Hindawi Publishing Corporation
International Journal of Geophysics
Volume 2012, Article ID 673506, 7 pages
doi:10.1155/2012/673506

Research Article

Lg Coda Variations in North-Central Iran

Mojtaba Naghavi,[1] Zaher Hossein Shomali,[1] and Mehdi Zare[2]

[1] *Institute of Geophysics, University of Tehran, Tehran, 14155-6466, Iran*
[2] *International Institute of Earthquake Engineering and Seismology (IIEES), Tehran, 19395-3913, Iran*

Correspondence should be addressed to Mojtaba Naghavi, mmnaghavi@ut.ac.ir

Received 22 July 2011; Revised 5 November 2011; Accepted 7 November 2011

Academic Editor: P. Talwani

Ground motion records in north-central Iran have been used in order to obtain the Lg coda Q, using stack spectral ratio method. The lateral variations in Q_0 and its frequency dependence are estimated in the 0.3–7.0 Hz frequency range which led to $Q = 267(\pm 32) \times f^{0.71(\pm 0.14)}$. The observed variations in quality factor show low values of Q_0 in western part of the study region where bounded by relatively high values in southern and northern parts. Since the seismicity of the study area is quite shallow the obtained results can be attributed to the upper 30 km of the crust. The Damavand volcano and its surrounding region also exhibit variations in the value of Q_0 which result in low and intermediate values of Q_0 in western and eastern parts, respectively. Current seismicity in Damavand is mostly confined to its southwestern part, whereas our results proved to possess low values of Q_0. In general, most of Q factor variations can be attributed to the lateral heterogeneity as well as the severity of the crustal velocity gradient, and as expected the north-central Iran is well inferred as a tectonically active region.

1. Introduction

The energy of a seismic wave decays while passing through a “real” medium such as the earth which is not completely elastic. The decay in energy due to nonelastic phenomena is called intrinsic attenuation and is characterized with the Q parameter, the large values of which represent small values of attenuation and as Q approaches zero the pertaining attenuation will become quite strong. Therefore, Q could be considered as a measure of elasticity of the media.

In the present study, the Q factor is obtained for the Central Alborz in Iran using the Lg coda method. The Lg phase was originally observed using earthquakes occurred in California and has similar characteristics as SH phase with an average group velocity in the order of 3.5 km/s [1]. The regional Lg phase, comprised of multiple shear wave reverberations trapped in the crust, is often used to determine the quality factor (Q) variations for event-station distances less than 1500 km. The Lg phase is typically the most prominent short-period seismic phase observed over continental paths at distances greater than 200 km [2]. Lg phase can be treated as a sum of higher modes of surface waves, or multiple supercritically reflected S waves trapped in the crust [2]. The average group velocity of Lg phase is in order of 3.3∼3.6 km/s, while in stable shields show faster velocities than young active regions [3]. In this study, the Lg coda Q is estimated using ground motions recorded at 35 short-period seismic stations in north-central Iran, using stack spectral ratio (SSR) procedure developed by Xie and Nuttli [4]. This method is widely applied to Lg code studies in the crustal structures in different parts of the world [3, 5–7].

Frequency dependency of Lg phase, due to inelasticity and wave scattering through the crust, significantly depends on tectonic environment and local seismicity. Stable continents are characterized by low-frequency dependence and high-quality factor. In the case of active regions, that is, regions with complex structures in crust and upper mantle, the energy attenuation results in a reduced quality factor and an increased frequency dependence [8]. The method used in

