ESTIMATION OF CODA WAVE ATTENUATION FOR EAST OF CENTRAL-IRAN REGION USING LOCAL EARTHQUAKES

Majid MAHOOD [1], and Hossein HAMZEHLOO[2]

ABSTRACT

The occurrence of various seismic events in the East of Central-Iran in the Jiroft region has permitted us to study the seismic attenuation in the short-distance and high frequency range. This study has been performed using coda waves and applying Single Back-Scattering method. *Qc* for coda-waves is determined for the East of Central-Iran, as a function of frequency in the range 1.5–18 Hz. The *Qc* estimates were made for six frequency bands centered at 1.5, 3.0, 6.0, 9.0, 12.0 and 18.0 Hz through five lapse time windows from 20 to 60 s. The estimated average frequency dependence quality factor gives the relation, $Q_c = (88.17 \pm 6.3)\, f^{(1.1 \pm 0.06)}$, while the average *Qc* values vary from *137.4±16.1* at 1.5 Hz to *2151±59.7* at 18 Hz central frequencies. The estimated average frequency dependent relations of *Qc* vary from $(67.45 \pm 7.3)\, f^{(1.15 \pm 0.09)}$ to $(113.95 \pm 8.8)\, f^{(1.04 \pm 0.07)}$ at 20 to 60 sec lapse time window length respectively. *Qc* values depend clearly with frequency and lapse time and results show that *Qc* increases with frequency. The variation of the quality factor *Qc* has been estimated at different lapse times to observe its effect with depth. The lapse time dependence is interpreted as a depth dependence of the seismic attenuation in region. The estimated average values of *Qc* show that *Qc* increases as lapse time window increases. The variation of *Qc* with frequency and lapse time shows that the upper crustal layers are seismically more active compared to the lower lithosphere. The decreasing value of the frequency parameter with increasing lapse time shows that the lithosphere acquires homogeneity with depth. Our results suggest that scattering effects are an important factor affecting the decay of the attenuation functions in the region. This frequency dependence may suggest that scattering loss due to random heterogeneities in the earth medium plays an important role in seismic-wave attenuation in the lithosphere.

Keywords: *Qc*; Coda wave; Attenuation; Lapse time; Scattering; Jiroft (East of Central-Iran).

INTRODUCTION

A seismogenic region can be characterized by tectonic, seismic and volcanic activities in addition to geological formation and geological history. All these properties quantify the behavior of the seismic energy propagation in the lithosphere and can be utilized for seismic hazard mitigation. As the seismic energy propagates through the earth medium, its energy (amplitude) decays due to geometrical spreading, intrinsic attenuation and scattering attenuation (Stein and Wysession, 2003). Intrinsic

1 Ph.D. Student, Seismology Research Center, International Institute of Earthquake Engineering and Seismology (IIEES), I.R. Iran, Email: m.mahood@iiees.ac.ir
2 Assistant Professor, Seismology Research Center, International Institute of Earthquake Engineering and Seismology (IIEES), I.R. Iran, Email: hhamzehloo@iiees.ac.ir

attenuation converts the seismic energy to heat due to anelastic absorption and scattering attenuation redistributes the energy at random heterogeneities present in the upper earth medium. Therefore, the attenuation of seismic waves in the lithosphere is an important property for studying the regional earth structure and seismotectonic activity (Kumar et al., 2005). Jin and Aki (1988) state that the coda quality factor, Q_0 (inverse of seismic attenuation factor) at a frequency of 1 Hz can be useful to quantify the seismicity of regions. Jin and Aki (1989) strongly correlated the coda-Q^{-1} with the degree of fracture in the lithosphere associated with the seismicity.

Usually, seismic wave attenuation is determined from the analysis of direct waves (P & S-wave), surface waves and coda waves. However, in most studies the decay of coda waves of local earthquakes, characterized by Coda Qc, is used to measure the attenuation in the earth's crust. The single backscattering method given by Aki and Chouet (1975) is used to analyse the coda wave of local earthquakes. According to this model the coda waves of local earthquakes recorded within 100 km of epicentral distance are considered as the super-position of backscattered body waves (S-waves) scattered due to numerous heterogeneities present in the earth's crust and upper mantle. Therefore, coda waves provide the average information of the medium instead of the information about the single path connected from source to receiver (Paul et al., 2003).

