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ORIGINAL ARTICLE

Attenuation of P, S, and coda waves in Koyna region, India

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Abstract The attenuation properties of the crust in the Koyna region of the Indian shield have been investigated using 164 seismograms from 37 local earthquakes that occurred in the region. The extended coda normalization method has been used to estimate the quality factors for P waves (Q_α) and S waves (Q_β), and the single back-scattering model has been used to determine the quality factor for coda waves (Q_c). The earthquakes used in the present study have the focal depth in the range of 1–9 km, and the epicentral distance vary from 11 to 55 km. The values of Q_α, Q_β and Q_c show a dependence on frequency in the Koyna region. The average frequency dependent relationships (Q=$Q_0 f^n$) estimated for the region are $Q_\alpha = (59 \pm 1)f^{(1.04\pm.04)}$, $Q_\beta = (71 \pm 1)f^{(1.32\pm.08)}$ and $Q_c = (117 \pm 2)f^{(0.97\pm.07)}$. The ratio Q_β/Q_α is found to be greater than one for the frequency range considered here (1.5–18 Hz). This ratio, 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 Q_c and Q_β in the present study shows that $Q_\beta < Q_c$ for frequencies below 4 Hz and $Q_\beta > Q_c$ for the frequencies greater than 4 Hz. This may be due to the multiple scattering effect of the medium. The outcome of this study is expected to be useful for the estimation of source parameters and near-source simulation of earthquake ground motion, which in turn are required in the seismic hazard assessment of a region.

Keywords Attenuation · Coda normalization · Quality factor · Seismic waves

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1 Introduction

The study of attenuation of seismic waves in a region is required for the determination of earthquake source parameters as well as for simulation of earthquake ground motions. Therefore, it is important for estimating the seismic hazards of a region. The overall attenuation is composed of several factors that include geometrical spreading, scattering due to inhomogeneities in the medium and, inelasticity. Because of the non-elastic nature of the medium, a part of the energy in the wave is dissipated through the medium. This type of attenuation of seismic waves 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).

The attenuation of seismic waves has been widely studied in different regions of the world using different techniques (Aki 1980; Takemura et al. 1991; Scherbaum and Sato 1991; Sato and Matsumura 1980; Yoshimoto et al. 1993; Hough and Anderson 1988; Masuda 1988; Campillo and Plantet 1991; Yoshimoto et al. 1998). A number of different approaches have been used to quantify the attenuation from different parts of the seismograms (e.g. Aki 1969; Hermann 1980; Mitchell 1995). Aki (1980) proposed the coda normalization method and estimated the frequency dependent Q for Kanto area, Japan. Sato and Matsumura (1980) applied this method to a data set of deep borehole observation. Yoshimoto et al. (1993) extended the coda normalization method for simultaneous measurement of Q_α and Q_β. There are few studies that simultaneously estimated the frequency dependent Q_α and Q_β in the world (e.g., Hough and

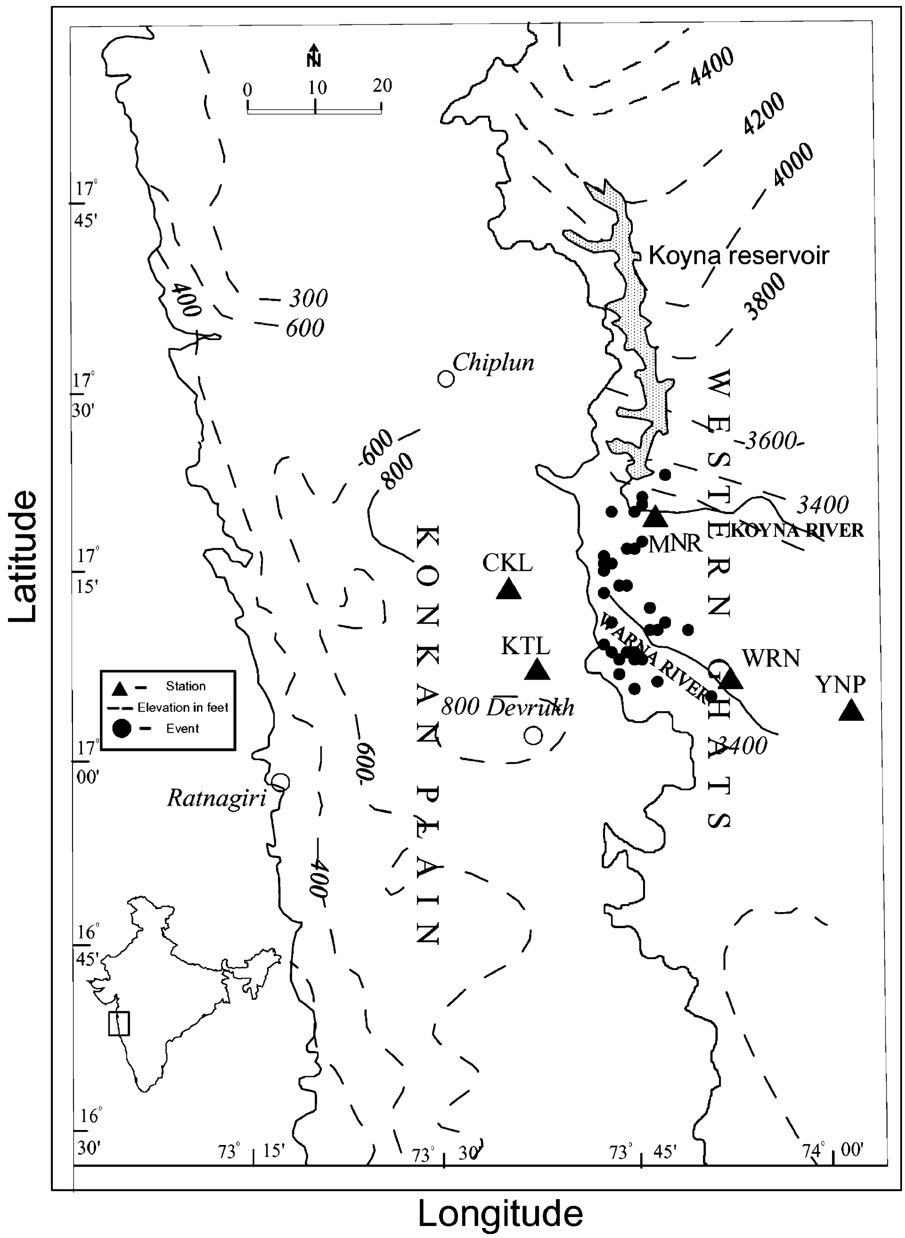


Fig. 1 Map showing the Koyna region and seismological network deployed by NGRI, Hyderabad, in the Koyna region along with the stations and events considered for the present study

Table 1 Names, codes, locations, and rock geology of five stations used in the present study

S no.	Station name	Code	Latitude (°N)	Longitude (°E)	Geology in terms of rock
1	Maneri	MNR	17.34	73.79	Basalt
2	Chikhali	CKL	17.24	73.59	Laterite
3	Warna	WRN	17.12	73.88	Basalt
4	Katwali	KTL	17.12	73.62	Laterite
5	Yenpe	YNP	17.11	73.04	Basalt

Anderson 1988, Masuda 1988, and Campillo and Plantet 1991; Yoshimoto et al. 1993).