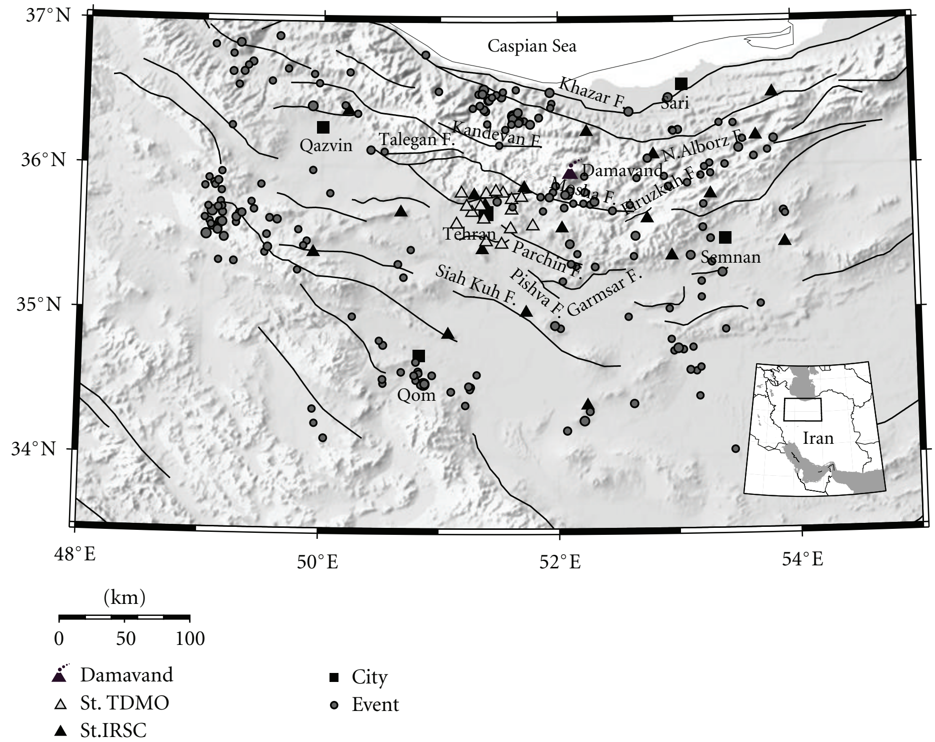

Figure 1: Topographic map of the study area accompanied with the distribution of recording stations and the earthquakes used for the study. Solid lines illustrate the major faults, rectangles represent significant cities, the circles show earthquake epicenters, and triangles indicate seismic stations.

this research to estimate the attenuation dose not distinguish between intrinsic and scattering attenuation but produces an apparent attenuation for the study area.

2. Tectonic Settings of the Studied Area

The study area is located in the northern seismotectonic province of Iran (Alborz). The term "Alborz" is usually used for the mountain range in northern Iran (south of the Caspian Sea) and some of surrounding regions. The Damavand peak is the most prominent geological as well as topographic feature in the region.

The Alborz mountain range, in northern Iran, consists of several sedimentary and volcanic layers and numerous active faults. This mountain belt has an eastwest trend and its width and length are approximately 100 km and 600 km, respectively. The entire system is limited to the Talesh mountains in west and Kopeh Dagh mountains in the east [9, 10]. This area has experienced several destructive earthquakes [11] and accommodates the general motion between the central Iran and southern Caspian Sea [12]. Damavand volcano is the prevalent geo-seismological feature in this mountain range.

Central Alborz is an active mountain-belt and is a part of Alpine-Himalayan mountain belt. The tectonic activity in the Alborz mountain range is predominately affected by two mechanisms, northsouth shortening between Eurasia plate and central Iran and northwest ward motion of the south Caspian basin [13].

The study region is located in central Alborz, bounded by 37°N to the north, 34°N to the south, 49°W to the west, and 54°W to the east. The area of study, distribution of earthquakes as well as the recording stations used in this research are shown in Figure 1.

3. Data Set and Data Processing

Two main seismological networks are used in this study. The first network, Iranian Seismological Center (IRSC) is the national short period seismic network operated by the Institute of Geophysics, University of Tehran (IGUT; http://geophysics.ut.ac.ir/En/) consisting of 54 seismic stations across the country. These stations are equipped with three component seismometers with an eigen-frequency of 1–1.25 Hz (negative feedback SS-1 Ranger Seismometers). The second seismic network is the Tehran city Seismic Network (TCSN), operated by Tehran Disaster Management and Mitigation Organization (TDMMO; http://www.tdmmo.ir/), equipped with three component short-period seismometers established in June 2004 in order to monitor stress field variations and seismicity of Tehran city and its vicinity (Figure 1).