The region of Jiroft, in Kerman province, is seismically active. To record the local earthquake activity in the region a seven-station digital local network was deployed in November 2004. The network has recorded local earthquakes in the region which provided the opportunity to study seismic-wave attenuation characteristics in high frequency range (1-25 Hz). The data set consists of six digitally recorded local earthquakes occurred in the region within 100 km epicentral distance. The data set was acquired during November, 2004- February, 2005. The coda waves of 32 seismograms of these earthquakes have been analyzed to estimate Q_c in the region. Network sensors were CMG-6TD (Guralp system). The CMG-6TD is three-component digital output seismometer. Each sensor is sensitive to ground vibrations over a wide frequency range (0.033 – 50 Hz as standard).

GEOLOGY AND TECTONICS OF THE REGION

The present-day N-S convergence between the Arabian and the Eurasian plates is accommodated in Southern Iran along the Zagros fold and thrust belt (with a shortening of ~8 mm/yr) and by the subduction of the Oman oceanic lithosphere beneath the Makran (with a rate of 18mm/yr). The analysis of the velocities (together with the measurements of the global network of Iran) leads to that. West of the Lut block at the latitude of Khanuj, the N-S trending Sarduiyeh-Jiroft-Sabzevaran fault system is characterized by a 2 mm/yr right strike slip motion (Bayer et al., 2002). The total convergence rate between Arabia and Eurasia is estimated to range between 23 and 35 mm yr^{-1} in a NNE-trending direction. The deformation through the Minab-Zendan system is accommodated within two fault systems, the western N160°E-trending Minab-Zendan fault system and the eastern north-south Sabzevaran-Jiroft fault system (Regard et al., 2005)(Figure1).

A general review of earthquake patterns along the major strike-slip faults of the western Lut block since 1900, shows a southward and left-step progressing trend of medium-to-large magnitude earthquake clusters along the Kuh Banan (28 November 1933, 6.2; 19 December 1977, 5.7), to the Gowk (11 June 1981, 6.6; 28 July 1981, 7.1; 20 November 1989, 5.8; 14 March 1998, 6.6), and to the Bam fault (26 December 2003, 6.6) systems. About 10 months after the Bam earthquake of 2003, several local earthquakes occurred around the city of Jiroft (Table 1). The population of the city of Jiroft, located adjacent to the Sabzevaran fault, was approximately 60,000 in 1996 (with the township population of 208,000) (Berberian, 2005).

Table 1. Some aftershocks occurred in the region

Date	Time (Local / GMT)	ML
2004/07/13	06:50:15 / 02:20:15	4.0
2004/10/06	14:46:22 / 11:14:22	5.1
2004/10/07	10:43:08 / 07:17:08	4.5
2004/10/24	15:49:15 / 12:19:15	3.7

