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Crustal Stresses and Seismodynamic Characteristics in the Upper Crust

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Abstract

In this paper an approach to estimate near-surface seismodynamic features by using distance-amplitude reduction with geotectonic characteristics of the upper crust in the Eastern Anatolia is discussed. The data set used in this study consists of 287 regional earthquakes in the magnitude range of 3.0 - 6.1, epicentral distances between 15 km and 202 km and their focal depths reaching up to 13 km. The entire study area is divided into three tectonic blocks according to the distributions of the earthquakes and the location of the fault segment. The estimated quality factor $Q_{P\text{-}S}$ values for the three regions ranged from 28.6 to 65, highlighting the regional differences in the seismodynamics of the crust. In Eastern Anatolia, the relatively low average quality factor Q values (Q_P: 37, Q_S: 55) show average σ (0.217) and average δ values (δ_P: 0.0166, δ_S: 0.017). The lowest Q_S/Q_P value 1.39 and the highest V_p/V_s value 1.65 are found at the Mus station. The highest Poisson's ratio σ and lowest absorption coefficient δ were found in the Mus area. The variation in Q, δ and σ indicates that the northern part (Erc and Kem region) of East Anatolia appears to be more active and heterogeneous compared with the southern part (Mus region) of East Anatolia.

Keywords

Body Wave, Seismodynamic Parameters, Seismotectonics, Upper Crust

1. Introduction

Amplitude reduction is generally frequency-dependent and, more importantly, attenuation characteristics can reveal unique information about lithology, physical state and the degree of rock saturation [1]. Although some authors suggest that near-surface Q may be frequency-dependent [2] [3] following the laboratory results [4]

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and different work [5] that Q is independent of frequency, allowing determination of Q as a function of depth based on the amplitude attenuation of Rayleigh-wave data. The quality factor Q is a function of depth, which is directly related to the material damping ratio [6] [7]. It is of fundamental interest in earthquake engineering, [8] geotechnical engineering, ground-water, and environmental studies, as well as in oil exploration and earthquake seismology. The study [9] also indicates that at surface pressure most dry rocks have $Q_S/Q_P > 1$. The Eastern Anatolia fault system is examined using the epicentre distance-amplitude reduction relations model and the work focuses on the seismic body wave's absorption which reflects the seismotectonic and seismodynamic features belonging to the lithosphere. Regional attenuation changes in body waves can be an indicator to determine the seismotectonic properties of the inner crust. These seismodynamic properties must be known in order to fully understand crustal deformation in the earth. From this information I aim to relate crustal inelasticity with the seismotectonic patterns in the inner crust of Eastern Anatolia.

There are numerous mechanisms contributing to attenuation and some conditions can affect the attenuation pattern significantly [1] [10]. The V_p/V_s attribute will only detect a lateral variation in lithology if the geological anomaly can be detected in the actual sections [11]. The variability of the near-surface properties is caused by changes in porosity, permeability, fractures, fluids, compaction, diagenesis and metamorphism [12]. The motivation behind V_p/V_s analysis is that the *P*-wave to *S*-wave velocity ratio is an effective indicator of lithology and/or fractures, cracks and pore space [13]. Poorly consolidated or fractured material will also exhibit high V_p/V_s values. In addition, V_p/V_s analysis can yield estimates of Poisson's ratio [11]. Poisson's ratio (or V_p/V_s) is a key parameter in studying the petrologic properties of crustal rocks [14] and can provide tighter constraints on the crustal composition than either *P* or *S* wave velocity alone [15]. It is suggested that seismic energy dissipation could become anisotropic as a result of the application of a uniaxial stress [16].

2. Tectonics of Eastern Anatolia

The north-south intercontinental collision between Arabia and Eurasia since the middle-late Miocene [17] [18] and the initiation of the back-arc extension in the Aegean Sea since the late Oligocene [19] [20] are the boundary conditions allowing the westward mass transfer of Anatolia, which is usually considered to be a rigid plate bordered by the North Anatolian Fault (NAF) and the East Anatolian Fault (EAF), which meet at Karliova. The high elevations of East Anatolia should not be related to the intercontinental convergence between the Arabian and Eurasian plates, but to mantle up welling, leading to lithospheric thinning and recent extension [21]. The most important tectonic feature is symbolized by high and young topography in the seismically active zone along the Zagros-Bitlis suture resulting from the collision of the Arabian plate with Eurasia (**Figure 1**) [22].