The data used in this study consists of 1020 velocity time histories recorded from 205 earthquakes occurred between 2000 and 2009 with magnitudes between M_L 3.5 and 6.5. The

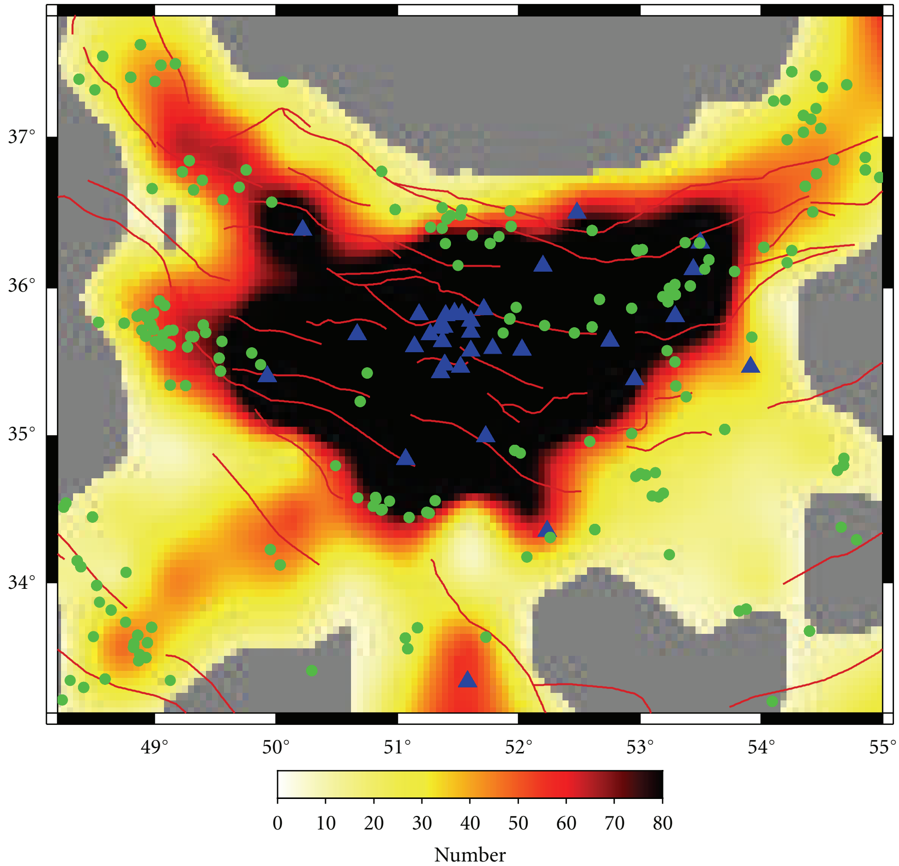

Figure 2: The path-coverage density variation in the study area. Circles and triangles represent earthquake epicenters and seismic stations, respectively.

data come from 19 stations of IRSC and 16 stations of TCSN (triangles in Figure 1). Data acquisition is performed at a sampling rate of 50 and 75 samples per second for IRSC and TCSN networks, respectively. Figure 1 illustrates the stations as well as the recorded seismicity used in this study.

The initial data set consisted of 6470 waveforms. Since the Lg phase is predominantly observed on the vertical components of stations with epicentral distances greater than 140 km, as the first step of data processing, the records of such stations were chosen and their Z-components were selected. As the next step, only the waveforms with high signal-to-noise ratios were selected for the following calculations. Iaspe91 [14] model was also used in order to pick P and S phases on the selected waveforms. As the final step, these waveforms were individually addressed by accurate (manual) phase picking and thus the final data set was prepared.

The path coverage of the data used in this study is shown in Figure 2. The path coverage exhibits large number of crossing paths in the central part of the study area. The resolution is decreased towards the marginal parts of the model.

