Pure appl. geophys. 153 (1998) 713–731
0033–4553/98/040713–19 $ 1.50 + 0.20/0

Pure and Applied Geophysics

Coda Q Estimates in the Koyna Region, India

S. C. Gupta,[1] S. S. Teotia,[2] S. S. Rai[3] and Navneet Gautam[4]

Abstract—The coda Q, Q_c, have been estimated for the Koyna region of India. The coda waves of 76 seismograms from thirteen local earthquakes, recorded digitally in the region during July–August, 1996, have been analyzed for this purpose at nine central frequencies viz., 1.5, 2.0, 3.0, 4.0, 6.0, 8.0, 12.0, 16.0 and 24.0 Hz using a single backscattering model. All events with magnitude less than 3 fall in the epicentral distances less than 60 km and have focal depths which range from 0.86 to 9.43 km. For the 30 sec coda window length the estimated Q_c values vary from 81 to 261 at 1.5 Hz and 2088 to 3234 at 24 Hz, whereas the mean values of Q_c with the standard error vary from 148 ± 13.5 at 1.5 Hz to 2703 ± 38.8 at 24 Hz. Both the estimated Q_c values and their mean values exhibit the clear dependence on frequency in the region and a frequency dependence average attenuation relationship, $Q_c = 96f^{1.09}$, has been obtained for the region, covering an approximate area of 11 500 km^2 with the surfacial extent of about 120 km and depth of 60 km.

Lapse time dependence of Q_c has also been studied for the region, with the coda waves analyzed at five lapse time windows from 20 to 60 sec duration with the difference of 10 sec. The frequency dependence average Q_c relationships obtained at these window lengths $Q_c = 66f^{1.16}$ (20 sec), $Q_c = 96f^{1.09}$ (30 sec), $Q_c = 131f^{1.04}$ (40 sec), $Q_c = 148f^{1.04}$ (50 sec), $Q_c = 182f^{1.02}$ (60 sec) show that the frequency dependence (exponent n) remains mostly stationary at all the lapse time window lengths, while the change in Q_0 value is significant. Lapse time dependence of Q_c in the region is also interpreted as the function of depth.

Key words: Q_c, coda waves, Koyna region, single backscattering and lapse time window.

1. Introduction

The knowledge of both seismic wave attenuation and velocity, in a given region, is necessary as these two physical parameters effect the propagation of seismic waves and therefore are required for the exact determination of earthquake source parameters and also for the assessment of seismic hazards in a region.

[1] Department of Earthquake Engineering, University of Roorkee, Roorkee 247 667, India. Fax: 01332-76899, E-mail: quake@rurkiu.ernet.in
[2] Department of Geophysics, Kurukshetra University, Kurukshetra 136 119, India.
[3] National Geophysical Research Institute, Hyderabad 500 006, India.
[4] CGG Pan India Ltd., Gurgaon 122015, India.

Attenuation of seismic waves is described by the dimensionless quantity called quality factor 'Q' (KNOPOFF, 1964), which expresses the decay of wave amplitude during its propagation in the medium. It is a combination of both intrinsic attenuation, the loss of elastic energy to heat or other form of energy, and scattering, which is deflection and/or mode conversion of elastic energy due to heterogeneities in the transmitting medium.

High frequency coda waves recorded during the occurrence of local earthquakes, which arrive at station after the arrival of all direct phases, are assumed to be the superposition of backscattered primary S waves generated by the numerous heterogeneities distributed randomly in the earth's crust and upper mantle. These waves arrive at the station on different time intervals and form a coda. Therefore, the decay of these waves with time, in a seismogram, provides the average attenuation characteristics of the medium instead of the property of a single path connecting from a source to the station. As these waves are the result of numerous heterogeneities distributed randomly, they cannot be explained by any deterministic approach in which a number of parameters is required to describe a small portion of seismogram. However, they can be solved by applying the statistical method in which a small number of parameters is sufficient to describe the properties of coda waves. AKI (1969) and AKI and CHOUET (1975) are pioneers in this field and they proposed a single backscattering model to use the coda waves of local earthquakes for the estimation of quality factor (Q_c) of coda waves in a region.

Numerous studies have been carried out in different parts of the world to determine the seismic wave attenuation properties of the medium. These studies analyze the coda waves of local earthquakes for the estimation of Q_c values, using the single backscattering model (e.g., ROECKER *et al.*, 1982; PULLI, 1984; REHA, 1984; IBANEZ *et al.*, 1990; WOODGOLD, 1994; AKINCI *et al.*, 1994; GUPTA *et al.*, 1995, 1996). A frequency-independent Q study has been done in the Koyna region applying the strong motion acceleration data (GUPTA and RAMBABU, 1994). However, a frequency-dependent Q study has not been conducted in the region.

In the present study, the Q_c values have been estimated for the Koyna region by analyzing the high frequency coda waves of local earthquakes at various central frequency bands. The single backscattering model is used for the estimation of Q_c values and to provide average attenuation properties of the medium around the Koyna region. The coda waves amplitudes have also been analyzed, at five different lapse time window lengths, to study the variation of estimated Q_c values with the lapse time windows.

2. *Study Area*

The Koyna region (Fig. 1) of the Indian Peninsula is a seismically active region. Seismicity of this zone started after the impoundment of the reservoir in 1963 for the construction of the Koyna dam. The Koyna earthquakes' sequence is considered as one of the most outstanding examples of the reservoir-induced seismicity (e.g., GUPTA *et al.*, 1972; GUPTA, 1985). Intense seismicity, with a 6.3-magnitude earthquake, occurred during the period 1967–1969, subsequent to reaching the appropriate reservoir filling level which again increased during 1973–1980 when earthquakes of magnitude 5 occurred (RASTOGI *et al.*, 1992). High seismic flow rate continues in the vicinity of Koyna, and on average 2 to 3 local earthquakes occur per day in the region.

