Frequency dependent attenuation of seismic waves for Delhi and surrounding area, India

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ABSTRACT

The attenuation properties of Delhi and surrounding region have been investigated using 62 local earthquakes recorded at nine stations. The frequency dependent quality factors Q_α (using P-waves) and Q_β (using S-waves) have been determined using the coda normalization method. Quality factor of coda-waves (Q_c) has been estimated using the single backscattering model in the frequency range from 1.5 Hz to 9 Hz. Wennerberg formulation has been used to estimate Q_i (intrinsic attenuation parameter) and Q_s (scattering attenuation parameter) for the region. The values Q_α, Q_β, Q_c, Q_i and Q_s estimated are frequency dependent in the range of 1.5Hz-9Hz. Frequency dependent relations are estimated as $Q_\alpha = 52f^{1.03}$, $Q_\beta = 98f^{1.07}$ and $Q_c = 158f^{0.97}$. Q_c estimates lie in between the values of Q_i and Q_s but closer to Q_i at all central frequencies. Comparison between Q_i and Q_s shows that intrinsic absorption is predominant over scattering for Delhi and surrounding region.

1. Introduction

The attenuation of seismic waves provides important information about the medium characteristics which is required for the determination of earthquake source parameters as well as for prediction of earthquake ground motions. Attenuation of seismic waves is controlled by geometrical spreading, scattering due to inhomogeneities in the medium and damping. The attenuating property of a medium is described by the dimensionless quantity called quality factor Q, which expresses the decay of wave amplitude during its propagation in the medium [Knopoff 1964]. Various studies have been done worldwide to understand the attenuation characteristics by estimating Q using P-waves (Q_α), S-waves (Q_β) and coda waves (Q_c). Aki and Chouet [1975] gave the single backscattering model to estimate Q_c. The coda normalization method to estimate Q_β, was developed by Aki [1980] and later on Yoshimoto et al. [1993] extended coda normalization method to estimate Q_β also. The estimates of Q have been found to be frequency dependent by several researchers worldwide [e.g., Aki and Chouet 1975, Rautian and Khalturin 1978, Aki 1980, Sato and Matsumura 1980, Roecker et al. 1982, Hough and Anderson 1988, Masuda 1988, Woodgold 1990, Campillo and Plantet 1991, Sekiguchi 1991, Takemura et al. 1991, Mayeda et al. 1992, Yoshimoto et al. 1993, Gupta et al. 1995, Gupta et al. 1998, Mandal et al. 2001, Sharma et al. 2007, Sharma et al. 2008, Sharma et al. 2009, Sharma et al. 2011].

Various methods have been developed to measure the relative contribution of intrinsic attenuation Q_i and scattering attenuation Q_s to the total attenuation. Wu [1985] proposed a method for an estimation of the relative contribution of Q_s and Q_i from the dependence of total S-wave energy on hypocentral distance. Frankel and Wennerberg [1987] used the energy flux model of seismic coda to obtain the separate estimates of Q_s and Q_i based on coda amplitude and decay. Hoshiba et al. [1991] developed a method based on Monte Carlo simulations of the temporal shape of the coda envelope. Wennerberg [1993] provided the formulation to determine the contribution of Q_s and Q_i attenuation to the total attenuation.

The objective of the present study is to understand the attenuation mechanism of medium beneath Delhi and surrounding region, India by estimating Q using different parts of the seismograms and to estimate the relative contribution of Q_i and Q_s in the region. The extended coda normalization method [Yoshimoto et al. 1993] has been used to estimate the frequency-dependent relations for Q_α and Q_β. Single backscattering model of Aki and Chouet [1975] has been used to estimate Q_c. Wennerberg's [1993] formulation has been used to estimate the relative contribution of Q_i and Q_s.

2. Seismotectonics and geology of the area

The Delhi and surrounding area had active seismic history [Tandon 1975, Verma et al. 1995, Mohanty 1997,

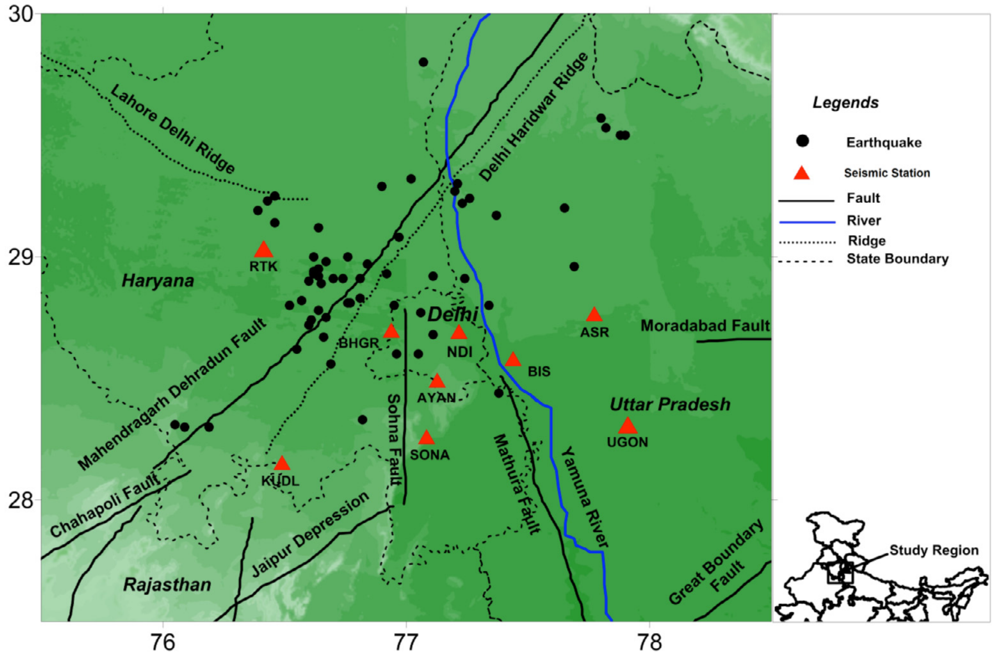

Figure 1. Epicentral locations of earthquake events and seismological stations in and around Delhi area.