The objective of the present study is to understand the attenuation characteristics of the Koyna region of the Indian shield using different parts of the seismograms. For this purpose, 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 the Koyna region. It is the first estimate of this kind for this region. The relationships for coda-

Table 2 Hypocentral parameters of the events considered in the present study (taken by the help of NGRI)

S no.	Date	Origin time			Latitude (°N)	Longitude (°E)	Focal depth (km)
		h	min	s			
1	2/12/96	8	52	15.56	17.29	73.75	8
2	2/12/96	23	55	43.27	17.27	73.72	9
3	3/12/96	07	48	54.12	17.39	73.78	1
4	5/12/96	12	23	49.61	17.18	73.77	7
5	5/12/96	21	07	34.63	17.19	73.71	3
6	6/12/96	08	30	23.40	17.14	73.75	1
7	18/12/96	00	59	35.34	17.26	73.7	1
8	19/12/96	00	58	19.64	17.15	73.71	4
9	19/12/96	21	37	47.31	17.18	73.76	5
10	28/11/96	09	05	46.33	17.11	73.77	4
11	28/11/96	16	20	19.98	17.24	73.72	1
12	25/10/96	04	03	39.60	17.14	73.72	5
13	28/10/96	09	58	23.26	17.1	73.74	4
14	3/12/96	14	50	01.60	17.29	73.74	6
15	9/10/96	20	48	38.29	17.23	73.70	7
16	24/11/96	00	59	46.75	17.12	73.72	5
17	14/11/96	05	39	00.18	17.24	73.73	5
18	18/12/96	02	06	10.47	17.27	73.7	4
19	18/12/96	02	30	24.72	17.27	73.7	4
20	18/12/96	06	59	00.71	17.09	73.84	1
21	7/12/96	10	46	28.03	17.15	73.74	5
22	7/12/96	14	14	10.19	17.16	73.71	6
23	9/12/96	13	34	59.58	17.34	73.74	7
24	13/12/96	00	09	54.21	17.11	73.77	5
25	16/12/96	13	40	34.01	17.21	73.76	8
26	19/10/96	14	30	58.12	17.14	73.75	5
27	21/10/96	19	45	29.40	17.14	73.72	5
28	20/10/96	14	56	16.39	17.29	73.73	3
29	20/10/96	16	29	27.26	17.35	73.75	6
30	20/10/96	11	52	30.32	17.16	73.7	6
31	20/10/96	13	41	37.89	17.19	73.77	9
32	20/10/96	16	56	02.61	17.36	73.75	5
33	17/11/96	04	14	30.72	17.15	73.74	5
34	17/11/96	05	51	58.64	17.15	73.73	5
35	25/11/96	02	17	59.04	17.29	73.74	7
36	26/11/96	04	30	45.32	17.18	73.81	2
37	26/11/96	19	08	10.84	17.14	73.74	5

Table 3 Low cut-off, high cut-off, and central frequencies used to filter the earthquake waveform data

S no.	Low cut-off	Central frequency (CF)	High cut-off
1	1	1.5	2
2	2	3	4
3	4	6	8
4	8	12	16
5	12	18	24

Q have been obtained using the single back-scattering model of Aki and Chouet (1975). The coda-Q estimates for the Koyna region have been previously obtained by Gupta et al. (1998) and Mandal and Rastogi (1998) using the different data sets. To compare the estimates of the Q obtained from different parts of the seismograms, coda-Q has also been determined using the single back-scattering model of Aki and Chouet (1975) from the same data set used for the estimation of Q_α and Q_β in this study. The results obtained here have been compared with those obtained in the different regions in the world including the Indian regions.

2 Methodology

(a) Coda normalization method

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):

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

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 Eq. 2 by 1, taking logarithm and simplifying, we get (Yoshimoto et al. 1993):

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

The contribution of $R_{\theta\phi}$ disappears by averaging over many different focal plane solutions, and the ratio $G(f, \psi)/G(f)$ becomes independent of ψ by averaging over many earthquakes. Therefore, we get the following equation:

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

where $\langle \ln\left[A_s(f,r)r^{\gamma}/A_c(f,t_c)\right]\rangle_{r\pm\Delta r}$ 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 $\langle \ln\left[A_s(f,r)r^{\gamma}/A_c(f,t_c)\right]\rangle_{r\pm\Delta r}$ versus r by means of a least square 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):

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

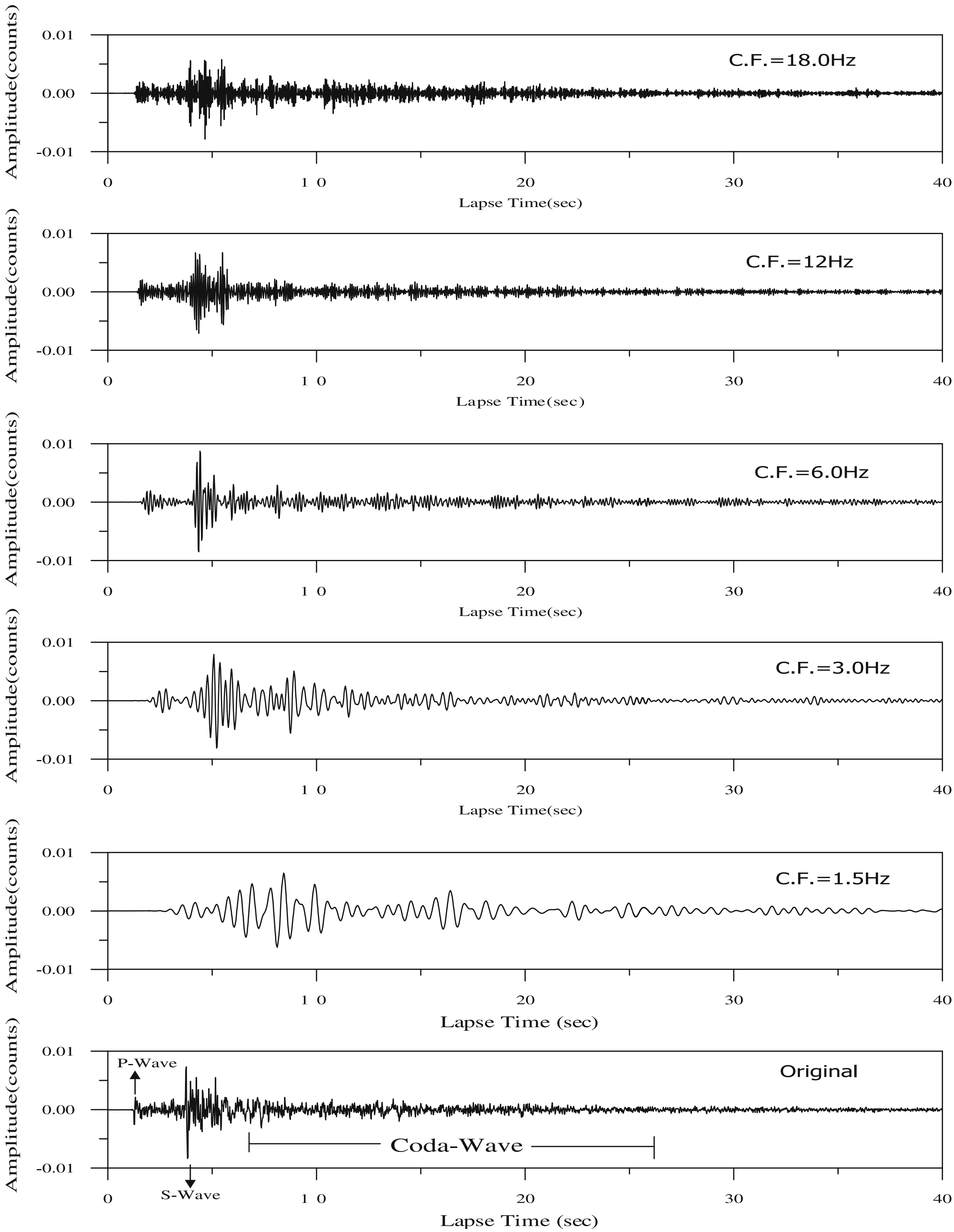


Fig. 2 An example of the P, S, and coda wave portion and filtered seismograms recorded on 11/9/96 at the WRN station (*CF* central frequency)