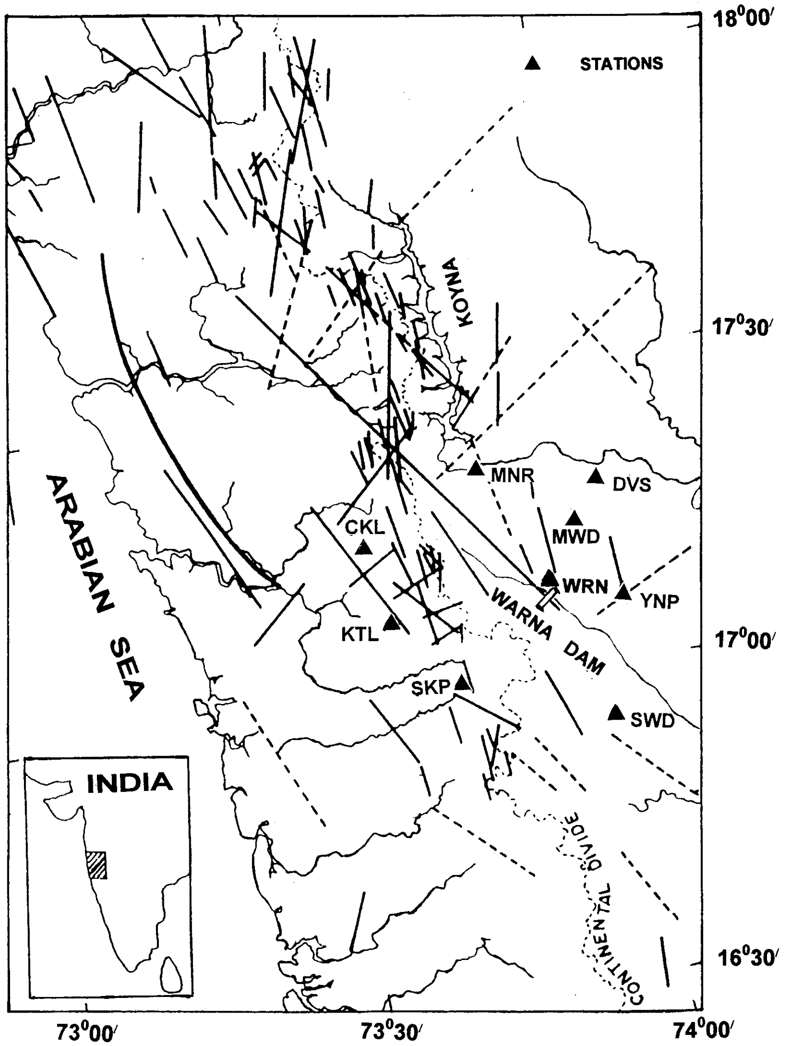


Figure 1
Map showing lineaments in the Koyna–Warna region along with the stations location of the seismological network installed in the region (originally prepared by LANGSTON, 1981 and modified by RASTOGI *et al.*, 1992).

Table 1

Parameters of seismological stations (e.g., name, codes and their locations)

Sl. No.	Station name	Code	Latitude (°N)	Longitude (°E)
1	Warna	WRN	17–07.41	73–53.06
2	Sakharpa	SKP	16–59.77	73–42.81
3	Shahuwadi	SWD	16–54.84	73–57.21
4	Katwali	KTL	17–07.23	73–37.25
5	Chikhali	CKL	17–14.83	73–35.15
6	Marathwadi	MWD	17–14.27	73–56.26
7	Divasi	DVS	17–17.84	73–59.07
8	Yenpe	YNP	17–06.45	74–02.26
9	Maneri	MNR	17–20.51	73–47.73

From a different view the seismicity of this region is related with the two lineaments, NW and NE are present in the area (Langston, 1981). A major lineament is in the NW direction, coinciding with the Warna river in its southeastern part. This is probably a deep fault which is currently active. A deep NNW-trending fault has also been detected by Deep Seismic Soundings just west of the Koyna reservoir (Kaila *et al.*, 1981a,b). This trending fault, with an 8-m throw on the western side, has been observed along the Warna river course for a few meters length in the excavation done for the Warna Dam (Rawat, 1982). In this region, where the geological observation of faults is difficult, there is a cover of volcanic basalt about 2 km thick. Faults are occasionally seen in fresh excavations.

The geology of the Koyna region is fundamental. For miles around to great depths the rocks are all Deccan traps. The basement under the trap consists of meta sedimentary gneisses, schists and granite of Dharwarian and Cuddapah age. The Deccan rocks include a variety of textures, compact, fine-grained, occasionally porphyritic basalt. Crude columnar joints and extensive curved fractures are common to these homogeneous hard, brittle rocks (Krishnan, 1960).

3. The Data Set and Analysis

The data consisting of 76 seismograms of thirteen local earthquakes recorded during July–August, 1996, have been used in the study. These earthquakes were obtained from the operation of the Seismological Network (Fig. 1) deployed by the National Geophysical Research Institute, Hyderabad in the Koyna–Warna region. All events were recorded digitally on 4 to 7 stations, using short-period (1 Hz) three-component seismometers, employing Ref-Teck recording instruments at the sampling rate of 100 samples/sec. However, in the present study, the events recorded only on vertical components have been used. The outstation parameters (e.g., names, codes and locations) are given in Table 1 and their locations are marked on the map of the region (Fig. 1). At all stations the time signals were electronically impinged using GPS, which ensures the accuracy of the time for an event recorded at these stations.

The hypocentral parameters, namely origin time, latitude, longitude and focal depth of the events, have been computed using the HYPO71PC computer program (LEE and LAHR, 1975) and are listed in the Table 2. All events are of local origin with magnitudes less than 3 and are recorded in the epicentral distances of 11 to 55 km with shallow depths from 0.86 to 9.43 km. The epicentral locations of these events are shown in Figure 2.

The coda waves of 76 seismograms related to thirteen local earthquakes have been analyzed to estimate the quality factor (Q_c) for the Koyna region employing the single backscattering model. According to this model, the RMS coda wave amplitudes, $A(f, t)$ in a seismogram, for a central frequency f over a narrow bandwidth signal and lapse time (t), measured from the origin time of the seismic event, can be expressed as

$$A(f, t) = C(f)t^{-a} \exp(-\pi f t/Q_c) \tag{1}$$

where, $C(f)$ is the coda source factor which is considered as constant; a is the geometrical spreading factor ($a = 1$ for body waves), and Q_c is the quality factor of coda waves representing the average attenuation properties of the medium for a given region.

Taking the natural logarithm of equation (1) and rearranging the terms we get,

$$\ln[A(f, t) \cdot t] = c - bt \tag{2}$$

Table 2

Hypocentral parameters of the events considered in this study

Sl. No.	Date	Origin time (IST) hr	min	sec	Latitude (°N)	Longitude (°E)	Focal depth (km)
1	960711	05	47	02.44	17–15.98	73–43.86	6.13
2	960713	15	12	48.82	17–15.85	73–41.99	2.26
3	960715	20	47	55.83	17–16.00	73–41.52	4.68
4	960717	21	55	59.58	17–16.03	73–42.92	8.48
5	960718	09	05	44.95	17–15.98	73–43.00	7.98
6	960721	07	44	48.82	17–13.86	73–45.24	5.76
7	960801	09	39	44.37	17–09.92	73–42.98	1.43
8	960804	04	20	29.23	17–16.21	73–42.84	9.43
9	960812	07	27	16.52	17–06.68	73–46.10	0.86
10	960815	17	51	21.88	17–09.77	73–42.98	5.57
11	960816	01	07	13.37	17–09.66	73–43.29	5.66
12	960816	08	27	46.90	17–09.68	73–43.18	5.13
13	960817	06	40	28.55	17–09.40	73–43.22	1.29

