ANISOTROPIC P_n TOMOGRAPHY OF TURKEY AND SURROUNDING REGIONS

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ABSTRACT:

We analysed P_n travel times to determine lateral variations of velocity, anisotropy at uppermost mantle and crustal thickness beneath Turkey and surroundings. From 1999 to 2010 more than 50,000 P_n arrivals are compiled from 700 regional earthquakes by the 832 stations of permanent and temporary networks operated in the study area. The P_n velocities show very fast (>8.4km/s) and very slow (<7.6km/s) anomalies, indicating a heterogeneous lithospheric structure. P_n anisotropy has maximum amplitude of ±0.6 km/s in the study area. The largest and coherent anisotropic anomalies are observed in the western Anatolia, Aegean Sea, Cyprian Arc. P_n anisotropy in western Anatolia, Aegean sea and Greece correlate well with the present tectonic deformation and GPS velocities.

KEY WORDS: P_n waves, tomography, anisotropy, upper mantle

1. INTRODUCTION

In order to investigate the upper mantle velocity and anisotropic structure at local and regional scales P_n tomography had been proven to be very useful (Hess 1964; Backus 1965; Hearn and Ni, 1994; Hearn 1996; Hearn 1999). First study is performed by Hearn & Ni (1994) on the upper mantle structure beneath Turkish-Iranian Plateau. They obtained P_n velocities varying between 7.6 km s^{-1} to 8.2 km s^{-1}. Low P_n velocities (< 7.9 km s^{-1}) beneath most of the Turkish-Iranian Plateau, high P_n velocities (> 8.1 km s^{-1}) beneath Black Sea and southern Caspian Sea were observed. Average P_n velocities beneath southwestern Mediterranean were obtained between 8.0-8.1 km s^{-1}. Hearn (1999) also computed P_n velocity distribution beneath the European region and part of the Aegean Sea. Beneath tectonically active mantle of southern Europe he obtained much lower seismic velocities (7.6-8.1 km s^{-1}) than the more stable mantle of the sub-African plate of Adriatic Sea (8.3 km s^{-1}). A tomographic study by Papazachos et al. (1995) revealed strong velocity variations and crustal thickness beneath Aegean. They presented P velocities for different depth ranges. P velocities beneath northern and southern Aegean vary between 7.5 – 7.9 km s^{-1} for the depth of 30 km to 40 km.

Al-Lazki et al. (2004) obtained the variations of the P_n velocities and anisotropy at the junction of Arabian, Eurasian and African plates. They observed a broad scale (~500 km) low P_n velocity structures (< 8.0 km s^{-1}) underlying the Anatolian plate and smaller scale (~200 km) very low P_n anomalies (< 7.8 km s^{-1}) beneath central Turkey and Isparta angle. They associated low and very low P_n velocities with active volcanism since Late Miocene beneath eastern Turkey, northeastern Iran and the Caucasus. A most recent study is done by Gans et al (2010) relatively smaller area and dataset in central Turkey. The obtained high P_n velocities (> 8.1 km s^{-1}) on the western part of the NAF and very low velocities (< 7.8 km s^{-1}) on the eastern part of the fault.

P_n velocity anisotropy was also investigated for both oceanic and continental lithosphere (Backus, 1965). Information on the structure of the upper mantle can be obtained from the measurements of anisotropy. The fast polarization directions of SKS measurements let to investigate relation between plate movement and mantle

flow. Recent studies on SKS splitting provided more details on the mantle anisotropy beneath the Aegean-Anatolian domain (Hatzfeld et al. 2001; Sandvol et al., 2003; Biryol et al., 2009; Evangelidis et al., 2011).

