ANNALS OF GEOPHYSICS, VOL. 50, N. 2, April 2007

Crustal shear wave velocity structure of Turkey by surface wave dispersion analysis

Timur Tezel ([1]), **Murat Erduran** ([2]) **and Ömer Alptekin** ([3])
([1]) *General Directorate of Disaster Affairs Earthquake Research Department, Ankara, Turkey*
([2]) *Karadeniz Technical University, Engineering Faculty, Department of Geophysics, Trabzon, Turkey*
([3]) *Bogazici University, Kandilli Observatory and Earthquake Research Institute, Istanbul, Turkey*

Abstract
The shear wave velocity structure of the crust and upper mantle in Turkey was determined using single-station measurements of Rayleigh and Love wave group velocities in the 8-50 s period ranges. Group velocity dispersion data of fundamental mode constituted 19 paths for Western and 10 paths for Eastern Turkey. Dispersion curves are measured by applying the multiple filter technique to properly rotated three component digital seismograms. A differential inversion technique is applied to these group velocity dispersion data to determine the *S*-wave velocity structures of the crust and uppermost mantle. Our results show upper mantle *S*-wave velocities between 4.0-4.5 km/s, and a crustal thickness varying between 25-40 km from Western to Eastern Turkey.

Key words *crustal structure – inversion – shear wave velocity – surface waves – Turkey*

1. Introduction

The purpose of this study was to determine the *S*-wave velocity structure of the crust and uppermost mantle beneath Western and Eastern Turkey from surface wave dispersion analysis, and to expound the related tectonic significance. Extracting the fundamental mode of surface waves and determining their dispersion it is possible to estimate the average velocity structure of the Earth along the path that waves have traveled.

Turkey is seismically one of the most active regions in the world. It is located within the «Mediterranean Earthquake Belt», where complex deformations result from the continental collision between the African and Eurasian plates (fig. 1). The neotectonics of Turkey is basically governed by three major structural elements: 1) the Aegean-Cyprean Arc, a convergent plate boundary where the African plate is subducting beneath the Anatolian plate; 2) the dextral north Anatolian Fault Zone; and 3) the sinistral East Anatolian Fault Zone (fig. 1). Seismic activity in this area is the result of interactions between northward moving African and Arabian plates and the relatively stable Eurasian plate (Bozkurt, 2001). Although much is known about the general tectonics of this region (*e.g.*, McKenzie, 1972; Le Pichon and Angelier, 1979; Rotstein and Kafka, 1982; Kasapoğlu and Toksöz, 1983; Jackson and McKenzie 1984; Rotstein and Ben-Avraham 1986; Taymaz *et al.,* 1991; Ambraseys and Jackson 1998), new reliable data for the crust and uppermost mantle velocity structure can contribute to the explanation of structural processes.

The velocity structures of crust and mantle in Turkey have been studied by many authors (Canıtez and Toksöz 1980; Chen and Molnar

Mailing address: Timur Tezel, General Directorate of Disaster Affairs Earthquake Research Department, Eskişehir Yolu 10 km Lodumlu, 06530 Ankara, Turkey; e-mail: tezel@deprem.gov.tr

