phi}$) disappears by averaging over many different focal-plane solutions.
2. After normalizing, the site amplification factor $G(f, \psi)/G(f)$ ratio becomes independent of the incidence angle (ψ) by averaging over many earthquakes.

Under these assumptions, the spectral amplitude of body waves (in this case S wave) given by Eq. 2 divided by the spectral amplitude of coda waves (Eq. 1) gives the normalized source spectral amplitude of S wave according to the following expression:

$$\ln\left[\frac{A_S(f, r)r}{A_C(f, t_C)}\right] = -\frac{\pi f}{Q_S(f)V_S}r + \text{const}(f), \quad (3)$$

where $Q_S(f)$ is the quality factor of the S wave and V_S is the average S wave velocity in the study region. We can estimate $Q_S(f)$ from a linear regression of $\ln[A_S(f, r)r^{\gamma}/A_C(f, t)]$ versus the hypocentral distance r by means of the least-squares method.

Yoshimoto *et al.* (1993) extended the coda normalization method by assuming that the ratio of P to S wave source spectra is constant for a small range of magnitudes. The method works based on the proportionality of the coda spectral amplitude $A_C(f, t_C)$ versus the source spectral amplitude of P and S waves, i.e., $S_P(f)$ and $S_S(f)$, respectively. This means that we may use the spectral amplitude of the S-coda wave for normalization of the P-wave source spectral amplitude, whence we get Eq. (4) for P wave, similar to Eq. (3).

$$\ln\left[\frac{A_P(f, r)r}{A_C(f, t_C)}\right] = -\frac{\pi f}{Q_P(f)V_P}r + \text{const}(f), \quad (4)$$

where $Q_P(f)$ is the quality factor of the P wave and V_P is the average P wave velocity in the study region.

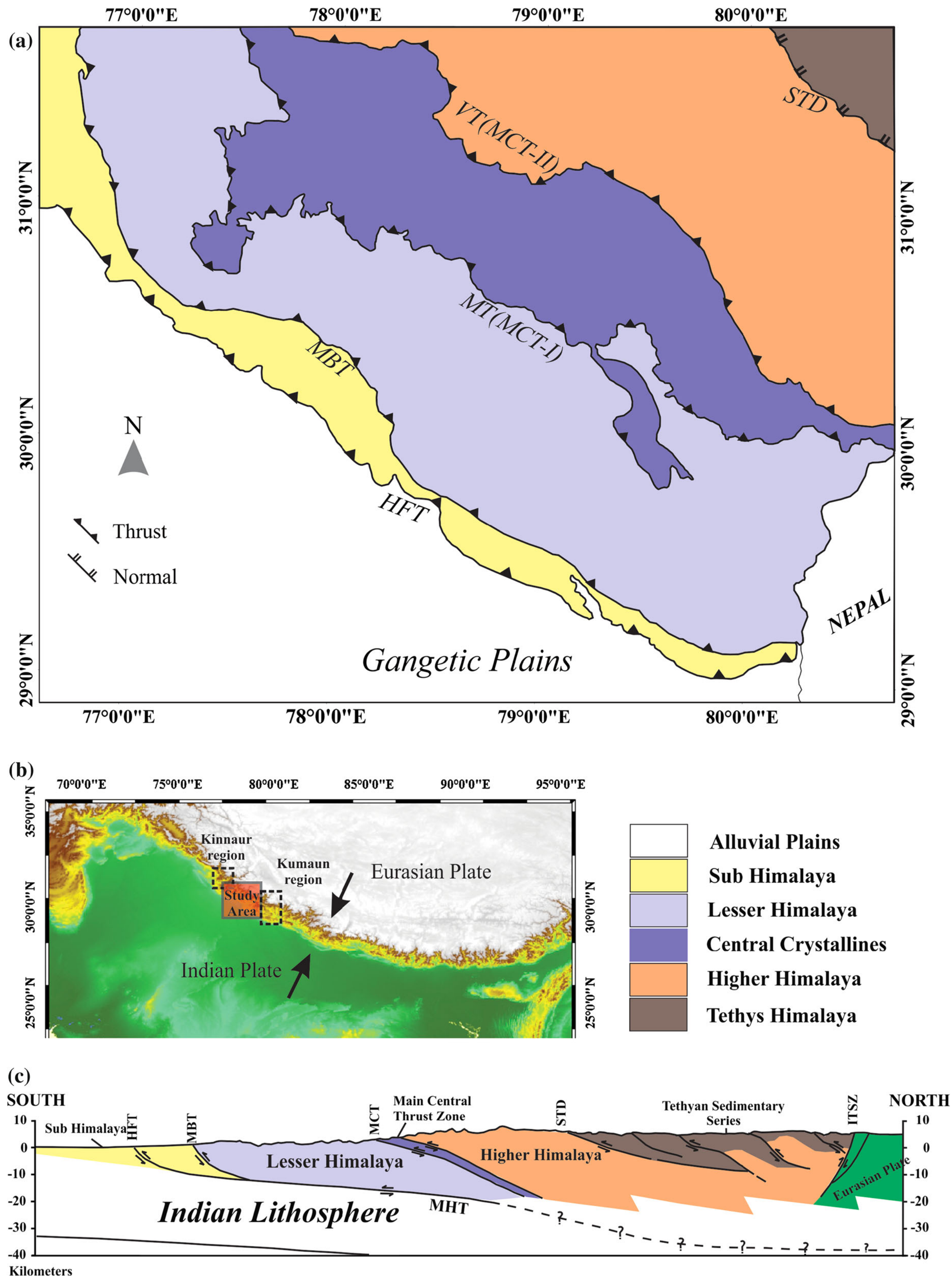
This method uses the spectral amplitude of the earthquake source normalized by the spectral amplitude of coda waves at fixed lapse time, enabling us to measure Q_P and Q_S, at a single station. Using Eqs. (3) and (4), we estimate the slope (m) by linear regression of a plot of the coda-normalized spectral amplitude $\ln[A_{S,P}(f, r)r^{\gamma}/A_C(f, t)]$ versus the hypocentral distance (r) by means of the least-squares method, where the slopes for P (m_P) and S (m_S) waves are given as

$$m_P = -\frac{\pi f}{Q_P V_P}, \quad (5)$$

$$m_S = -\frac{\pi f}{Q_S V_S}. \quad (6)$$

Figure 1 ▸

a Tectonic map of the Garhwal–Kumaun region of northwest Himalaya, showing the major tectonic units in the region (modified after Thakur and Rawat, 1992). **b** Location of study area shown by square (in transparent *red*) in the SRTM image of India. *Arrows* show the direction of movement of the Indian and Eurasian Plates. *Dashed rectangles* show adjacent regions of Kinnaur and Kumaun Himalaya. **c** Simplified cross section of the Himalaya showing the main lithotectonic units: ITSZ, Indus–Tsangpo suture zone; STD, South Tibetan Detachment; MCT, Main Central Thrust; MBT, Main Boundary Thrust; HFT, Himalayan Frontal Thrust; MHT, Main Himalayan Thrust [modified after Hauck *et al.* (1998) and Lave and Avouac (2001)]


(a)
77°0'0"E
78°0'0"E
79°0'0"E
80°0'0"E
31°0'0"N
30°0'0"N
29°0'0"N
STD
VT(MCT-II)
MT(MCT-I)
MBT
HFT
N
Thrust
Normal
NEPAL
Gangetic Plains
(b)
70°0'0"E
75°0'0"E
80°0'0"E
85°0'0"E
90°0'0"E
95°0'0"E
35°0'0"N
30°0'0"N
25°0'0"N
Kinnaur region
Kumaun region
Study Area
Eurasian Plate
Indian Plate
Alluvial Plains
Sub Himalaya
Lesser Himalaya
Central Crystallines
Higher Himalaya
Tethys Himalaya
(c)
SOUTH
NORTH
Sub Himalaya
HFT
MBT
MCT
Main Central Thrust Zone
STD
Tethyan Sedimentary Series
ITSZ
Lesser Himalaya
Higher Himalaya
Eurasian Plate
Indian Lithosphere
MHT
10
0
-10
-20
-30
-40
Kilometers