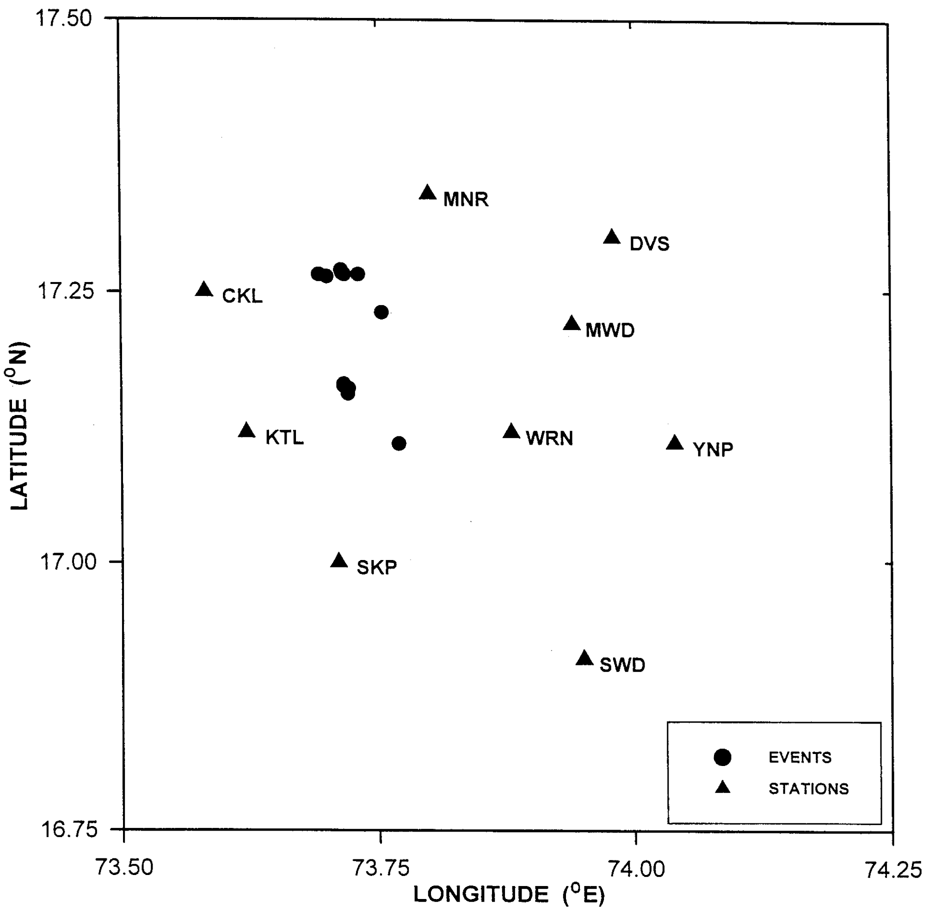


Figure 2
Epicenter map of events located around the Koyna region along with the stations' locations.

where, $b = \pi f / Q_c$ and $c = \ln C(f)$.

Equation (2) represents a straight line and slope of which $b(= \pi f / Q_c)$ provides the Q_c values at a central frequency f. This equation (2) has been used for the estimation of Q_c for the Koyna region.

Each seismogram is filtered using the Butterworth bandpass filter of eight poles (STEARNS and DAVID, 1988). Nine frequency bands (bandwidth $0.67 f_c$, where f_c is the central frequency) are used for this purpose, low cut-off and high cut-off of these bands are given in Table 3. The response of this filter, for a bandwidth of 10 to 20 Hz, is shown in Figure 3.

Seismograms thus filtered are used for the detailed study of the decay of coda wave amplitudes with time to estimate Q_c values at nine central frequencies. Figure 4a shows an example of a seismogram recorded on 15.08.96 at station SWD and

Table 3

Central frequency components of bandpass filter with low and high cut-off frequencies

Low cut-off	Central frequency (f) (Hz)	High cut-off
1.00	1.5	2.00
1.33	2.0	2.67
2.00	3.0	4.00
2.67	4.0	5.33
4.00	6.0	8.00
5.33	8.0	10.67
8.00	12.0	16.00
10.67	16.0	21.33
16.00	24.0	32.00

filtered at five central frequencies. The coda waves of a fixed time window for each filtered seismogram, which starts from the lapse time $t > 2t_s$ where t_s is the direct S-wave travel time (RAUTIAN and KHALTURIN, 1978), are chosen for the analysis. The coda waves of five window lengths of 20, 30, 40, 50 and 60 sec lapse time for each seismogram are used for the study. The arrows (↑) in Figure 4a show the coda window length of 30 sec. The coda wave amplitudes of this window length are smoothed, using a root-mean-square technique which calculates the RMS value of amplitudes of the filtered seismograms in a window of 512 samples (for 1.5 Hz) and 256 samples (for 2, 3, 4, 6, 8, 12, 16 and 24 Hz) with a sliding window along the coda in steps of half of the window, i.e., 256 and 128 samples respectively, and

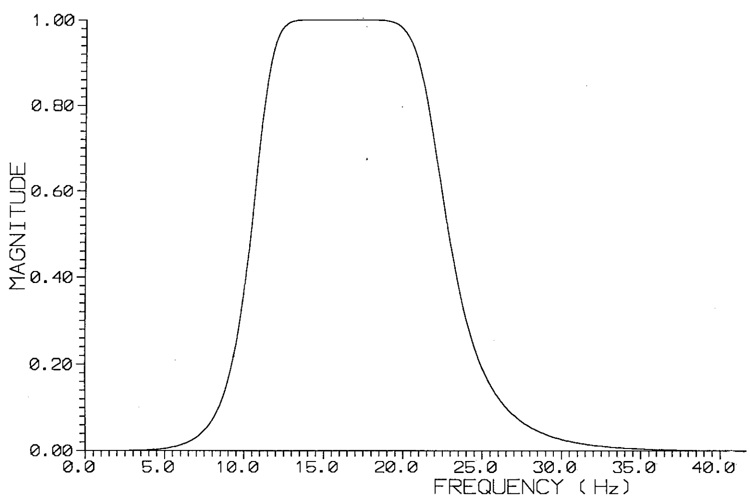
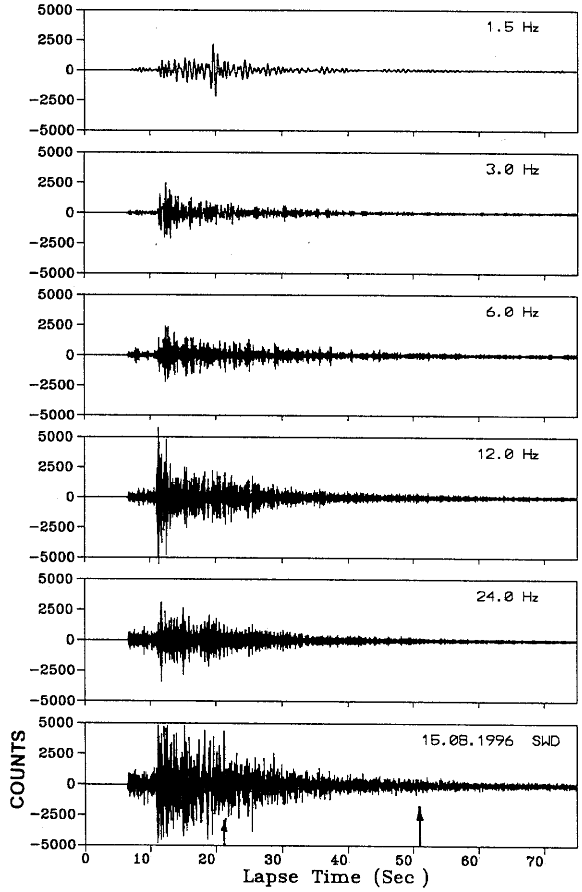


Figure 3
Response of the Butterworth bandpass filter for frequency band 10 to 20 Hz.