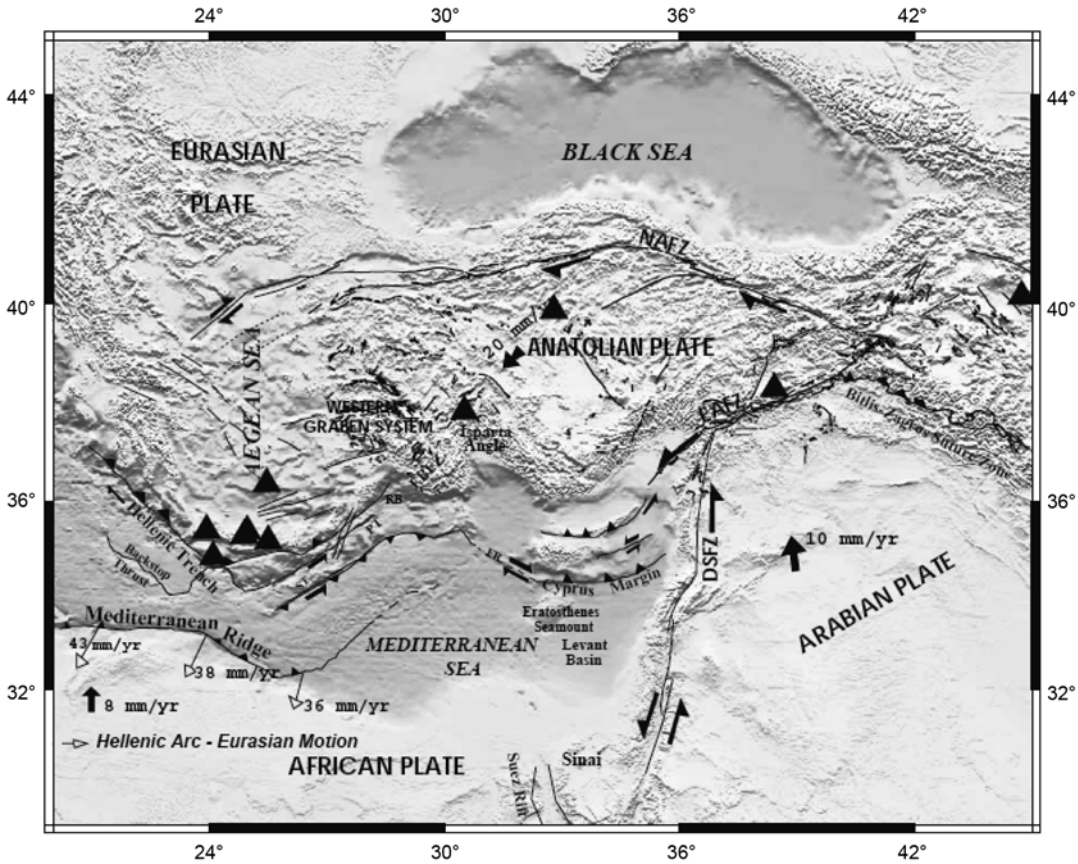


Fig. 1. Simplified tectonic map of Anatolia and surrounding region. Abbreviations: DSFZ – Dead Sea Fault Zone; EAFZ – East Anatolian Fault Zone; NAFZ – North Anatolian Fault Zone; FBFZ – Fethiye-Burdur Fault Zone; PT and ST – Plinny and Strabo Trenchs; GF – Gierrmann Fault. Topograpy data is downloaded from www.noaa.gov web page and faults on land from Şaroğlu *et al.* (1992).

1980; Türkelli, 1985; Mindevalli and Mitchell 1989; Sandvol *et al*., 1998; Saunders *et al*., 1998; Karagianni *et al*., 2002; Meijde *et al*., 2003; Zor *et al*., 2003; Al-Lazki *et al.,* 2004; Çakır and Erduran, 2004). Most of the crustal models for Turkey are based on the rough or large scale velocity models which are mainly obtained from a few regional and local seismological studies. In this case, the seismic structure of Turkey is less well known. Mindevalli and Mitchell (1989) utilized single-station surface wave recordings from station ANTO to determine the lithospheric structure beneath Eastern and Western Anatolia. Sandvol *et al.* (1998) studied receiver functions for the crust structure beneath station ANTO (Ankara), and placed the Moho discontinuity at 37±1.3 km depth. Saunders *et al.* (1998) estimated a graditional Moho between 34 and 38 km depth beneath station ANTO. Saunders *et al*. (1998) also studied receiver structures of two other localities to the west of station ANTO and concluded that the crust thinned towards the west (32-35 km). Recently, Al-Lazki *et al.* (2003) inverted *Pn* phase traveltime residuals collected throughout the broadband Eastern Turkey Seismic Experiment

(ETSE), and concluded that the very low *Pn* velocities (<8 km/s) they found in the region may indicate the absence of mantle lid but asthenospheric material directly beneath the crust. Using data from the ETSE, Gök *et al.* (2003) interpreted the inefficient *Sn* phase propagation under most of the Turkish plateau in terms of hot lithosphere that resulted from the collision between the Arabian and Eurasian plates. Zor *et al.* (2003) inverted the ETSE receiver functions for the crust structure beneath Eastern Turkey. They reported an average crustal thickness of 45 km and an average crustal shear velocity of 3.7 km/s. Maggi and Priestly (2005) used surface waveform tomography to elucidate the uppermantle shear wave velocity structure beneath the Turkey-Iranian plateau and adjacent regions. They obtained a low shear wave velocity anomaly in the uppermost mantle beneath the Turkey.