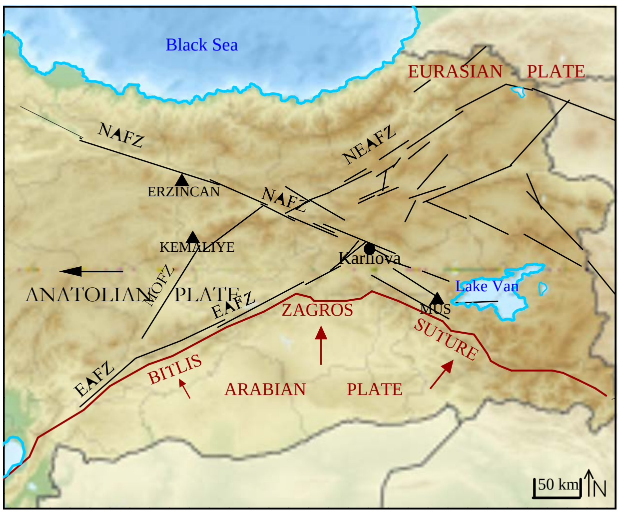

Figure 1. Map showing the study area (rectangle) and the three seismic stations (filled triangles) used in this study. Stations show blue filled triangles, Erzurum (ERZ), Erzincan (ERC), Palu (PALU) and Muş (MUS). NAFZ-North Anatolian Fault Zone; MOFZ-Malatya Ovacık Fault Zone; EAFZ-East Anatolian Fault Zone; NEAFZ-North East Anatolian Fault. Orange dotted line show major fold and thrust belt BZSZ-Bitlis-Zagros structure zone.

Eastern Anatolia is seismically active and is dissected by numerous seismogenic faults, predominantly in a strike-slip motion. The study areas are characterized by both the North Anatolian Fault Zone and the East Anatolian Fault Zone (**Figure 1**). Eastern Anatolia has been affected by several strong earthquakes (December 26, 1939 MS = 7.9, and in 1992, MS = 6.8, Erzincan earthquakes, 13 September, 1924, MS = 6.8 Pasinler (Erzurum) earthquake, 30 October 1983 MS = 5.2, Horasan-Narman, and 23 October 2011 MS = 7.1 Van earthquake). In particular the December 26, 1939 Erzincan quake was the most destructive in Turkey, during which Erzincan and the vicinity affected lost as much as half of its population.

3. Data

The analyzed events occurred along the three selected active seismic areas encompassing three different geological and seismotectonics contexts and are associated with various types of tectonic mechanisms in the Eastern Anatolia region. The digital events data utilized for seismodynamic properties was recorded during 2006-2010 at the regional seismograph network of three seismic stations by the Earthquake Research Centre, Atatürk University, Erzurum. The Ercstation is situated on a sedimentation fan in the vicinity of high tectonic and seismic activity. The Kemstation is situated at alluvial basin near recent tectonic and moderate seismic activity, and the Musstation is on a thick alluvial layer away from tectonic and seismic activities at high altitude (**Table 1**). All stations are equipped with CMG-3TD broadband seismographs with a dynamic range of 96 dB and a sampling rate of 100 samples per second. The data detection is based on magnitude, epicentre distance and hypocentre depths. The selected data set consists of 287 vertical recorded waveforms of 141 events with a focal depth between 1.4 km and 12.8 km, epicentre distance between 15 km and 202 km, magnitude ranging between 3 and 6.1 (**Figure 2**).