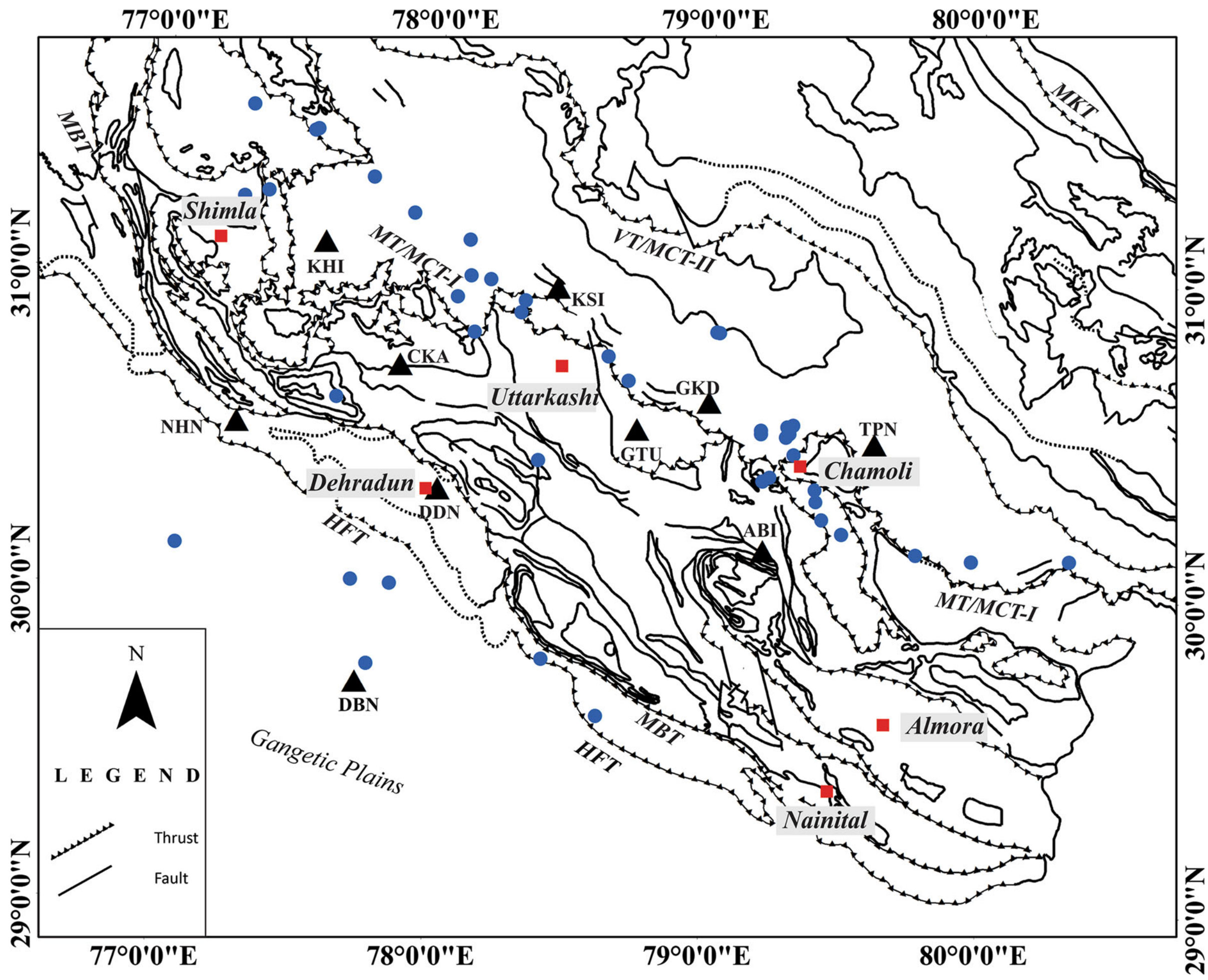


Figure 2
Tectonic map of Garhwal region (modified after THAKUR and RAWAT, 1992) showing the earthquake events (*blue filled circles*). Broadband seismic station locations are shown by *triangles* (*filled black*). The tectonic boundaries are described in Fig. 1. *Squares* (*filled red*) show important localities (towns) in the study region

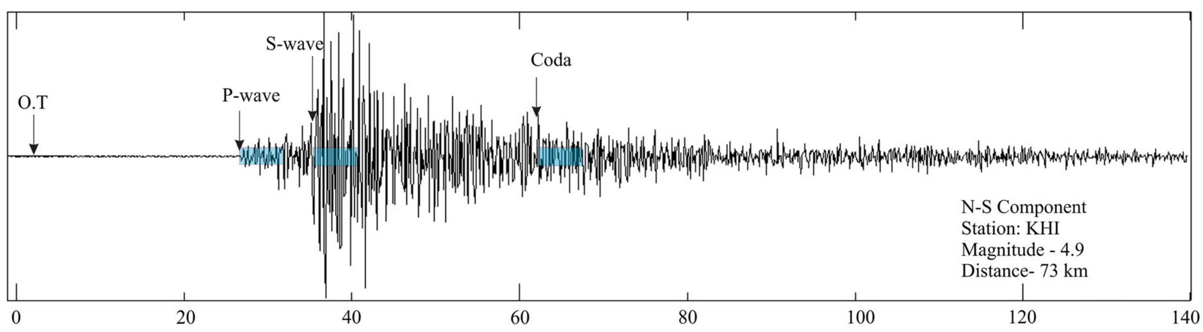


Figure 3
Example of a horizontal (N–S) component seismogram showing the time of arrival of P, S, and coda waves marked by *down arrows*. The *transparent box* (in *blue*) shows the 5 s window of P, S, and coda waves, where coda is measured at $t_C = 60$ s from the earthquake origin time (O.T)

Table 1

Central frequencies with their bandpass limits to filter the waveform

Lower band frequency (f_L)	Central frequency (f_C)	Upper band frequency (f_U)
1	1.5	2
1.33	2	2.67
2	3	4
2.67	4	5.33
4	6	8
5.33	8	10.67
6.67	10	13.33
8	12	16
10.67	16	21.33

Since the ratio of P- to S-wave spectra depends on seismic moment or earthquake magnitude, it is necessary to restrict the earthquakes for analysis to a small magnitude range when we estimate Q_P by using Eq. (4).

4.1. Analysis

To evaluate the frequency-dependent $Q^{-1}_{(P,S)}$, we analyzed filtered seismograms where each seismogram was digitally bandpass-filtered using a phaseless four-pole Butterworth filter with the eight passbands given in Table 1. The bandwidths were chosen to maintain relative constant bandwidth. A window length of 5 s was chosen after experimenting with various durations (Fig. 3). Each window is cosine tapered (5 %) and Fourier transformed. The coda spectral amplitude $A_C(f, t_C)$ is calculated for a 5-s time window centered at fixed lapse time $t_C = T_0 + 60$ s, where T_0 is the earthquake origin time. This is to ensure that t_C is twice the S wave travel time or greater (Aki and Chouet, 1975; Rautian and Khalturin, 1978a).

From the filtered seismograms, we measured the maximum peak-to-peak amplitude of direct P and S waves. Half values of the peak-to-peak amplitudes represent $A_P(f, r)$ and $A_S(f, r)$, respectively. We used *Z*-component records for the P-wave analysis. Since the maximum amplitudes of S waves are nearly equal in both the N–S and E–W components, we used the N–S component for the S wave analysis (Fig. 4). We measured the coda spectral amplitude $A_C(f, t_C)$ from the root-mean-squares (rms) coda amplitude (Kumar *et al.*, 2014) of the N–S component for each frequency band. The observed values were substituted into Eqs. (3) and (4) to estimate Q_P and Q_S using the least-squares method.

The average velocities V_P (6.4 km/s) and V_S (3.7 km/s) of the lithosphere were taken from the velocity model given by Mahesh *et al.* (2013) and Kumar *et al.* (2009). The structure of the lithosphere beneath the Garhwal Himalaya is very complex, where the Indian Plate interacts with the Tibetan Plate. In these regions, geometrical spreading plays an important role as it affects the decay rate of the seismic wave amplitude (Yoshimoto *et al.*, 1993).

Studying the attenuation properties of S wave in New York State and South Africa, Frankel *et al.* (1990) reported that Q_S^{-1} does not depend on frequency after changing the value of the geometrical spreading exponent (γ) from 0.7 to 1.3. In contrast to those results, Yoshimoto (1993) in a similar attempt for Kanto region reported that the Q^{-1} values in each frequency band did not change significantly with variation of gamma to 0.75, 1, and 1.25, but the frequency dependence becomes smaller for larger γ. He also explained that the value of γ is 1 for earthquakes with hypocentral depth deeper than the Moho, whereas in case of crustal earthquakes, reflections from the Conrad and/or Moho discontinuity may change the value of γ from 1. However, from their study, the expected apparent trends from the effect of reflections were not found to be satisfactory. Therefore, we take a geometrical spreading exponent $\gamma = 1$ in our study region. This gives an inverse power law with hypocentral distance of r^{-1}, which is generally accepted and commonly used for estimation of direct body wave attenuation in the crust (Chin and Aki 1991; Ishida, 1992; Yoshimoto *et al.*, 1993; Singh *et al.*, 2012, Kumar *et al.*, 2014). The coda-normalized amplitude of P and S waves are plotted against hypocentral distance for each station at each frequency band in Fig. 5. To minimize the sum of the absolute deviations of the differences between the data and the data estimated by the model, we applied least-squares fitting as shown in Fig. 5. The slopes in Eqs. (5) and (6) were then used to estimate the quality factor (Q) of P and S waves.