Continental scale studies are an important complement to global studies and allow us to concentrate on specific regions and processes in more detail. To do this, we make use of group velocity dispersions, and concentrate on the crust and upper mantle beneath Turkey. The purpose of this study is to determine the *S*-wave velocity structure of the crust under Turkey and to expound the related tectonic significance. The present study analyzes the group velocity dispersion of surface waves using more recent and high quality data with improved spatial coverage. Both Rayleigh and Love wave group velocity dispersion curves over a total of 29 paths traversing the study area from 16 earthquakes to Incorporated Research Institute for Seismology (IRIS) stations are analyzed. We believe that the results obtained in this study constitute a valuable basis for future velocity structure studies in this region.

2. Data and method

The records of the stronger local and regional earthquakes serve as a good database for structural studies of crust and upper mantle from the inversion of surface-wave dispersion curves.

Table I. Focal parameters of used earthquakes for Western Turkey.

No.	Date (d/m/y)	Origin Time (UTC)	Latitude (N°)	Longitude (E°)	Magnitude (M_w)	Station	Distance (km)
1	18/03/1993	15:47:00	38.34	22.16	5.8	ANTO (39.87°N, 32.79°E)	933.350
2	23/05/1994	06:46:16	35.56	24.73	6.1	GNI (40.15°N, 44.74°E)	1826.26
3	13/10/1997	13:39:37	36.38	22.07	6.5	ANTO	1014.89
						GNI	2018.85
4	29/04/1998	03:30:37	35.9883	22.0396	5.2	ISP (37.84°N, 30.51°E)	780.950
5	13/09/1999	11:55:28	40.71	30.05	5.9	SANT (36.37°N, 25.46°E)	626.140
						KRIS (35.18°N, 25.50°E)	732.650
						SKD (35.41°N, 23.93°E)	796.140
						IDI (35.29°N, 24.89°E)	753.070
6	12/11/1999	16:57:19	40.76	31.16	7.2	GVD (34.84°N, 24.09°E)	904.550
7	06/06/2000	02:41:49	40.69	32.99	6.0	SANT	812.070
						KRIS	897.780
						SKD	986.400
						GVD	1016.75
						FODE (35.38°N, 24.96°E)	917.810
8	03/02/2002	07:11:28	38.57	31.27	6.5	GNI	1171.16
9	03/02/2002	09:26:43	38.63	30.90	5.8	GNI	1201.10
10	06/07/2003	19:10:27	40.42	26.11	5.6	MLT (38.31°N, 38.43°E)	1084.72
11	01/03/2004	00:36:01	37.22	22.26	5.5	MLT	1425.90

Since surface waves are generated over a wide frequency range, they are recorded best with instruments that employ very broadband and broadband seismometers with high dynamic range digital acquisition equipment. We selected a total of 11 earthquakes for western and 5 earthquakes for Eastern Turkey that were recorded on broadband stations (ANTO, APE, FODE, GNI, GVD, IDI, ISP, KRIS, MLT, SANT, SKD) to study the crustal structure (table I and table II). The path lengths range from 600 to 2000 km. When available, seismograms from multiple earthquakes are used for the same wave paths to ensure data repeatability. Epicenters of selected earthquakes and the locations of used stations are shown in fig. 2. At the selection of earthquakes we considered that they were with a good signal-to-noise ratio, moderate magnitude

Table II. Focal parameters of used earthquakes for Eastern Turkey.

No.	Date (d/m/y)	Origin Time (UTC)	Latitude (N°)	Longitude (E°)	Magnitude (M_w)	Station	Distance (km)
1	13/04/1998	15:14:31	39.3061	41.0663	5.0	ISP (37.84°N, 30.51°E)	932.240
2	19/12/1998	16:15:18	40.0646	42.0154	4.9	ISP	1025.15
3	03/12/1999	17:06:54	40.36	42.35	5.8	SKD (35.41°N, 23.93°E)	1705.03
						IDI (35.29°N, 24.89°E)	1631.56
4	25/03/2004	19:30:49	39.93	40.86	5.5	ISP	925.570
						SKD	1570.72
						APE (37.07°N, 25.53°E)	1370.62
5	11/08/2004	15:48:27	38.38	39.25	5.5	SANT (36.37°N, 25.46°E)	1238.60
						IDI	1322.74
						APE	1215.29