4. Analysis Method

The group velocity of Lg phase may vary from one region to another depending on different geological settings of the uppermost crust. If there are layered sediments along the propagation path, the velocity will decrease significantly.

In this method, as the very first step, the beginning of P and S phases are marked accurately on each waveform. Then by windowing the waveform, the Lg window spectral ratios are found for each subsequent window (Figure 3) and the quality factor is determined based on frequency estimation by stack spectral ratio and linear regression.

The investigation method is based on the stack spectral ratio procedure developed by Xie and Nuttli [4]. This method can be used to obtain frequency-dependent $Q(f)$ estimates from Lg coda. The use of the stacking procedure is a major development in obtaining stable estimates of $Q(f)$, while there is no need to remove the response of seismograph.

Having estimated the arrivals of P and S waves, the Lg coda time series are obtained using the average Lg-phase group velocity. The time series are divided into several

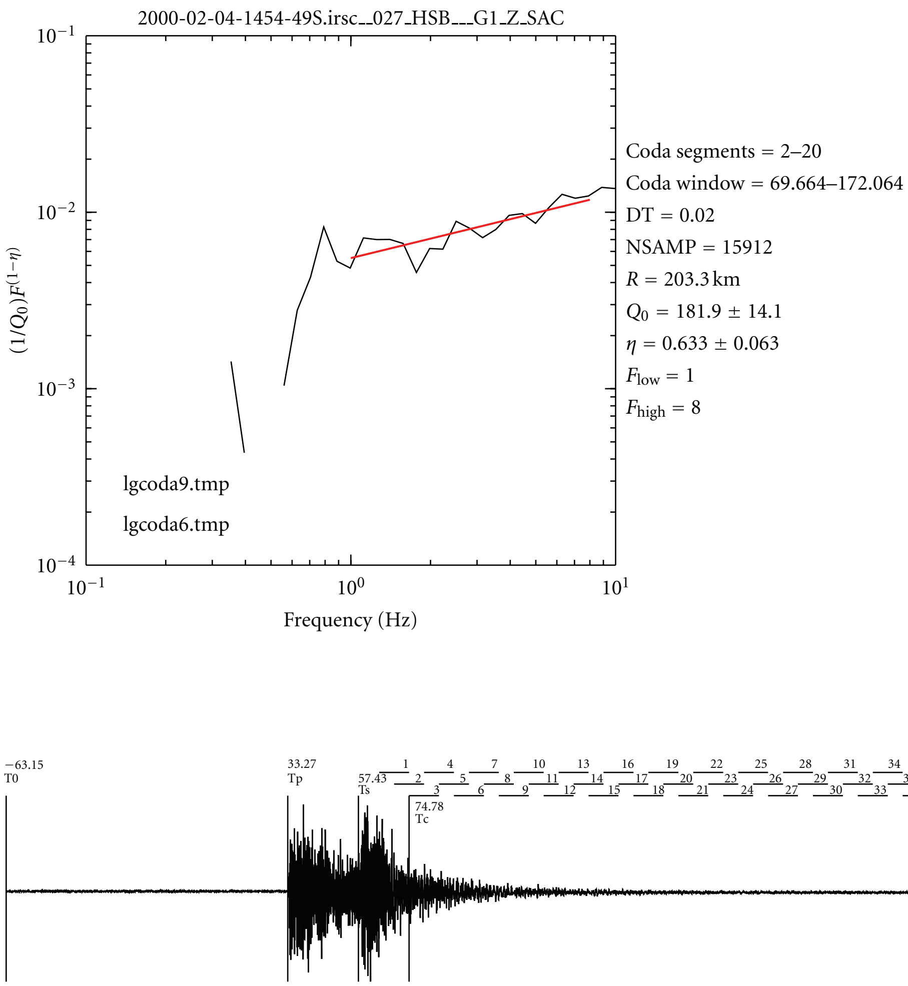

Figure 3: Logarithmic $(1/Q_0)F^{1-\eta}$ versus frequency diagram for earthquakes with epicentral distance of 203 km. Windows are shown on the waveform. Average Q_0 and η are estimated using a linear regression (solid line). The y-intercept of this line gives the quality factor Q_0. Estimated errors are also indicated in the corresponding frequency ranges.