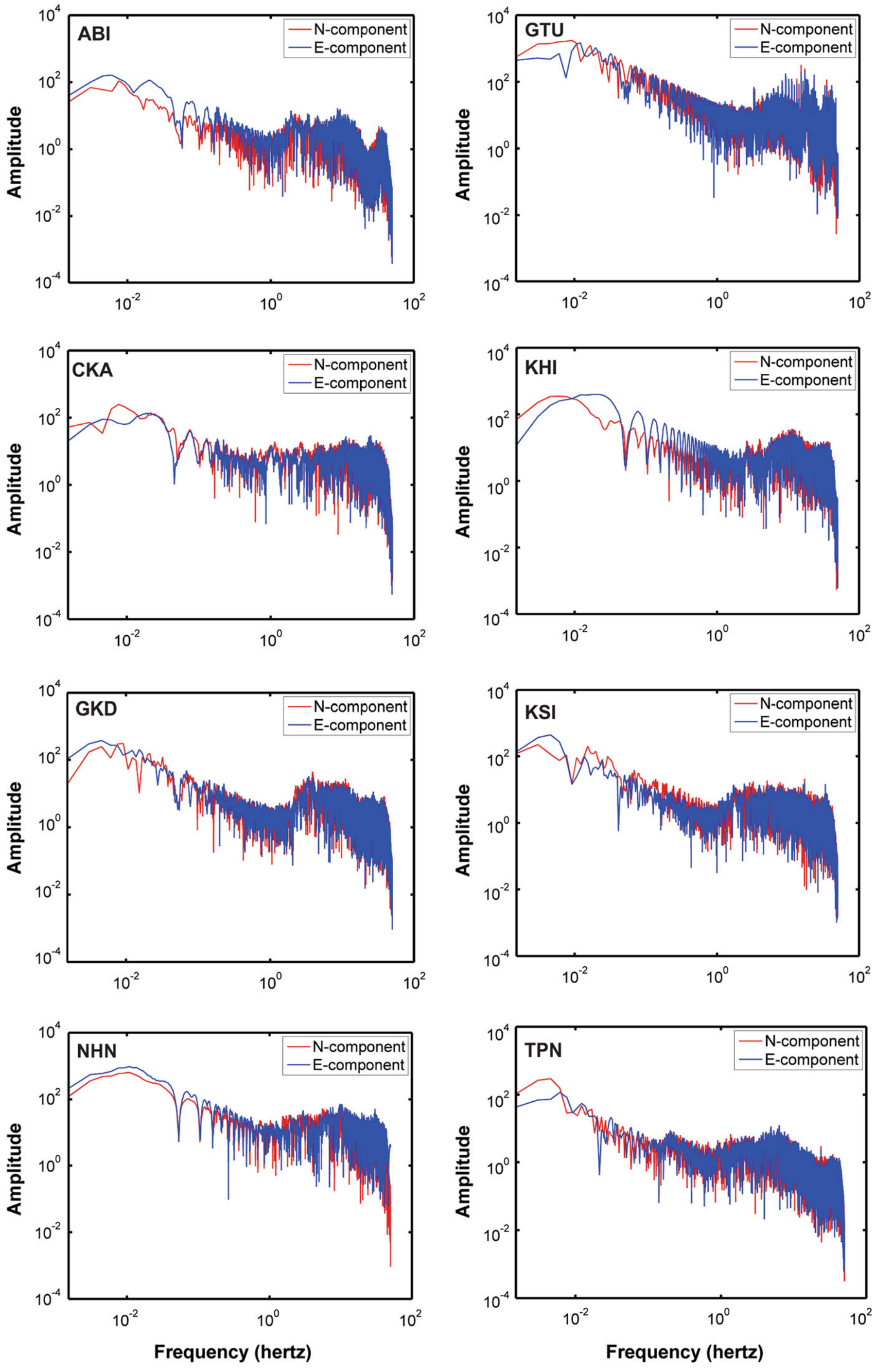


Figure 4
Comparison between the velocity spectra of the north component to the east for a single earthquake at eight stations considered in the present study

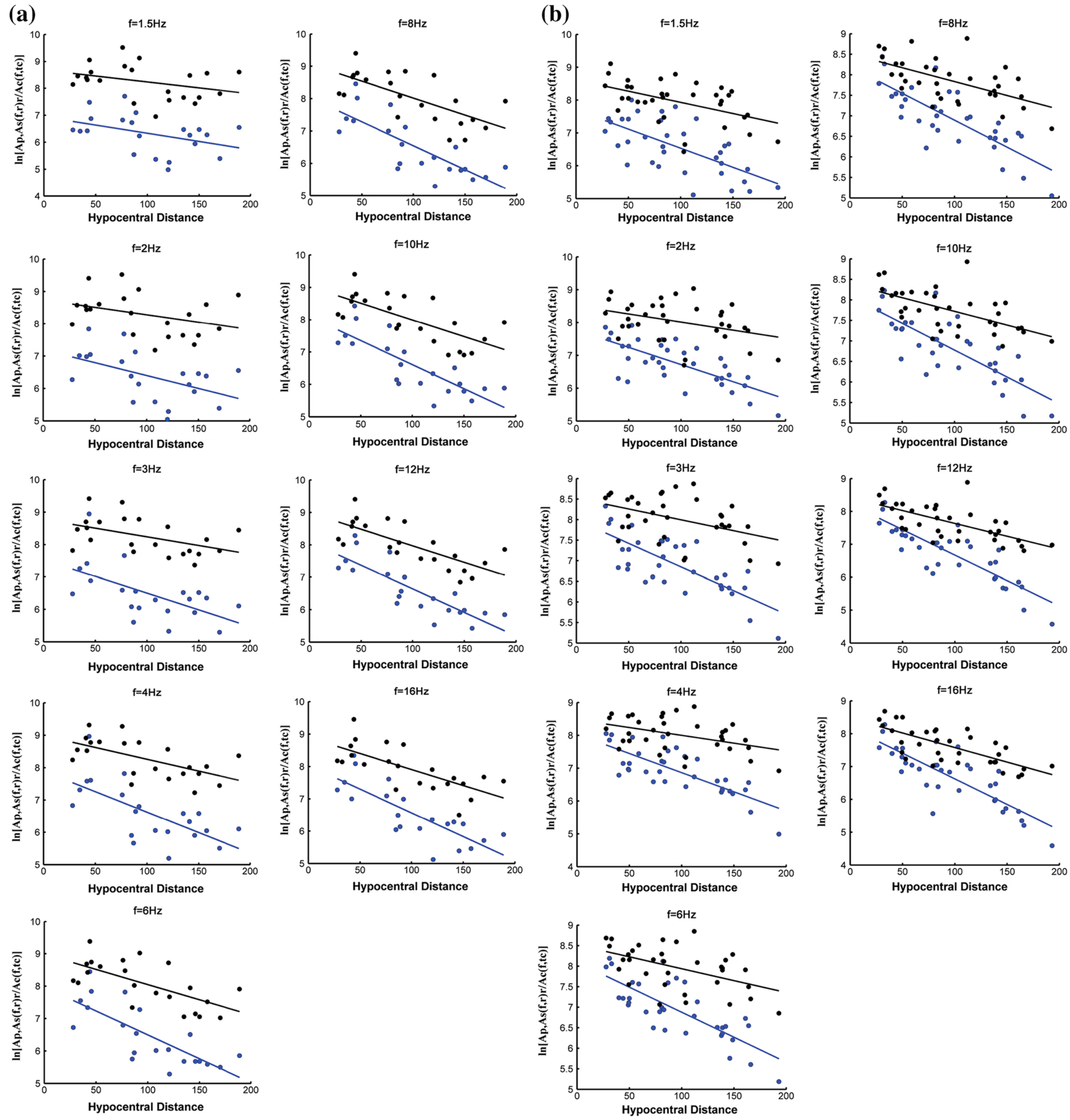


Figure 5

Coda-normalized peak amplitude decay of P waves (*blue circles*) and S waves (*black circles*) with hypocentral distance for stations **a** ABI, **b** CKA, and **c** GKD, at different central frequencies (Table 1). *Solid lines* indicate least-squares fits for the whole earthquakes for P and S waves, respectively

5. Results and Discussion

By using the extended coda normalization method given by Yoshimoto *et al*. (1993), we calculated Q_P and Q_S for the study region. We found that both quality factors for P (Q_P) and S (Q_S) depend strongly on frequency (Fig. 6), increasing from about $Q_P = 88$ and $Q_S = 202$ at 1.5 Hz to $Q_P = 773$ and $Q_S = 1{,}512$ at 16 Hz. The slopes of the best fit lines as indicated in Fig. 5 were used to estimate Q_P and

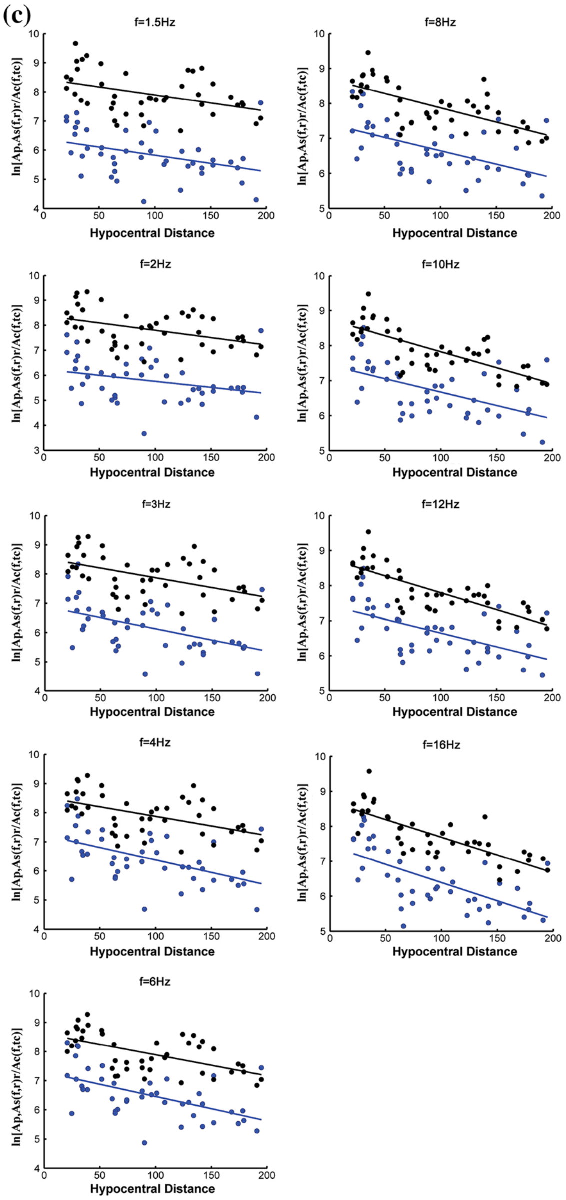


Figure 5
continued

Q_S for each station using the relations in Eqs. (3, 4) (Table 2). The values of Q_P and Q_S obtained for each station against frequency were averaged to estimate the Q_P and Q_S for the Garhwal region (Table 3). The frequency-dependent relations, fitted by a power law, take the form $Q = Q_0 f^n$ (where Q_0 is Q at 1 Hz and n is the frequency relation parameter) as shown in Fig. 6 and Table 3. The standard errors represented by the vertical error bars for Q_P and Q_S are much smaller at low than higher frequencies (Fig. 6). The following power laws were estimated for Garhwal Himalaya region based on the above analysis:

(i) $Q_P = 56 \pm 8 f^{0.91 \pm 0.002}$.
(ii) $Q_S = 151 \pm 8 f^{0.84 \pm 0.002}$.