Bansal et al. 2008, Singh et al. 2010, Bansal and Verma 2012, Prakash and Srivastava 2012]. The first reported earthquake with intensity IX occurred in the Delhi region on July 15, 1720 [Tandon 1975, Chandra 1992]. The estimated intensity of these earthquakes on the Modified Mercalli Scale was found to be between VII and IX at Delhi and its surrounding region, as indicated by the damage pattern. The earthquake of August 27, 1960, was another significant earthquake of magnitude 6.0 with its epicenter between Delhi and Gurgaon. The seismicity of Delhi and surrounding region show maximum concentration of epicenters in north-south trending Sonepat-Sohna fault, west of Delhi and at the tri-junction of Delhi-Haridwar ridge, Delhi-Lahore ridge and the axis of Delhi folding. It has been indicated that there are numerous hidden faults in the thick alluvial deposits of the Indo-Gangetic plains. According to the seismotectonic studies of the region, Haridwar-Delhi ridge, Sohna fault, Aravalli Fault and Moradabad fault are the prominent tectonic features in Delhi and the surrounding areas [Mohanty 1997, Bansal and Verma 2012, Prakash and Srivastava 2012]. The entire Delhi and its surrounding area exhibit moderate seismicity and fall under seismic zone IV of the Seismic zonation map of India [Singh et al. 2010]. It is important to consider seismic factors for urban planning, industrialization, designing and construction of civil engineering structures.

S. No.	Station with station code	Latitude (Deg min)	Longitude (Deg min)
1	Ayanagar (AYAN)	28°28.93	77°07.60
2	Sohana (SONA)	28°14.70	77°03.78
3	Bhadurgarh (BHGR)	28°41.26	76°56.33
4	Rataul (RTL)	28°49.93	77°20.51
5	Bisrakh (BIS)	28°34.26	77°26.34
6	Kuldal (KUDL)	28°08.65	76°29.35
7	Asauara(ASR)	28°45.35	77°46.33
8	Unchagaon (UCG)	28°18.60	77°54.60
9	New Delhi (NDI)	28°35.41	77°12.13

Table 1. Epicentral locations, origin time, date and depths of the events use in the present study.

The rock formations exposed in the Delhi area are mainly quartzite of the Alwar series of the Delhi Supergroup which are 1500 million years in age and overlain by unconsolidated Quaternary to recent sediments which are 1.65 Ma old. The terrain is generally flat except for a low NNE-SSW trending Delhi Ridge in the southern and central part of the area which consists of Quartzite while the Quaternary sediments, comprising the older and newer alluvium cover the rest of the area. The older alluvium comprises silt, clay with minor lenticular fine sand and kankar beds [Choudhary et al. 1984]. The newer alluvium mainly consists of sand, silt and clay occurring in the older and active flood plains of the Yamuna River. Thickness of the alluvium, both on the eastern and western side of the ridge, is variable but west of the ridge, it is generally thicker nearly 300m [Mohanty et al. 2009, Bansal and Verma 2012]. Figure 1 shows the area of present study along with the seismological stations, earthquake locations and major tectonic features of the area.

3. Methodology

In the present study single backscattering model of Aki and Chouet [1975] is used to estimate Q_c. Extended coda normalization method [Yoshimoto et al. 1993] is used to calculate Q_α and Q_β and Wennerberg formulation [Wennerberg 1993] is applied to estimate Q_i and Q_s. These methods are described as below.

Single backscattering model

The Q_c has been estimated using the single backscattering model proposed by Aki and Chouet [1975]. According to this model, the coda waves are interpreted as backscattered body-waves generated by numerous heterogeneities present in the Earth's crust and upper mantle. It implies that scattering is a weak process and outgoing waves are scattered only once before reaching the receiver. Under this assumption, the coda amplitudes, $A_c(f,t)$, in a seismogram can be expressed for a central frequency f over a narrow bandwidth signal, as a function of the lapse time t, measured from the origin time of the seismic event, as [Aki 1980]:

$$Ac(f,t) = S(f)t^{-a}\exp\frac{(-\ \pi ft)}{Q_c} \qquad (1)$$

where $S(f)$ represents the source function at frequency f, and is considered a constant as it is independent of time and radiation pattern, and therefore, not a function of factors influencing energy loss in the medium; a is the geometrical spreading factor, and taken as 1 for body waves. The swapping of geometrical spreading factor and Q could give rise to unreasonable values of these parameters. To minimize the risk to get unreasonable values an inversion method based on a parabolic expression of the coda-normalization equation has been developed by de Lorenzo et al. [2013]. For various Indian regions the attenuation properties are estimated by several researchers [Gupta et al. 1995, Sharma et al. 2007, Sharma et al. 2008, Mohanty et al. 2009, etc.] and in all the related studies carried out for various parts of Indian subcontinent the geometrical spreading factor is considered to be unity. Q_c is the apparent quality factor of coda waves representing the attenuation in a medium. The above equation can be rewritten as

$$ln(Ac(f,t)) = ln(S(f)) - \frac{(\ \ f)}{Q_c}t \qquad (2)$$

It is a linear equation with the slope $-\frac{(\ \ f)}{Q_c}$ from which Q_c is estimated.