overlapping windows, and the spectral ratio is obtained for each two successive windows. Following Xie and Nuttli [4], the Lg coda spectrum is defined in a fixed width window with a centered time as given below:

$$S(f, t_i) = A_0 G(r, t_i) e^{-\pi f t_i / Q(f)}, \quad (1)$$

where $S(f, t_i)$, f, r, $G(r, t_i)$, and A_0 represent the spectra of the windows, frequency, epicentral distance, geometrical spreading function, and total effects of site, source, and instrument, respectively. We focused on events with epicentral distances greater than 140 km for two reasons. Firstly, in many cases with short epicentral distances, it was difficult to determine the presence of Lg because of interference with that of the higher amplitude S arrivals. Secondly, by using events with distances greater than 140 km, we can assume a constant, frequency-independent geometrical spreading of order of 0.5 [15–18].

The spectral ratio for two successive windows centered at t_1 and t_2 can be written as the following:

$$\text{RATIO}_{12} = \frac{(S(f, t_2)/G(r, t_2))}{(S(f, t_1)/G(r, t_1))} = e^{-\pi f (t_2 - t_1)/Q(f)}. \quad (2)$$

This ratio is not stable due to variations of amplitude spectrum in different successive windows. To improve the estimation of Q the following conditions should be provided.

(1) Applying an appropriate function to window the seismogram. This, prior to the calculation of Fourier transform would result in a smooth amplitude spectrum.

(2) Selecting a wide enough time difference $t_2 - t_1$.

(3) Calculating the mean-value for a large number of spectral ratios which could be expressed as:

$$\text{LNRATIO} = \frac{\ln \text{RATIO}_{ij}}{-\pi \left(t_i - t_j \right)}, \quad (3)$$

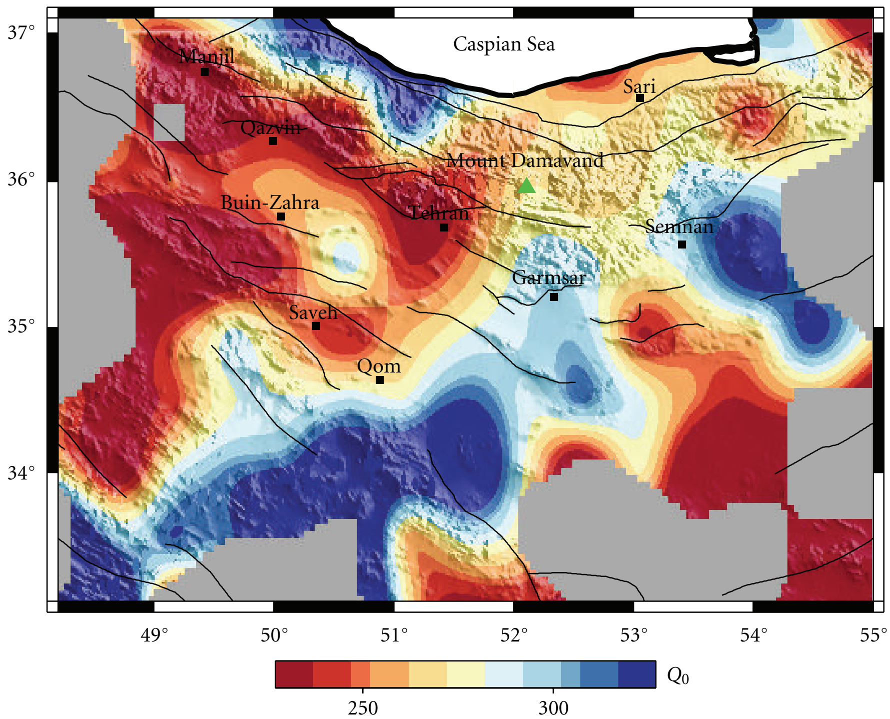

FIGURE 4: Q_0 variations in the study area. Triangles and squares show Damavand volcano and main cities, respectively. Major faults are marked by black lines.