Compared with Q_P, the Q_S values are found to be high for a given frequency range. The ratio $Q_S/Q_P > 1$ indicates the presence of scatterers in the medium (Hough and Anderson, 1988). Also, a high value of Q_S/Q_P is expected in regions partially saturated with fluids (Toksoz *et al*. 1979; De Lorenzo *et al*. 2013; Hauksson and Shearer 2006). Earlier results from various studies show that such low Q_P and Q_S values characterize and correspond to those of seismically active areas in the world rather than stable areas (Sato and Fehler, 1998). A comparative study of Q_C relationships for different seismically active regions was discussed by Joshi (2006), suggesting low Q_0 and high n values for these regions. The results obtained for $Q_P(f)$ and $Q_S(f)$ in the present study show good agreement with other studies, with low Q_0 (<200) and high n (>0.8) values, which are characteristic of tectonically and seismically active regions (Kumar *et al*., 2005; Joshi, 2006). The power law defining the frequency dependence of Q_P and Q_S is characterized by high $n = 0.91$ and $n = 0.84$, respectively. The quality factor for P wave is less than that for S wave over the entire frequency range.

The frequency-dependent nature of attenuation, manifesting less pronounced attenuation at high compared with lower frequencies, characterizes the presence of complex structures in tectonically active zones (Padhy and Subhadra, 2010). Such frequency-dependent relations for the region of Garhwal Himalaya could possibly be explained by the tectonics, being attributed to the ongoing underthrusting of the Indian Plate beneath the Eurasian Plate along the whole Himalayan range with differential rates (Molnar and Tapponnier, 1975; Nandy and Dasgupta, 1991).

The study of scattering and intrinsic attenuation for Garhwal and Kumaun region by Mukhopadhyay *et al*. (2010) suggests that scattering attenuation primarily contributes to seismic wave attenuation, with much higher values compared with intrinsic attenuation at frequency of around 1 Hz. A strong

Table 2

Frequency-dependent values of Q_P and Q_S for eight stations in Garhwal Himalaya

f(Hz)	ABI	CKA	GKD	GTU	KHI	KSI	NHN	TPN
Q_P								
1.5	121 ± 11	63 ± 4	132 ± 1	78 ± 6	122 ± 6	56 ± 4	61 ± 2	72 ± 1
2	124 ± 3	94 ± 2	203 ± 20	86 ± 1	147 ± 4	72 ± 1	80 ± 2	103 ± 4
3	143 ± 5	129 ± 2	192 ± 16	123 ± 7	184 ± 7	100 ± 10	129 ± 3	129 ± 2
4	155 ± 15	168 ± 3	229 ± 26	185 ± 1	222 ± 16	153 ± 11	166 ± 3	163 ± 3
6	200 ± 20	242 ± 6	352 ± 16	268 ± 11	361 ± 1	321 ± 11	241 ± 4	226 ± 6
8	266 ± 11	300 ± 4	513 ± 16	378 ± 9	437 ± 12	422 ± 7	300 ± 2	301 ± 1
10	330 ± 1	376 ± 11	640 ± 34	454 ± 25	520 ± 19	550 ± 18	349 ± 13	361 ± 3
12	405 ± 16	380 ± 17	749 ± 45	632 ± 9	658 ± 3	698 ± 23	439 ± 2	415 ± 6
16	534 ± 43	504 ± 12	752 ± 37	996 ± 79	961 ± 63	1312 ± 112	560 ± 10	562 ± 9
Q_S								
1.5	288 ± 6	186 ± 14	229 ± 13	153 ± 1	215 ± 0	135 ± 0	234 ± 37	177 ± 7
2	368 ± 20	343 ± 31	288 ± 15	197 ± 4	261 ± 9	179 ± 2	297 ± 39	277 ± 19
3	475 ± 28	481 ± 37	378 ± 9	264 ± 21	360 ± 21	249 ± 15	439 ± 29	365 ± 19
4	464 ± 17	711 ± 91	511 ± 28	408 ± 2	486 ± 18	392 ± 7	620 ± 7	382 ± 14
6	542 ± 47	874 ± 52	704 ± 35	596 ± 3	706 ± 25	642 ± 32	866 ± 32	559 ± 2
8	646 ± 55	1000 ± 1	826 ± 11	761 ± 19	1010 ± 14	838 ± 28	1207 ± 114	724 ± 10
10	818 ± 23	1271 ± 20	923 ± 21	930 ± 32	1281 ± 39	997 ± 5	1388 ± 123	824 ± 7
12	993 ± 15	1295 ± 80	1049 ± 36	1177 ± 5	1500 ± 40	1091 ± 52	1336 ± 21	946 ± 10
16	1367 ± 111	1524 ± 186	1332 ± 43	1885 ± 155	1941 ± 48	1674 ± 28	1232 ± 173	1129 ± 40

frequency dependence of attenuation due to scattering is observed when the heterogeneities responsible for scattering are of sizes comparable to the lowest frequency analyzed (e.g., Tuvè *et al.*, 2006; Giampiccolo *et al.*, 2006; Akinci and Eydŏgan, 2000; Canas *et al.*,1998; Akinci *et al.*, 1995; Mayeda *et al.*, 1992). This can be inferred as an indirect indicator of macroscale earth heterogeneity (Leary, 1995). According to Mukhopadhyay *et al.* (2010), the values of attenuation due to scattering for Garhwal–Kumaun region lie approximately in the middle of all other global values. This is supported by the results obtained in this study and by comparing these results with other regional and global studies (in Sects. 5.1, 5.2, and 5.3).

The seismic attenuation study carried out by Ashish *et al.* (2009) in the Garhwal region through analysis of L_g waveforms from regional earthquakes indicates high attenuation below the Higher Himalaya compared with that under the Lesser Himalaya. They suggested that the high attenuation is due to the low viscosity and partial melt beneath the Higher Himalayan crust. The present study was constrained along the MCT and to its south, covering a very small part of Higher Himalaya (Fig. 2). The low values of Q_P in comparison with Q_S (Table 3) for the given frequency range indicate high attenuation of P waves. This suggests that the attenuation in the region could not be influenced by low-viscosity material or the partial melt, as the effect of fluid or melt fraction in the crust shows dominance in attenuation ($1/Q$) of S-wave velocity (Mitchell, 1995). Additionally, another reason for the high attenuation may be the occurrence of graphite-rich layers along the metasedimentary sequences of Indian Lesser Himalaya (Rawat *et al.*, 2011) and in the Higher Himalayan Crystallines along the zone of MCT (Sachan *et al.*, 2001). Graphite in the form of fault gouges along the fault zone acts as a lubricating agent which can effectively reduce fault strength and work as a weakening agent (Oohashi *et al.*, 2013). According to Oohashi *et al.* (2013), fault weakening by graphite may also be important at depths where other fault lubricants such as hydrated clay minerals become unstable. In the shallow parts, graphite-bearing fault zones may weaken mature faults more significantly.

Also, the high *b*-value in the Garhwal Himalaya, explicitly for Uttarkashi (Kayal *et al.*, 1996) and Chamoli area (Kayal *et al.*, 2001), possibly accounts for higher heterogeneity. A high *b*-value may also indicate the presence of low-strength rocks in the crust that invariably undergo brittle failure at lower stress level, resulting in high seismicity (Wason *et al.*, 2002; Lowrie, 1997; Khan, 2003). These arguments might explain the high seismicity and high attenuation indicating the high heterogeneities observed in the crust of Garhwal Himalaya.

In addition to the above facts, P waves above geothermal systems exhibit anomalously high seismic attenuation (Young and Ward, 1980). The ubiquitous presence of hot springs along the MCT zone in Garhwal and Kumaun Himalaya (Valdiya, 1980) and in the Nepal Himalaya (Derry *et al.* 2009; Bhattarai, 1980) testifies to the high level of hydrothermal fluids channeled upwards along the MCT zone (Searle *et al.*, 2008), suggesting high saturation zone around the MCT, and this also explains the high attenuation in the crust of Garhwal Himalaya.

5.1. Comparison of Q_S and Q_C in Garhwal Himalaya

Similarity in the frequency dependence of the Q_S and Q_C values has been reported from different regions (e.g., Aki, 1980; Roecker *et al.*, 1982; Rovelli *et al.* 1988; Kvamme and Havskov, 1989). This supports the concept that coda waves are composed of S waves (Aki, 1992) and that the attenuation mechanism for coda waves is similar to that of direct S waves (Aki, 1980). However, as discussed in Sect. 1, some uncertainty still remains regarding how the apparent attenuation inferred from coda waves is related to the attenuation of direct S waves. The coda attenuation parameter in the Indian lithosphere has been estimated by various workers (Gupta *et al.*, 1995, 1998; Mandal and Rastogi, 1998; Mandal *et al.*, 2001, 2004; Tripathi and Ugalde, 2004; Kumar *et al.*, 2005; Mukhopadhyay *et al.*, 2006). In parts of northwest Himalaya, mainly in Garhwal Himalaya, the S-wave coda attenuation (Q_C^{-1}) has been extensively studied (Gupta *et al.*, 1995; Mukhopadhyay *et al.*, 2010). The Q_S relation

Table 3

Average values of Q_P and Q_S along with their standard deviations at different central frequencies

Frequency (Hz)	Q_P	Q_S
1.5	88 ± 4	202 ± 5
2	114 ± 4	276 ± 3
3	141 ± 6	376 ± 2
4	180 ± 9	497 ± 6
6	276 ± 5	686 ± 3
8	365 ± 3	877 ± 5
10	448 ± 4	1,054 ± 5
12	547 ± 5	1,173 ± 22
16	773 ± 37	1,511 ± 20
$Q = Q_0 f^n$	$56 \pm 8f^{0.91\pm0.002}$	$151 \pm 8f^{0.84\pm0.002}$

obtained in the present study can be compared with the frequency-dependent Q_C given by GUPTA *et al.* (1995) and MUKHOPADHYAY *et al.* (2010) for the same region (Fig. 7).