Extended coda normalization method

This 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 spectral amplitude, $Ac(f,t_c)$, of the coda at a lapse time t_c can be written as [Aki 1980]:

$$Ac(f,tc) = Ss(f)P(f,tc)G(f)I(f) \qquad (3)$$

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 $I(f)$ is the instrumental response.

The spectral amplitude of the direct S wave, $A_s(f,r)$ can be expressed as

$$A_s(f,r) = R_{\theta\phi}S_s(f)r^{-a}\exp\left(-\frac{fr}{Q_\beta(f)V_s}\right)G(f,\psi)I(f) \qquad (4)$$

where $R_{\theta\phi}$ is the source radiation pattern and a denotes the geometrical exponent which is taken unit value as explained in the previous section. $Q_\beta(f)$ 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 (4) by Equation (3), taking the logarithm and simplifying, we get [Yoshimoto et al. 1993]:

$$ln\left(\frac{As(f,r)r}{Ac(f,tc)}\right)_{r\pm\ r} = -\frac{fr}{Q_\beta(f)V_s} + const(f) \qquad (5)$$

Using a similar equation the quality factor for the P-waves can be obtained [Yoshimoto et al. 1993].

$$ln\left(\frac{Ap(f,r)r}{Ac(f,tc)}\right)_{r\pm\ r} = -\frac{fr}{Q_\alpha(f)V_p} + const(f) \qquad (6)$$

The quality factor for P waves can be obtained from the linear regression of $\left(\frac{Ap(f,r)r}{Ac(f,tc)}\right)_{r\pm\ r}$ versus r by means of least-squares method as done for S-waves.

Wennerberg formulation to estimate Q_i and Q_s

Wennerberg [1993] provided the formulation based on Zeng et al. [1991] model to estimate Q_i and Q_s. According to Zeng et al. [1991], we can write the observed value of Q_c in terms of Q_i and Q_s as below:

$$\frac{1}{Q_c} = \frac{1}{Q_i} + \frac{(1-2\delta(\tau))}{Q_s} \qquad (7)$$

where, $\delta(\tau)$ is $-\frac{1}{(4.44+0.738)}, \tau = \frac{\omega t}{Q_s}$, ω is the angular frequency and t is the lapse time. Assuming Q_d as the quality factor of direct wave evaluated in the Earth volume equivalent to the volume sampled by coda waves, it can be written as [Wennerberg 1993]:

$$\frac{1}{Q_s} = \frac{1}{2\delta(\tau)}\left(\frac{1}{Q_d} - \frac{1}{Q_c(\tau)}\right) \tag{8}$$

$$\frac{1}{Q_i} = \frac{1}{2\delta(\tau)}\left(\frac{1}{Q_c(\tau)} + \frac{(2\delta(\tau)-1)}{Q_d}\right) \tag{9}$$

If Q_c is measured as a function of lapse time t, Q_i and Q_s can be estimated using Equations (7), (8) and (9), where Q_d is measured as a function of distance.

Data analysis

Earthquake data of 62 events with Ml 2.0-4.9 recorded by the digital seismic telemetric network operated by India Meteorological department in and around Delhi. The data is recorded using short period sensors at 20 samples per second (sps), which limits the Nyquist frequency 10 Hz. Figure 1 shows the epicentral locations of events and stations considered. Locations of the stations along with the station codes are given in Table 1. The vertical component of each seismogram have been filtered at five different frequency bands (1-2) Hz, (2-4) Hz, (4-6) Hz, (6-8) Hz and (8-10) Hz using a Butterworth band pass filter. On the filtered seismograms, the root-mean-square amplitudes of coda waves amplitude measurement starts at twice the travel time of the S-waves in a window length of 256 samples and lapse time window length of 30 seconds have been used to estimate Q_c. Figure 2 shows one original and filtered seismogram recorded at SONA station on June 7, 2006, and Figure 3 shows the variation of *ln(Ac(f,t).t)* with lapse time *t* along with the least-squares-fitted line for different central frequencies at SONA for the same event. Figure 4 represents the plot of Q_c values as a function of frequency obtained at 30 sec lapse time window. Data used in the present study is analysed visually for the signal to noise ratio. The seismograms having signal to noise ratio less than two is not considered in the present study. Table 2 shows the events selected for the present study.