$Q(f)$ can be then expressed by (4)

$$Q(f) = Q_0 f^{\eta}. \quad (4)$$

By working on (4) and adding ε as the random error we obtain

$$\ln\left(\frac{f}{Q(f)}\right) = (1-\eta) \times \ln(f) - \ln Q_0 + \varepsilon. \quad (5)$$

Plotting $(1/Q_0)F^{1-\eta}$ versus f on a logarithmic scale by using a linear regression, the mean value of Q_0 is estimated (Figure 3). A Comparison between the obtained results from theoretical and empirical shows that the stack spectral ration estimates a stable Q in which the error value pertaining to Q_0 is one order less than Q_0 itself.

5. Estimating the Quality Factor for the Study Area

In this study to calculate the lateral variations in quality factor over the region of study we use back projection method to create a tomographic image of the distribution of Q_0 in the studied area.

In this technique, the study area is divided into a grid of rectangular cells, from which the quality factor is calculated for each record and each grid/cell. The median quality factor value between the lowest and the highest values over all the paths crossing each grid/cell is used to start the inversion process. For each record, a residual term is calculated and a new estimate of the quality factor for each grid/cell is found by back-projecting [6, 19] the residual term into the inverse of the quality factor. The quality factor is updated through the iterative application of the inversion until the residual term falls below acceptable minimum threshold.

An estimation of quality factor is determined for each ray-path which corresponds to each pair of station-event. We divided the study area to different grids and then we tested various grid-size in the process, and the results presented in this research (a grid by 0.05°× 0.05° units) is considered robust in relation to the resolution of the final image and the quality of the data. The final results, Q_0 variation in the study area, are shown in Figure 4. Note that the area with less number of ray paths is masked.

Frequency dependency of Q-factor resulted from this study is given below:

$$Q = 267(\pm 32) \times f^{0.71(\pm 0.14)}, \quad (0.3 \leq f \leq 7.0\,\text{Hz}). \quad (6)$$

The weighted least-squares of $Q(f)$ fit to the Q_0 estimates from this study (north-central Iran) are compared in Figure 5 with other regions including: Alaska [20], south-central Alaska [21], the northeastern United States (NEUS) the Basin and Range province (BRP) [22], the Tibetan Plateau [23], and South-Central Alaska [24].

Figure 5 shows apparent $Q(f)$ values, from several previous researches estimating over a variety of tectonic regions. Tectonically active regions such as the north-central Iran, the BRP, and south-central Alaska generally have low values of Q_0 and high-frequency dependence, while high Q_0 and low η values are observed in tectonically stable continental regions

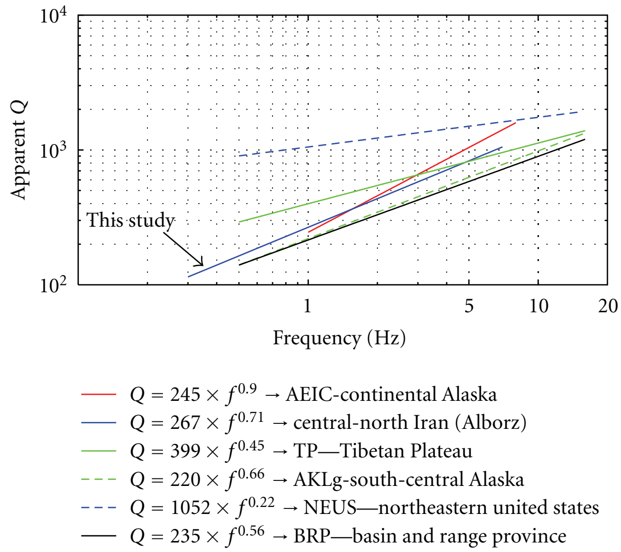

FIGURE 5: Comparison between the proposed formulas for other tectonic regions in the world. It can be seen that the proposed formulas has an acceptable conformity with other functions of quality factor.

like the NEUS. The quality factors determined from this study, as expected the north-central Iran, are more indicative of a tectonically active region.