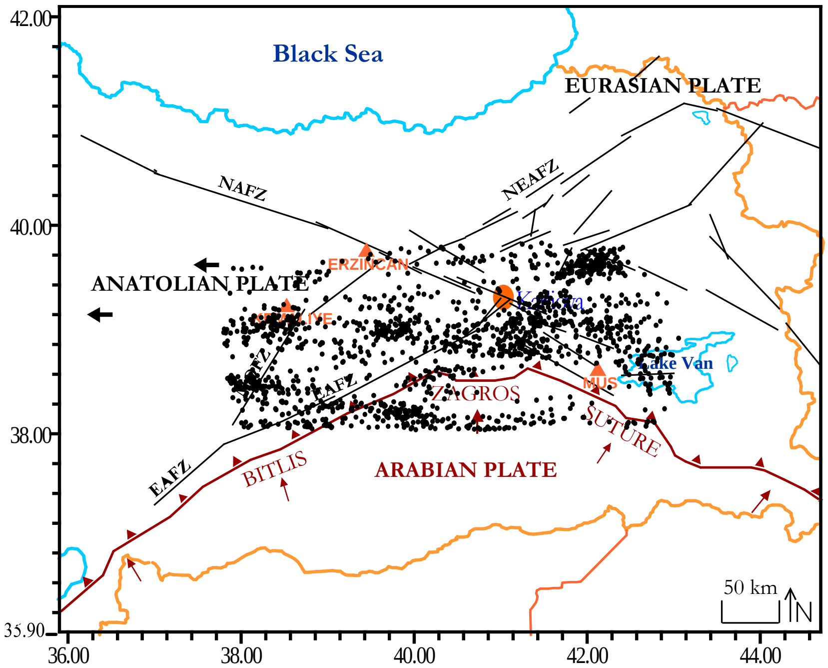

Figure 2. Map of the simplified tectonics and distribution of the epicentral locations of 202 earthquakes used in this study (black filled circles), seismic stations and cities (red filled triangles).

Table 1. The parameters of the seismic stations used in this study.

Station	Lat°	Long°	Altitudes	Lithology of the Station
Kemaliye (Kem)	39.2667	38.5139	1000	Alivual Basin
Erzincan (Erc)	39.7587	39.5059	1200	Sedimentation Fan
Mus (Mus)	38.7416	41.4991	1322	Alluvial Fan

The epicentres corrections were made because of the differing distances. Studies of seismic wave attenuation in Eastern Anatolia have been limited due to a limited number of available seismic stations. Other seismic station data is not of sufficient quality for this type of work. Personally, I preferred the vertical P_g and S_g wave amplitudes for this study due to the fact that they can be observed clearly in the vertical component in the inner crust. In order to remove the effect of the magnitudes on the amplitudes, the magnitude normalisation process has been performed for a reference value $M_L = 4$, 0. The maximum amplitude values, P_g and S_g arrival time have been obtained with the scream software (**Figure 3**). In general, the quality factor and Poisson's ratio is computed without considering the regional seismic velocity differences. In order to eliminate this unfavourable situation vertical P_g and S_g wave velocities for each region have been estimated (**Figure 3** and **Table 2**). These P_g and S_g wave velocities are used to determine the attenuation coefficient and Poisson's ratio. The seismodynamic properties of the Earth's crust beneath three selected research areas in Eastern Anatolia were examined using a method based on the decrease of body wave amplitude in time. The three station and the epicentral locations of the earthquakes are presented in the **Table 1** and **Figure 2**. All raw data was filtered using the Butterworth filter for 1 Hz. I used P_g and S_g amplitude normalisation methods for reference values $M_L = 4$, so as to correct the effects of the magnitudes. The maximum amplitudes were used to calculate the attenuation coefficient. P_g and S_g local amplitudes are used to determine the attenuation coefficients (δ_P and δ_S) of the three different tectonics area in Eastern Anatolia.

4. Methods

By contrast to $G(x)$ (and consequently also to Q_0 and η), the "effective attenuation" parameter (Q_e) in eq. denotes the frequency-dependent effects of the intrinsic attenuation and scattering on random, small-scale heterogeneities, *i.e.*, for Rayleigh- or Mie-type scattering [23].

$$\ln A(f, x) = \ln S(f) + \ln R(x, f) - v\ln t - \gamma t - \frac{\pi}{Q_e} ft \tag{1}$$

Further, by making, the seismic wave amplitude rate is a parameter that reflects the seismodynamic features of media. The logarithmic decrement, α is defined as follows [24]. The usual assumption that the spectral site responses $R(x, f)$ are similar or that they can be corrected to a common spectrum [25], the effects of $S(f)$ and $R(x, f)$ can be removed by constructing time-lag normalized spectral ratios at different observation times (and/or receiver positions):