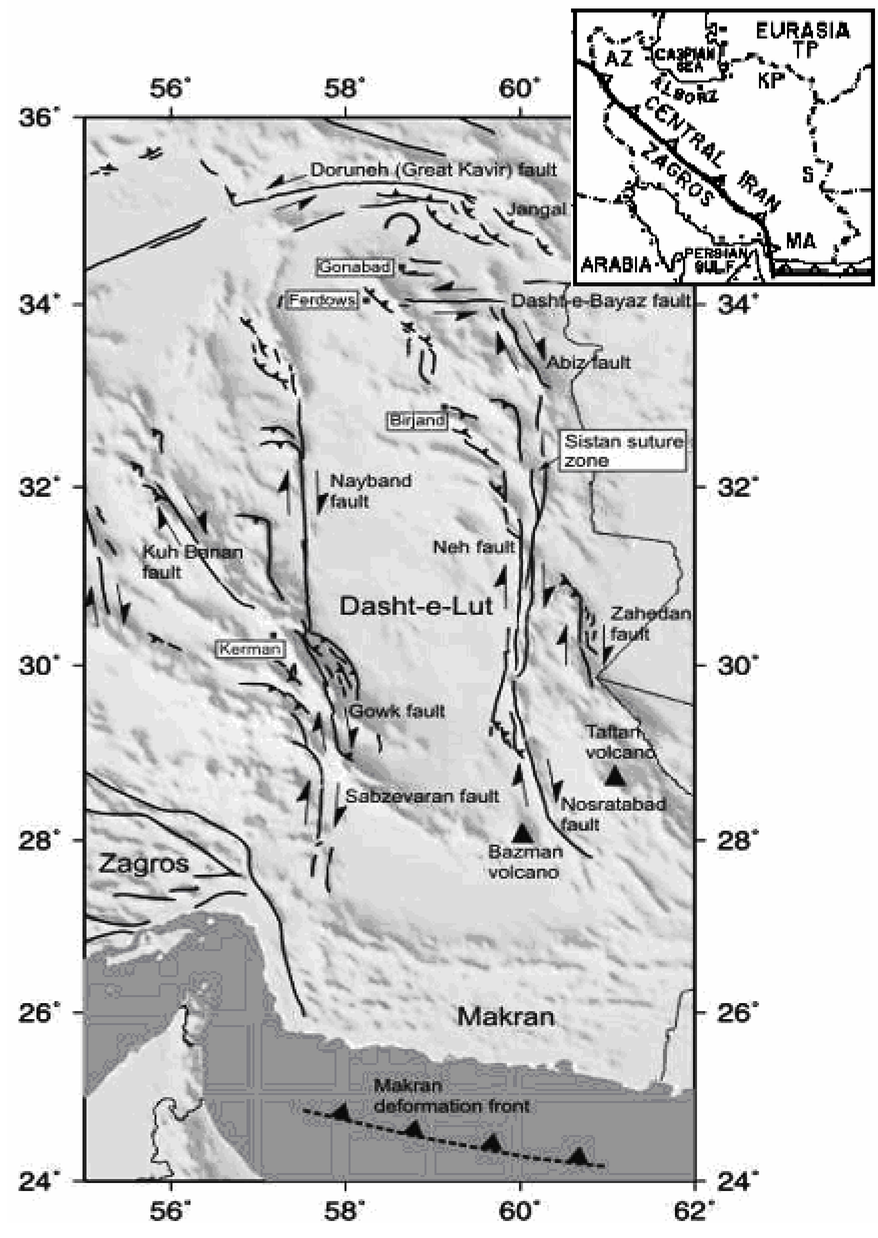

Figure 1. Fault map of eastern Iran (Walker et al., 2004)

METHODOLOGY

The single backscattering method (Aki and Chouet, 1975) has been adopted to analyse the coda wave part of local earthquakes and strong motion records of moderate-sized earthquakes. According to the single backscattering method, the coda wave amplitude, $A(f,t)$, for a narrow bandwidth signal centred at frequency f and at lapse time t, is described as :

$$A(f,t) = S(f)t^{\alpha} \exp(-\pi ft/Qc) \qquad (1)$$

where $S(f)$ represents the source function at frequency f and is considered as constant, α is the geometrical spreading factor and taken as unity for body waves, and Qc is the quality factor representing the average attenuation characteristics of the medium. Qc is estimated from the slope $(= b)$ of the equation after rewriting the above equation in the form:

$$\ln[A(f, t)t] = C - bt \qquad (2)$$

where $C = \ln S(f)$ and $b= \pi f/Qc$. Normally, lapse time t is taken as twice the S-wave travel time, but for strong motion records, t is taken from the point where regular decay of coda waves on the strong motion records, has been started (Rautian and Khalturian, 1978). To estimate Qc at different frequency bands, the coda waves of local earthquake records are filtered at a number of frequency bands (Gupta et al., 1995, Gupta, 1999, Paul et al., 2003) using eight-pole Butterworth bandpass filter. To estimate Qc-value at different frequency bands, the coda waves are filtered at six frequency bands centered at 1.5, 3, 6, 9, 12 and 18 Hz (Table3).