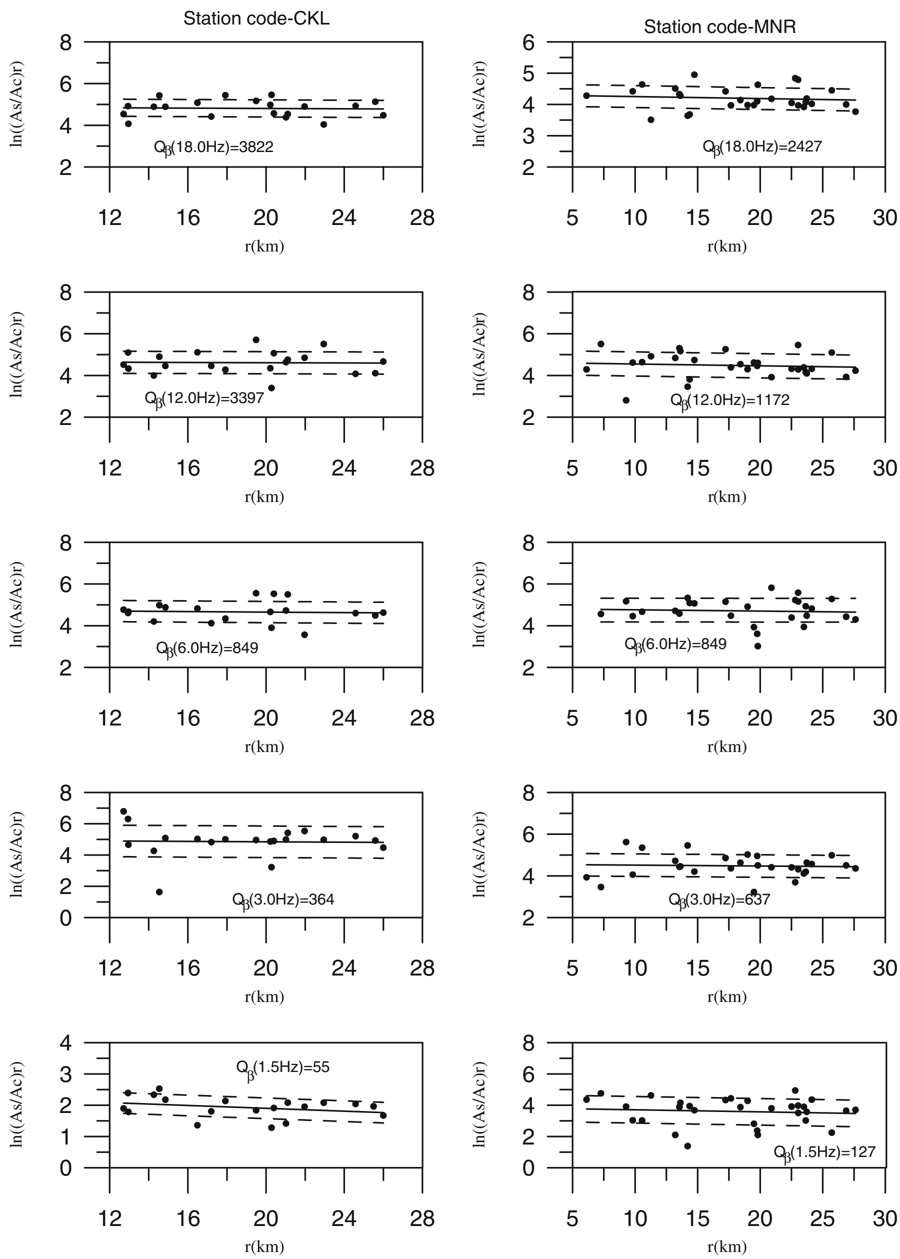


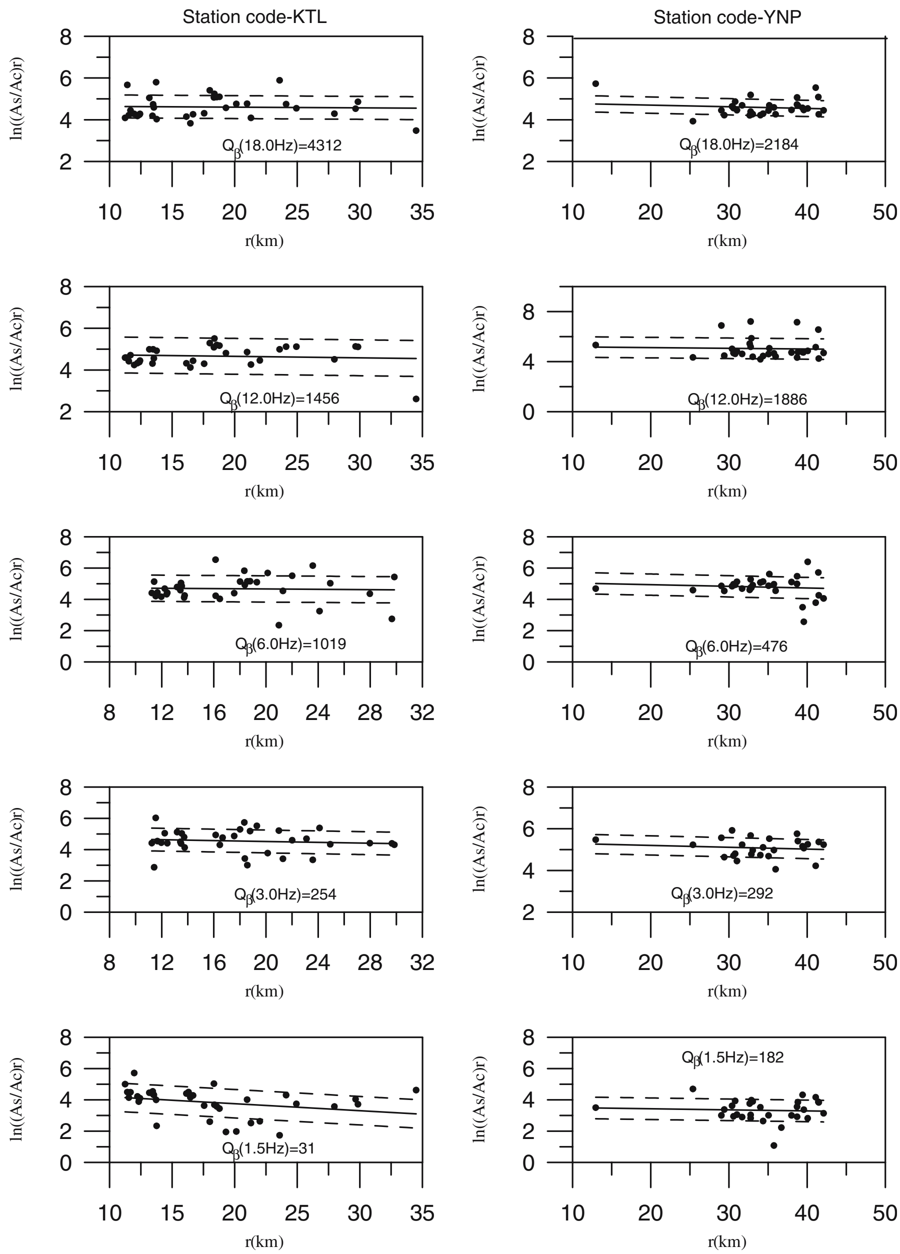
Fig. 3 Coda-normalized peak amplitude decay of S waves with hypocentral distance at five central frequencies. The fitted lines of one standard deviation (s.d.) are also shown at each station

where $A_p(f, r)$ is the spectral amplitude of the direct P wave, and V_p is the average P-wave velocity. The quality factor for P waves can be obtained from the linear regression of $\langle \ln\left[A_p(f,r)r^{\gamma}/A_c(f,t_c)\right]\rangle_{r\pm\Delta r}$ versus r by means of the least square method as done for S waves.