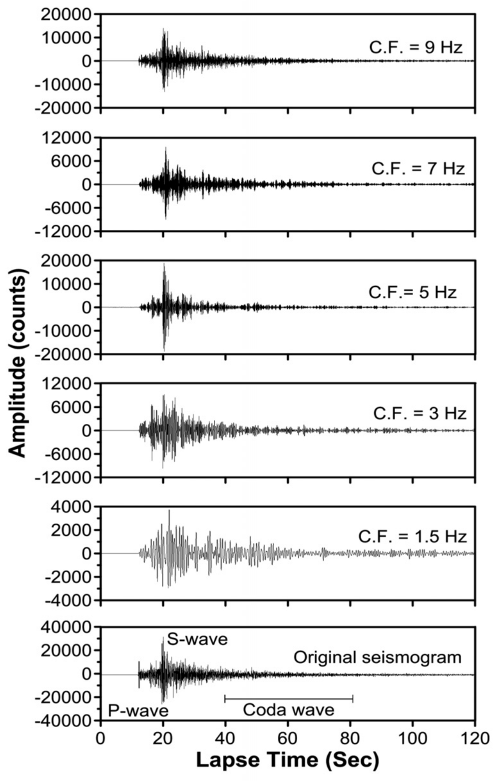

Figure 2. A sample of original and filtered seismogram at different frequency bands for SONA station recorded on June 7, 2006.

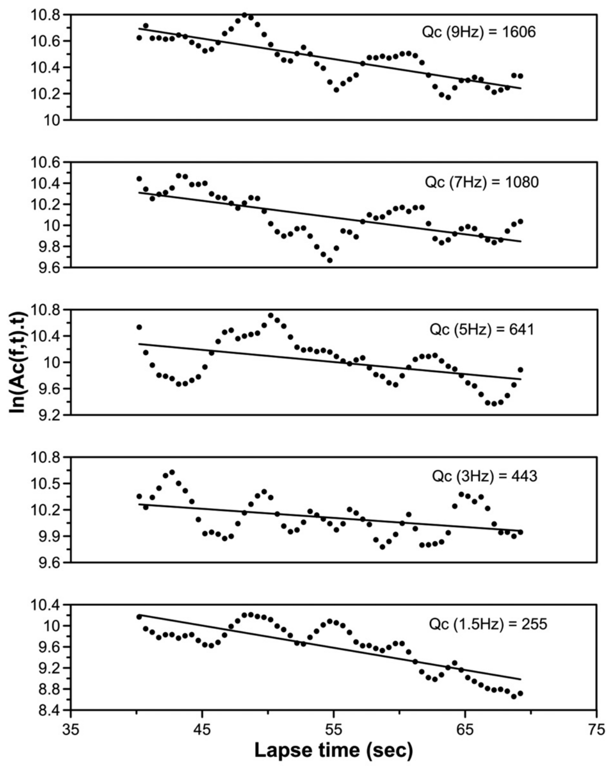

Figure 3. The variation of *ln*(*Ac*(*f*,*t*).*t*) with lapse time t along with the least-squares-fitted line for different central frequencies at SONA for the event of June 7, 2006.

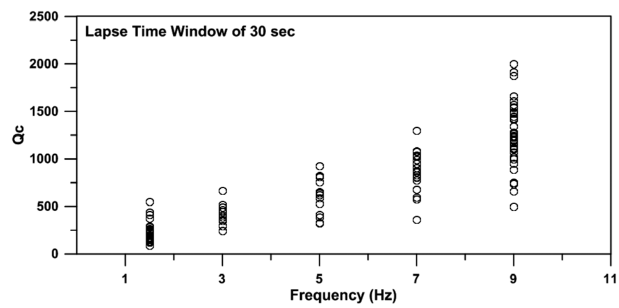

Figure 4. The plot of Q_c values as a function of frequency obtained at 30 sec lapse time window.

S. No.	Year	Month	Day	Hr	Min	Sec	Latitude (°N)	Longitude (°E)	Magnitude (ml)	Depth (km)
1	2001	1	28	15	22	42.4	28.74	76.61	2.4	5
2	2001	4	28	13	28	29.3	28.62	76.55	2.3	4
3	2001	8	10	12	19	32.8	28.91	77.24	3.2	13
4	2001	8	12	21	9	30.2	28.96	77.69	2.7	26
5	2001	8	23	18	23	20.3	29.08	76.97	2.4	9
6	2001	9	14	14	31	29.9	29.22	77.23	2.1	15
7	2001	10	9	23	18	15.5	29.17	77.37	2.2	10
8	2002	10	22	21	43	12.9	28.68	77.11	2.7	15
9	2002	10	23	20	52	31.7	28.91	76.81	2.2	15
10	2002	10	30	5	10	10	28.77	77.06	2.1	23
11	2002	10	31	0	59	23.2	28.8	76.95	2.1	22
12	2002	11	6	2	12	0.5	28.97	76.84	2.9	10
13	2003	2	15	6	37	6.1	29.3	77.21	2.6	5
14	2004	5	3	16	55	5.7	29.25	76.46	3	5
15	2004	5	15	3	12	53.9	29.19	76.39	2.3	13
16	2004	5	22	14	45	55	29.14	76.46	2.6	18
17	2004	5	3	16	55	5.7	29.25	76.46	3	5
18	2004	5	15	3	12	53.9	29.19	76.39	2.3	13
19	2004	5	22	14	45	55	29.14	76.46	2.6	18
20	2004	8	22	22	47	53.6	28.44	77.38	2.1	12
21	2004	10	9	11	34	41.5	29.23	76.43	2.8	5
22	2004	12	18	15	39	16.9	29	76.62	2.7	4
23	2004	12	20	1	11	57.5	28.92	77.11	2.6	28
24	2004	12	23	19	21	1.7	28.56	76.69	2.5	6
25	2005	6	10	23	53	20.6	29.32	77.02	2.6	9
26	2005	6	13	17	31	48.6	28.3	76.19	2.2	5
27	2006	1	19	8	12	38.3	28.82	76.57	2.4	5
28	2006	3	15	5	5	54.5	28.91	76.7	2.3	17
29	2006	4	7	18	56	40.3	28.93	76.92	3.3	5
30	2006	4	10	14	11	58.7	29.12	76.64	3	5
31	2006	4	11	23	21	8.5	29.29	76.9	2.4	40
32	2006	4	11	23	26	23.7	28.83	76.81	2.7	10
33	2006	5	7	16	1	0.2	28.72	76.6	4.2	4
34	2006	5	11	7	0	10.4	28.67	76.66	2.7	15
35	2006	5	12	1	30	55.2	28.89	76.65	2.3	10
36	2006	7	9	2	30	34.1	28.91	76.74	2.5	25
37	2006	10	31	12	59	3.1	28.75	76.67	2.1	5
38	2006	12	9	18	52	4.3	28.95	76.64	2.8	10