This shows similarity between the frequency-dependent Q_S and Q_C in Garhwal Himalaya, supporting the concept and mechanism that coda waves are similar to direct S waves (AKI, 1992, 1980). However, results for the higher frequencies (>8 Hz) show $Q_C > Q_S$ (Fig. 7). Such deviation of Q_S above 8 Hz has also been reported for the Chamoli region in the Garhwal Himalaya by SHARMA *et al.* (2009), suggesting the dominance of scattering attenuation in

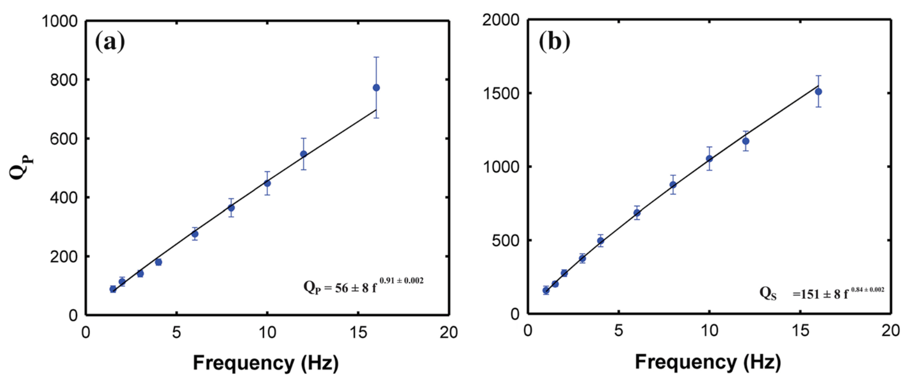


Figure 6
Plots of mean value of Q_P and Q_S against frequency, for the whole Garhwal Himalaya. A power law of the form $Q = Q_0 f^n$ is fitted. *Vertical lines* are standard error bars

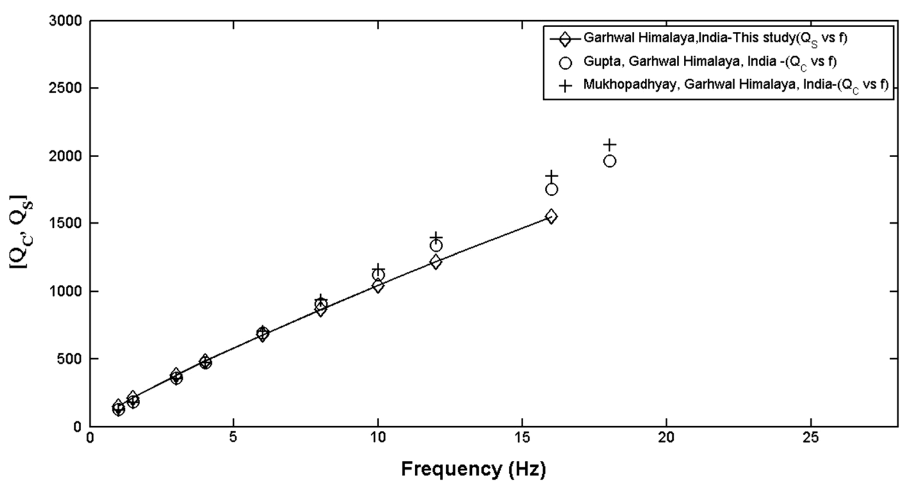


Figure 7
Comparison between Q_S and Q_C against frequency in Garhwal Himalaya

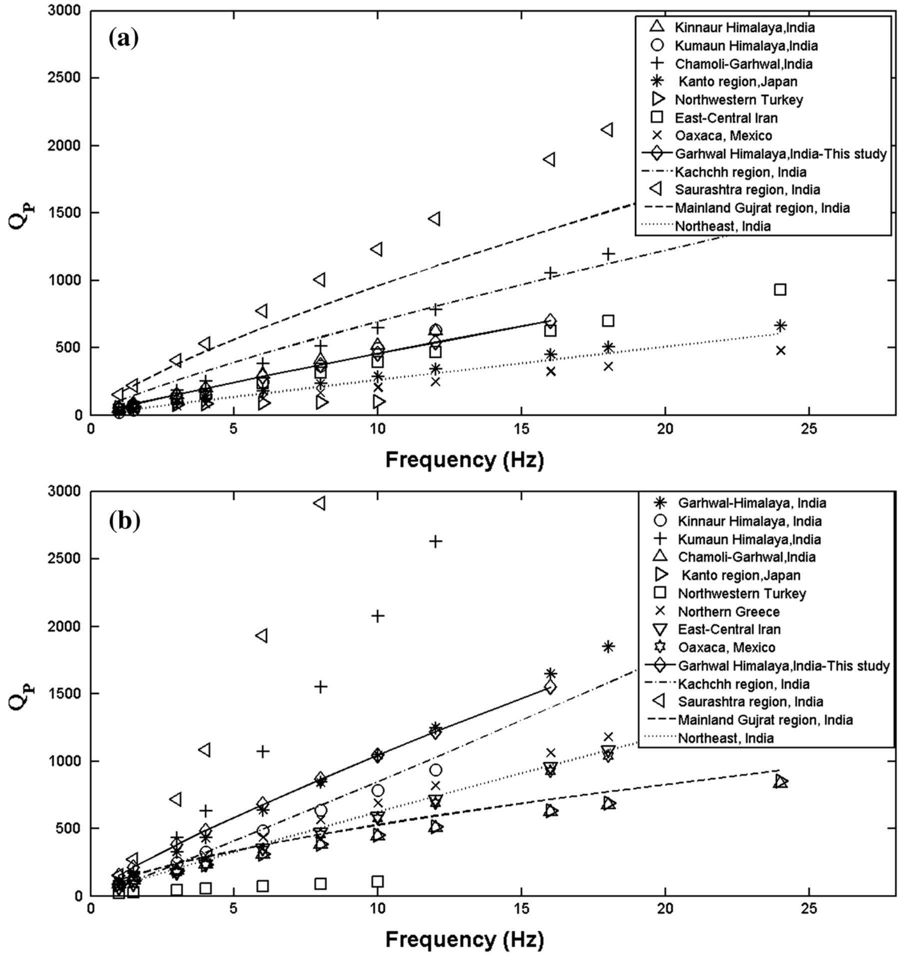


Figure 8

Comparison of **a** Q_P and **b** Q_S values of this study with regions of different tectonic settings of the world. The compared relations for $Q_{(P,S)}$ versus frequency are as follows: Kanto, Japan (Yoshimoto *et al*. 1993); East-Central Iran (Ma'hood *et al*., 2009); Kumaun Himalaya (Singh *et al*., 2012); Northeast India (Padhy and Subhadra, 2010); Kachchh, India (Chopra *et al*., 2011); Saurashtra Region (Chopra *et al*., 2011); Mainland Gujarat, India (Chopra *et al*., 2011); Kinnaur Himalaya, India (Kumar *et al*., 2014); Garhwal region, India (Joshi, 2006); Oaxaca, Mexico (Castro and Munguia, 1993); Northwestern Turkey (Bindi *et al*., 2006); Chamoli region, India (Sharma *et al*., 2007); Northern Greece (Hatzidimitriou, 1995)

the region Sharma *et al*. (2009). The dominant scattering effects in the crust of Garhwal Himalaya are also discussed in Sects. 5 and 5.3.

5.2. *Comparison of Regional and Global Attenuation Characteristics*

The results obtained for Q_P and Q_S for the Garhwal Himalaya, India (Fig. 5) are compared here with those reported from several studies globally (Fig. 8a, b). The low values of Q_P and Q_S indicate the region to be seismically active, whereas stable regions show high values of Q_P and Q_S (Sharma *et al*., 2007; Yoshimoto *et al*., 1993; Singh *et al*., 2012; Kumar *et al*., 2014; Kim *et al*., 2004; Kvamme and Havskov, 1989). Figure 8a, b shows a global comparison plot of Q_P and Q_S for the Garhwal Himalaya, indicating the study region to be among the seismically active regions in the world. The values obtained in this study for the frequency-dependent $Q_P(f)$ shows similarity with the neighboring areas of Kinnaur and Kumaun Himalaya (Fig. 8a). The comparison of Q_P at low frequencies shows slightly higher values for Garhwal region,

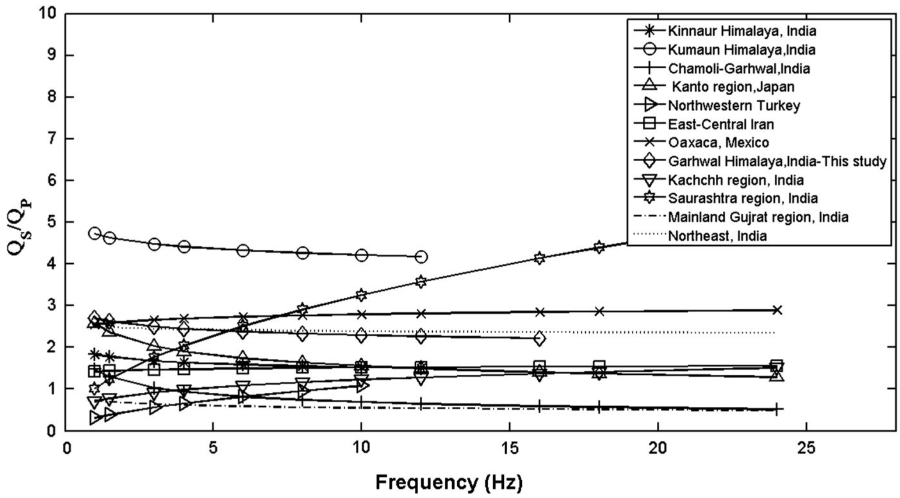


Figure 9
Global comparison plot of Q_S/Q_P for Garhwal Himalaya for the entire frequency range

whereas with increasing frequency the value decreases, indicating higher attenuation at high frequencies with respect to both adjoining regions.