(b) Single back-scattering model

The decay of coda amplitude with time can be used for estimating the quality factor for coda waves (Aki and Chouet 1975). In this model, the coda waves are interpreted as back-scattered body waves generated by the numerous heterogeneities present in the earth's crust and upper mantle. The coda amplitudes have been analyzed using a single scattering model, as well as multiple scattering models (e.g. Frankel and Wennerberg 1987; Jin et al. 1994). We have, in this study, used the simple and most common approach, the single back-scattering model. Under this ap-

Fig. 3 (continued)



proach, the coda amplitudes, $A_c(f, t)$ in a seismogram can be expressed for a central frequency f over a narrow band width signal, as a function of the lapse time T, measured from the origin time of the seismic event, as (Aki and Chouet 1975):

$$A_c(f, T) = A_0(f)t^{-a} \exp(-\pi f T/Q_c) \quad (7)$$

where $A_0(f)$ represents the coda source factor that is considered a constant, a the geometrical spreading factor and taken as 1 for body waves, and Q_c the apparent quality factor of coda waves representing the attenuation in the medium. The above equation can be simplified as:

$$\ln(A_c(f, T)T) = \ln A_0(f) - (\pi f/Q_c)T \quad (8)$$

It is an equation of straight line with the slope $-\pi f/Q_c$ from which Q_c can be estimated.

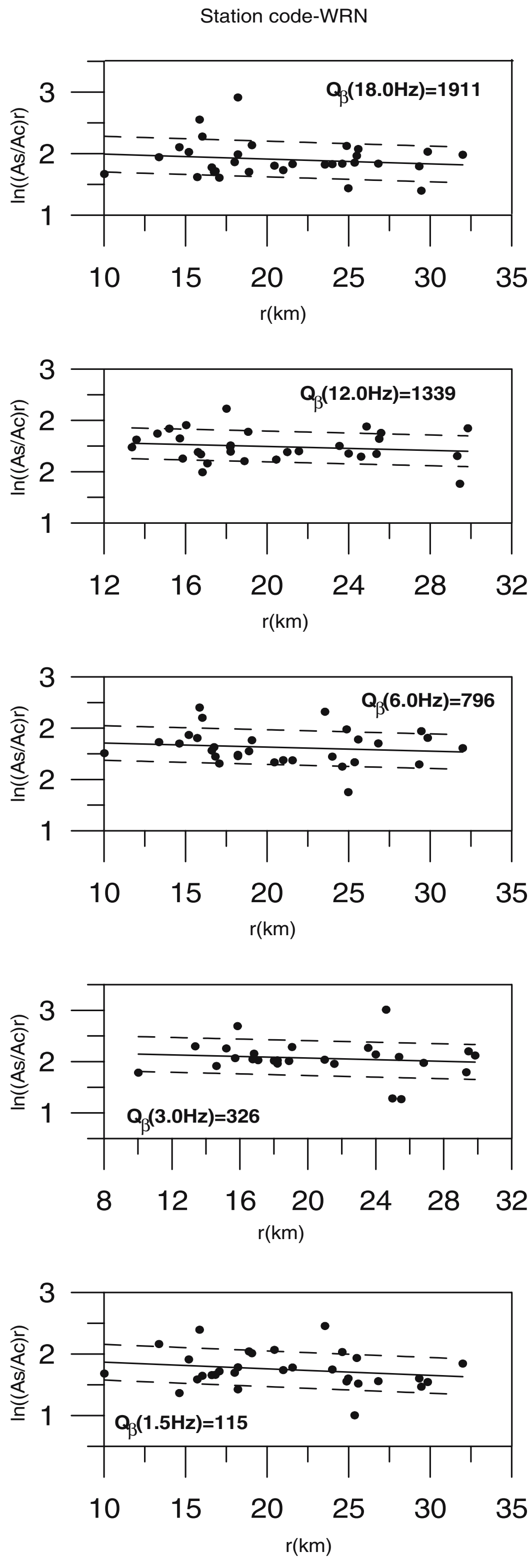


Fig. 3 (continued)

3 Study area

The Indian subcontinent is under severe compressive stress resulting from the collision of the northward-moving Indian plate with the Eurasian plate about 50 million years ago, producing the Himalayan mountain range and the Tibetan plateau. Whereas Himalayan earthquakes are associated with plate collision, the earthquakes of peninsular India are preliminary intra-plate activities caused by crustal faults and epirogenic vertical moment of crustal blocks. In this region, rocks are all Deccan traps. The basement under the traps consists of metasedimentary gneisses, schist, and granite of Dhawarian and Cuddapah age. Crude columnar joints and extensive curved fractures are common to these homogeneous, hard brittle rocks (Krishnan 1960). The Koyna–Warna region of the Indian peninsula is a seismically active region. Seismicity of this zone started after the impoundment of Shivajisagar Lake in 1963 by the construction of the Koyna Dam. The Koyna earthquake sequence is considered as one of the most outstanding example of the reservoir-induced seismicity (Rastogi et al. 1992). Earthquakes of small magnitude are still continuing in the vicinity of Koyna. The seismicity in this region was increased during 1973 when an earthquake of magnitude 5 occurred and three earthquakes of magnitude 5 occurred in 1980 (Rastogi et al. 1992).

The two lineaments, NW and NE, are present in the area (Langston 1981). A major lineament is in NW direction, coinciding with the Warna River in its southeastern part and which is currently active. A deep NNW trending fault is present in the west direction of the Koyna reservoir (Kaila et al. 1981a, b). This fault has probably an 8-m throw on the western side, which has been observed along the Warna River course for a few meters length in the excavation done for the Warna Dam (Rawat 1982). The areas of intersection of NW trend with NE appear to be more seismically active, and relocated depths are within 12 km of this region (Rastogi and Talwani 1980). The 30-km long NS seismic zone extending southward from the Koyna Dam has been active all the time from 1967 onwards (Rastogi et al. 1997). Talwani (1997) relocated the seismicity between 1963–1995 for the Koyna region and concluded that the area lying between Koyna and Warna Rivers can be divided into several seismogenic crustal blocks. Figure 1 shows the tectonic features of

