Lateral structural variations of Poisson’s ratio and attenuation coefficient in the upper crust of eastern and south-eastern Anatolia

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ABSTRACT

In this study, lateral 2D Poisson’s ratio and local attenuation coefficient changes have been examined using the 2473 digital earthquake data of eastern and south-eastern Turkey. Data used for this work came from the seismic records of events recorded by the stations of the Boğaziçi University Kandilli Observatory and Earthquake Research Institute (KOERI) as well as the Atatürk University Earthquake Research Centre (AUERC). The method used in this study was based on 2D Poisson’s ratio calculated from P- and S- velocity values and epicentre distance-amplitude attenuation coefficient methods. The estimated Poisson’s ratio values for the 17 stations ranged from 0.142 to 0.309. Attenuation coefficient ratios were found to be between 1.072 and 1.362, with an average of 1.226. P- and S- wave velocity values for eastern and south-eastern Anatolia were determined as 6.317 and 3.608 km/s, respectively. These values were obtained from earthquake data with epicentre distances ranging from 15 to 184 km and focus depths ranging from 1.3 to 11.2 km. The lowest attenuation coefficients were obtained at the URFA station, while the highest attenuation coefficient values were observed at the SIRT and MALT stations. High σ values were observed in the northern part of the study area and SW of the Bitlis-Zagros thrust belt, whereas the lowest σ values were obtained at the Karliova triple junction and its surroundings. This study shows that different tectonic structures and actively deformed systems can be described by dynamic parameters such as local attenuation values and Poisson’s ratio of the near-upper Earth crust.

Key words: Attenuation coefficient, Poisson’s ratio, solid Earth dynamics, geodynamic variation, different tectonic zones.

1. Introduction

Attenuation is one of the fundamental properties of seismic waves from which material and physical conditions in the Earth’s interior can be inferred (Aki, 1980). Moreover, attenuation is considered a key element in defining the tectonic regime of the crust (Mitchell and Romanowicz, 1998). Seismic waves are attenuated by travelling through the crust due to the elasticity and heterogeneity of the medium (Ricker, 1953; Futterman, 1962; White, 1983; Kneib and Shapiro, 1995). There are numerous mechanisms contributing to the attenuation, and some conditions can affect the attenuation pattern significantly (Toksöz and Johnston, 1981; Aki, 1985). Various
observations in different regions of the world have indicated a striking difference in the rate of amplitude decay between tectonically active and stable regions (Mahood and Hamzehloo, 2011). This reduction is generally frequency dependent and, more importantly, attenuation characteristics can reveal unique information about lithology, physical state, and degree of rock saturation (Toksöz and Johnston, 1981).

Poisson’s ratio is diagnostic of medium composition and properties such as lithology and rheology (Rudnick and Fountain, 1995; Christensen, 1996; Fernández-Viejo et al., 2005). The unevenness of near-surface properties is caused by changes in porosity, permeability, fractures, fluids, compaction, diagenesis, and metamorphism (Toksöz et al., 1976). It is recognized that Poisson’s ratio for crustal rocks varies mostly between 0.2 and 0.3 (e.g., Lillie, 1998). Attenuation structures have been calculated via various approaches in eastern Turkey (Aydın and Kadirov, 2007; Aydin et al., 2009, 2012; Aydin and Sahin, 2011), calculating the S-wave attenuation coefficient and quality factor for eastern Anatolia using the model based on epicentre–amplitude relations.

Digital seismic data components include tectonic differences as well as the physical and chemical properties of the interior of the Earth’s upper crust. The tectonic differences of the near upper crust can be explained by referring to seismodynamic parameters on seismic records. We developed two-dimensional mapping of Poisson’s ratio and local attenuation using earthquake data obtained from a wider region (eastern and south-eastern Anatolia) than those obtained in former studies.