The results obtained in this study using broadband seismograms for frequency-dependent shear wave $Q_S(f)$ in the Garhwal region can also be compared with the results obtained from strong motion seismograms by Joshi (2006), for the same region. The study by Joshi (2006) provides the relation $Q_S = 112f^{0.97}$, using the least-squares inversion technique. The Q_S values obtained from the present work are in good agreement for all the frequency ranges, moreover following the same trend (Fig. 8b).

The regional comparison of $Q_S(f)$ indicates that the shear wave attenuation is lowest in the Kumaun region, moderate in the Garhwal region, and highest in the Kinnaur region for all frequency ranges (Fig. 8b). This indicates a variation in lateral heterogeneity from eastern to western parts of the northwest Himalaya. Such variations in lateral heterogeneity may occur due to the presence of low-viscosity and partial melt material within the crust (Ashish *et al.*, 2009).

5.3. Comparison of Global Q_S/Q_P ratio

The ratio Q_S/Q_P was originally derived from a theoretical consideration which accounts for attenuation of low-frequency seismic waves of ≤ 0.1 Hz (Anderson *et al.*, 1965), whereas for high frequencies it is significantly larger than 4/9 (Yoshimoto *et al.*, 1993). The obtained $Q_S/Q_P > 1$ has also been observed in the upper crust of many other regions with a high degree of lateral heterogeneity (Bianco *et al.*, 1999; Sato and Fehler, 1998). The ratio Q_S/Q_P does not depend on distance, suggesting a higher homogeneity of the properties that control this ratio (Bindi *et al.*, 2006). In the present analysis, we find that P waves are attenuated more strongly than S waves ($Q_S/Q_P > 1$) for the entire frequency range (Fig. 9; Table 3). Sharma *et al.* (2009) calculated the ratio $Q_S/Q_P > 1$ for the Chamoli region in Garhwal Himalaya and inferred scattering to be a dominant phenomenon in seismic wave attenuation. They also validated the dominance of scattering by comparing the attenuation relation for S waves with that of coda waves obtained by Mandal *et al.* (2001), showing $Q_C > Q_S$ for higher frequencies (>8 Hz). Similar results are obtained in this study, where we find the Q_c obtained by Gupta *et al.* (1995) and Mukhopadhyay *et al.* (2010) is high for the higher frequencies (>8 Hz) (Fig. 7). The curve for Q_S/Q_P for the study region indicates that the study region lies in a zone of seismically very unstable regions of the world (Fig. 9).

A high degree of structural heterogeneities is expected in the crust of Garhwal Himalaya, as revealed by studying the lapse time dependence of the coda Q in the Garhwal region (Mukhopadhyay *et al.*, 2008) with a high degree of lateral heterogeneity on the basis of tomographic analysis (Mukhopadhyay and Sharma, 2010). In the vicinity, the Kumaun region is more heterogeneous and less stable compared with the Garhwal Himalaya (Paul *et al.*, 2003; Singh *et al.*, 2012).

6. Conclusions

We applied the extended coda normalization method to investigate attenuation of P and S waves in the crust beneath the Garhwal Himalaya region, by analyzing seismograms of 40 local earthquakes. The frequency-dependent Q_P and Q_S in the lithosphere beneath the Garhwal region were obtained as $56 \pm 8f^{0.91\pm0.002}$ and $151 \pm 8f^{0.84\,\pm\,0.002}$ in the frequency range of 1.5–16 Hz. The estimated Q_P and Q_S are found to be strongly frequency dependent, proportional to $f^{0.91}$ and $f^{0.84}$, respectively. The low values of frequency-dependent $Q_S(f)$ and $Q_P(f)$ and high values of the frequency relation parameter n for the study area indicate that the region lies in a tectonically active area of the world. It has also been observed that at higher frequencies the attenuation is low. The frequency dependence of shear wave is very similar to the frequency dependence of the coda Q for the Garhwal Himalaya, substantiating the fact that coda waves are composed of S waves and the attenuation mechanism for both waves is similar in the region. Above 8 Hz, the comparison shows $Q_C > Q_S$, indicating dominance of scattering attenuation in the region.

Also, the high value of $Q_S/Q_P > 1$ and the strong frequency dependence of Q suggest that scattering may be one of the important factors contributing to attenuation of body waves in the Garhwal Himalaya. The results obtained here will help to constrain the frequency dependence of seismic attenuation in the earth's crust, which is crucial to further correct the velocity dispersion due to attenuation in the region.

Acknowledgments

The authors are grateful to the Director, Wadia Institute of Himalayan Geology, Dehradun for his encouragement in carrying out the research work. Sincere thanks are due to the Ministry of Earth Science, New Delhi for generous financial assistance for the project "VSAT linked seismic network for seismic hazard studies in Garhwal Himalaya," whose data have been used in this paper. We gratefully acknowledge many fruitful discussions with Amit Kumar (IIT-Roorkee). We greatly thank Dr. Koushik Sen for his constructive inputs to our manuscript. Thanks are due to the handling editor and anonymous reviewers for significantly improving the manuscript through their valuable suggestions.

References

Abdel-Fattah, A.K. (2009), *Attenuation of body waves in the crust beneath the vicinity of Cairo Metropolitan area (Egypt) using coda normalization method*, J. Geophys. Int. *176*, 126–134.

Aki, K. (1969), *Analysis of the seismic coda of local earthquakes as scattered waves*, J. Geophys. Res. *74*, 615–631.

Aki, K. (1980), *Attenuation of shear waves in the lithosphere for frequencies from 0.05 to 25 Hz*, Phys. Earth Planet. Interiors *21*, 50–60.

Aki, K., and Chouet, B. (1975), *Origin of the coda waves: source, attenuation, and scattering effects*, J. Geophys. Res. *80*, 3322–3342.

Aki, K. (1992), *Scattering conversion P to S vs. S to P*, Bull Seismol. Soc. Am. *82*, 1969–1972.

Akinci, A., Del Pezzo, E, and Ibanez, J. M. (1995), *Separation of scattering and intrinsic attenuation in southern Spain and western Anatolia (Turkey)*. Geophys. J. Int. *121*(2), 337–353.

Akinci, A, and Eyidogan, H. (2000), *Scattering and anelastic attenuation of seismic energy in the vicinity of north Anatolian fault zone, eastern Turkey*, Phys. Earth Planet. Interiors *122*(3), 229–239.

Anderson, D. L., Ben-menahem, A., Archambeau, C. B. (1965), *Attenuation of seismic energy in the upper mantle*, J. Geophys. Res. *70*, 1441–1448.

Ashish, P. A., Rai, S. S., Gupta, S. (2009), *Seismological evidence for shallow crustal melt beneath the Garhwal High Himalaya, India: implications for the Himalayan channel flow*, Geophys. J. Int. *177*(1), 1111–1120.

Bhattarai, D. R. (1980), *Some geothermal springs of Nepal*. Tectonophysics, *62*(1), 7–11.

Bianco, F., Castellano, M., Del Pezzo, E., Ibañez, J.M. (1999), *Attenuation of short-period seismic waves at Mt. Vesuvius, Italy*, Geophys. J. Int. *138*, 67–76.

Bindi, D., Parolai, S., Grosser, H., Milkereit, C., Karakisa, S. (2006), *Crustal attenuation characteristics in northwestern Turkey in the range from 1 to 10 Hz*, Bull. Seismol. Soc. Am. *96*(1), 200–214.

Caldwell, W. B., Klemperer, S. L., Lawrence, J. F, and Rai, S. S. (2013), *Characterizing the Main Himalayan Thrust in the Garhwal Himalaya, India with receiver function CCP stacking*, Earth Planet Sci. Lett. *367*, 15–27.

CAMPILLO, M., PLANTET, J.-L., BOUCHON, M. (1985), *Frequency-dependent attenuation in the crust beneath central France from Lg waves: data analysis and numerical modeling*, Bull. Seismol. Soc. Am. *75*, 1395–1411.

CANAS, J. A., UGALDE, A., PUJADES, L. G., CARRACEDO, J. C., SOLER, V., BLANCO, M. J., (1998), *Intrinsic and scattering seismic wave propagation in the Canary Islands*, J. Geophys. Res. Sol. Ea. *103*, 15037–15050.

CASTRO, R. R., MUNGUIA, L. (1993), *Attenuation of P and S waves in the Oaxaca, Mexico, subduction zone*, Phys. Earth Planet. Interiors *76*(3), 179–187.

CHIN, B. H., and AKI, K. (1991), *Simultaneous study of the source, path, and site effects on strong ground motion during the 1989 Loma Prieta earthquake: a preliminary result on pervasive nonlinear site effects*, Bull. Seismol. Soc. Am. *81*(5), 1859–1884.

CHOPRA, S., KUMAR, D, and RASTOGI, B. K. (2011) *Attenuation of high frequency P and S waves in the Gujarat region, India*, Pure Appl. Geophys. *168*(5), 797–813.

CHUNG, T.W., and SATO, H. (2001), *Attenuation of high-frequency P and S waves in the crust of southeastern South Korea*, Bull. Seismol. Soc. Am. *91*, 1867–1874.