DATA SET AND ANALYSIS

To record the local earthquake activity in the region a seven-station digital local network was deployed at the latest 2004. This network recorded data of local earthquakes that occurred in the region which provided the opportunity to study seismic-wave attenuation characteristics in high frequency range. The network was deployed by the Seismology Research Center, International Institute of Earthquake Engineering and Seismology (IIEES). It comprises of seven stations of medium-band three component seismometer to generate the velocity time history of ground motion in digital form at a sampling rate of 100 samples/sec. Network sensors were CMG-6TD (Guralp system). The CMG-6TD is three-component digital output seismometer. Each sensor is sensitive to ground vibrations over a wide frequency range (0.033 – 50 Hz as standard). The locations of the stations and earthquakes are shown on figure2. Six local earthquakes in digital form recorded within 100 km of epicentral distance are used in this study (Figure2, Table2). The coda waves of 20, 30, 40, 50, 60 sec duration, observed on all the event-station pairs, have been analysed. The quality factor of the coda waves (Qc) has been estimated at six frequency bands (Table3) for the Jiroft region adopting the single backscattering method (Aki and Chouet, 1975). The band-width of $0.67f$ (f is central frequency) has been used in the present study to filter the coda waves using the Butterworth bandpass filter.

Table 2. Hypocentral parameters of the events considered in this study

Sl. No	Date Yr/Mn/D	Origin time (GMT) Hr/Mn/Sec	Latitude (ºN)	Longitude (ºE)	Mag. M_L	Focal Depth (km)
1	04 11 22	02 32 31.5	28.90	57.19	3.4	16
2	04 11 24	15 49 51.6	28.10	57.57	4.1	14
3	04 12 10	19 02 54.2	29.73	57.63	3.6	18
4	04 12 23	11 01 10.3	28.53	57.07	4.0	14
5	05 01 10	18 38 28.1	28.68	57.86	4.0	14
6	05 02 19	19 12 54.4	28.28	55.99	3.3	14

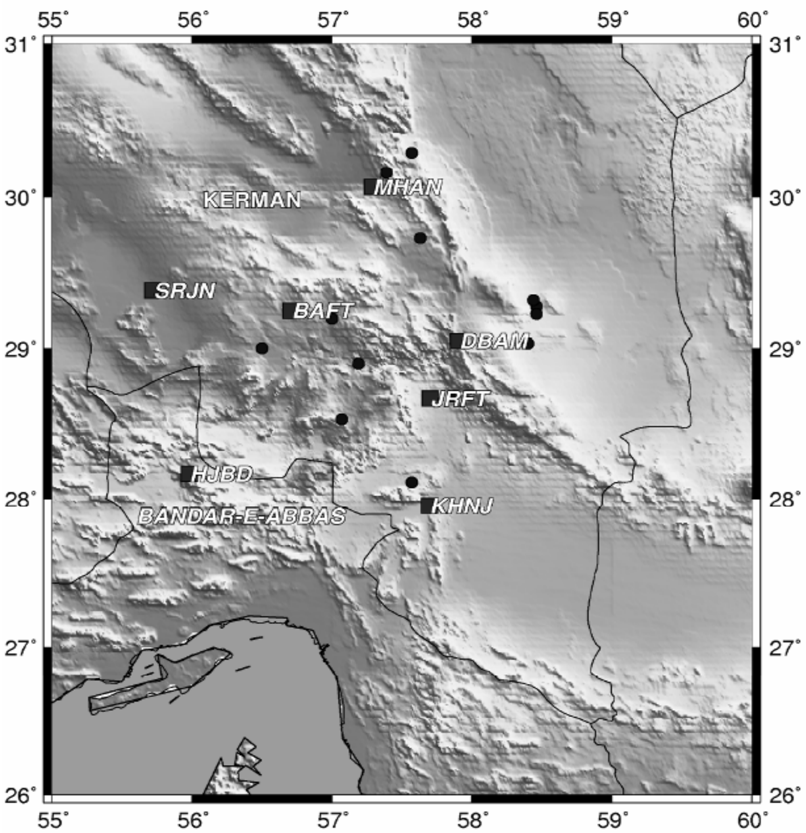

Figure2. Local network(dark squares) and some local earthquakes(dark circles)

Table 3. Parameters of butterworth band pass filter used for filtering the local earthquake data

Low cutoff (Hz)	Central frequency (f_c) (Hz)	High cutoff (Hz)
1.0	1.5	2.0
2.0	3.0	4.0
4.0	6.0	8.0
6.0	9.0	12.0
8.0	12.0	16.0
12.0	18.0	24.0