2. Tectonic setting and seismology

Eastern and south-eastern Anatolia is seismically active and is crossed by numerous seismogenic faults with a predominant strike-slip component. The study areas are characterized by both the North Anatolian Fault Zone and the East Anatolian Fault Zone (Fig. 1). The Bitlis suture is a complex continent-continent and continent-ocean collisional boundary that lies north of the fold-and-thrust belt of the Arabian platform extending from south-eastern Turkey to the Zagros Mountains in Iran (Bozkurt, 2001). The most important tectonic feature (Fig. 1) is characterized by an elevated and young topography in the seismically active zone along the Bitlis-Zagros Suture (BZS), resulting from the collision of the Arabian plate with Eurasia (Şengör and Kidd, 1979). The higher elevations of east Anatolia are most likely not related to the intercontinental convergence between the Arabian and Eurasian plates, but to mantle upwelling, leading to lithospheric thinning and the recent extension (Dhont and Chorowicz, 2006). In addition, a thrust faulting belt extends from the Karlıova triple junction (Bingöl-Karlıova-Erzincan triple junction - KTJ), where the North and East Anatolian Faults meet, eastwards into the interior of the Turkish-Iranian Plateau (Fig. 1) (Copley and Jackson, 2006).

3. Method

A simple linear relationship for amplitude and epicentre distances was assumed as follows for estimating the local magnitude:
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\[ M_L = a \log (A) + b \Delta + c \]  

(1)

where, \( M_L \) is the local magnitude, \( A \) is the largest vertical amplitude of the seismic wave, \( \Delta \) is the epicentre distance and \( a, b, \) and \( c \) are the geological coefficients as defined by Richter (1958).

The attenuation coefficients (\( \delta \)) were estimated using the epicentre distance-amplitude relations. Poisson’s ratio (\( \sigma \)) has been ascertained by utilizing the model based on the S and P seismic velocity relations. The attenuation coefficients (\( \delta_s, \delta_P \)) were obtained via normalized amplitude values. For propagating waves, the directly measurable parameter that truly exists is the spatial attenuation coefficient (Chernov, 1960). Epicentre distance-amplitude relations at 1 Hz are given in relevant literature as:

\[ A_1 = A_0 e^{-\delta r_0} \]  

(2)

\[ A_2 = A_0 e^{-\delta (r_0 + \lambda)} \]  

(3)

\[ \ln(A_1/A_2) = \ln(e^{\delta \lambda}) \]  

(4)

\[ A_r = A_0 e^{-\lambda \delta r} \]  

(5)

\[ \delta \Delta = \ln A_0 - \ln A_r \]  

(6)
where $A_r$ is the amplitude at any distance $r$ from the source, $A_0$ is the initial or reference amplitude, $\Delta$ is the epicentre distance, $\lambda$ is wavelength, and $\delta$ is the attenuation coefficient.

The $V_p/V_s$ analysis can provide estimates for the Poisson’s ratio (Sheriff, 1991). The relationship is applied to find the elastic parameter of $\sigma$ (Mavko et al., 2009). By definition, Poisson’s ratio is the ratio of radial contraction to axial elongation:

$$\sigma = \frac{V_p^2 - 2V_s^2}{2(V_p^2 - 2V_s^2)}$$

where $V_p$ is the P-wave velocity, $V_s$ is S-wave velocity, $\sigma$ is Poisson’s ratio.

Fig. 2 - The epicentral distribution of earthquakes used in this study has been shown as circles. The green triangles indicate seismic stations. The solid green triangle represents Karliova Triple Junction.

4. Data

The 17 research stations in eastern and south-eastern Anatolia were examined using methods based on the reduction of body wave maximum amplitude in time. The selected data set consists of 2473 vertical recorded waveforms of 1856 events with a focal depth between 1.3 and 11.2 km, epicentre distance between 15 and 184 km, magnitude ranging between 3.0 and 6.3 (Fig. 2). The data used in this study came from seismic records of the events recorded by six stations from AUERC and eleven stations of KOERI (Fig. 2). Digital data were recorded during 2006-2013 at the seismograph networks. 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. Data detection is based on magnitude, epicentre distance, and hypocentre depths. Epicentre corrections were
made due to differing distances. All raw data were filtered via Butterworth filter for 1 Hz. Pg and Sg amplitude normalization methods were used as reference values $M_L=4.0$, so as to correct the effects of the magnitudes (Fig. 3).