Table 2 (continues on next page). Coordinates of the stations along with their station codes in and around Delhi region.

S. No.	Year	Month	Day	Hr	Min	Sec	Latitude (°N)	Longitude (°E)	Magnitude (ml)	Depth (km)
39	2006	12	23	5	9	32.1	28.31	76.05	2.4	10
40	2006	12	28	13	40	46.8	28.98	76.67	2	10
41	2006	12	30	18	31	52.4	28.3	76.09	2.5	5
42	2007	1	8	12	1	0.6	28.81	76.76	2.5	10
43	2007	1	23	1	48	26.1	28.33	76.82	2.3	20
44	2007	1	29	20	26	0.4	28.9	76.6	2.2	10
45	2007	2	27	20	37	58.5	29.24	77.26	2.5	10
46	2007	3	6	3	14	4.4	28.93	76.62	2.2	9
47	2007	3	12	5	51	26.9	28.6	76.96	2.2	13
48	2007	4	3	15	35	11.2	28.94	76.62	2.8	10
49	2007	5	14	7	22	47.9	28.92	76.64	3.2	5
50	2007	5	14	10	51	22	28.81	76.77	2.2	33
51	2007	5	16	12	56	7.9	28.78	76.64	2.3	18
52	2008	5	27	21	51	59.4	29.8	77.07	2.0	15
53	2008	8	29	3	43	27.1	28.8	77.34	2.3	15
54	2008	10	19	7	56	48.4	29	76.76	3.9	6
55	2008	10	28	20	29	48.1	28.8	76.52	4.9	10
56	2009	01	07	14	53	29.5	29.57	77.8	3.9	5
57	2009	02	01	18	32	9.6	29.5	77.88	2.8	10
58	2009	03	10	12	22	26.7	29.5	77.9	3.6	10
59	2009	03	14	2	22	54.7	29.27	77.2	4.2	10
60	2009	05	30	8	00	00	29.2	77.65	2.3	7
61	2009	06	17	12	07	31.7	29.53	77.82	4.2	11
62	2011	09	07	17	58	16.3	28.6	77.05	4.3	10

Table 2 (continued from previous page). Coordinates of the stations along with their station codes in and around Delhi region.

In order to estimate Q_α and Q_β, the rms amplitudes of P- and S-waves have been taken from the filtered seismograms and normalized by the coda wave amplitude. Figure 5 shows a plot of $ln((As/Ac)r)$ with respect to hypocentral distance r (km) and corresponding plots of S-waves at five different central frequencies for NDI. The slopes of the best-fitted lines are used to estimate Q_α and Q_β by using Equations (5) and (6). The average velocities of 7.02 km/sec and 4.06 km/sec for P and S waves respectively, have been used in the present study [IMD 2000]. Afterwards, Q_s and Q_i are estimated according to Equations (8) and (9) with the help of values of Q_c and Q_β calculated using single backscattering and coda normalization methods assuming the Q_β as quality factor of direct wave.

4. Results and discussions

In the present study the attenuation properties of the crust for Delhi, India have been estimated. For this purpose, 62 local earthquakes recorded by 9 stations in Delhi and surrounding area have been used. The estimated mean values of Q_α, Q_β, Q_c, Q_i and Q_s along with the standard deviation error at different central frequencies for the region considered in the present study are given in Table 3. The average value of Q_c varies from 274 at 1.5 Hz to 1656 at 9 Hz. The average values of Q_α and Q_β vary from 77 and 156 at 1.5 Hz. to 538 and 969 at 9 Hz, respectively. The increase in Q values with increasing frequency indicates the frequency-dependent nature of the Q estimates in the region. In order to obtain the frequency-dependent relations, the estimated average Q_α, Q_β and Q_c values as a function of frequency are plotted in Figure 6. The frequency-dependent relationships estimated for the region along with the standard deviation are: $Q_\alpha = (52\pm4) f^{(1.03\pm.07)}$, $Q_\beta = (98\pm7) f^{(1.07\pm.09)}$ and $Q_c = (158\pm9) f^{(0.97\pm.08)}$. The small lateral variation found in the estimated Q values may be attributed to the heterogeneities present in the re-