DE LORENZO S., BIANCO F., DEL PEZZO E. (2013), *Frequency dependent* Q_α *and* Q_β *in the Umbria- Marche* (*Italy*) *region using a quadratic approximation of the coda normalization method*, Geophys. J. Int. *193*,1726–1731

DERRY, L. A., EVANS, M. J., DARLING, R., and FRANCE-LANORD, C. (2009), *Hydrothermal heat flow near the Main Central thrust, central Nepal Himalaya*, Earth Planet. Sci. Lett. *286*(1), 101–109.

FEDOTOV, S.A., and BOLDYREV, S.A. (1969), *Frequency dependence of the body-wave absorption in the crust and the upper mantle of the Kuril Island chain*, Izv. Akad. Nauk USSR *9*, 17–33.

FRANKEL, A., and WENNERBERG, L. (1987), *Energy-flux model of seismic coda: separation of scattering and intrinsic attenuation*, Bull Seismol. Soc. Am. *77*, 1223–1251.

FRANKEL, A., MCGARR, A., BICKNELL, J., MORI, J., SEEBER, L., and CRANSWICK, E. (1990), *Attenuation of high frequency shear waves in the crust: measurements from New York State, South Africa, and Southern California*. J. Geophys. Res.-Sol. Ea. *95*(*B11*), 17441–17457.

FRANKEL, A. (1991), *Mechanisms of seismic attenuation in the crust: scattering and anelasticity in New York, South Africa, and Southern California*, J. Geophys. Res. – Sol. Ea. *96*, 6269–6289.

GANSSER, A. (1964), Geology of the Himalayas, London, Wiley Interscience, pp. 289.

GIAMPICCOLO, E., TUVÈ, T., GRESTA, S., PATANE, D., 2006. *S-waves attenuation and separation of scattering and intrinsic absorption of seismic energy in southeastern Sicily* (*Italy*), Geophys. J. Int. *165*, 211–222.

GUPTA, S. C., and KUMAR, A. (2002), *Seismic wave attenuation characteristics of three Indian regions: a comparative study*, Curr. Sci., *82*(4), 407–412.

GUPTA, S. C., SINGH, V. N., KUMAR, A. (1995) *Attenuation of coda waves in the Garhwal Himalaya, India*, Phys. Earth Planet. Interiors *87*(3), 247–253.

GUPTA, S. C., TEOTIA, S. S., RAI, S. S., GAUTAM, N. (1998), Coda Q estimates in the Koyna region, India, In Q of the Earth: Global, Regional, and Laboratory Studies, Birkhäuser Basel (pp. 713–731).

HATZIDIMITRIOU, P. M. (1995), *S-wave attenuation in the crust in northern Greece*, Bull. Seismol. Soc. Am. *85*(5), 1381–1387.

HAUCK, M., NELSON, K., BROWN, L., ZHAO, W., ROSS, A. (1998), *Crustal structure of the Himalayan orogen at 90 east longitude from Project INDEPTH deep reflection profiles*, Tectonics. *17*, 481–500.

HAUKSSON, E., and SHEARER P. M. (2006) *Attenuation models* (*Qp and Qs*) *in three dimensions of the southern California crust: inferred fluid saturation at seismogenic depths*. J. Geophys. Res. – Sol. Ea. *111*: B05302, doi:10.1029/2005JB003947

HERRAIZ, M., and ESPINOZA A. F. (1987), *Coda waves: a review*, Pure Appl. Geophys. *125*, 499–577.

HERRMANN, R. B. (1980), *Q estimates using the coda of local earthquakes*, Bull. Seismol. Soc. Am. *70*, 447–468.

HOUGH, S. E., and ANDERSON, J. G. (1988) *High-frequency spectra observed at Anza, California: implications for Q structure*. Bull. Seismol. Soc. Am. *78*(2), 692–707.

HOUGH, S.E., ANDERSON, J.G., BRUNE, J., VERNON, F., II, BERGER, J., FLETCHER, J., HAAR, L., HANKS, T., BAKER, L. (1988), *Attenuation near Anza, California*, Bull. Seismol. Soc. Am. *78*, 672–691.

ISHIDA, M. (1992), *Geometry and relative motion of the Philippine Sea plate and Pacific plate beneath the Kanto-Tokai district, Japan*, J. Geophys. Res.-Sol. Ea. *97*, 489–513.

JEFFREYS, H. (1965), *Damping of S waves*, Nature. *208*, 675.

JOSHI, A. (2006), *Use of acceleration spectra for determining the frequency-dependent attenuation coefficient and source parameters*, Bull. Seismol. Soc. Am. *96*(6), 2165–2180.

KARATO, S. I. (1993), *Importance of anelasticity in the interpretation of seismic tomography*, Geophys. Res. Lett. *20*(15), 1623–1626.

KAYAL, J. R. (1996), *Precursor seismicity, foreshocks and aftershocks of the Uttarkashi earthquake of October 20, 1991 at Garhwal Himalaya*, Tectonophysics. *263*(1), 339–345.

KAYAL, J. R. (2001), *Microearthquake activity in some parts of the Himalaya and the tectonic model*, Tectonophysics. *339*(3), 331–351.

KHAN, P. K. (2003), *Stress state, seismicity and subduction geometry of the descending lithosphere below the Hindukush and Pamir*, Gondwana Res. *6*, 867–877.

KIM, K. D., CHUNG, T.W., KYUNG, J. B. (2004), *Attenuation of high-frequency P and S waves in the crust of Choongchung provinces, Central South Korea*. Bull. Seismol. Soc. Am. *94*, 1070–1078.

KOHKETSU, K., SHIMA, E. (1985), Q_P *structure of sediments in the Kanto plain*, Bull Earthq. Res. Inst. Univ. Tokyo. *60*, 495–505.

KUMAR, N., SHARMA, J., ARORA, B. R., MUKHOPADHYAY, S. (2009), *Seismotectonic model of the Kangra–Chamba sector of Northwest Himalaya: constraints from joint hypocenter determination and focal mechanism*, Bull. Seismol. Soc. Am. *99*(1), 95–109.

KUMAR, N., PARVEZ, I.A., VIRK, H.S. (2005), *Estimation of coda wave attenuation for NW Himalayan region using local earthquakes*, Phys. Earth Planet. Interiors *151*, 243–258.

KUMAR, N., MATE, S., MUKHOPADHYAY, S. (2014), *Estimation of Qp and Qs of Kinnaur Himalaya*, J. Seismol. *18*(1), 47–59.

KVAMME, L. B. and HAVSKOV, J. (1989), *Q in southern Norway*, Bull Seismol. Soc. Am. *79*, 1575–1588.

LAVE, J., and AVOUAC, J. P. (2001), *Fluvial incision and tectonic uplift across the Himalayas of central Nepal*, J. Geophys. Res - Sol. Ea. *106* (B11), 26561–26591. Am. J. Sci. *275*:1–44

LEARY, P. C. (1995), *Quantifying crustal fracture heterogeneity by seismic scattering*. Geophys. J. Int. *122*, 125–142.

LIENERT, B. R., BERG, B. E., FRAZER, L. N. (1986), *Hypocenter: an earthquake location method using centered, scaled and adaptively damped least squares*, Bull. Seismol. Soc. Am. *76*, 771–783.

Liu, H. P., Anderson, D. L., and Kanamori, H. (1976), *Velocity dispersion due to anelasticity; implications for seismology and mantle composition*, Geophys. J. Int. *47*(1), 41–58.

Lomnitz, C. (1957). *Linear dissipation in solids*. J. Appl. Phys. *28*(2), 201–205.

Lowrie, W. (1997), Fundamentals of Geophysics, Cambridge University Press, Cambridge, p. 354.

Ma'hood, M., Hamzehloo, H., Doloei, G.J. (2009), *Attenuation of high frequency P and S waves in the crust of the East-Central Iran*, Geophys. J. Int. *179*, 1669–1678.

Mahesh, P., Rai, S. S., Sivaram, K., Paul, A., Gupta, S., Sharma, R., and Gaur, V. K. (2013), *One dimensional reference velocity model and precise locations of earthquake hypocenters in the Kumaon–Garhwal Himalaya*, Bull. Seismol. Soc. Am. *103*(1), 328–339.

Mandal, P., and Rastogi, B. K. (1998), *A frequency-dependent relation of coda Qc for Koyna-Warna region, India*. Pure Appl. Geophys. *153*, 163–177.

Mandal, P., Padhy, S., Rastogi, B. K., Satyanarayana, H. V. S., Kousalya, M., Vijayraghvan, R., and Srinavasan, A. (2001), *Aftershock activity and frequency dependent low coda Qc in the epicentral region of the 1999 Chamoli earthquake of Mw 6.4*, Pure Appl. Geophys. *158*, 1719–1735.

Mandal, P., Jainendra, Joshi, S., Kumar, S., Bhunia, R., and Rastogi, B.K. (2004), *Low coda Qc in the epicentral region of the 2001 Bhuj earthquake of Mw 7.7*, Pure Appl. Geophys., *161*, 1635–1654.

Mayeda, K., Koyanagi, S., Hoshiba, M., Aki, K., Zeng, Y. (1992), *A comparative study of scattering, intrinsic and coda 1/Q for Hawaii, Long Valley and Central California between 1.5 and 15.0 Hz*, J. Geophys. Res. Sol. Ea. *97*, 6643–6660.

Mitchell, B.J. (1995), *Anelastic structure and evolution of the continental crust and upper mantle from seismic surface wave attenuation*, Rev. Geophys. *33*, 441–462.

Molnar. P. and Tapponier, P. (1975), *Cenozoic tectonics of Asia: effects of a continental collision*, Science. *189*, 419–426.