Seismograms with good S/N ratio are used in this study. The detailed epicentral information of seismic events is given in Table 2. A few more local events are discarded due to low signal to noise ratio and other set criteria for coda *Q* calculation. The lapse times are selected at 2*ts to avoid the data of the direct S-wave. The observations by Roecker et al., (1982), Havskov et al., (1989), Gupta et al., (1998), Giampiccolo et al., (2002) from different regions of the world indicate increased value of *Qc* with lapse time, which is due to greater penetration of waves in the deeper part where the attenuation is less. Therefore, five window lengths are taken from 20 to 60 s with a variation of 10 s to estimate the attenuation at different lapse times for observing the effect with depth. At these window lengths all the seismograms are band pass filtered at central frequencies (*fm*) of 1.5, 3.0, 6.0, 9.0, 12.0 and 18.0 Hz with bandwidths of 1.0, 2.0, 4.0, 6.0, 8.0 and 12.0, respectively. An increasing frequency band is used for increasing central frequency to avoid ringing and to take constant relative bandwidths for getting equal amount of energy into each band as suggested by Havskov and Ottemoller (2003). The RMS amplitude of the last 5 s data of lapse time window is divided by noise data of same length before the onset of the P wave to calculate the S/N ratio. The logarithm of product of RMS amplitude and lapse time is plotted against lapse time as shown in Fig.3 for calculating *Qc* from slope of the linear regression curve of ln(*A(f,t)t*) and *t*. An example of unfiltered and filtered seismograms recorded at MHAN station on 10/12/2004, the slope of linear equation fitted between logarithmic coda amplitudes and lapse time and the *Qc* values obtained at 3 and 18 Hz central frequency are shown in figure 3.