In this work, a total of 700 earthquakes with magnitudes greater than 4.0 and earthquakes occurred between 1999 – 2010 are selected. The first arrivals between 180 and 1500 km distance range are defined as P_n arrivals. More than 50.000 P_n arrivals recorded to study mantle lid velocity and anisotropy beneath the region. For tomographic images 832 seismic stations were used. Tomographic inversion of regional P_n travel time residuals used to image lateral variations of seismic velocity within the uppermost mantle of region is determined. Both isotropic and anisotropic velocity distributions and estimated variations of the crustal thickness computed. P_n velocities are found to be highest in the eastern Mediterranean Sea and Zagros suture (> 8.3 km s^{-1}) and lowest in eastern Turkey (< 7.6 km s^{-1}). An anomalous low velocity zone is obtained in central Anatolia. The tomographic method of Hearn et al. (1999) applied to determine P_n velocities, anisotropy and station delays. A number of checker board tests were used to investigate the resolving power of the tomographic system and Bootstrap method used to calculate standard deviation of P_n velocities, anisotropy and station delays. The previous P_n travel time tomography and anisotropy results discussed.

2. DATA PROCESSING

A waveform database from 1999 to 2010 was formed from the permanent and temporary stations operated in the region (Figure 1). The National Network of Turkey operated by Kandilli Observatory and Earthquake Research Institute (KOERI) network has been continuously upgraded since 2004 and the total number of broadband stations has exceeded 130 in 2010. Supplementary data were obtained for the permanent stations from IRIS and ORFEUS in the region. The data from Eastern Turkey Seismic Experiment (ETSE) (Sandvol et al., 2003), Western Anatolia Seismic Recording Experiment (WASRE) (Akyol et al., 2006), Seismic Imaging beneath Aegean-Anatolia Domain (SIMBAAD) (Paul et al., 2008), the temporary networks, were also included in the analysis. KOERI, International Seismological Centre (ISC) and European-Mediterranean Seismological Centre (EMSC) bulletins were compiled for initial P_n tomography catalogue. A total of 700 earthquakes with magnitudes Ml>4.0 were re-located. Waveform database was constructed for the selected events (Figure 1). With the available waveform data more than 50,000 P_n arrival times recorded at 832 seismic stations were manually picked. P_n arrivals are defined as the first arrivals between 180 km and 2000 km. The data quality was generally good and only clear P_n arrivals were picked.