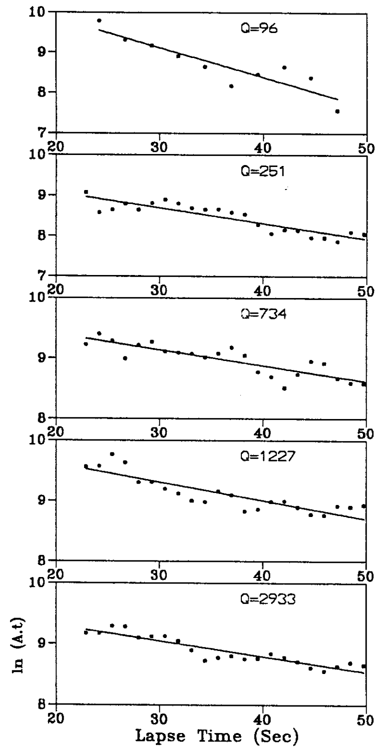


Figure 4a

An example of original and bandpass-filtered seismograms from station SWD recorded on 15.08.96 (no. 10 in Table 2). The coda waves portion of 30 sec window length is indicated by arrows (↑).

Figure 4b

Plot of logarithmic of geometrical spreading corrected and smoothed coda amplitudes as a function of lapse time for the window selected in Figure 4a. The best fitted linear line and estimated Q_c value for each central frequency are also shown in the figure.

which evaluates the RMS value at each step in the same frequency band. These RMS values constitute a smoother envelope of the coda which multiply by the lapse time (t) for applying the geometrical spreading correction. Figure 4b displays the logarithmic smoothed geometrical spreading corrected coda amplitudes of the coda part of filtered seismograms as shown in Figure 4a versus lapse time. The slope of this least-squares straight line, corresponding to each plot, provides the Q_c value for each central frequency using equation (2).

4. Results and Discussion

The quality factor of coda waves (Q_c) has been estimated for the Koyna region, using the digital data of thirteen local earthquakes. The events considered for the analysis are of local origin, with magnitudes less than 3, epicentral distances less than 55 km and focal depths are shallow and lie between 0.86 to 9.43 km. The single backscattering model has been applied on the coda waves of five lapse time windows of 20, 30, 40, 50 and 60 sec duration for 76 seismograms of these local earthquakes. Nine frequency bands of central frequency e.g., 1.5, 2.0, 3.0, 4.0, 6.0, 8.0, 12.0, 16.0 and 24.0 Hz have been used for this purpose. First, the results obtained on Q_c estimation using a 30 sec window length have been discussed, and later the Q_c values estimated as a function of lapse time windows are studied.

From the analysis of coda waves of 30 sec window length, a total 684 Q_c measurements were made in the nine frequency bands however, due to the constraint of high background noise level at some events/stations/frequencies, only 321 Q_c measurements of those which fulfill the criteria of having correlation coefficients (≥ 0.75), are considered. Values of Q_c measurements vary from 81 to 261 at frequency 1.5 Hz and from 2088 to 3234 at frequency 24.0 Hz, and as a

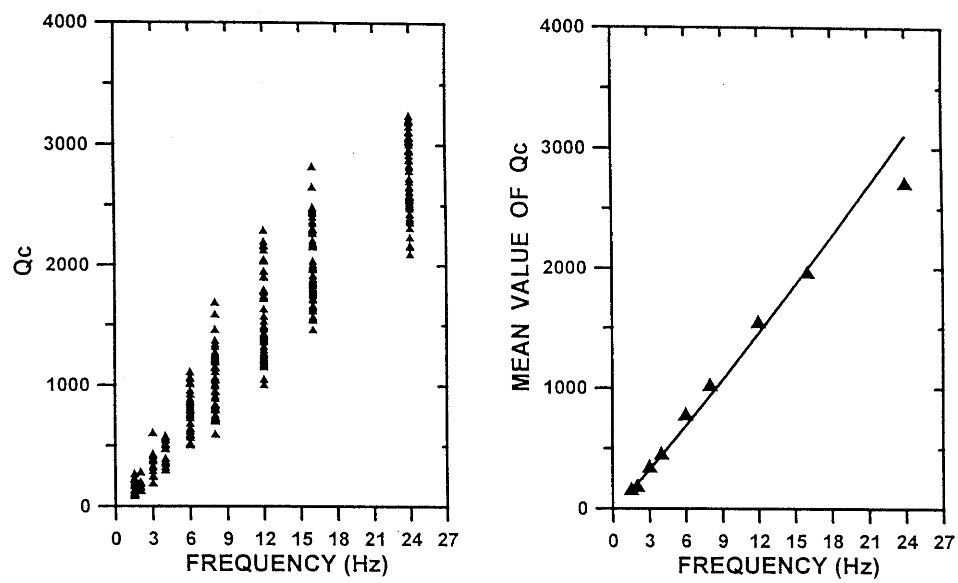


Figure 5a
Plot of all Q_c values as a function of frequency obtained for the Koyna region using 30 sec coda window length.
Figure 5b
Plot of mean values of Q_c as a function of frequency. A power law of the form $Q_c = Q_0 f^n$ has also been fitted, using all mean values and a relationship $Q_c = 96f^{1.09}$, is obtained for the Koyna region.

Table 4

Mean value of Q_c and estimated error at each lapse time window length. N is the total number of observations made for each central frequency

	Mean value of Q_c and error at lapse time window of 20 sec		30 sec		40 sec		50 sec		60 sec	
f (Hz)	Q_c	N	Q_c	N	Q_c	N	Q_c	N	Q_c	N
1.5	105 ± 11.8	14	148 ± 13.5	17	187 ± 14.6	21	206 ± 13.2	18	233 ± 13.7	15
2.0	116 ± 16.4	6	178 ± 17.3	8	228 ± 13.1	14	250 ± 11.2	12	322 ± 18.8	13
3.0	247 ± 27.1	10	335 ± 26.3	15	421 ± 19.8	23	480 ± 22.3	20	560 ± 25.7	13
4.0	354 ± 13.1	8	443 ± 23.9	16	588 ± 29.5	24	714 ± 36.5	23	845 ± 40.7	14
6.0	640 ± 31.3	27	768 ± 29.8	37	1004 ± 37.2	43	1139 ± 44.8	36	1429 ± 55.9	32
8.0	768 ± 25.8	39	1014 ± 39.2	44	1325 ± 46.6	52	1524 ± 51.6	43	1839 ± 66.8	41
12.0	1231 ± 40.2	54	1539 ± 44.7	60	1784 ± 36.8	61	2144 ± 47.7	57	2493 ± 58.2	54
16.0	1604 ± 40.6	61	1956 ± 41.8	63	2209 ± 37.8	61	2535 ± 41.2	60	2849 ± 60.5	57
24.0	2229 ± 44.3	63	2703 ± 38.8	61	3002 ± 41.0	58	3252 ± 48.2	53	3531 ± 52.9	50