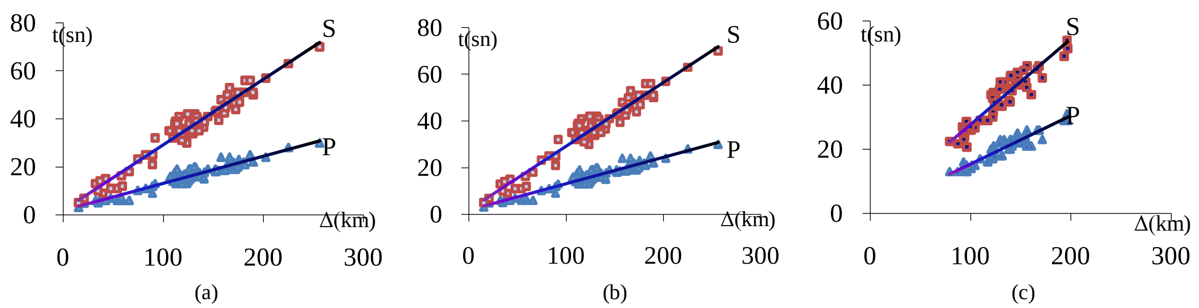

Figure 3. The plots of Δ (km) and *t* (sn) are used to estimate P_g and S_g wave velocity values for the stations in: (a) Kemaliye; (b) Erzincan; and (c) Mus.

Table 2. δ, Q_P, Q_S and σ values for Kem, Erc, and Mus stations.

Stat.	V_p	V_s	V_p/V_s	δ_s	δ_p	δ_s/δ_p	Q_S	Q_P	Q_S/Q_P	σ	Event
Kem	6.30	3.58	1.759	0.0214	0.0202	1.05	61	41	1.48	0.229	99
Erc	6.25	3.65	1.712	0.0187	0.0176	1.06	40	29	1.39	0.209	95
Mus	6.61	3.74	1.767	0.0130	0.0120	1.08	65	40	1.65	0.232	93
Avar.	6.38	3.65	1.74	0.0177	0.0166	1.06	55	37	1.5	0.223	287

$$\alpha = \ln \frac{A(f, x_2, t_2)}{A(f, x_1, t_1)} \Big/ (t_2 - t_1) = -v \frac{(\ln t_1 - \ln t_2)}{t_2 - t_1} - \gamma - \frac{\pi}{Q_e} f \tag{2}$$

where A_1 and A_2 are spectral amplitudes at different depths. In this description, γ represents the uncompensated geometrical spreading, and Q_e is the attenuation, which turned out to be frequency-independent in all data examples considered so far. The spectral ratio Equation (2) allows inversion for the three types of attenuation parameters. The properties of elastic crustal attenuation describe the loss of seismic energy in the crust to internal pressure, such as the absorption by fluids in compressional and strain or friction along seismotectonic boundaries. It is denoted by a Q value, $Q = 2\pi E/\Delta E$ where E being the energy and ΔE —the energy dissipation during a one wave cycle [26].

$$\frac{1}{Q} = \frac{-\Delta E}{(2\pi E)} \cong \frac{1}{Q(w)} = \frac{-A}{(2\pi A)} \tag{3}$$

where (ϖ) is angular frequency, Q is the quality factor, Δ is the epicentre distance, and ΔE is the peak strain energy lost in the cycles. For propagating waves, the parameter that truly exists and is directly measurable is the spatial attenuation coefficient [27]. In the literature the attenuation coefficient at 1 Hz is given as:

$$A_r = A_0 e^{(-\delta r)} \tag{4}$$

$$A_r = A_0 e^{-\pi f \int \mathrm{d}s/Qv} \tag{5}$$

$$\ln A_r / A_0 = -\delta \delta \tag{6}$$

$$\ln A_r - \ln A_0 = -\delta \Delta \tag{7}$$

where A_r is the amplitude at any distance from the source, r is distance, A_0 is the initial or reference amplitude, δ is the attenuation coefficient, and Δ is the epicentre distance. The normalized maximum amplitude of the P_g and S_g wave vertical components were used in order to compute the absorption calculations (**Figure 4**). The seismic quality factor (Q) and the attenuation coefficient (δ) are strongly affected by the tectonic pattern of the crust in any region [28]. Active tectonic regions are associated with low Q_0 values [29]-[31].

The quality factor Q is defined as the energy loss per unit cycle due to inelasticity [24]. ΔE and ΔA values are energy and amplitude respectively, which are lost in each energy cycle. Q can be written as:

$$\delta = \pi \frac{f}{Qv}, \quad Q = \pi \frac{f}{\delta v} \tag{8}$$

where, f is 1 Hz frequency, δ is the absorption coefficient, V is the P_g and S_g wave velocity, and Q are the quality factors that can be easily computed by Equation (8). The relationship of $(V_P/V_V)^2 = 2(1-\sigma)/(1-2\sigma)$ is used to determine the elastic parameter of Poisson's ratio (σ) [32]. By definition, Poisson's ratio is the ratio of radial contraction to axial elongation. Its value in common rock type's ranges from 0.20 to 0.35. P_g and S_g local velocities are used to determine the local quality factor $(Q_{P\text{-}S})$, local quality factor $(\delta_{P\text{-}S})$ the regional Poisson's ratio (σ) for three different regions.