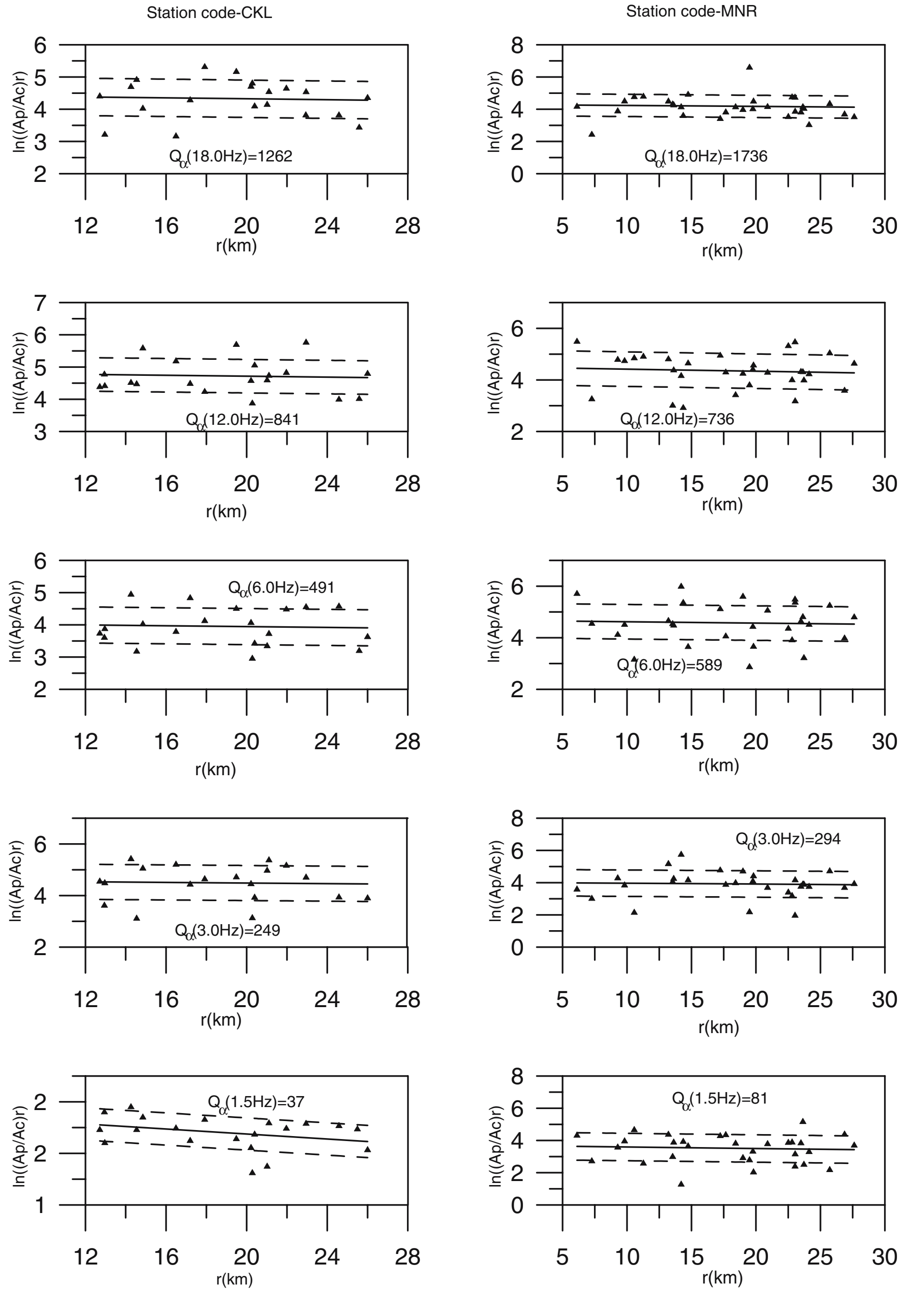


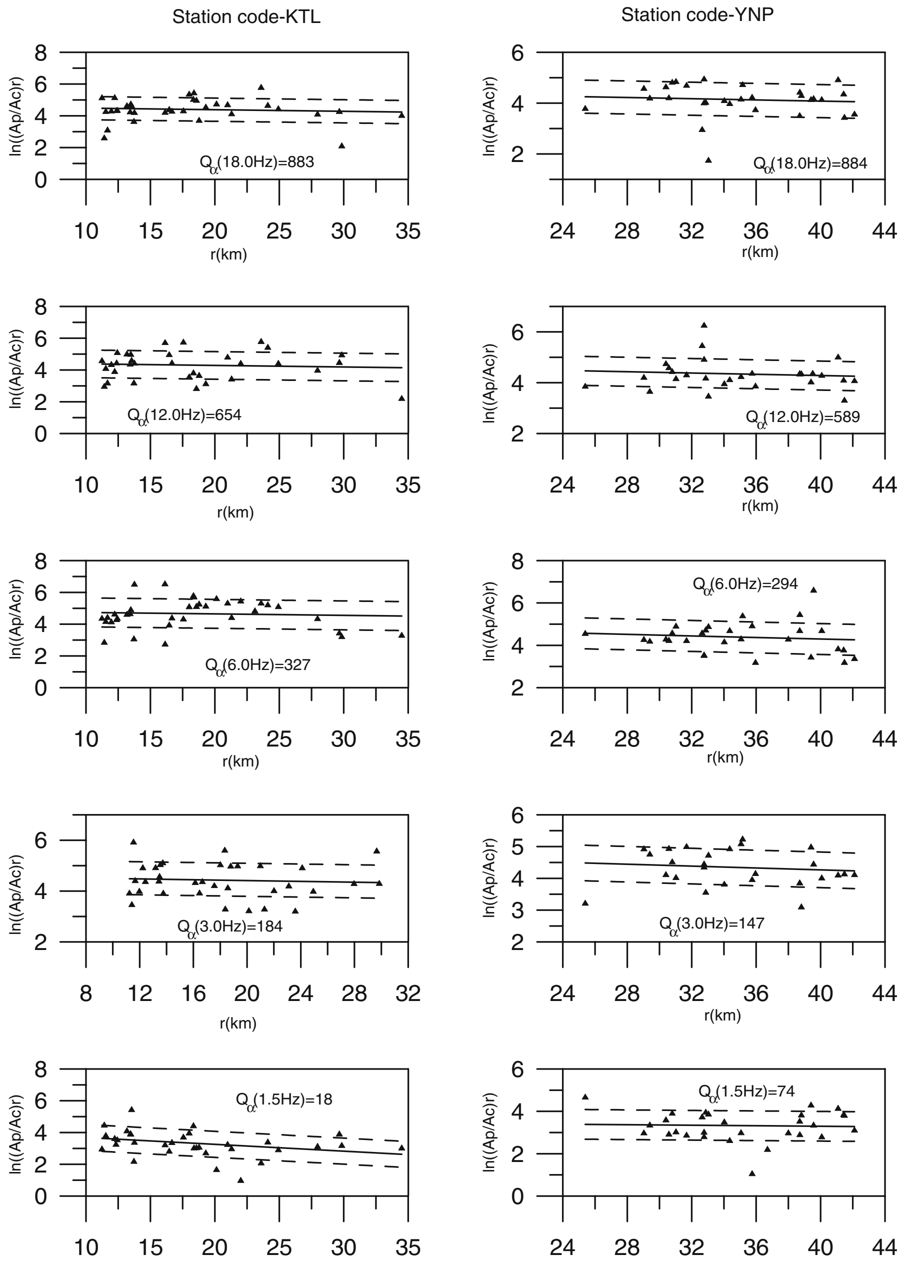
Fig. 4 Coda normalized peak amplitude decay of P waves with hypocentral distance at five central frequencies. The fitted lines of one standard deviation (s.d.) are also shown at each station

the Koyna region along with the locations of the events and recording stations used in this study.

4 Data

The present study is based on 164 seismograms of 37 local earthquakes recorded during the year 1996 in the Koyna region (Fig. 1). These earthquakes were recorded by seismological network deployed by the National Geophysical Research Institute (NGRI), Hyderabad (India) in the Koyna–Warna region. All events were recorded digitally on four to seven stations, using short-period three-component seismometers (1 Hz) at the sampling rate of 50 samples/s, employing Ref-Tek recording instruments. The re-

Fig. 4 (continued)



sponse of the instrument is constant for frequencies above 1 Hz. The events recorded on five stations have been used for the present analysis. The parameters, i.e., names, codes, and locations of the five stations are given in Table 1. The hypocentral parameters, namely origin time, longitude, latitude, and focal depth of the events have been listed in Table 2. These hypocentral parameters have been determined by NGRI. All events are of local origin and are recorded in epicentral distance range from 11 to 55 km with shallow focal depths from 1 to 9 km. Only vertical components have been used in the present study.

5 Results and discussions

The seismograms have been filtered using Butterworth bandpass filter with five different frequency bands.