5. Results

The velocity values obtained for all of the 17 regions seen in Fig. 4 are displayed on the left-hand side, the attenuation coefficients can be seen on the right, and the velocity and attenuation coefficient values calculated for the whole region are shown at the very bottom. Poisson’s values can be obtained for 2473 earthquakes, whereas the absorption coefficient values are obtained for all 17 regions. Poisson’s ratio results for all the studied areas are presented in Figs. 5 and 6. The attenuation coefficient, seismic velocities, and Poisson’s ratio, and their associated values are listed in Table 1. The seismic velocities and attenuation are obtained from the slopes of the linear fit (Fig. 4). The Pg- and Sg- wave velocity were determined as 6.3171 km/s and 3.6088 km/s, respectively, and $\delta_P$ and $\delta_S$ values were determined as 0.0168 km$^{-1}$ and 0.0197 km$^{-1}$ for the whole study area. The $V_p/V_s$ ratios were calculated as 1.72-1.79 with an average of 1.75. The $\delta_S/\delta_P$ ratios were found to be 1.072-1.362, with an average value of 1.226. Poisson’s ratio ($\sigma=0.2057$) and attenuation coefficient ($\delta_P=0.0168$ km$^{-1}$, $\delta_S=0.0197$ km$^{-1}$) have been obtained for the whole study area. The average Poisson’s ratio for eastern and south-eastern Anatolia has been determined as $\sigma=0.211$ with average $\delta$ values of $\delta_P=0.0164$ km$^{-1}$, $\delta_S=0.0202$ km$^{-1}$. The $\delta_S/\delta_P$ values vary between 0.066 and 0.017, and the Poisson’s ratios vary between 0.142 and 0.309 (Table 1 and Figs. 1 and 6).

The highest Poisson’s ratio (i.e.: the medium attenuation coefficient) is obtained from the OLTU, BAYT, and ERZM station data. The lowest attenuation values are observed in the MAZI, ERZM, and DYBB areas. The greatest difference between attenuation values $\delta_S-\delta_P$ was observed for MALT and SIRT, while the smallest difference between $\delta_S-\delta_P$ was observed in the ERZM

Fig. 3 - An example of earthquake data process. The vertical component part of a local earthquake recorded at ERZM station. |AB| is maximum Pg amplitude. |CD| is maximum Sg amplitude. Pmax is the largest amplitude of the Pg wave, Smax is the largest amplitude of the Sg wave.
Fig. 4 - Plots of $\Delta$ and $t$ are used to estimate the P- and S-wave velocity values: S-wave velocity (light green), P-wave velocity (dark green), and epicentre distance ($\Delta$) for 17 stations and all study areas. Plots of $\Delta$ and Ln ($A$) are used to estimate the P- and S-wave absorption coefficient values: S-wave absorption coefficient (light green), the P-wave absorption coefficient (dark green).
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Table 1 - $\delta_P$ (attenuation coefficient of P wave), $\delta_S$ (attenuation coefficient of S wave), $V_P$, $V_S$ (P- and S-wave velocities), $\sigma$ (Poisson’s ratio) calculated from data obtained from the 17 stations located in the studied subregions in eastern and south-eastern Anatolia.