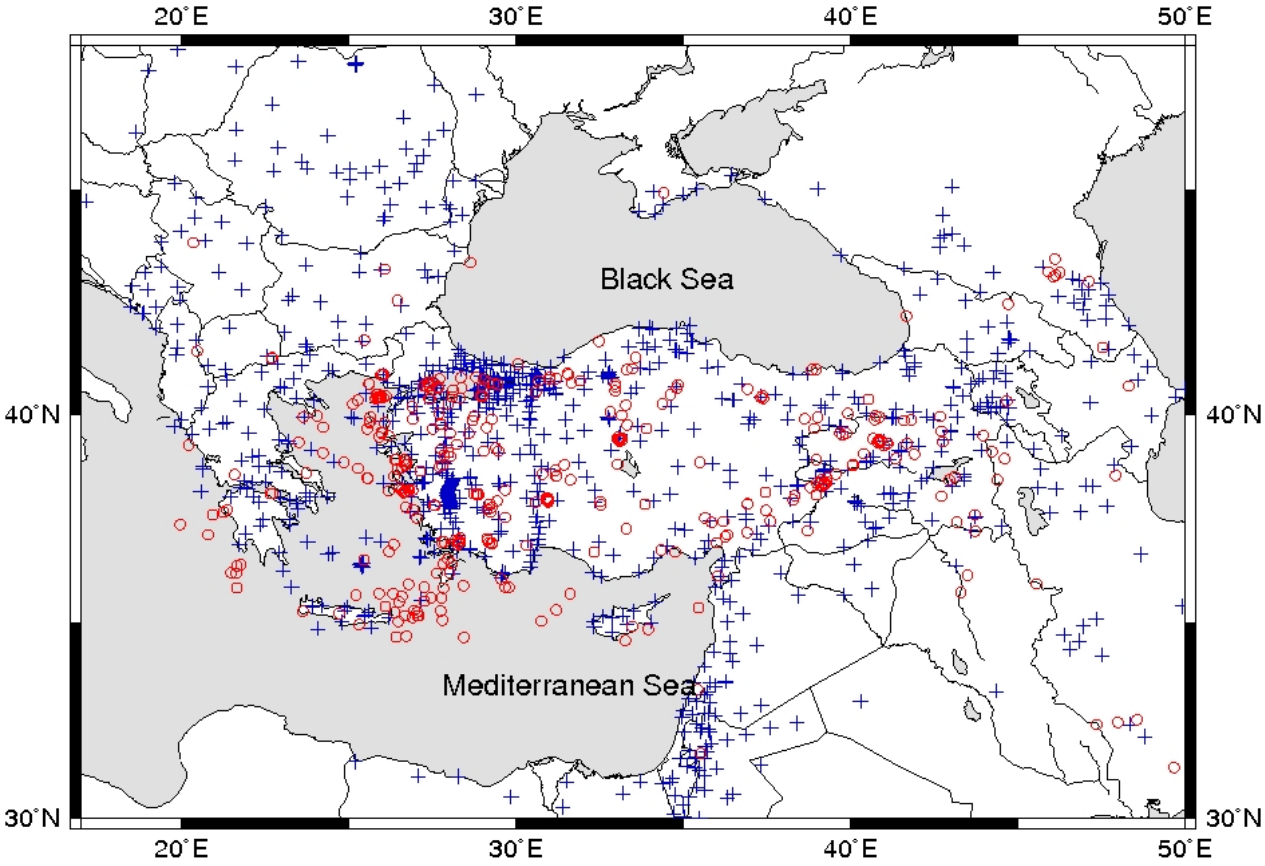

Figure 1. Seismic stations (+) used for P_n tomography. A total of 695 stations from both permanent and portable networks and selected 596 earthquakes (o) with magnitudes greater than 4.0 occurred between the years of 1999 and 2010 are displayed.

The station spacing was not regular with greater density in the Marmara and Aegean region and relatively less dense in the central and eastern Anatolia. The earthquake distribution was also non uniform. The majority of the earthquakes are located along the active seismic zones such as North Anatolian Fault (NAF), East Anatolian Fault (EAF) and Aegean. Few earthquakes were included from Caucasus and Iran.

Average P_n velocity and crustal delay for the data set by a least squares fit was determined as 8.0 km s^{-1} for P_n velocity. An average crustal velocity of 6.3 km/s and crustal thickness of 34 km were obtained from the slope of the P_g travel times and intercept time, respectively. Lateral variations of P_n velocity were imaged as perturbations from the average velocity of 8.0 km/s. Topography corrections at the station sites were applied assuming a constant velocity of 5.5 km/s. These initial estimates are used as the starting model for the subsequent tomographic inversion.

Figure 2 shows the the ray paths between events and stations. A total of 532 earthquakes and 695 stations were used to compute ray paths. Dense path coverage exists in the central and eastern Anatolia and relatively high coverage exist in the northwestern Turkey and Aegean region. The coverage is poor in the Black sea, Caucasus and southern Mediterranean.