function of frequency are plotted in Figure 5a. The variation in the Q_c values observed at various central frequencies may be due (i) to the difference in local site geological conditions of various recording stations, (ii) to the difference in focal depths of the events (from 0.86 to 9.43 km), and (iii) to the difference in the epicentral distances of various events/stations pairs from 11 to 55 km. However, we tried to minimize this variation by considering a mostly similar coda analysis window length (e.g., 20–50 sec in the case of 30 sec window) for all the seismograms. It can be further minimized by reducing above differences in the data set. Therefore, to provide an average picture of the region, averaging of all the Q_c has been done by computing mean values of Q_c from all estimated Q_c values at each central frequency. For the 30 sec coda window length, these mean values of Q_c along with their errors from mean values estimated from the standard deviation are listed in Table 4, which vary from 148 ± 13.5 at 1.5 Hz to 2703 ± 38.8 at 24 Hz. These mean values of Q_c are plotted as a function of frequency in Figure 5b and a power law of the form ($Q_c = Q_0 f^n$) has been obtained as $Q_c = 96f^{1.09}$ for the Koyna region, where $Q_0 = 96$ at $f = 1$ Hz and $n = 1.09$. Figures 5a and 5b and their relationship, $Q_c = 96f^{1.09}$, illustrate that the Q_c is a function of frequency for the Koyna region and the Q_c value increases as frequency increases. The frequency-dependent Q_c relationship, $Q_c = 96f^{1.09}$, provides an average attenuation characteristic of the medium properties of a localized zone around the Koyna region, covering an approximate surface area of about 11 500 km^2 with the lateral extent of about 120 km and depth of approximately 60 km.

To study any lateral changes in Q_c estimates in the region, all Q_c value measurements have been divided into two ellipsoids, A1 and A2. The area of A1 ellipsoid falls in the northern part of the region while the area of A2 ellipsoid falls in the southern part of the region (Fig. 6). The attenuation characteristics for A1 ellipsoid are obtained on the basis of 189 Q_c values estimated from the analysis of coda waves recorded at four stations namely, MNR, DVS, MWD and CKL, while the attenuation characteristics of A2 ellipsoid obtained from the 201 Q_c values estimated from the coda waves of six stations namely, MWD, YNP, WRN, SWD, SKP and KTL. Some of the area in both ellipsoids A1 and A2 is found to be common and some paths of events-stations-pairs for both these ellipsoids are also shown in Figure 6. The frequency-dependent Q_c relationships obtained for both these ellipsoids are $Q_c = 110f^{1.03}$ (for A1) and $Q_c = 92f^{1.10}$ (for A2). The study shows a small lateral variation in Q_c values from north to south. The variation in Q_0 and n indicates that the area of the southern part of the region seems to be more heterogeneous/active compared to the northern part of the region.

Gupta and Rambabu (1994) obtained Q in the region by using the data of thirty-one accelerograms with strong motion record of local earthquakes which have a hypocentral distance extending to 30 km. They found that Q value obtained in the region corresponds to the frequency-independent anelastic attenuation. A

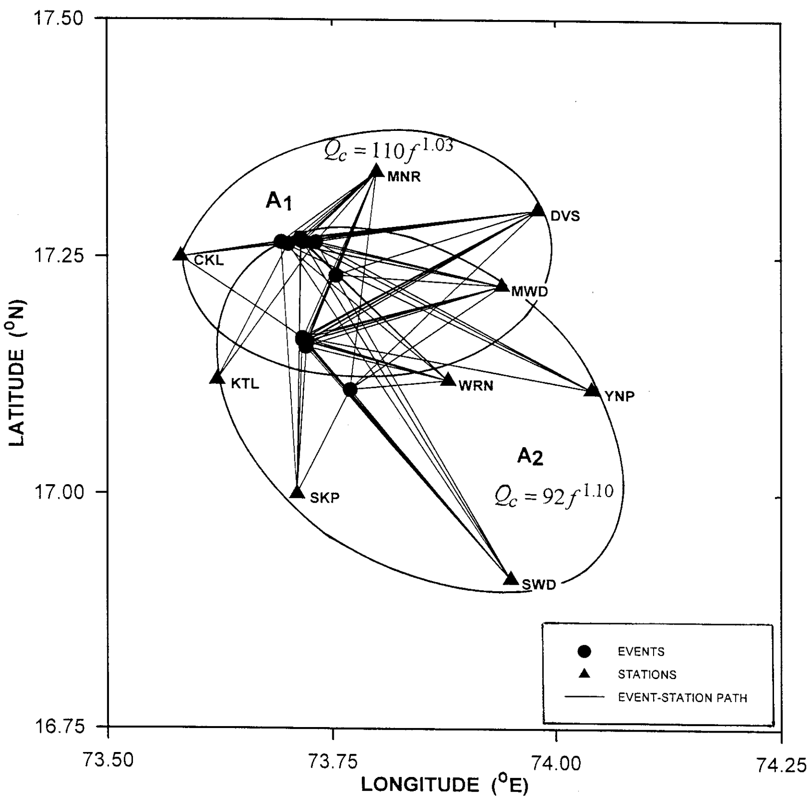


Figure 6
Map showing two zones of ellipsoids A1 and A2 located in north and south directions. Frequency dependence Q_c relationships obtained for both these ellipsoids are also given in the figure.

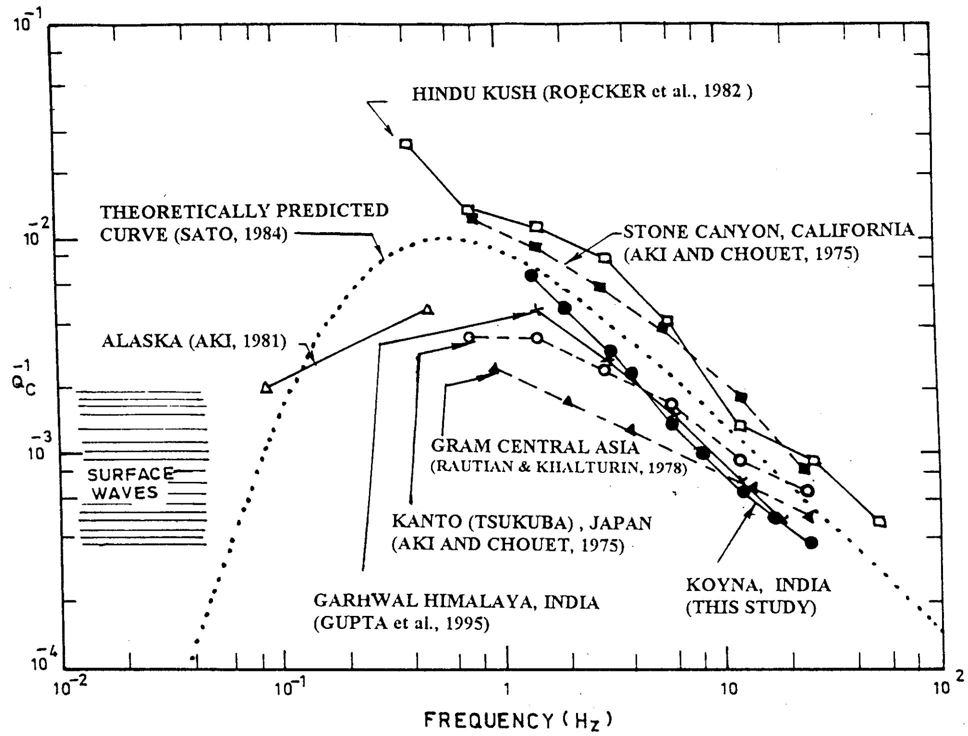


Figure 7
A comparison of Q_c^{-1} as a function of frequency obtained for the Koyna region with other tectonic regions in the world (modified after HERRAIZ and ESPINOSA, 1987).