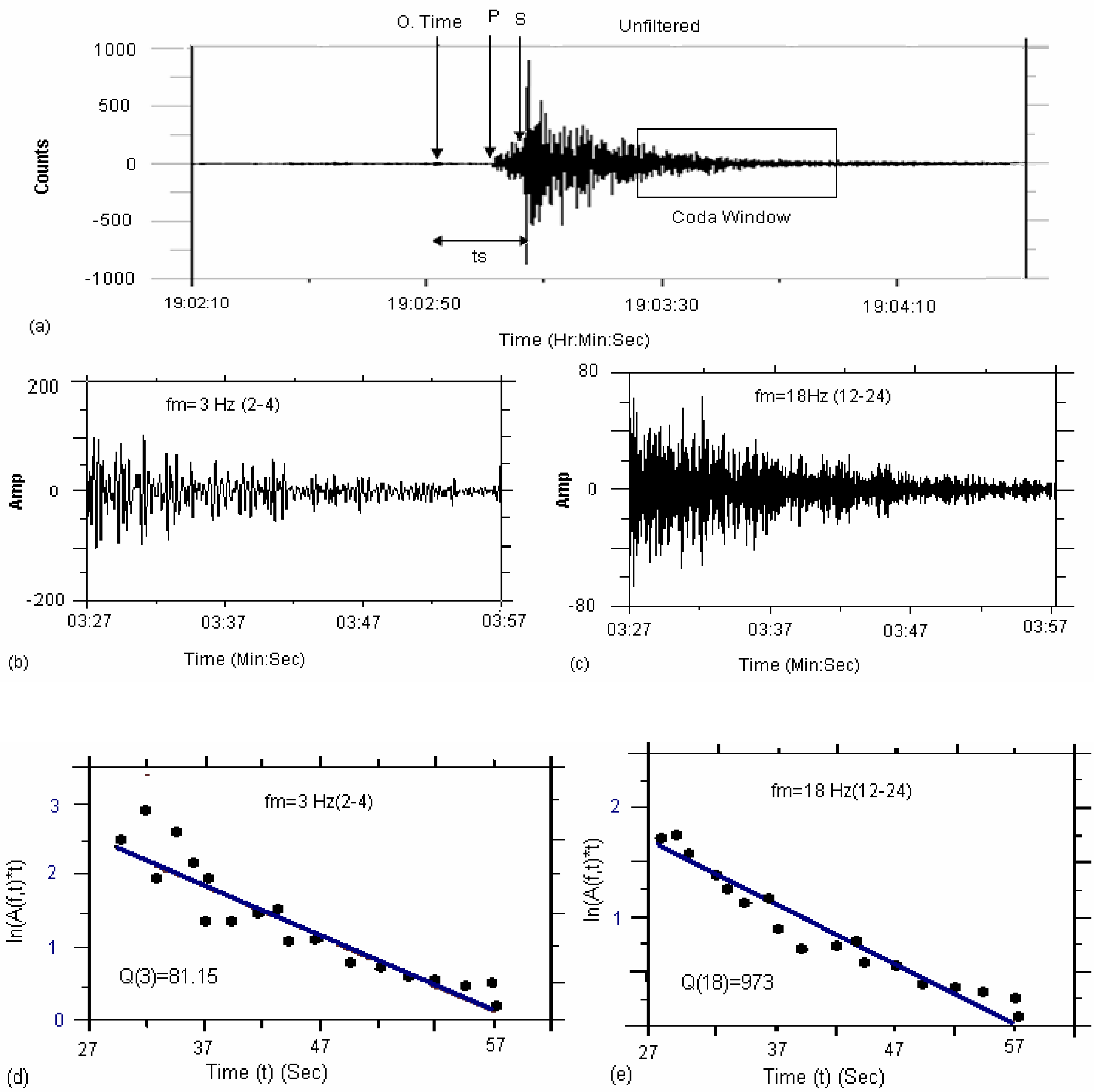

Figure 3. Plot of event recorded at MHAN station on 10/12/2004 from 52 km epicentral distance. (a)Unfiltered data trace with coda window, (b) and (c) bandpass filtered displacement amplitudes of coda window at 2–4 Hz and 12–24 Hz respectively, (d) and (e) the RMS amplitude values multiplied with lapse time along with best square fits of selected coda window at central frequencies of 3.0 and 18.0 Hz respectively. The *Qc* is determined from the slope of best squareline. Abbrevations are: O. Time: Origin time; P: P-wave time; S: S-wave time.

RESULTS AND DISCUSSION

The quality factor, *Qc* has been estimated at six frequency bands of 1.5, 3, 6, 9, 12 and 18 Hz, to assess the effect of tectonic and seismic activity in the Jiroft region in Kerman province (the Kerman province is located on the seismic area in east of Iran where was suffered from several recent events such as Bam earthquake (*Mw 6.6*), Zarand earthquake (*Ms 6.5*) and etc). *Qc* have been derived in this region using the coda waves of 20, 30, 40, 50 and 60sec window length. 30sec coda window from local network stations of 6 events have been used for estimation of *Qc*. The *Qc*-values vary from *137.4±16.1* at 1.5 Hz to *2151±59.7* at 18 Hz. These values are plotted, as a function of frequency, in figure 4 and their mean value is computed at each frequency. Figure 4 demonstrates that *Qc* is frequency dependent and its value increases as frequency increases. The average *Qc* values of the region for all lapse times and frequencies are mentioned in Table 4. Using this data set a frequency-dependent *Qc* relationship in the form of power law, $Q_c = (88.17 \pm 6.3)\, f^{(1.1 \pm 0.06)}$, is obtained for the region which represents the average attenuation characteristics for the Jiroft and surrounding region. The low value of Q_0 and nearly constant high value of frequency parameter indicate that the upper lithosphere around this data group is seismically active and contains more heterogeneities. The study of frequency dependence coda *Q* is interpreted as a tectonic parameter and regions of high tectonic activity are characterized by low *Qc* compared to stable regions where *Qc* is high. Further, the frequency dependent *Qc*-relationship, in the form of $Qc = Q_0 f^n$, generally provides Q_0 (*Qc* at *1*Hz) which represents the level of medium heterogeneities and *n*, power of frequency dependence, represents the level of tectonic activity of the region. Higher *n* value shows that the regions manifest higher tectonic activity.