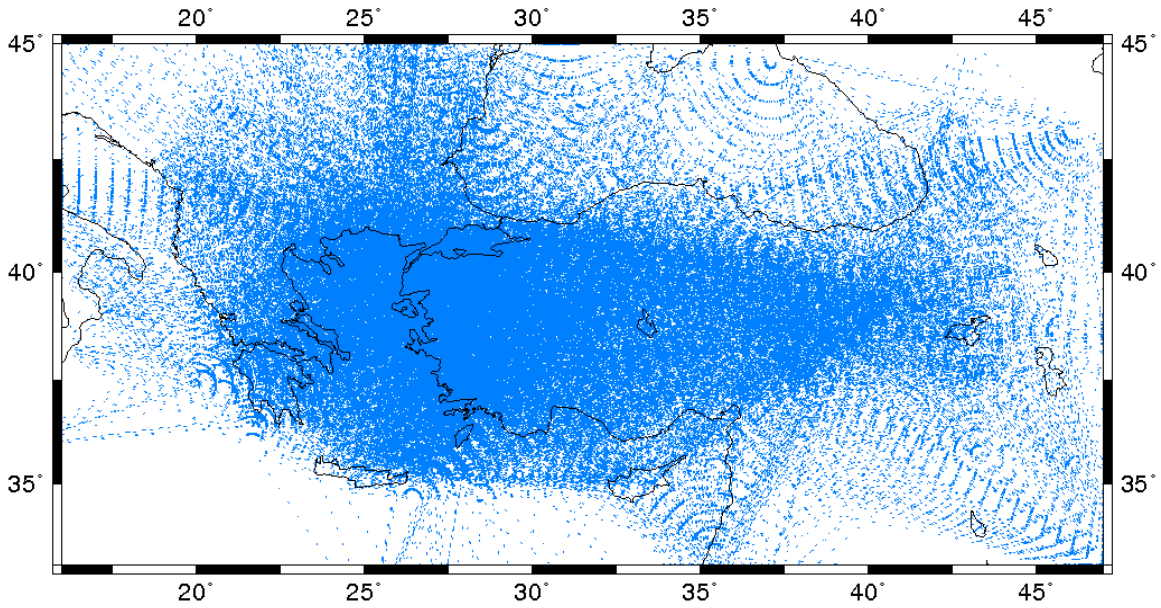

Figure 2. P_n raypaths for tomographic inversion.

Before selecting the optimum cell size, smoothing and weighting parameters, a number of analyses were performed using both real and synthetic data. The checkerboard test is a widely used method to evaluate the solution quality, ray coverage effect, parameterization of the model space and damping factors. Source-receiver configurations of the observations were also used for checkerboard tests. Tests are performed with alternating input velocity patterns and optimum damping parameters were determined. In the areas with low ray coverage such as Black Sea and the Mediterranean Sea the patterns smaller than 2° could not be well resolved. The smearing of the patterns also indicates insufficient ray coverage in the Arabian plateau. The highest level resolution was obtained in the Aegean region and western Turkey. The anisotropic anomalies could not be determined accurately when the azimuthal coverage is poor. A better resolution for anisotropy occurs in the central and eastern Turkey and northern Mediterranean coast.

3. CONCLUSION

The most striking feature of the P_n velocity maps in this study is the observation of very fast and very slow anomalies across the region which clearly shows the presence of a heterogeneous lithospheric structure (Figure 3). High P_n velocities (8.1-8.5km/s) are found beneath the oceanic crusts, i.e., Mediterranean Sea, Hellenic arc, Adriatic Sea as well as Black Sea and Zagros suture zone. Low velocity anomalies are mainly observed on the east (>35^{o}E) of central Anatolia and lowest P_n velocities are sited on eastern Anatolia plateau (<7.6km/s) (Figure 3). Low velocities in P_n tomography correlate well with the volcanic activity in Eastern Anatolia Plateau (Figure 3).