source-site distance-dependent Q relationship, $Q = (6.456 \pm 1.093)D$, has been obtained for the region, where D is the hypocentral distance. They have also computed an empirical relationship as $Q = 19.22D\, e^{-0.214 M_L}$ for the estimation of magnitude and distance-dependent Q for the region.

A comparison of Q_c^{-1} measurements, as a function of frequency, for the Koyna region, has been made in Figure 7 with the Q_c^{-1} observations of other tectonic regions in the world obtained by numerous investigators. Figure 7 represents that the Q_c^{-1} values of the Koyna region follow a substantially similar trend of Q_c^{-1} decay with frequency as the other tectonic regions and also a theoretically predicted curve is given by SATO (1984).

To study the effect of increasing time window length on the estimation of Q_c values in the region, the coda waves of all 76 seismograms have been analyzed at five lapse time window lengths of 20, 30, 40, 50 and 60 sec duration. The distribution of Q_c observations, made for each lapse time window, which fulfill the criteria of having correlation coefficient (≥ 0.75), are represented in Figure 8 and plots of these Q_c values as a function of frequency are shown in Figure 9.

Averaging of Q_c values has been accomplished at each frequency and their mean values of Q_c, along with the error estimated using the standard deviation, are listed in Table 4. The mean values of Q_c as a function of frequency show an increasing trend with the increasing window length (Fig. 10). This figure shows the empirical relationships, in the form of power law, obtained from the fitting of all the mean values as a function of frequency for each window length and these relationships along with the errors in Q_0 and n. Additionally the correlation coefficients for each window length are listed in Table 5. The increase in Q_c values with lapse time is attributed to an increase of Q_c with depth since the longer the analysis window, the larger will be the sampled area of the earth's crust and upper mantle (Table 5). The increase in Q_c with lapse time has also been interpreted as a function of depth by many investigators (e.g., ROECKER *et al.*, 1982; KVAMME and HAVSKOV, 1989; IBANEZ *et al.*, 1990; WOODGOLD, 1994; AKINCI, 1994; GUPTA *et al.*, 1996).

According to WOODGOLD (1994), the increase in Q_c with lapse time can be caused by any of several factors such as (i) consideration of non-zero source-receiver distance with the nonisotropic scattering, (ii) use of a 2-D model instead of a 3-D model, (iii) use of a single scattering model where multiple scattering is significant. How these factors are taken into consideration in the present study are briefly discussed here.

The consideration of source-receiver distance becomes significant in the case in which the lapse time window length is small enough and close to the direct S-wave arrival. However, in the present analysis, the starting time of all five lapse time

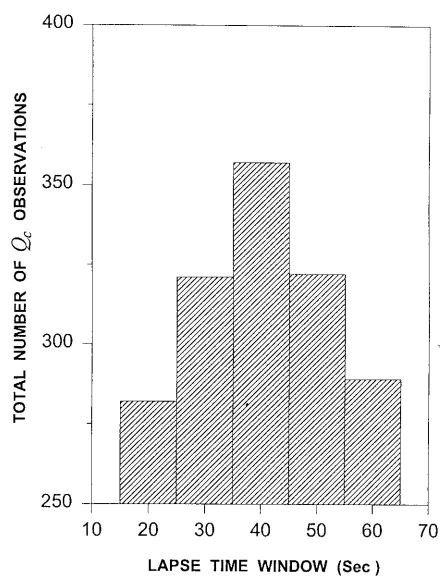


Figure 8
Distribution of Q_c observations made for five lapse time window lengths.

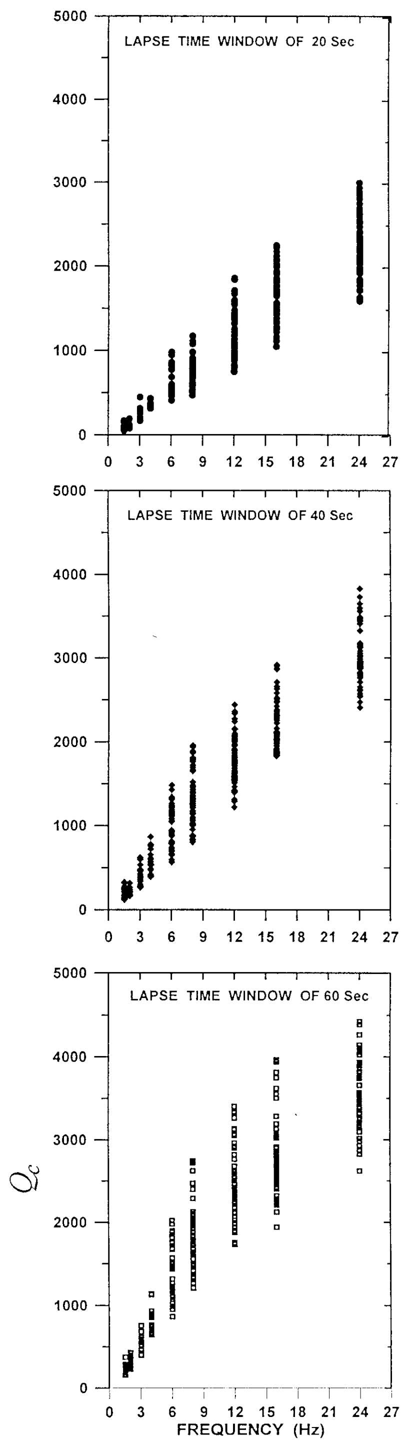


Figure 9
Plot of all Q_c values as a function of frequency obtained at different lapse time windows.

windows has been taken twice of the S-wave travel time (RAUTIAN and KHALTURIN, 1978). This time, in the seismogram, falls long after the arrival of all direct waves and where only backscattered waves arrive (AKI and CHOUET, 1975). Therefore, the consideration of the source receiver as coincident with isotropic scattering will have a similar effect on the results obtained from all the coda window lengths.

The consideration of the single scattering model for all the time windows will also effect the results in a similar manner as KOPNICHEV (1977) and GAO *et al.* (1983) demonstrated that the effect of multiple scattering becomes insignificant for local events with a lapse time less than 100 sec duration, and in the present analysis the lapse time for all the window lengths falls less below than that of the 100 sec duration.