6. Discussion and Conclusions

The quality factor is related to seismicity and the characteristics in seismotectonic and thermal variations. Therefore based on the results obtained in this research most of the studied region is considered as an active region from the seismicity point of view. This implies a great inhomogeneous region in Alborz active seismic zone and at its vicinity. Alborz mountain range is part of Alpide belt. It forms a barrier between the south Caspian basin and the central plateau of Iran.

Damavand volcano and its surrounding regions are characterized by relatively low Q_0 in the eastern area and a high gradient of Q_0 can be observed in the region. A change (strong gradient) in Q_0 value is observed in the results ranging from anomalously low Q_0 values in the western side although the current seismicity is mostly confined to the eastern side. Most of Damavand's recent earthquakes have occurred in the central and southwestern parts of the Damavand volcano which appear with relatively low Q_0 in the final image. Figure 4 shows that western part of the studied region has been surrounded by low Q_0 anomaly through two zones with relatively high Q_0 in the south and in the north. It seems that this model is related to high rate of probability in seismicity and therefore further investigation is required.

According to the results obtained in this study, Damavand volcano and its surrounding region are characterized with a change (strong gradient) in Q_0 value, ranging from anomalously low Q_0 values in the western side although the current seismicity is mostly confined to the eastern side.

Considering the distribution of the past earthquakes and comparing it with the shape of quality factor's change (Figure 4), it was observed that the Q_0 value in the eastern part is larger than that of the western part.

According to the results, in Damavand region, Q_0 has a relatively higher gradient than that of the surrounding region. It sharply declines moving from east to west. The Q_0 map (Figure 4) correlates well with the large-scale tectonic units of the studied area and also several clear trends corresponding to different characteristics of seismic activity and attenuation field. Most of Q factor variations can be attributed to the lateral heterogeneity as well as the severity of the crustal velocity gradient. It should be noted that that the Q_0 results, such as the one shown in Figure 4, are taken as mean values of each propagation path. Since the seismicity in the area is quite shallow (earthquake depths mostly are less than 30 km), the Q_0 results can be attributed to the average of upper part of the 30 km of the crust of the study area.

It is worth noting that our results impose reliable constraints and interpretations where density of crossing rays allows. On the other hand, we must be cautious interpreting results where the crossing rays are relatively low, in particular at the edge of the network.

Acknowledgments

The authors sincerely thank Iranian Seismological center (IRSC) and TCSN for providing the earthquake data needed for the research.

References

[1] F. Press and M. Ewing, "Two slow surface wave across north America," *Bulletin of the Seismological Society of America*, vol. 42, pp. 219–228, 1952.

[2] J. Xie, Z. Wu, R. Liu, D. Schaff, Y. Liu, and J. Liang, "Tomographic regionalization of crustal Lg Q in eastern Eurasin," *Geophysical Research Letters*, vol. 33, Article ID L03315, 2006.

[3] B. J. Mitchell, Y. Pan, J. Xie, and L. Cong, "Lg coda Q variation across Eurasia and its relation to crustal evolution," *Journal of Geophysical Research B*, vol. 102, no. 10, pp. 22767–22779, 1997.

[4] J. Xie and O. W. Nuttli, "Interpretation of high-frequency coda at large distances: stochastic modelling and method of inversion," *Geophysical Journal*, vol. 95, no. 3, pp. 579–595, 1988.

[5] S. Baqer and B. J. Mitchell, "Regional variation of Lg coda Q in the continental United States and its relation to crustal structure and evolution," *Pure and Applied Geophysics*, vol. 153, no. 2–4, pp. 613–638, 1998.

[6] L. Cong and B. J. Mitchell, "Lg coda Q and its relation to the geology and tectonics of the Middle East," *Pure and Applied Geophysics*, vol. 153, no. 2–4, pp. 563–585, 1998.