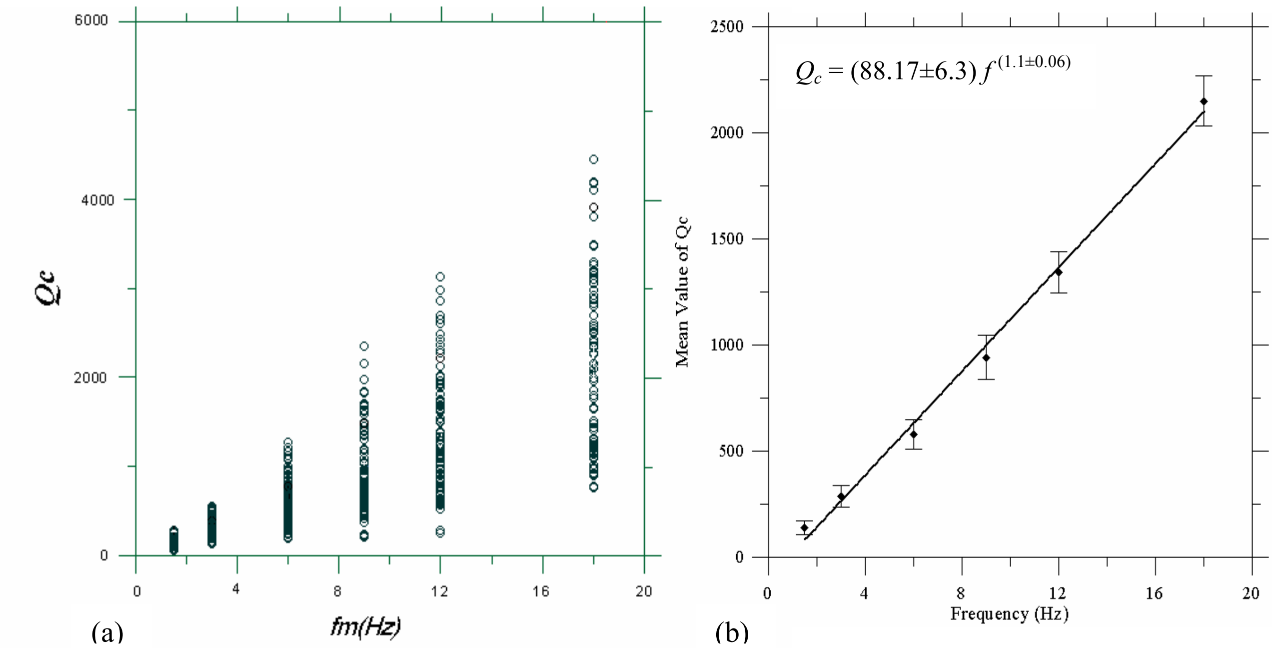

Figure 4. (a) Plot of estimates as a function of frequency. (b) Plot of mean values of Q_c for the Jiroft. Bars show standard error from mean at each frequency. A frequency dependent Q_c relationship in the form of power law has also fitted. A frequency dependent *Qc* relationship $Qc = 88.17\, f^{1.1}$ is obtained for the region.

Table 4. Average quality factor at different frequencies and lapse times

Lapse times(s)	1.5 Hz(1-2) *Qc*	*N*	3 Hz(2-4) *Qc*	*N*	6 Hz(4-8) *Qc*	*N*	9 Hz(6-12) *Qc*	*N*	12 Hz(8-16) *Qc*	*N*	18 Hz(12-24) *Qc*	*N*
20	109.89	93	240.46	92	498.45	92	830.20	92	1224.68	92	1903.44	90
30	137.42	94	287.59	93	579.19	93	941.61	93	1344.15	93	2151.56	93
40	156.82	93	309.82	92	626.31	92	1016.09	92	1398.55	92	2192.74	90
50	172.56	90	324.49	89	667.19	89	1072.60	89	1474.67	88	2310.94	87
60	183.32	87	339.29	86	727.49	86	1164.88	86	1529.25	84	2414.60	81

From a synthesis of available results, Aki (1982) showed that Qc^{-1} increases systematically from tectonically stable to active regions in the frequency range of 0.1 to 25 Hz. He argued that *Qc* can be used as a measure of tectonic intensity for a given region. Jin and Aki (1986) interpreted *Qc* as a tectonic parameter and the regions with high tectonic activity are characterized by low *Qc* values. Further, a strong correlation between n and the level of tectonic activity of the region has been observed by several investigators (Pulli and Aki, 1981, Aki, 1982, Akinci et al., 1994, Jin and Aki, 1986, Kumar et al., 2005). In general, the regions having high *n* value are characterized by the tectonically active regions and tectonically stable regions show low *n* value. For example, for a tectonically stable region such as central United States, almost no frequency dependence is observed ($Qc=1000f^{0.2}$) in the frequency range of interest (Singh and Herrmann, 1983). However, for a tectonically active region such as subduction zone of Japan, *Qc* was found to be a strong function of *n* in the frequency range from 1.5 Hz to 25 Hz (Aki, 1975).