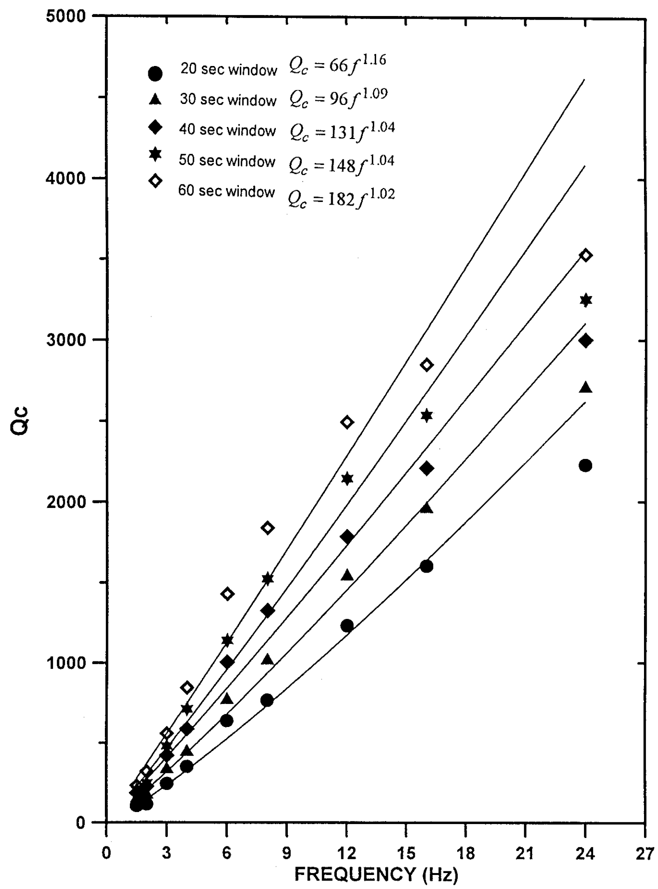


Figure 10
A comparison of mean values of Q_c as a function of frequency obtained at five lapse time windows. Power law fitted for each window is also shown in the figure.

Table 5

Empirical relationships for five lapse time windows are obtained from the mean values of Q_c (Table 4). The ranges given in Q_0 and n are computed at 90 percent confidence interval. The area coverage is computed using the formulation given by PULLI *(1984)*

Lapse time window (sec)	Empirical relationship	Correlation coefficient	Coverage of area (km^2)	depth (km)
20	$Q_c = (66 \pm 11)f^{(1.16 \pm 0.10)}$	0.99	8500	50
30	$Q_c = (96 \pm 12)f^{(1.09 \pm 0.07)}$	0.99	11 500	60
40	$Q_c = (131 \pm 22)f^{(1.04 \pm 0.09)}$	0.98	15 400	70
50	$Q_c = (148 \pm 30)f^{(1.04 \pm 0.11)}$	0.97	20 000	80
60	$Q_c = (182 \pm 42)f^{(1.02 \pm 0.13)}$	0.97	25 500	90

The choice of the 2-D model (single scattering model) instead of the 3-D model seems to be appropriate as the analysis window is greater than 20 sec in which considerable energy is transferred into the mantle (WOODGOLD, 1994). However, the choice of the 2-D or 3-D model only has a small effect on the resultant Q_c value (JIN and AKI, 1988; WOODGOLD, 1994).

Variation in the degree of frequency dependence (n) with increasing lapse time window lengths has been observed in the study area. This value varies from 1.16 at the 20 sec window to 1.02 at the 60 sec window length. A strong correlation between the degree of frequency dependence and the level of tectonic activity in the area of measurement has also been made by several authors for a number of tectonic regions (e.g., AKI, 1980; PULLI and AKI, 1981; ROECKER *et al.*, 1982; VAN ECK, 1988; AKINCI *et al.*, 1994). They ascertained higher n value for tectonically active regions compared to the tectonically stable region. However, in an identical region of study, significant variation in the value of n with increasing lapse time as well as increasing depth, has also been observed by e.g., PULLI (1984) as $f^{0.95}$ (for <100 sec lapse time) and $f^{0.40}$ (for >100 sec lapse time), for New England from the data set with a depth range of 0 to 500 km, while ROECKER *et al.* (1982) obtained $f^{1.0}$ (100 km depth) to $f^{0.75}$ (400 km depth) and $f^{0.50}$ (1000 km depth) for the Hindukush region. Results from both these regions supply information for a very wide area with extensive depth. While in a region of study with smaller lapse time window lengths and shallow focal depths of events, no significant variation in n with lapse time has been observed, which can also be considered as constant (e.g., IBANEZ *et al.*, 1990 and AKINCI *et al.*, 1994 for the Granada basin, South Spain and the western Antolia region, Turkey, respectively).

In the present study, from the analysis of coda waves at different lapse time windows, in the frequency range from 1.5 to 24 Hz, the variation in the value of n as a function of lapse time window is small, which can also be considered as stationary (Table 5). This minor variation in the value of n can be so interpreted that the scattering effect, which is the dominant contributor for the degree of frequency dependence (n), shows a decreasing trend with depth in the depth range from 50–90 km. This may be due to a decrease in heterogeneities (density variation and fractures, etc.) of the medium with depth beneath the Koyna region, while Q_0 value (Q_c at 1 Hz) increases significantly in the region, with a lapse time from 66 to 182. This demonstrates that the effect due to the intrinsic attenuation dominates in the region in the depth range from 50–90 km.

5. Conclusions

In the present study, the Q_c values have been estimated for the Koyna region. The coda waves of 76 seismograms from thirteen local earthquakes recorded digitally around the Koyna region have been analyzed for five lapse time window lengths (e.g., 20, 30, 40, 50 and 60 sec) at nine frequency bands with a central frequency in the range of 1.5 Hz to 24.0 Hz. The focal depths and epicentral distances of these events, with magnitudes less than 3, vary from 0.86 to 9.43 km and 11 to 55 km, respectively.

The estimated Q_c values, for the lapse time window of 30 sec, vary from 81 to 261 at 1.5 Hz and from 2088 to 3234 at 24.0 Hz, while the average value of Q_c along with the standard error from mean vary from 148 ± 13.5 at 1.5 Hz to 2703 ± 38.8 at 24 Hz. Both from the Q_c and their mean values it is clear that the Q_c is a function of frequency in the Koyna region. The Q_c values increase as frequency increases. A frequency-dependent relationship, $Q_c = 96f^{1.09}$, has also been obtained for the region, which represents the average attenuation properties of the medium of a localized zone around Koyna sampling an approximate surface area of about 11 500 km^2, with the surface extent of about 120 km and depth coverage of about 60 km by assuming the single scattering.