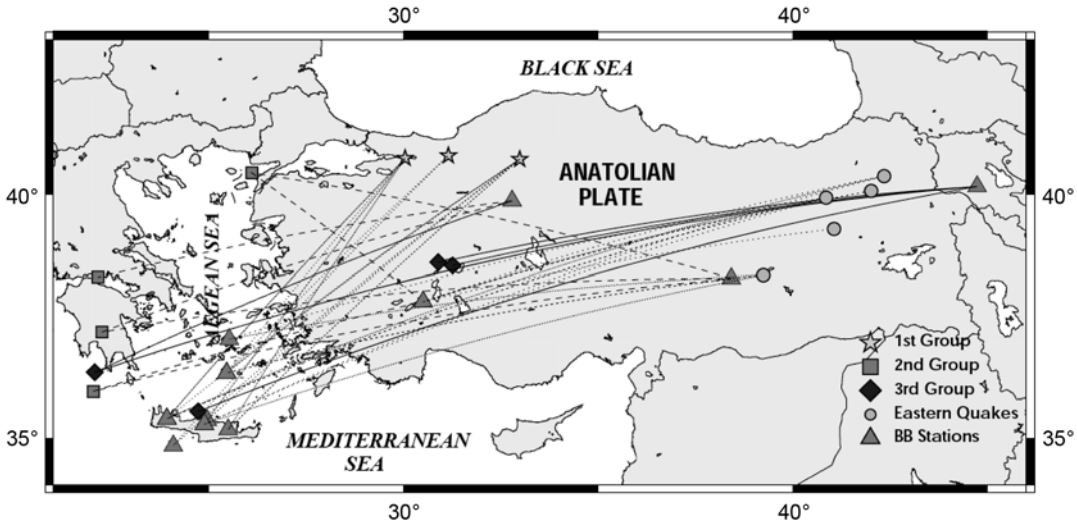


Fig. 2. Map shows single station paths for Western and Eastern Turkey. Stars, squares and diamonds denote epicenters of group 1, 2 and 3 for the Western Turkey respectively. Circles are implied Eastern Turkey earthquakes. Triangles denote used broadband seismic stations.

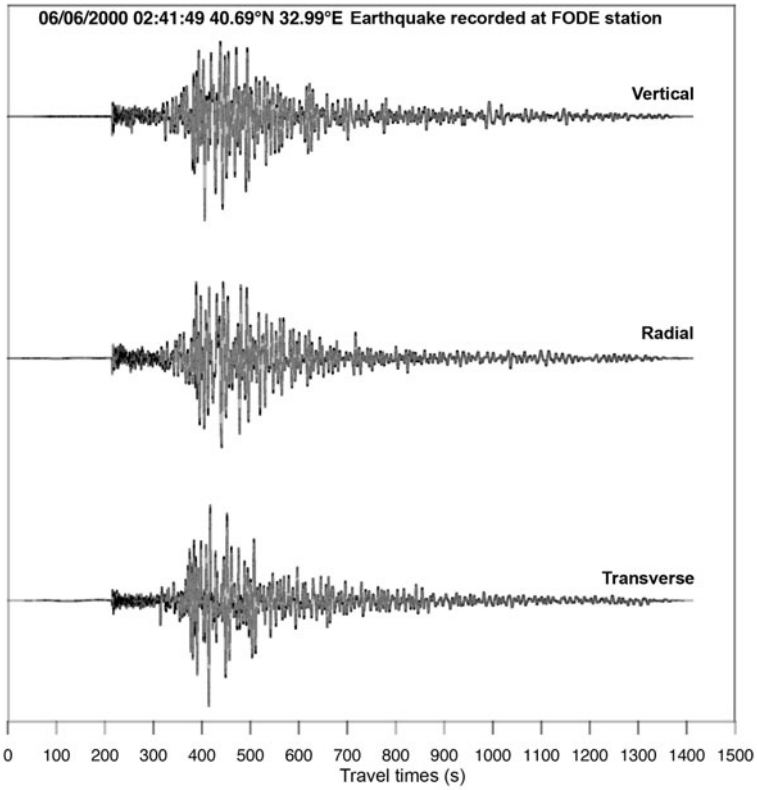


Fig. 3. A sample three-component seismogram recorded on the FODE station for the June 6, 2000 earthquake.

(M>5.5) and adequate epicenteral distance. In this case they show dispersion well. Rayleigh wave group velocities were obtained from the radial and vertical components, and the Love wave velocities from the transverse component. Figure 3 shows a sample three component (vertical, radial and transverse) records of the earthquake number 7 in table I. During the computation of observed group velocities, firstly the records are corrected for instrumental response and than a 10%-cosine time window with maximum 5 km/s and minimum 2 km/s group velocity limits are applied. To see the signal to noise improvement at lower periods, seismograms are band-pass filtered at 8-80 *Sn* cut off periods with a two-sided, two-poled Butterworth filter. A multiple filtering analysis (Dzie-wonski and Hales, 1972; Herrmann, 1973) is applied to each surface wave train to obtain the fundamental mode group velocity curve. Typical contoured plots of relative amplitude of wave energy arrivals of the June 06, 2000 earthquake recorded at FODE station are shown in fig. 4a for the vertical component of Rayleigh waves, and in fig. 4b for the transverse component of Love waves respectively.