5. Results

The great difference of $Q_{S\text{-}P}$ $(Q_S - Q_P = 25)$ were found in the Mus region. It may be potentially important for the interpretation of regional variations in attenuation. It is estimated the regional Poisson's ratio by calculated speeds of the seismic body waves. The highest V_p/V_s is found at the Mus station, the Zagros-Bitlis Suture and its vicinity, and the western side of the Mus station and its vicinity. The highest σ value is observed in the Kem and Mus region while lowest σ value is observed in the Mus region (**Figure 5**). The highest Poisson's ratio-σ and lowest absorption coefficient-δ was found in the Mus area. The lowest Q and high δ values were found in the Erc region (**Table 2**).

Numerous studies have been carried out in different parts of the world in order to determine the attenuation of seismic waves in the crust [3] [30] [33]-[38], which determined the attenuation seismic waves in a number of tectonically stable and active areas. In the 1982 found that the Q_S/Q_P ratio to be unity for air dry rocks and less than unity for fully saturated rocks [39]. Our result on Q_S/Q_P ratio is in the range of 1.39 - 1.65 (**Table 2**)

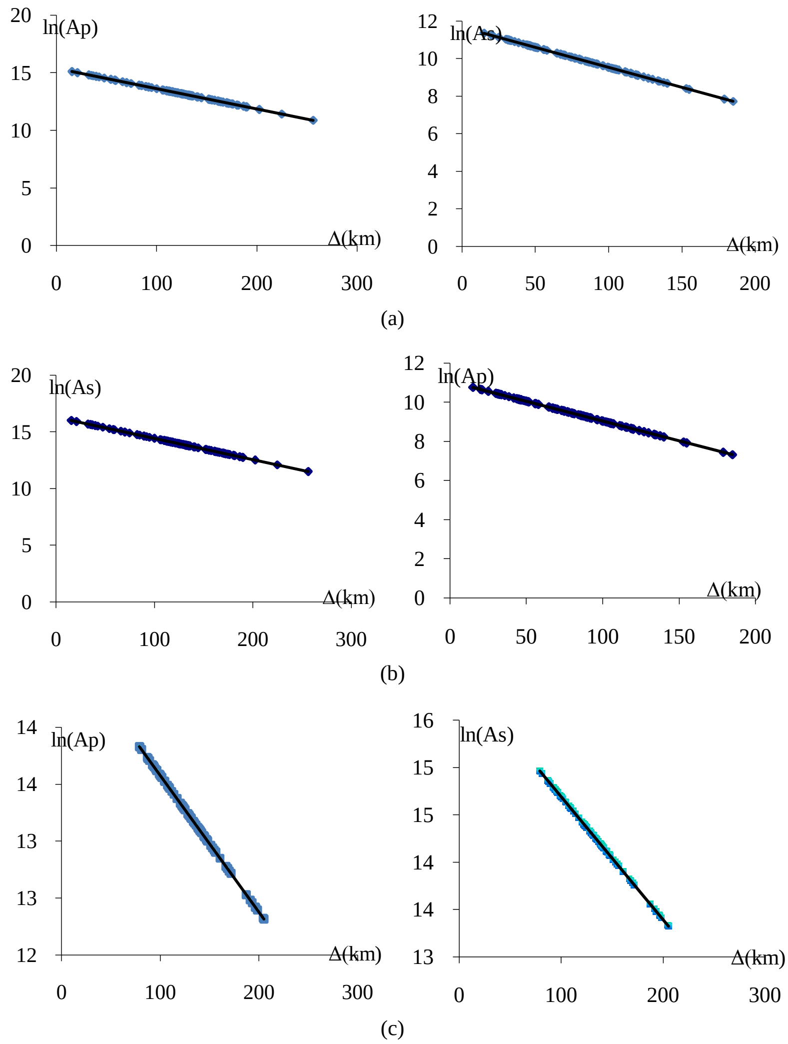

Figure 4. Plots of the absorption for ln (Ap) and ln (As) versus distance for the stations in: (a) Kem; (b) Erc; and (c) Mus.