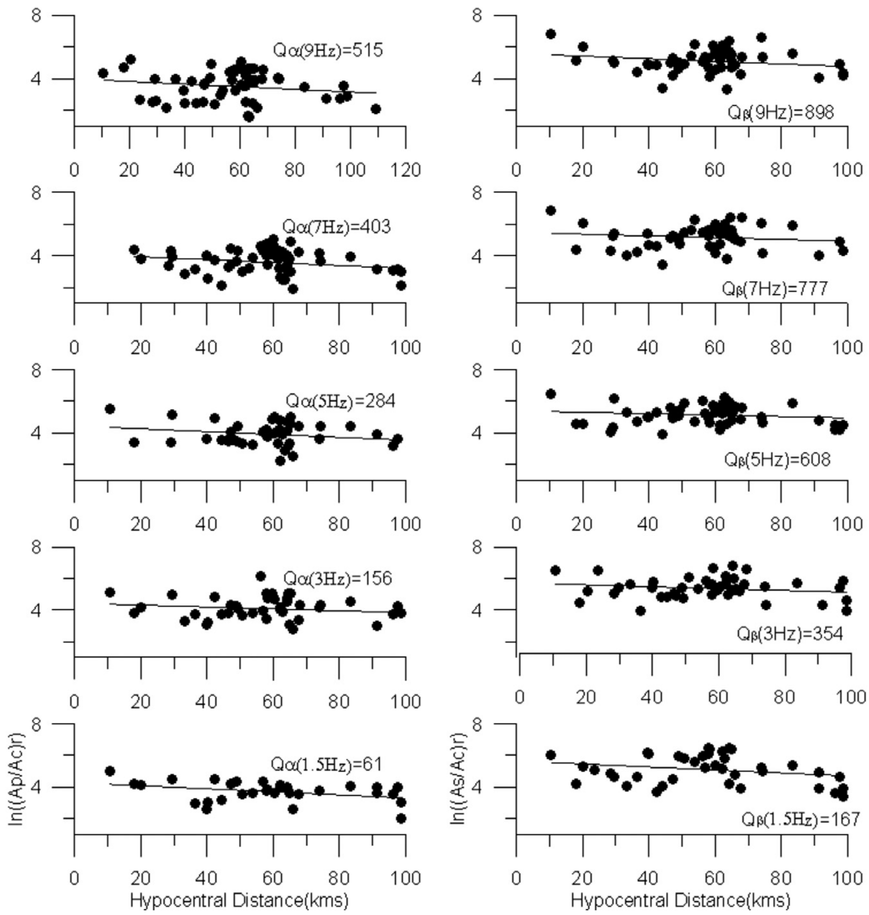

Figure 5. Plot of *ln((As/Ac)r)* with respect to hypocentral distance *r* (km) and corresponding plots of *S*-waves at five different central frequencies for NDI station.

gion and difference in distances of the events from the recording stations. The estimate of Q_c is found to be higher than Q_β in this region. The effect of intrinsic and scattering attenuation combine in a manner that Q_c is more than Q_β as shown in Figure 6. This supports the Zeng et al.'s [1991] model which predicts the idea of coda enrichment over Q_β. According to Wennerberg [1993] formulation, Q_c is separated in terms of scattering and intrinsic attenuation in the present study. The estimated Q_i values vary from 472 at 1.5 Hz to 2525 at 9 Hz. The estimated Q_i values vary from 232 at 1.5 Hz to 1937 at 9 Hz. It has been reported in literature and using laboratory measurements that coda-Q is very close to Q_i [Frankel and Wennerberg 1987, Matsunami 1991]. However, Mayeda et al. [1992] have found that this observation is valid at higher frequencies while Q_c is intermediate between Q_i and Q_s. It has been observed

C.F.	Q_α	Q_β	Q_c	Q_i	Q_s
1.5	77±14	156±11	274±25	232±25	472±22
3	185±17	363±19	730±79	591±33	941±23
5	277±12	583±21	931±94	816±18	2040±25
7	382±19	764±16	1265±216	1096±16	2520±32
9	538±26	969±12	1656±91	1937±31	2525±46

Table 3. Values of different quality factors estimated at different central frequencies.

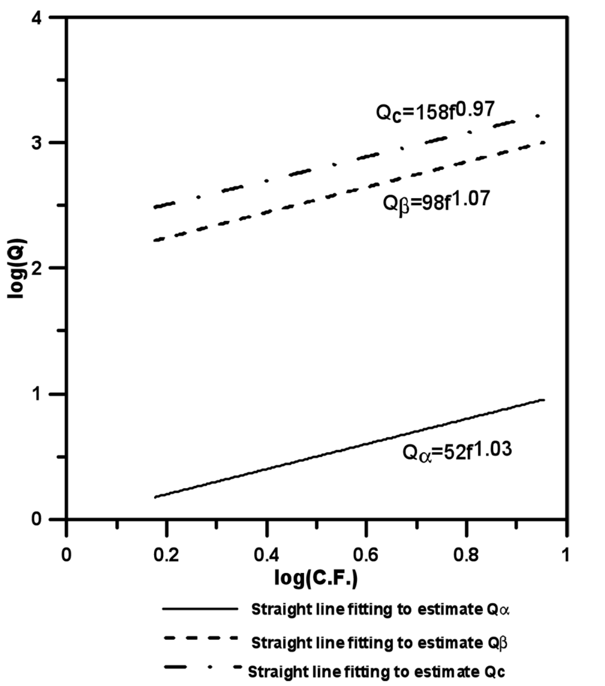

Figure 6. Plot of estimated average Q_a, Q_b and Q_c values as a function of frequency.