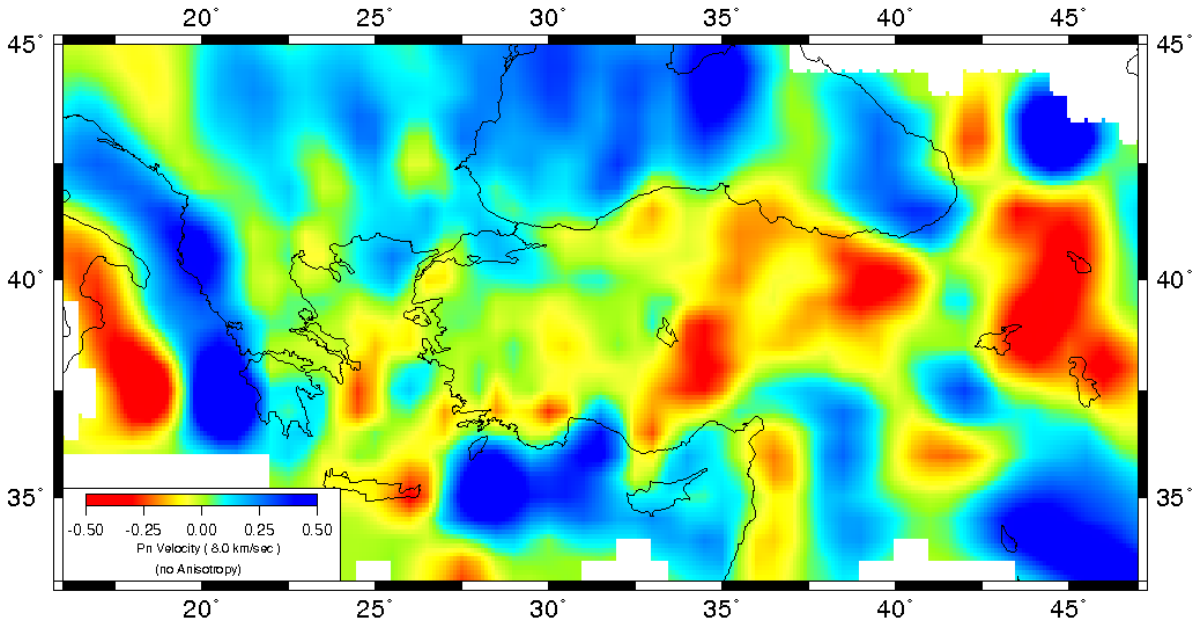

Figure 3. P_n velocity distribution with isotropic model only. Variations from a mean P_n velocity (8.9km/sec) are represented by colors. Only cells with more than 10 arrivals are plotted.

The anisotropy anomalies observed in this study show higher level of lateral variations than P_n velocity anomalies (Figure 4). A maximum value of 0.6km/s which corresponds to about 8% of anisotropy is observed. Large anisotropic anomalies on the southern coast of Anatolia, western Anatolia and central Greece were obtained. Large perturbations in anisotropy are observed in the areas of volcanic activity with no clear orientation. Both directions and magnitudes of the fast axis are varying drastically in eastern Anatolia with low P_n velocities (Figure 4).There is a zone of low apparent anisotropy on the northwest of Lake Van. The anisotropy is varying in clockwise direction around this zone showing no apparent correlation with the absolute plate motion. In western Anatolia, the fast axis is almost in the N-S direction and the amplitude is increasing towards the south (Figure 4). However deviations are apparent from N-S direction in the south which may be related to the subduction geometry. There is more consistency between the anisotropy directions and the maximum extension directions determined from GPS observations (Aktuğ et al., 2009).

The station delays provide information only on the relative crustal thickness variations (Figure 5). Early arrivals indicate thicker-slower crust while late arrivals indicate thinner-faster crust. The station residuals in central Anatolia show very low values (<0.1s) indicating relatively flat Moho topography. Early arrivals are observed at the stations in Marmara, western Anatolia and Aegean Sea. Large positive delays are sited along the southern coast of Anatolia and Hellenides-Dinarides. In eastern Anatolia positive station delays are observed while very small or negative stations delays are observed on the south of Bitlis Suture zone (Figure 5).