<table>
<thead>
<tr>
<th>Event</th>
<th>Station</th>
<th>Code</th>
<th>$V_P$ (km/s)</th>
<th>$V_S$ (km/s)</th>
<th>$V_P/V_S$</th>
<th>$\delta_P/\delta_S$</th>
<th>$\delta_P$ (km-1)</th>
<th>$\delta_S$ (km-1)</th>
<th>$\delta_P - \delta_S$</th>
<th>$\sigma$</th>
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<td>0.0141</td>
<td>0.0033</td>
<td>0.142</td>
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<td>0.0160</td>
<td>0.0027</td>
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<td>1.7217</td>
<td>1.2611</td>
<td>0.0134</td>
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<tr>
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<tr>
<td>18</td>
<td>$\Sigma$ 2.473</td>
<td>Q$_T$-TOTAL</td>
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<td>3.6088</td>
<td>1.7504</td>
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<td>0.0168</td>
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<td>0.0038</td>
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Fig. 5 - Three images of the Poisson’s ratio tomography results in the study area. The black triangle shows thrusts on faults. Black thick lines show active fault zones and blue thin lines represent Poisson’s ratio counters.
and DYBB regions (Figs. 5 and 6, and Table 1). Poisson’s ratio values obtained from the MUS, KEMA, and ERZC stations and the surrounding area are relatively low in comparison with the average value of 0.205 (Fig. 5). Only the Poisson’s ratio value obtained from the OLTU station is much higher than the average value. The highest $\delta_s - \delta_p$ values are observed at the KARS station, while the lowest $\delta_s - \delta_p$ values are observed at the MAZI station, and the maximum difference of $\delta_s - \delta_p$ is found in the MALT station data (Table 1, Fig. 6). The details of comparable results for the 17 stations and all studied areas have been presented in the discussion and conclusion sections.

Poisson’s ratio can be obtained for the data from each earthquake (Fig. 5), whereas the attenuation coefficient can be obtained from a group of earthquakes and is a regional parameter (Fig. 4).

6. Discussion

Poisson’s ratio has been proven to be very effective for the clarification of seismogenic behavior of the crust, particularly regarding the role of crustal fluids in the nucleation and growth of earthquake ruptures (Zhao et al., 2002). The most general feature of the topographic images in the study area, characterized by low Poisson’s ratio around KTJ with KMLY, is often associated with fracture density and total stress values within the upper crust (Fig. 5). Large differences in attenuation values are obtained along the BZSZ, but no clear difference in compression effect related to thrust deformation has been observed. Regarding the spatial distribution of the findings, the Bitlis-Zagros Suture and vicinity can be characterized by high absorption and low Poisson’s ratio.

The attenuation coefficient is strongly affected by the tectonic pattern of the crust in any region (Mitchell, 1995). Essentially, the attenuation function can be used in the modelling of Earth structures with the application of seismic hazard assessment (i.e., Montaldo et al., 2005). The areas of ERZC and KEMA are similar with regard to low attenuation coefficient and low Poisson’s ratio values. These regions are also sites of high tectonic activity revealed by several earthquakes along active faults. The upper crust is under high pressure at KMLY and ERZC stations and their vicinities, originating from the NAFZ and MOFZ tectonic structures (Fig. 2). These two regions are present because of the harder and more brittle upper-crust structure. The lowest attenuation coefficients and high Poisson’s ratio values obtained at URFA station ($\delta_p=0.103 \text{ km}^{-1}, \delta_s=0.0130, \sigma=251$) may possibly be caused by thick sedimentary material in addition to less fracture with low seismic activity and low total stress. (Table 1 and Fig. 6). Fig. 6 indicates that there is a direct correlation between absorption coefficient and Poisson’s ratio.

7. Conclusion

Poisson’s ratio tomographic values for the Karlova triple junction and the surrounding area are consistently low. This can be explained by the fact that KTJ is the combination of two major fault zones: the North Anatolian and East Anatolian Faults (Fig. 5). The absorption coefficient is obtained from seismic data reflecting an active tectonic structure and heterogeneities in eastern and south-eastern Anatolia. However, much stronger heterogeneities were determined between BZSZ and NAFZ. These heterogeneities are related to the different thicknesses of the upper crust and the complex tectonic structure caused by the high compression forces of the North
Anatolian Fault Zone and Bitlis-Zagros thrust belt (Figs. 5 and 6). The whole study area, which had extremely dissimilar absorption coefficient values and was dissimilar to Poisson’s ratio, can be explained by severe and complex deformations with high tectonic activity (Figs. 6 and 7). These results are compatible with the present geometry and the crustal dynamics of eastern and south-eastern Anatolia (Table 1, Fig. 5). The Poisson’s ratio tomographic finding obtained for the study area as a whole, along with the 17 regional attenuation coefficient findings, indicate the tectonic heterogeneity of the upper crust of eastern and south-eastern Anatolia.

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