Monsalve, G., Sheehan, A., Schulte-pelkum, V., Rajaure, S.,Pandey, M. R., and Wu, F. (2006), *Seismicity and one-dimensional velocity structure of the Himalayan collision zone: earthquakes in the crust and upper mantle*, J. Geophys. Res. *111*, B10301; doi:10.1029/2005JB004062.

Mukhopadhyay, S., Tyagi C., Rai S. S. (2006), *The attenuation mechanism of seismic waves for NW Himalaya*, Geophys, J. Int. *167*:354–360.

Mukhopadhyay, S., Sharma, J., Massey, R., Kayal, J.R. (2008), *Lapse time dependence of coda Q in the source region of the 1999 Chamoli earthquake*, Bull. Seismol. Soc. Am. *98*, 2080–2086.

Mukhopadhyay, S., Sharma, J., Del-pezzo, E., Kumar, N. (2010), *Study of attenuation mechanism for Garwhal–Kumaun Himalayas from analysis of coda of local earthquakes*, Phys. Earth Planet. Interiors *180*, 7–15.

Mukhopadhyay, S., and Sharma, J. (2010), *Crustal scale detachment in the Himalayas: a reappraisal*, Geophys. J. Int. *183*(2), 850–860.

Nandy, D.R., and Dasguptha, S. (1991), *Seismotectonic domains of northeastern India and adjacent areas*, Phys. Chem. Earth. *18*, 371–384.

Nath, S.K., Shukla, K., and Vyas, M. (2008), *Seismic hazard scenario and attenuation model of the Garhwal Himalaya using near-field synthesis from weak motion seismometry*, J. Earth. Sys. Sci. *117*(2), 649–670.

Ni, J., Barazangi, M. (1984), *Seismotectonics of the Himalayan collision zone: geometry of the underthrusting Indian plate beneath the Himalaya*, J. Geophys. Res. *89*, 1147–1163.

Novelo-Casanova, D. A. and Lee, W. H. K. (1991). *Comparison of techniques that use the single scattering model to compute the quality factor Q from coda waves*, Pure Appl. Geophys.*135*, 77–89.

Oohashi, K., Hirose, T., and Shimamoto, T. (2013), *Graphite as a lubricating agent in fault zones: an insight from low to high velocity friction experiments on a mixed graphite quartz gouge*, J. Geophys. Res. - Sol. Ea.*118* (5), 2067–2084.

Padhy, S. (2009), *Characteristics of body wave attenuations in the Bhuj crust*, Bull. Seismol. Soc. Am. *99*, 3300–3313.

Padhy, S., and Subhadra, N. (2010), *Frequency-dependent attenuation of P and S waves in northeast India*, Geophys. J. Int. *183*(2), 1052–1060.

Pandey, M. R., Tandulkar, R. P., Avouac, J. P., Vergne, J. and Heritier, T.H. (1999), *Seismotectonics of the Nepal Himalaya from a local seismic network*, *J. Asian Earth Sci. 17*, 703–712.

Paul, A., Gupta, S.C., Pant, C. (2003), *Coda Q estimates for Kumaun Himalaya*, Earth Planet. Sci. *112*, 569–576.

Paul, A., Wason. H.R., Sharma, M.L., Pant, C. C., Nirwani, A., Tripathi, H.B. (2004), *Seismotectonic implications of data recorded by DTSN in the Kumaun Region of Himalaya*, J. Geol. Soc. India *64*, pp. 43–51.

Phillips, W. S. and aki, K. (1986), *Site amplification of coda waves from local earthquakes in central California,* Bull. Seismol. Soc. Am. *76*, 627– 648.

Randall, M. J. (1976), *Attenuative dispersion and frequency shifts of the earth's free oscillations,* Phys. Earth Planet. Interiors. *12*(1), P1–P4.

Rastogi, B.K. (2000), *Chamoli earthquake of Magnitude 6.6 on 29 March, 1999*, J. Geol. Soc. India. *55*, 505–514.

Rautian, T.G., Khalturin, V.I. (1978a), *The use of the coda for the determination of the earthquake source spectrum*, Bull. Seismol. Soc. Am. *68*, 923–948.

Rautian, T.G., Khalturin, V.I., Martynov, V.G., Molnar, P. (1978b), *Preliminary analysis of the spectral content of P and S waves from local earthquakes in the Garm, Tadjikistan region*, Bull. Seismol. Soc. Am. *68*, 949–971.

Rawat, R., and Sharma, R. (2011), *Features and characterization of graphite in Almora Crystallines and their implication for the graphite formation in Lesser Himalaya, India*, J. Asian Earth Sci. *42*(1), 51–64.

Roecker, S. W., Tucker, B., King, G., Hatzfeld, D. (1982), *Estimates of Q in central Asia as a function of frequency and depth using the coda of locally recorded earthquakes*, Bull. Seismol. Soc. Am. *72*, 129–149.

Rovelli, A., Marcucci, S., Milana, G. (1988), *The objective determination of the instantaneous predominant frequency of seismic signals and inferences on Q of coda waves*, Pure Appl. Geophys. *128*(1-2), 281–293.

Sachan, H. K., Sharma, R., Sahai, A., Gururajan, N. S. (2001). *Fluid events and exhumation history of the main central thrust zone Garhwal Himalaya* (*India*). J. Asian Earth Sci. *19*(1), 207–221.

Sato, H. (1977), *Energy propagation including scattering effect: single isotropic scattering approximation*, J. Phys. Earth. *25*, 27–41.

Sato, H., Fehler, M.C. (1998), *Seismic Wave Propagation and Scattering in the Heterogeneous Earth*, Springer, New York. 308 pp.

Sato, H. (1990), *Unified approach to amplitude attenuation and coda excitation in the randomly inhomogeneous lithosphere*, Pure Appl. Geophys. 132, 93–121.

Schelling, D., and Arita, K. (1991), *Thrust tectonics, crustal shortening, and the structure of the far eastern Nepal Himalaya*, Tectonics. *10*(5), 851–862.

Searle, M.P. (1986), *Structural evolution and sequence of thrusting in the High Himalayan, Tibetan—Tethys and Indus suture zones of Zanskar and Ladakh, Western Himalaya*, J. Struct. Geol. *8*(8), 923–936.

Searle, M. P., Law, R. D., Godin, L., Larson, K. P., Streule, M. J., Cottle, J. M., Jessup, m. J. (2008), *Defining the Himalayan main central thrust in Nepal*, J. Geol. Soc. *165*(2), 523–534.

Sharma, B., Teotia, S.S., Kumar, D. (2007), *Attenuation of P, S, and coda waves in Koyna region, India*. J. Seismol. *11*, 327–334.

Sharma, B., Teotia, S. S., Kumar, D., and Raju, P. S. (2009), *Attenuation of P-and S-waves in the Chamoli Region, Himalaya, India*, Pure Appl. Geophys. *166*(12), 1949–1966.

Singh, C., Singh, A., Mukhopadhyay, S., Sekhar, M., Chadha, R.K. (2011). *Lg attenuation characteristics across the Indian Shield*, Bull. Seismol. Soc. Am.*101*, 2561–2567.

Singh, C., Singh, A., Bharathi, V. K., Bansal, A. R., Chadha, R. K. (2012), *Frequency dependent body wave attenuation characteristics in the Kumaun Himalaya*, Tectonophysics. *524*, 37–42.

Taylor, S. R., Bonner, B. P., and Zandt, G. (1986), *Attenuation and scattering of broadband P and S waves across North America*, J. Geophys. Res. - Sol. Ea. (1978–2012), 91(B7), 7309–7325.

Thakur, V. C., and Rawat, B. S. (1992), Geological Map of the Western Himalaya 1:1,200,000, Pergamon, 1992.

Toksoz, M. N., Johnston, D. H., Timur, A. (1979), *Attenuation of seismic waves in dry and saturated rocks: I. Laboratory measurements*, Geophysics. *44*: 681–690

Tripathi, J.N., and Ugalde, A. (2004), *Regional estimation of Q from seismic coda observation by the Gauribidanur seismic array* (*southern India*), Phys. Earth Planet. Interiors. 145, 115–126.

Tuvè, T., Bianco, F., Ibáñez, J., Patanè, D., Del pezzo, Bottari, A. (2006), *Attenuation study in the Straits of Messina area* (*southern Italy*), Tectonophysics. 421, 173–185.

Valdiya, K.S. (1980), Geology of Kumaun Lesser Himalaya. Wadia Institute of Himalayan Geology, Dehradun. pp 291.

Wason, H.R., Sharma, M.L., Khan, P.K., Kapoor, K., Nandini, D., Kara, V. (2002), *Analysis of aftershocks of the Chamoli Earthquake of March 29, 1999 using broadband seismic data*, J. Himalayan Geol., *23*, 7–18.

Yoshimoto, K., Sato, H., Ohtake, M. (1993), *Frequency-dependent attenuation of P and S waves in the Kanto area, Japan, based on the coda normalization method*, Geophys. J. Int. *114*, 165–174.

Yoshimoto, K., Sato, H., Ito, Y., Ito, H., Ohminato, T., Ohtake, M. (1998), *Frequency-dependent attenuation of high-frequency P and S waves in the upper crust in western Nagano, Japan*, Pure Appl. Geophys.*153*, 489–502.

Young, C. Y., and Ward, R. W. (1980), *Three dimensional Q^{-1} model of the Coso Hot Springs Known Geothermal Resource Area*, J. Geophys. Res. - Sol. Ea. (1978–2012), *85*(B5), 2459–2470.

Zeng, Y., Su, F., Aki, K. (1991). *Scattering wave energy propagation in a random isotropic scattering medium*. 1. *Theory*, J. Geophys. Res.-Sol. Ea. *96*, 607–619.

(Received July 13, 2014, revised October 16, 2014, accepted October 23, 2014, Published online November 27, 2014)