The variation of the quality factor *Qc* has been estimated at different lapse times to observe its effect with depth, and the lapse time dependence is interpreted as a depth dependence of the seismic attenuation in region. The estimated average values of *Qc* show that *Qc* increases as lapse time window increases. The *Qc* values increase with increasing the lapse time (Fig.5). The variation of *Qc* with frequency and lapse time shows that the upper crustal layers are seismically more active compared to the lower lithosphere. The decreasing value of the frequency parameter with increasing lapse time shows that the lithosphere acquires homogeneity with depth.

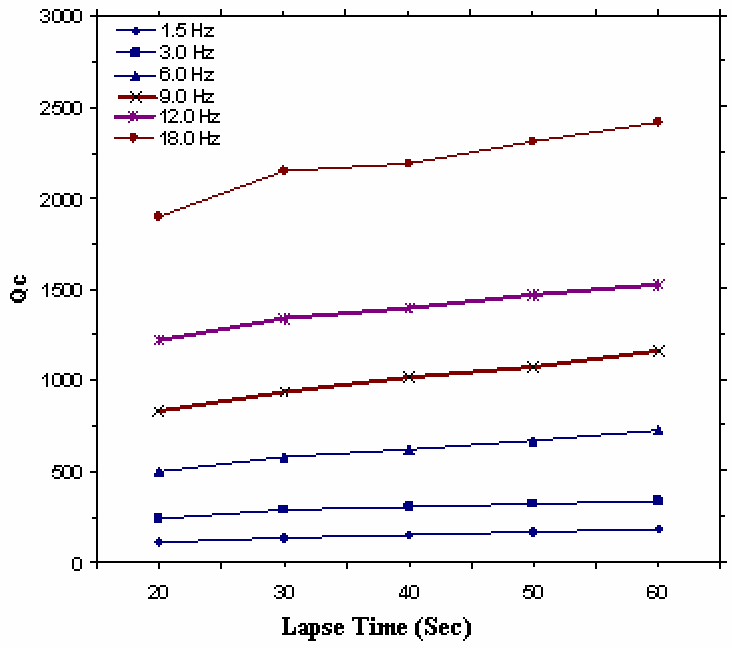

Figure 5. Plot of average values of *Qc* with lapse time at different central frequencies.

Conclusions

The estimated coda *Q* value of Jiroft (east of central-Iran), indicates that the attenuation is greater towards high tectonic and seismic active areas. The obtained *Qc*-values, using 30 sec coda window, vary from 57 to 287 at 1.5 Hz to 761 to 4750 at 18 Hz and their mean values vary from 138 at 1.5 Hz to 2152 at 18 Hz. This showed that *Qc*-values are frequency dependent in Jiroft and their values increase as frequency increases. A frequency dependent *Qc* relationship, $Qc = 88.17f^{1.1}$, is obtained for the region. The relationship provides the average attenuation characteristics for the Jiroft region. *Qc* values depend on clearly with frequency and lapse time and results show that *Qc* increases with frequency. The variation of the quality factor *Qc* has been estimated at different lapse times to observe its effect with depth, and the lapse time dependence is interpreted as a depth dependence of the seismic attenuation in region. The decreasing value of the frequency parameter with increasing lapse time shows that the lithosphere acquires homogeneity with depth. Results suggest that scattering effects are an important factor affecting the decay of the attenuation functions in the region. This frequency dependence may suggest that scattering loss due to random heterogeneities in the earth medium plays an important role in seismic-wave attenuation in the lithosphere.

AKNOWLEDGEMENTS

We acknowledge Dr.G. Javan for providing the data which used in this study. This work was performed to thanks to support from Seismology Research Center, International Institute of Earthquake Engineering and Seismology, Iran, Tenran (IIEES).

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