from the present study that Q_c values lie in between Q_i and Q_s at all frequencies (Table 3). A comparison between estimates of Q_i and Q_s in this study shows that intrinsic absorption is predominant over scattering for the frequency range (1.5 Hz - 9 Hz) considered here. It has been found that the value of Q_0 (Q_c at 1 Hz) varies from 47 to 200 and that of n varies from 0.70 to 1.10 for the active regions including Parkfield [Hellweg et al. 1995], Friuli, Italy [Rovelli 1982]. Singh et al. [2004] have estimated a relation $Q(f) = 800f^{0.42}$ for the Indian shield region using the dataset of four earthquakes recorded in the distance range of 240-2400 km. Using the accelerograms of the aftershocks of 2001 Bhuj earthquake, Bodin and Horton [2004] have obtained a relation $Q(f) = 790f^{0.35}$ for the Kachchh basin. The coda-based method used in this study gives Q of a very shallow portion of the crust, while Q estimates obtained by Singh et al. [2004] and Bodin and Horton [2004] sample deeper in the crust. Mohanty et al. [2009] have estimated coda wave attenuation for Delhi using local earthquakes and obtained frequency dependent relationship as $Q_c = 142f^{1.04}$. The frequency dependent relationship obtained using coda waves in the present study as: $(158\pm9)f^{(0.97\pm.0)}$, is comparable to that of Mohanty et al. [2009]. The study region of Mohanty et al. [2009] is same but they have computed only Q_c for the region and we have extended the attenuation study by separating the total attenuation parameter in terms of intrinsic (Q_i) and scattering parameters (Q_s). For this purpose we have also estimated Q_β, Q_α and Q_β/Q_α, which represent the attenuation of seismic waves for Delhi and surrounding region in a better way. Figure 7 shows the comparison of present estimates of Q_c with some attenuation studies of India and worldwide, which in turn shows a similar trend for Delhi Capital area as other tectonic regions. This shows that the attenuation characteristics of seismic waves in the Delhi region are similar to the seismically active regions of the world. In Figure 7, if we compare the Delhi Q_c with Indian regions, it is clear that Q_c values lie close to Koyna region at lower frequencies and match with Q_c values of Kachchh region at higher frequencies. This may lead to the conclusion that crust of Delhi and surrounding areas is less attenuative as compared to Kachchh and Koyna regions.

Using the aftershocks of 2001 Bhuj earthquake and Multiple Lapse Time Window Analysis, Hoshiba et al. [1991], Fehler et al. [1992] and Ugalde et al. [2006] have shown that intrinsic absorption is predominant over scattering for all frequencies except for 1-2 Hz in Kachchh region. Similarly for Delhi and surrounding region we found that intrinsic absorption is dominating over scat-

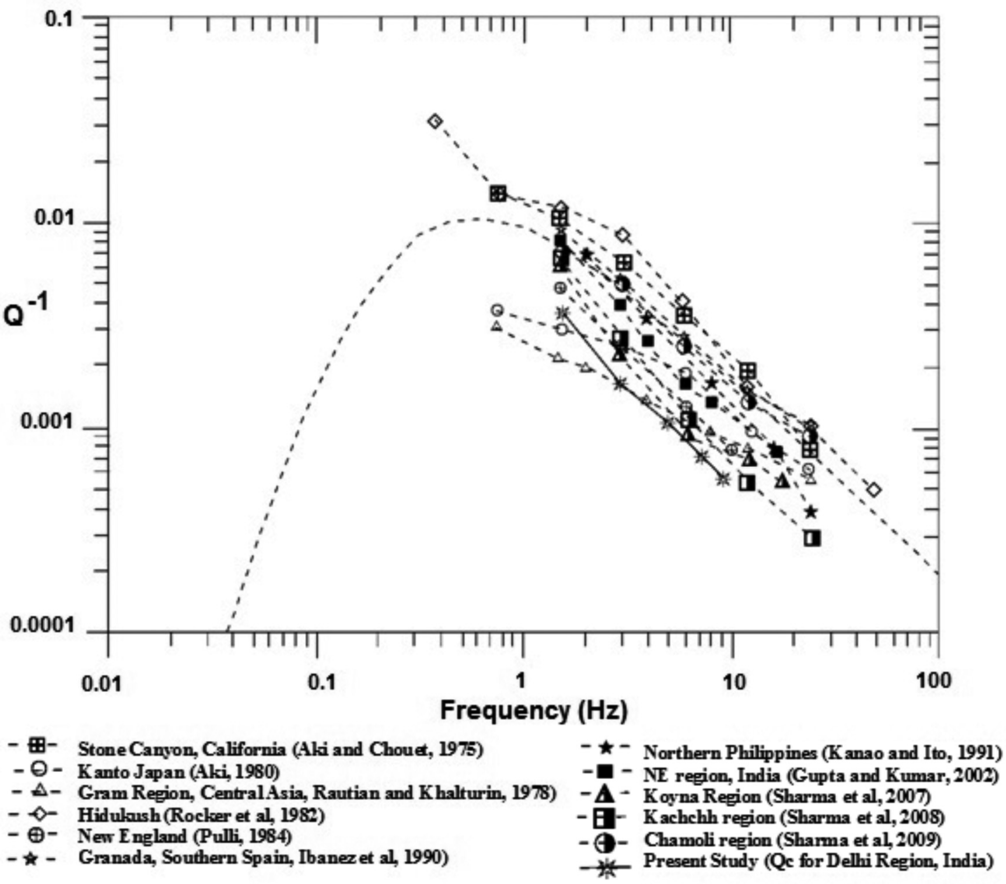

Figure 7. Comparison of present estimates of Q_c with some attenuation studies in India and worldwide.