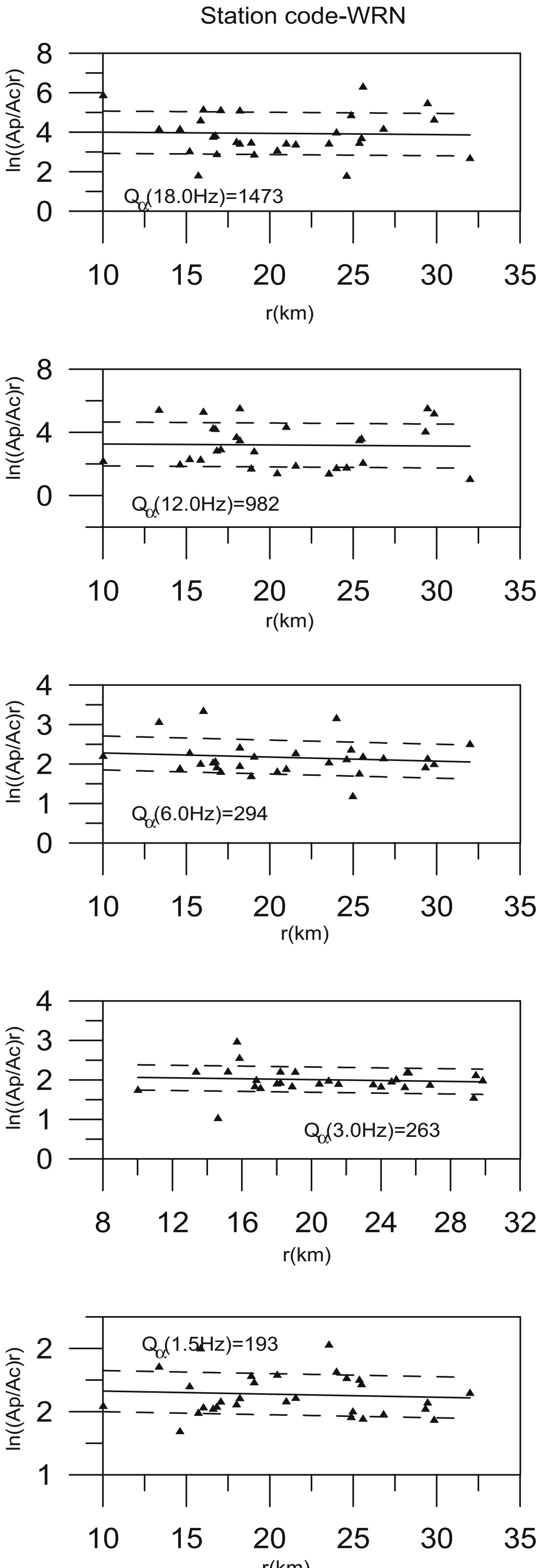


Fig. 4 (continued)

The low cut-off, high cut-off, and central frequencies of these bands are given in Table 3. A root mean square technique (RMS) is applied on these filtered seismograms, giving RMS amplitude of S, P, and coda waves. These amplitudes are used to compute the quality factors Q_α, Q_β, and Q_c. Figure 2 shows an example of the P, S, and coda waves portion and filtered seismograms recorded on 11/9/96 at WRN station. On the filtered seismograms, the amplitudes of direct P and S waves in a window length of 256 samples starting from the onset of both waves have been considered. The coda spectral amplitude has been measured for each frequency band in a window length of 256 samples having 20 s lapse time for each seismogram. Coda amplitude is measured by choosing to be longer than twice the S wave travel time. The average velocities of 6.5 and 3.7 km/s for P and S waves, respectively, have been used in the present study (Rastogi et al. 1992). We assume that geometrical spreading is proportional to r^{-1}.

The plots of the quantity $\ln((A_s/A_c)r)$ versus r along with the least-square-fitted lines at five sites are shown in Fig. 3. The fitted lines of ±1 s.d. are also shown. The corresponding plots for the P waves along with the fitted lines of ±1 s.d. are shown in Fig. 4. The slopes (θ) of the best-fitted lines are used to estimate Q_β and Q_α using the relation (Eq. 4 and 6):

$$Q = -\pi f / \theta V \qquad (9)$$

where Q is Q_α or Q_β and V is V_p or V_s, depending on the type of the waves used. The mean values of Q_α and Q_β, thus, obtained at different central frequencies for the five stations are given in Table 4. The average values obtained from the mean values of different stations are also given in Table 4.

Q_c has been estimated as mentioned earlier (with the help of Eq. 8) using the back-scattering model (Aki and Chouet 1975). Figure 5 shows the variation of $\ln(A_c(f, t)\, t)$ with lapse time t along with the least-square-fitted line using Eq. 8 for an event recorded at KTL on 17/11/96 as an example. The estimated mean values of Q_c at different central frequencies are given in Table 5. The average values of Q_c obtained from the mean values of different stations are also given in Table 5.

We note from Tables 4 and 5 that the estimated Q values increase with the increase in frequency. The average value of Q_α varies from 81 at 1.5 Hz to 1,248

Table 4 Values of Q_α and Q_β at five central frequencies (CF) along with average values

CF	MNR		KTL		CKL		YNP		WRN		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
1.5	81±9	127±6	18±3	31±5	37±4	55±6	74±9	182±14	193±15	115±12	81±8	102±9
3	294±16	637±19	184±13	254±17	249±18	364±27	147±11	292±20	263±17	326±27	228±15	379±22
6	589±18	849±25	327±19	1019±22	491±22	849±36	294±20	476±35	294±24	796±45	399±21	798±33
12	736±27	117±33	654±24	1456±38	841±29	3397±156	589±55	1886±87	982±56	1339±78	760±38	1850±78
18	1736±36	2427±149	883±29	4312±122	1262±87	3822±177	884±66	2184±111	1473±65	1911±75	1248±57	2831±127

at 18 Hz. The average values of Q_β and Q_c vary from 102 and 150 at 1.5 Hz to 2,831 and 1,776 at 18 Hz, respectively. The increase in Q values with the increase in frequency indicates the frequency-dependent nature of Q estimates in the region. To obtain the frequency-dependent relations, the estimated average Q values (Tables 4 and 5) as a function of frequency are shown in Fig. 6. The fitting of power law $Q=Q_0f^n$ gives the frequency-dependent relations for the region as $Q_\alpha = (59 \pm 1)f^{(1.04 \pm .04)}$, $Q_\beta = (71 \pm 1)f^{(1.32 \pm .08)}$ and $Q_c = (117 \pm 2)f^{(0.97 \pm .07)}$. The similar relations for each station are also obtained and are given in Table 6. We note that the estimated Q values show lateral variation in the region. This variation in Q values may be attributed to the heterogeneities present in the region and/or difference in the distances of the events from the recording stations. Gupta et al. (1998) also observed lateral variation in Q_c values in the same region.

A correlation between the degree of frequency dependence and the level of tectonic activity in the area of measurement have been made by several researchers for a number of tectonic regions (e.g., Aki 1980; Pulli and Aki 1981; VanEck 1988). They ascertained higher n values for tectonically active regions as compared to that of tectonically stable regions. For the coda-Q analysis, the value of Q_0 varies from 47 to 200 and that of n varies from 0.70 to 1.10 for the active regions, including the Parkfield (Hellweg et al. 1995), Friuli (Italy) (Rovelli 1982), and Garhwal Himalaya (India) (Gupta et al. 1995), regions of the world.

In Fig. 7, the Q_c values obtained in the present study have been compared with those estimated for different regions of the world. The relation for Q_c estimated in the present study shows that attenuation characteristics of coda waves in the Koyna region are close to the active regions, like Italy, Garhwal Himalaya, South Spain, Turkey, and South Central Alaska, of the world. Mandal and Rastogi (1998) also made the similar observation about the attenuation characteristics of the Koyna region. They obtained a relation Q_c=169$f^{0.77}$ for the Koyna region using the digital seismograms of 30 earthquakes recorded on one to three stations. Gupta et al. (1998) have estimated the relation Q_c=96$f^{1.09}$ for the same region using 76 seismograms from 13 earthquakes. Using the larger data set of 164 seismograms from 37 earthquakes, the relation Q_c=117$f^{0.97}$ has been estimated in the present