[7] J. L. De Souza and B. J. Mitchell, "Lg coda Q variations across South America and their relation to crustal evolution," *Pure and Applied Geophysics*, vol. 153, no. 2–4, pp. 587–612, 1998.

[8] M. Campillo, "Propagation and attenuation characteristics of the crustal phase Lg," *Pure and Applied Geophysics*, vol. 132, no. 1-2, pp. 1–19, 1990.

[9] M. Alavi, "Tectonostratigraphic synthesis and structural style of the Alborz mountain system in Northern Iran," *Journal of Geodynamics*, vol. 21, no. 1, pp. 1–33, 1996.

[10] A. M.C. Şengör, D. Altiner, A. Cin, T. Ustaömer, and K. J. Hsü, "Origin and assembly of the Tethyside orogenic collage at the expense of Gondwana Land," *Geological Society Special Publication*, vol. 37, no. 1, pp. 119–181, 1988.

[11] M. Berberian and R. S. Yeats, "Contribution of archaeological data to studies of earthquake history in the Iranian Plateau," *Journal of Structural Geology*, vol. 23, no. 2-3, pp. 563–584, 2001.

[12] J. Jackson, K. Priestley, M. Allen, and M. Berberian, "Active tectonics of the South Caspian basin," *Geophysical Journal International*, vol. 148, no. 2, pp. 214–245, 2002.

[13] J. F. Ritz, H. Nazari, A. Ghassemi et al., "Active transtension inside central Alborz: a new insight into northern Iran-southern Caspian geodynamics," *Geology*, vol. 34, no. 6, pp. 477–480, 2006.

[14] B. L. N. Kennett and E. R. Engdahl, "Traveltimes for global earthquake location and phase identification," *Geophysical Journal International*, vol. 105, no. 2, pp. 429–465, 1991.

[15] R. L. Street, R. B. Herrmann, and O. W. Nuttli, "Spectral characteristics of the Lg wave generated by central United States earthquakes," *Geophysical Journal of Royal Astronomical Society*, vol. 41, pp. 51–63, 1975.

[16] R. B. Herrmann and A. Kijko, "Modeling some empirical vertical component Lg relations," *Bulletin of the Seismological Society of America*, vol. 73, pp. 157–171, 1983.

[17] R. W. Burger, P. G. Somerville, L. S. Barker, R. B. Herrrnann, and D. V. Helmberger, "The effect of crustal structure on strong ground motion attenuation relations in eastern North America," *Bulletin of the Seismological Society of America*, vol. 77, pp. 120–139, 1987.

[18] G. M. Atkinson and R. F. Mereu, "The shape of ground motion attenuation curves in southeastern Canada," *Bulletin of the Seismological Society of America*, vol. 82, no. 5, pp. 2014–2031, 1992.

[19] J. Xie and B. J. Mitchell, "A back-projection ethodforimaginglarge-scale lateral variations of Lg coda Q with application to ontinental Africa," *Geophysical Journal International*, vol. 100, pp. 161–181, 1990.

[20] G. J. Steensma and N. N. Biswas, "Frequency dependent characteristics of coda wave quality factor in central and southcentral Alaska," *Pure and Applied Geophysics*, vol. 128, no. 1-2, pp. 295–307, 1988.

[21] R. Hansen, D. McNamara, E. Van Ark, and D. Christensen, "Lg ProPagation Continental Alaska," *Eos Transactions of American Geophysical Union*, vol. 79, article 79, 1998.

[22] H. M. Benz, A. Frankel, and D. M. Boore, "Regional Lg attenuation for the continental United States," *Bulletin of the Seismological Society of America*, vol. 87, no. 3, pp. 606–619, 1997.

[23] D. E. McNamara, T. J. Owens, and W. R. Walter, "Propagation characteristics of Lg across the Tibetan Plateau," *Bulletin of the Seismological Society of America*, vol. 86, no. 2, pp. 457–469, 1996.

[24] D. E. McNamara, "Frequency dependent Lg attenuation in south-central Alaska," *Geophysical Research Letters*, vol. 27, no. 23, pp. 3949–3952, 2000.