An analysis of coda waves at five lapse time window lengths indicates that Q_c is lapse time dependent in the region. The Q_c value increases as the time window increases. The increase in Q_c value with the time window is attributed to the increase in Q_c with depth. The frequency-dependent average Q_c relationships obtained at these window lengths are as $Q_c = 66f^{1.16}$ (20 sec), $Q_c = 96f^{1.09}$ (30 sec), $Q_c = 131f^{1.04}$ (40 sec), $Q_c = 148f^{1.04}$ (50 sec), $Q_c = 182f^{1.02}$ (60 sec) show that there is a significant increase in Q_0 value (Q_c at 1 Hz) with increasing window length, while there is a nominal decrease in the degree of frequency dependence (n) with increasing window length, which can be considered almost stationary. This can also be interpreted that the scattering effect in the region exhibits a decreasing trend, with increasing depth from 50 to 90 km, which may be due to a decrease in the heterogeneities level of the medium while the intrinsic attenuation manifests a dominant role in the region in this depth range.

Acknowledgements

The authors are grateful to the Department of Science and Technology, Earth Sciences (ESS), Govt. of India, New Delhi for providing funds to operate the Seismological Network around the Koyna–Warna region, deployed by the National Geophysical Research Institute, Hyderabad. The Head of Department Earthquake Engineering is acknowledged for providing facilities to carry out this study. Suggestions and comments from Aybige Akinci for enhancement of the manuscripts are highly appreciated.

REFERENCES

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 Inter. *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.

AKINCI, A., TAKTAK, A. G., and ERGINTAV, S. (1994), *Attenuation of Coda Waves in Western Anatolia*, Phys. Earth Planet Inter. *87*, 155–165.

GAO, L. S., LEE, L. C., BISWAS, N. N., and AKI, K. (1983), *Comparison of the Single and Multiple Scattering on Coda Waves for Local Earthquakes*, Bull. Seismol. Soc. Am. *73*, 377–389.

GUPTA, H. K. (1985), *The Present Status of the Reservoir-induced Seismicity with the Special Emphasis on Koyna Earthquake*, Tectonophysics *118*, 257–507.

GUPTA, H. K., RASTOGI, B. K., and NARAIN, H. (1972), *Some Discriminatory Characteristics of Earthquakes Near the Kariba*, *Kremasta and Koyna Artificial Lakes*, Bull. Seismol. Soc. Am. *62*, 493–507.

GUPTA, I. D., and RAMBABU, V. (1994), *High-frequency Q Values from Strong Motion Acceleration Data for the Koyna Dam Region*, *India*, Proc. of Tenth Symp. on Earthq. Engin., Nov. 16–18, 1994, held at University of Roorkee, 83–92.

GUPTA, S. C., SINGH, V. N., and KUMAR, A. (1995), *Attenuation of Coda Waves in the Garhwal Himalaya*, *India*, Phys. Earth and Planet, Inter. *87*, 247–253.

GUPTA, S. C., KUMAR, A., SINGH, V. N., and BASU, S. (1996), *Lapse-time Dependence of Q_c in the Garhwal Himalaya*, Bull. Ind. Soc. Earth. Tech. *33*, 147–159.

HERRAIZ, M., and ESPINOSA, A. F. (1987), *Coda Waves: A Review*, Pure appl. geophys. *125*, 499–577.

IBANEZ, J. M., PEZZO, E. D., DE MIGUEL, F., HERRAIZ, M., ALGUACIE, G., and MORALES, J. (1990), *Depth-dependent Seismic Attenuation in the Granada Zone (Southern Spain)*, Bull. Seismol. Soc. Am. *80*, 1232–1244.

JIN, A., and AKI, K. (1988), *Spatial and Temporal Correlation between Coda Q and Seismicity in China*, Bull. Seismol. Soc. Am. *78*, 741–769.

KAILA, K. L., REDDY, P. R., DIXIT, M. M., and LAZARENKO, M. A. (1981a), *Deep Crustal Structure at Koyna*, *Maharashtra Indicated by Deep Seismic Sounding*, J. Geol. Soc. India *22*, 1–16.

KAILA, K. L., MURTHY, P. R. K., RAO, V. K., and KHARETCHKO, G. E. (1981b), *Crustal Structure from Deep Seismic Sounding along the Koyna 11 (Kelsi-Loni) Profile in the Deccan Trap Area*, *India*, Tectonophysics *73*, 365–384.

KNOPOFF, L. (1964), *Q*, Rev. Geophys. *2*, 625–660.

KOPNICHEV, Y. F. (1977), *The Role of Multiple Scattering in the Formation of Seismogram's Tail*, Izv. Akad. Nauk. SSSR, Fiz. Zemli *13*, 394–398 (in Russian).

KRISHNAN, M. S., *Geology of India and Burma*, 4th ed. (Higginbothams, Madras, 1960).

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

LANGSTON, C. A. (1981), *Source Inversion of Seismic Waveforms: The Koyna India, Earthquake of September 13, 1967*, Bull. Seismol. Soc. Am. *75*, 1–24.

LEE, W. H. K., and LAHR, J. C. (1975), *HYPO71 (revised): A Computer Program for Determining the Hypocenter, Magnitude and First-motion Pattern of Local Earthquakes*, USGS Open File Report *75–311*, 1–116.

PULLI, J. J. (1984), *Attenuation of Coda Waves in New England*, Bull. Seismol. Soc. Am. *74*, 1149–1166.

PULLI, J. J., and AKI, K., *Attenuation of seismic waves in the lithosphere: comparison of active and stable areas*. In *Earthquakes and Earthquake Engineering: The Eastern United States* (ed. Beavers, J. E.) (Ann Arbor Science Publishers Inc., Ann Arbor, Michigan 1981) pp. 129–141.

RASTOGI, B. K., SHARMA, C. P. S., CHADDHA, R. K., and KUMAR, N., *Current Seismicity at the Koyna Reservoir*, *Maharashtra*, *India*, *Induced Seismicity* (Peter Knoll, ed., 1992) pp. 321–329.

RAUTIAN, T. G., and KHALTURIN, V. I. (1978), *The Use of the Coda for the Determination of the Earthquake Source Spectrum*, Bull. Seismol. Soc. Am. *68*, 923–948.

RAWAT, J. S. (1982), *Engineering Geological Studies at Warna Dam*, *Maharashtra*, *India*, Proc. 4th Congress Inter. Assoc. Eng. Geol. III, Theme I., 59–66.

ROECKER, S. W., TUCKER, B., KING, J., and HATZFIELD, 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.

REHA, S. (1984), *Q Determined from Local Earthquakes in the South Carolina Coastal Plain*, Bull. Seismol. Soc. Am. *74*, 2257–2268.

SATO, H. (1984), *Attenuation of Envelope Formation of Three-component Seismograms of Small Local Earthquakes in Randomly Inhomogeneous Lithosphere*, J. Geophys. Res. *89*, 1221–1241.

STEARNS, D. S., and DAVID, R. A., *Signal Processing Algorithms* (Prentice-Hall, Inc., Englewood Cliffs, New Jersey 07632, 1988).

VAN ECK, T. (1988), *Attenuation of Coda Waves in the Dead Sea Region*, Bull. Seismol. Soc. Am. *78*, 770–779.

WOODGOLD, C. R. D. (1994), *Coda Q in the Charlevoix*, *Quebec*, *Region: Lapse-time Dependence and Spatial and Temporal Comparison*, Bull. Seismol. Soc. Am. *84*, 1123–1131.

(Received December 2, 1997, received June 16, 1998, accepted July 25, 1998)