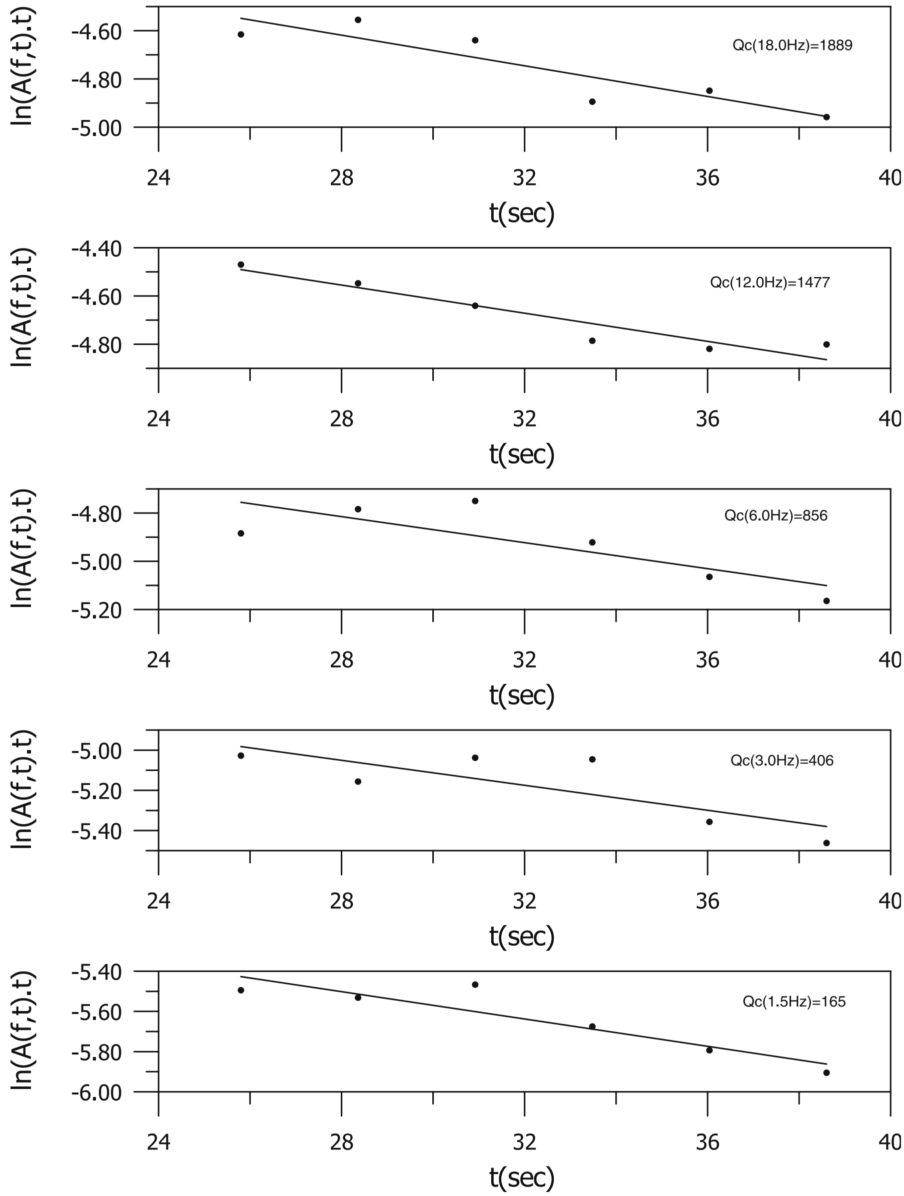


Fig. 5 An example to estimate Q_c at KTL for the event recorded on 17/11/96

study. The wave paths in the larger data set sample the region more completely. We note that the exponent n is higher in the present study as compared to that obtained by Mandal and Rastogi (1998). This may be due to the length of the average lapse time window used in these studies. It has been found that exponent n decreases with the increase in the lapse time window lengths (Pulli 1984; Rocker et al. 1982; Gupta et al. 1998). The lapse time window of 20 s has been used in the present study, while Mandal and Rastogi (1998) have used an average lapse time window of 65 s in their analysis.

The attenuation relations for P and S waves obtained in this study have been compared with those of other regions in Fig. 8a and b, respectively. We observe from Fig. 8a that the rate of increase of $Q(f)$ for P waves in the Koyna region is similar with those of other regions like the Kanto region and South Eastern Korea, although they differ in absolute values. The rate of increase of $Q(f)$ for S waves in Koyna region is comparable with other regions of the world (Fig. 8b).

Singh et al. (2004) have estimated a relation $Q(f)=800f^{0.42}$ for the Indian shield region. This gives the

Table 5 Values of Q_c at five stations at five central frequencies (CF) along with average values

CF	MNR		KTL		CKL		YNP		WRN		Average
	No of events	Q_c	No. of events	Q_c	No. of events	Q_c	No. of events	Q_c	No. of events	Q_c	Q_c
1.5	30	116±12	27	145±28	23	236±16	32	138±19	21	117±11	150±17
3	28	361±17	31	372±34	21	394±27	30	384±22	23	355±25	373±21
6	25	847±35	24	782±45	29	941±38	27	923±39	32	740±37	847±39
12	31	1193±47	34	1334±67	25	1291±45	23	1596±48	18	1177±47	1318±51
18	27	1509±77	22	1681±71	24	1865±81	19	2208±92	33	1616±69	1776±78

The number of events for which the values are estimated for the corresponding station are written.

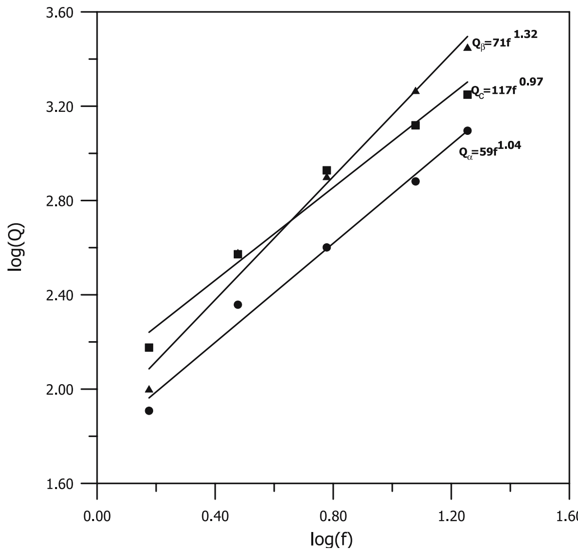


Fig. 6 Estimated average Q values as a function of frequency for P, S, and coda waves, and the corresponding fitting of power law

higher values of Q than estimated in the present study. This difference may be attributed to the data used in these studies. The study of Singh et al. (2004) is based on the earthquakes recorded at larger distances (240–2,400 km), while the data used in the present analysis is from smaller distances (11–55 km). The waves penetrate to deeper parts of the crust when propagating longer distances; therefore, the dependence of attenuation on distance is expected. The dependence of Q on distances has been shown in other regions also. For example, Modiano and Hatzfeld (1982) have obtained low Q values for the distances less than 40 km, while high Q estimates were obtained from the events at distances between 200 and 1,000 km in France (Campillo and Plantet 1991). Dinesh et al. (2005, 2006) have shown the distance dependence of Q for Himalayan earthquakes. The effect of scattering due to heterogeneities present at lower depths is more on the waves recorded at smaller distances.

From the values of Q for P and S waves (Fig. 6), the ratio Q_β/Q_α is greater than unity for the frequency range (1.5–18 Hz) considered in the present study. 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 detail analysis, Yoshimoto et al. (1993) have shown the reversal of Q_β/Q_α ratio at low frequencies (<1 Hz) to high frequencies (>1 Hz). It

Table 6 Frequency dependent Q_α, Q_β and Q_c relationships for five stations

Station code	Frequency dependent relationship using P wave	Frequency dependent relationship using S wave	Frequency dependent relationship using coda wave
MNR	$Q_\alpha = (67 \pm 0.4)f^{(1.09\pm.02)}$	$Q_\beta = (123 \pm 2)f^{(1.02\pm.03)}$	$Q_c = (98 \pm 2)f^{(1.01\pm.02)}$
KTL	$Q_\alpha = (19 \pm 0.1)f^{(1.49\pm.04)}$	$Q_\beta = (23 \pm 0.1)f^{(1.81\pm.06)}$	$Q_c = (112 \pm 2)f^{(0.99\pm.01)}$
CKL	$Q_\alpha = (36 \pm 0.2)f^{(1.3\pm.01)}$	$Q_\beta = (37 \pm 0.2)f^{(1.71\pm.07)}$	$Q_c = (166 \pm 3)f^{(0.84\pm.01)}$
YNP	$Q_\alpha = (51 \pm 0.4)f^{(0.99\pm.01)}$	$Q_\beta = (102 \pm 2)f^{(1.06\pm.04)}$	$Q_c = (102 \pm 2)f^{(1.1\pm.05)}$
WRN	$Q_\alpha = (154 \pm 3)f^{(0.49\pm.004)}$	$Q_\beta = (89 \pm 2)f^{(1.1\pm.03)}$	$Q_c = (95 \pm 2)f^{(1.02\pm.02)}$

has been revealed in the 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., Toksoz et al. 1979; Mochizuki 1982; Winkler and Nur 1982). The study of Johnston et al. (1979) also indicate 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 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,