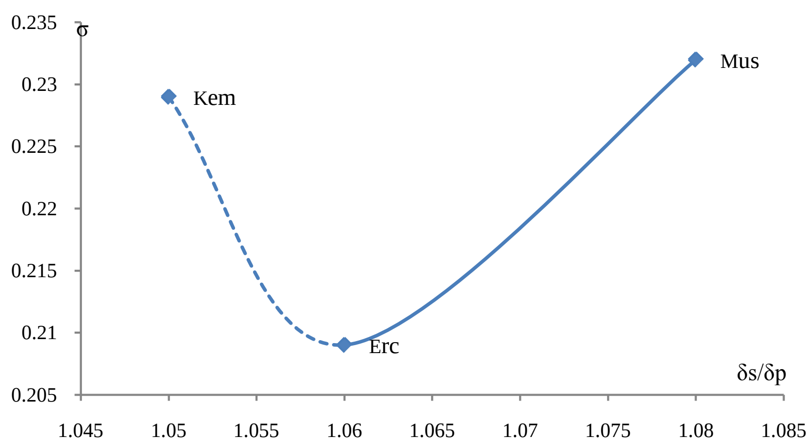

Figure 5. Plot of σ value versus δ_s/δ_p. Kem and Mus stations which do not differ significantly from the average value of Poisson's ratio for the area. Erc stations which differ significantly from the average value for the area.

and is in good agreement with the results obtained by the laboratory measurement and other experimental results mentioned down. In Eastern Anatolia, the relatively low average Q values (Q_P : 37, Q_S : 55) show average σ (0.223) and average δ values (δ_P : 0.0166, δ_S : 0.0177) (**Table 2**). In Eastern Anatolia, the Q_S/Q_P values are between 1.48 and 1.65. The highest Q_S/Q_P value 1.65 is observed in the Mus region, while the lowest Q_S/Q_P value 1.39 is observed in the Erc region (**Figure 3**). This study of results is quite comparable and in relation with tectonic and crustal structure is therefore similar. In this study I attempted to determine these different seismodynamic relationships among the North Anatolian Fault zone, the East Anatolian Fault zone and the Bitlis-Zagros structure in the Eastern Anatolia.

6. Discussion

The spatial variation of the regional coda quality factor has been utilized in order to obtain a better understanding of tectonics, seismicity, seismic risk analysis and engineering seismology [30] [40]. Seismic waves are attenuated travelling through crust due to Jin the elasticity and heterogeneity of the medium [41]-[44]. The average Q_P value calculated for Eastern Anatolia is approximately 37. This is equal to the value computed for the Erzurum region of Eastern Anatolia (Q_P : 37) [45] and greater than the Oltu region in Eastern Anatolia (Q_P : 33) [46]. It is calculated S wave attenuation coefficient and quality factor for Eastern Anatolia using the model based on the epicentre distance-amplitude relations [47]. Coda Q (Q_c) values are determined between 37 ± 14 and 724 ± 256 by using 196 earthquakes occurring between 2005-2010 in Eastern Anatolia [48].

The different stresses characteristics of Kem, Erc and Mus indicate the different velocity values and deviating seismodynamic values. The region is also the site of very high tectonic activity revealed by several recent high magnitude earthquakes along active faults. The highest attenuation was observed in Mus. It may be caused by certain geological structures. This study indicates that there is a relationship between seismodynamic properties and stress structures in the upper crust of Eastern Anatolia.

7. Conclusion

Compared to Poisson's ratios, the compression values can be a better indicator of the content of seismodynamic properties. For the three different regions, the amplitude dependency of average δ, Q and σ values show a range of heterogeneity in the upper crust. The lateral local Poisson's ratio can be explained by local variations of seismic velocity and different stresses structures. These are related to different seismodynamic and kinematic activities in the inner crust. The lowest Q and high δ values can be explained by tectonic activity, and severe deformation in the Erzincan region. A high Poisson's ratio and low absorption coefficient was found in the Mus area, which is consistent with the possibility of a partial melt in the upper crust and Bitlis-Zagros structure. Mus and the area around the Karliova Triple Junction fields can be considered to be pressure subduction zones, indicating the presence of greater compressional power at the Zagros-Bitlis Suture zone and its immediate surroundings, by which the structure of the NAF and EAFZ systemsin the north of the Bitlis-Zagros is formed. The variation of the seismodynamic parameter indicates that the seismotectonics and heterogeneity of the lithosphere affect the stress behaviour of the inner crust. The differentiation of seismodynamic properties in different areas is due to the heterogeneities along the inner crust. These differences in attenuation properties are due to actual crustal thickness differences and may be because that the stresses in the region have different patterns.

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