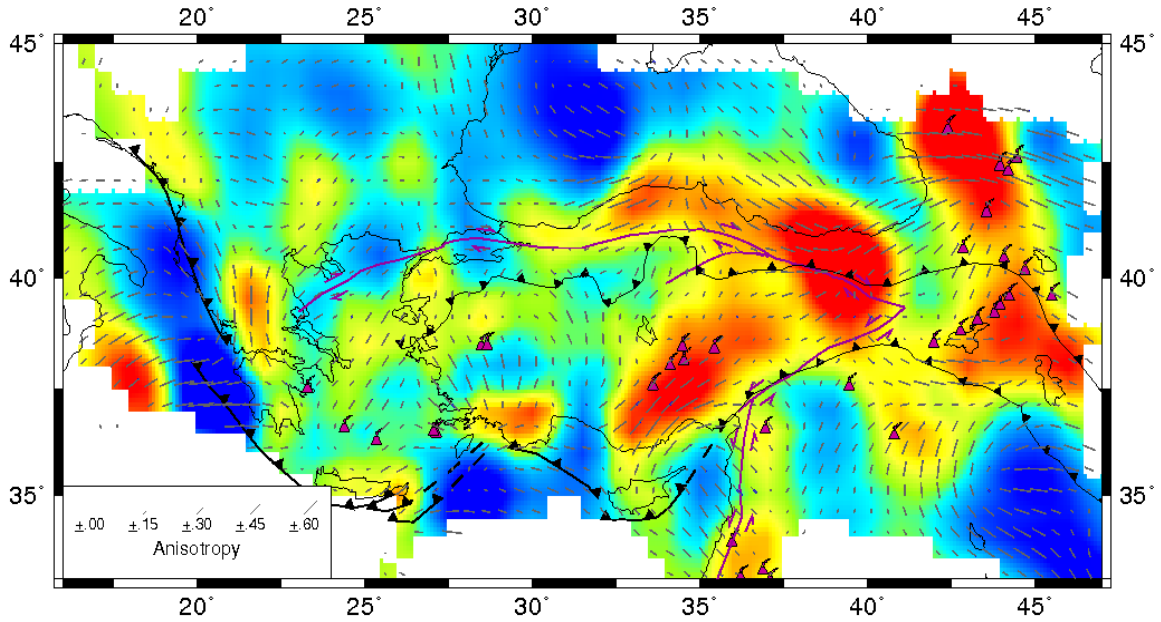

Figure 4. P_n velocity distribution with anisotropy. The fast directions of P_n anisotropy are represented by gray lines. Only cells with more than 10 arrivals are plotted.

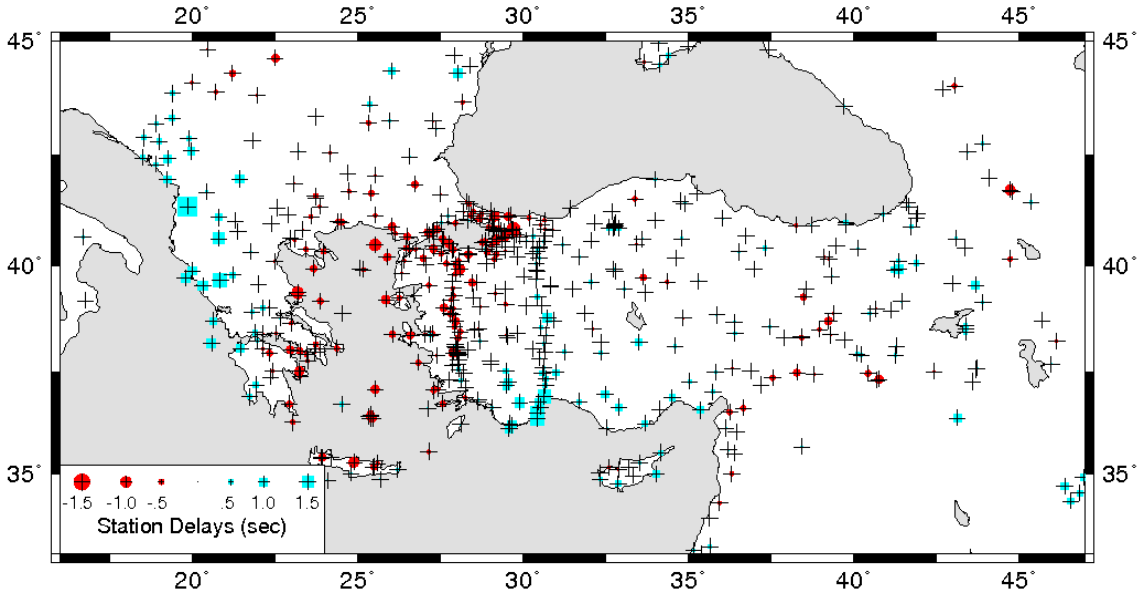

Figure 5. Station delays. Negative delays (circles) are indicative of a thinner crust (thinner than the average 34 km of the reference model); positive delays (crosses) are indicative of a thicker than average crust.

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