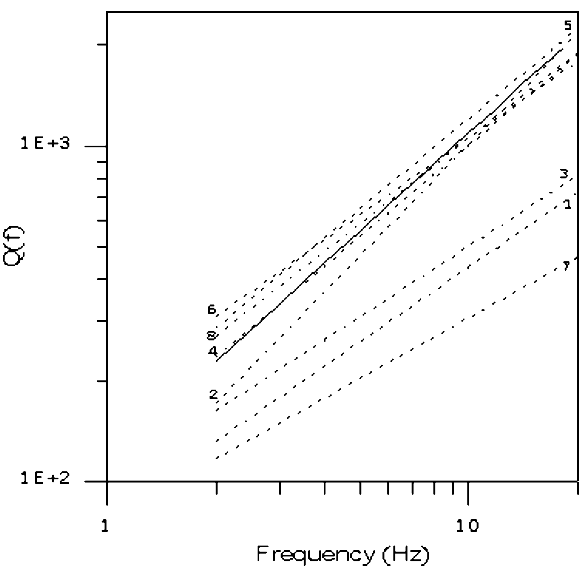


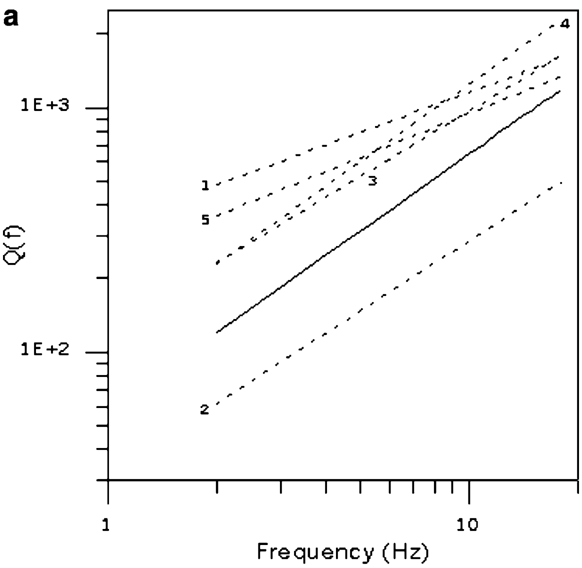
Fig. 7 Comparison of *Q(f)* for coda waves of the Koyna region obtained in this study (*solid line*, $Q(f)=117f^{0.97}$) with those of other regions of the world (*dash lines*). *Line 1* Parkfield, $Q(f)=79f^{0.74}$ (Hellweg et al. 1995); *line 2* Friuli, Italy, $Q(f)=80f^{1.10}$ (Rovelli 1982); *line 3* South Iberia, $Q(f)=100f^{0.70}$ (Pujades et al. 1991); *line 4* Garhwal Himalaya, $Q(f)=126f^{0.90}$ (Gupta et al. 1995); *line 5* South Spain, $Q(f)=155f^{0.89}$ (Ibanez et al. 1990); *line 6* West Anatolia, Turkey, $Q(f)=183f^{0.76}$ (Akinci et al. 1994); *line 7* Central Italy, $Q(f)=77f^{0.6}$ (Castro et al. 2002); *line 8* South Central Alaska, $Q(f)=152f^{0.84}$ (Dutta et al. 2004)

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 (Sato 1984; Hough and Anderson 1988). The ratio Q_β/Q_α along with the frequency dependence of quality factors estimated in this study indicates that scattering is an important factor contributing to the attenuation of body waves in the region.

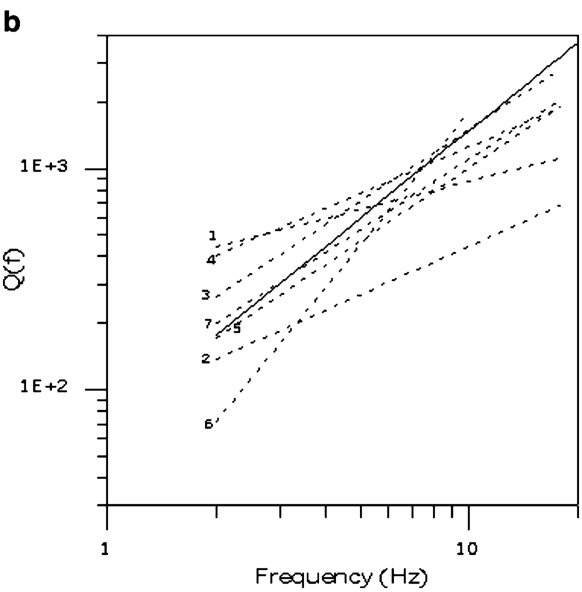
It has been shown by Aki (1969) and Aki and Chouet (1975) that the coda waves are dominated by S to S-back-scattered waves and have a common amplitude decay (e.g., Rautian and Khalturin 1978) for a lapse time greater than twice the S-wave travel time. A comparison of the estimates of Q_c and Q_β in the present study show that $Q_\beta < Q_c$ for frequencies below 4 Hz and $Q_\beta < Q_c$ for the frequencies greater than 4 Hz (Fig. 6). This may be due to the multiple scattering effects of the medium, as the scattering process may affect the two wave types differently. Dutta et al. (2004) have found that $Q_\beta < Q_c$ for frequencies between 0.6 to 3 Hz and $Q_\beta > Q_c$ for the frequencies greater than 3 Hz in south central Alaska region. The Q_β is found to be less than Q_c for the frequency range 2–3 Hz in Central Italy region, while it is reverse for the frequencies between 3–10 Hz (Castro et al. 2002). The results obtained in the present study may be further validated using multiple scattering model (e.g., Hoshiba 1991).

6 Conclusions

This study is an attempt to understand the attenuation characteristics of the Koyna region of the Indian



◀ **Fig. 8** **a** Comparison of $Q(f)$ for P waves of the Koyna region obtained in this study (*solid line*, $Q(f)=59f^{1.04}$) 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 Plantet 1991). **b** Comparison of $Q(f)$ for S waves of the Koyna region obtained in this study (*solid line*, $Q(f)=71f^{1.32}$) 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 Itlay, $Q(f)=18f^{2.0}$ (Castro et al. 2002); *line 7* South Central Alaska, $Q(f)=96f^{1.06}$ (Dutta et al. 2004)



shield using the different parts of the seismograms. The frequency-dependent estimates of body waves (Q_α and Q_β) have been obtained using the extended coda normalization method, and the single back-scattering model has been used to determine the relation for coda waves. The obtained relations are $Q_\alpha = (59 \pm 1) f^{(1.04 \pm .04)}, Q_\beta = (71 \pm 1) f^{(1.32 \pm .08)}$ and $Q_c = (117 \pm 2) f^{(0.97 \pm .07)}$. The values of Q_0 and n obtained in the present study show that attenuation characteristics of the Koyna region are close to active regions of the world. The ratio Q_β / Q_α is found to be greater than one in the present analysis, which is in agreement with the laboratory measurements and studies reported in the literature. The ratio Q_β / Q_α, along with the frequency dependence of quality factors estimated in this study, indicates that scattering is an important factor contributing to the attenuation of body waves in the region. A comparison of Q_β and Q_c obtained in the present analysis shows that $Q_\beta < Q_c$ for frequencies below 4 Hz and $Q_\beta > Q_c$ for the frequencies greater than 4 Hz. This may be due to the multiple scattering effects of the medium, as the scattering process may affect the two wave types differently. This needs further validation using multiple scattering models. The attenuation parameters obtained in this study are useful for the estimation of source parameters and near-source simulation of earthquake ground motions in the region.

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