tering. Figure 8 shows the comparison of the ratio Q_β/Q_α estimated here at different frequencies with those of other tectonic regions worldwide. We note that $Q_\beta/Q_\alpha \geq 1$ obtained in the present study for the frequencies considered here is comparable with other regions of the world. Mandal [2006] estimated the Q_β vs. Q_α relation for the Kachchh rift zone using the Sp converted phases on the accelerograms. He estimated that the ratio Q_β/Q_α lies in between 0.41 to 2.99 in Kachchh region. Also Padhy [2009] estimated $Q_\beta/Q_\alpha \geq 1$ for Bhuj region. To interpret the results, we compared our results with the laboratory measurements of Q_β and Q_α. Vassiliou et al. [1982] have given general observations of Q_β and Q_α relations in sedimentary rocks. $Q_\beta = Q_\alpha$ for dry rocks, $Q_\beta \geq Q_\alpha$ for partially saturated rocks and $Q_\beta \leq Q_\alpha$ for fully saturated rocks. In our case, we obtained $Q_\beta > Q_\alpha$, which shows that the region is comprised of partially saturated rocks or crustal pore fluids [de Lorenzo et al. 2013]. According to Figure 8, we analyze that Delhi and surrounding area are comprised of partially saturated sediments. Also, it is seen in Figure 8 that at lower frequencies Q_β/Q_α valves are lower than Bhuj region, but at frequencies between 5 and 6 Hz, Q_β/Q_α are nearly equal to that of Bhuj region of India and after that there is a decrease in Q_β/Q_α ratio. The bump at frequency 5-6 Hz in this figure may correspond to the sediments present in the subsurface of the Delhi region. It is known that if the Q_c values are lower than 200 then it depicts the seismically active region [Aki and Chouet 1975]. Our results for Delhi region show low Q (Q_c is 158), which corresponds to high attenuation and is comparable with other seismically active regions of India and world. The area has a considerable thick layer of partially saturated sediments demonstrated by $Q_\beta/Q_\alpha > 1$, due to which most part of the energy gets dissipated in the medium.

5. Conclusions

The present study is an attempt to understand the attenuation properties of Delhi, India and surrounding region, India. For this purpose quality factors Q_α, Q_β, Q_c, Q_i and Q_s are estimated. The analysis shows their dependence on the frequency in the range from 1.5 Hz to 9 Hz in the region. Power law relationships for the region along with the standard deviation are obtained as: $Q_\alpha = (52 \pm 4) f^{(1.03 \pm .07)}$, $Q_\beta = (98 \pm 7) f^{(1.07 \pm .09)}$ and $Q_c = (158 \pm 9) f^{(0.97 \pm .08)}$. The attenuation characteristics of coda waves in the Delhi region are close to other similar and tectonically active regions of the world. The estimates of Q_c are found to be higher than Q_β in the studied region. This observation shows that the effects of intrinsic and scattering attenuation combine in such a manner that Q_c is more than Q_β. The Q_c is separated

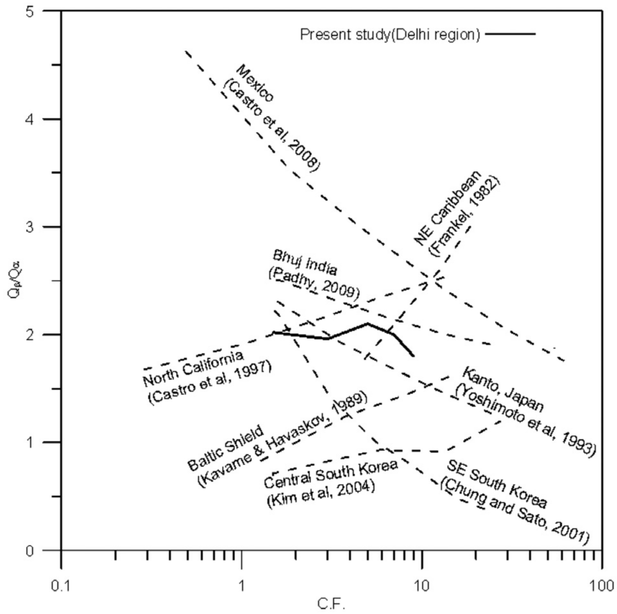

Figure 8. Comparison of the ratio Q_β/Q_α estimated at different frequencies with those of other tectonic regions of India and worldwide.

in terms of scattering and intrinsic attenuation parameter Q_i and Q_s. The Q_c estimates lie in between the estimates of Q_i and Q_s but are closer to Q_i at all frequencies. This is in agreement with the theoretical as well as laboratory observations/measurements. A comparison between Q_i and Q_s shows that intrinsic absorption is predominant over scattering in Delhi and surrounding region. $Q_\beta/Q_\alpha \geq 1$ obtained for the frequency range of 1.5 Hz to 9 Hz shows that the area of the present study is mainly comprised of partially saturated sediments. The results of present study indicate high attenuation which also corroborates well with the regional geology of Delhi and surrounding areas.

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