We also used a phase-matched filter (Goforth and Herrin, 1979) to identify and remove multipathing arrivals to improve the quality of the determined dispersion curves. It is remarkable that both Rayleigh and Love waves show almost the same scatter at short periods (<12 s) because of interference by *S*-waves. Thus, we exclude the short period dispersion data in subsequent inversion to obtain the *S*-wave velocity structure.

To obtain models for the region, we used inversion theory, as first proposed by Backus and

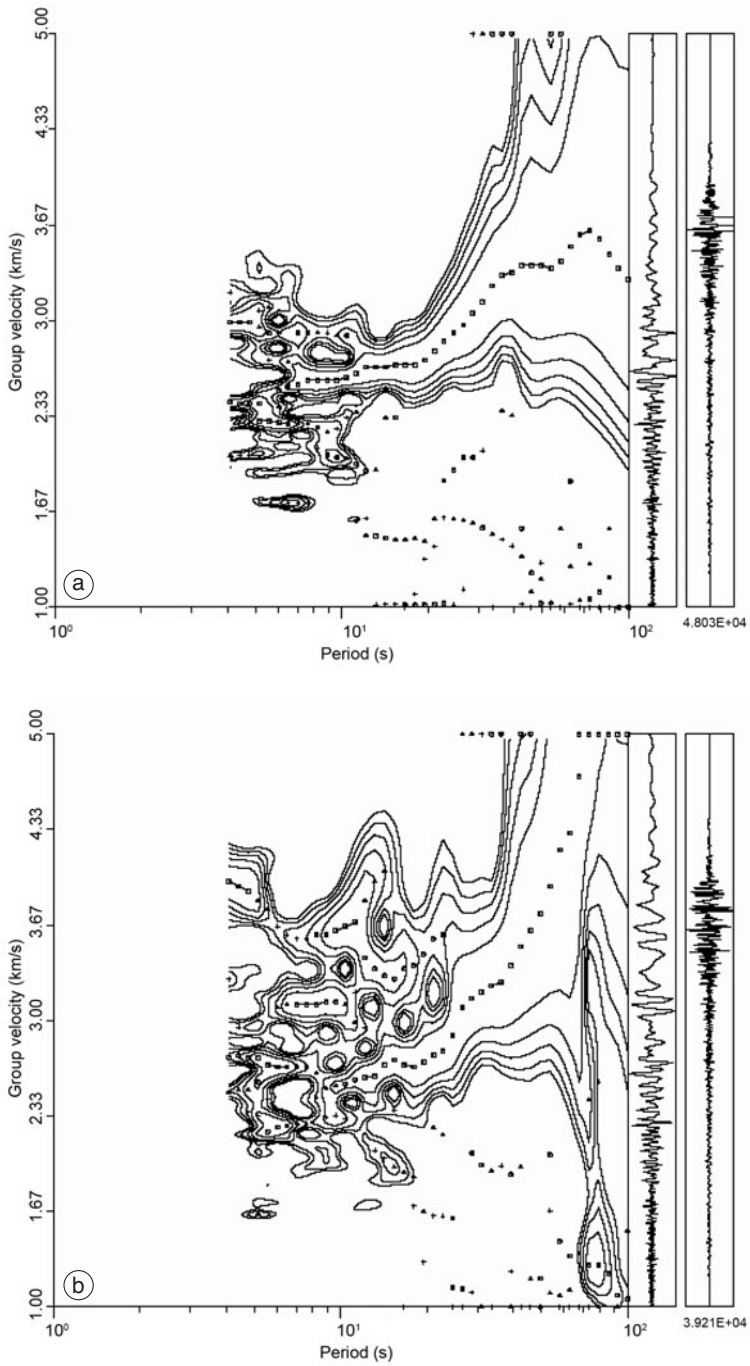


Fig. 4a,b. Typical contoured plots of relative amplitude of wave energy at FODE station a) for the vertical component of Rayleigh waves; and b) transverse component of Love waves.

Gilbert (1970). In the present study we used an interactive program developed by Russell *et al.* (1984). The program inverts observed group velocities for plane-layered shear velocity structure and uses singular value decomposition (Lawson and Hanson, 1974) in stochastic or differential form (Russell, 1984).

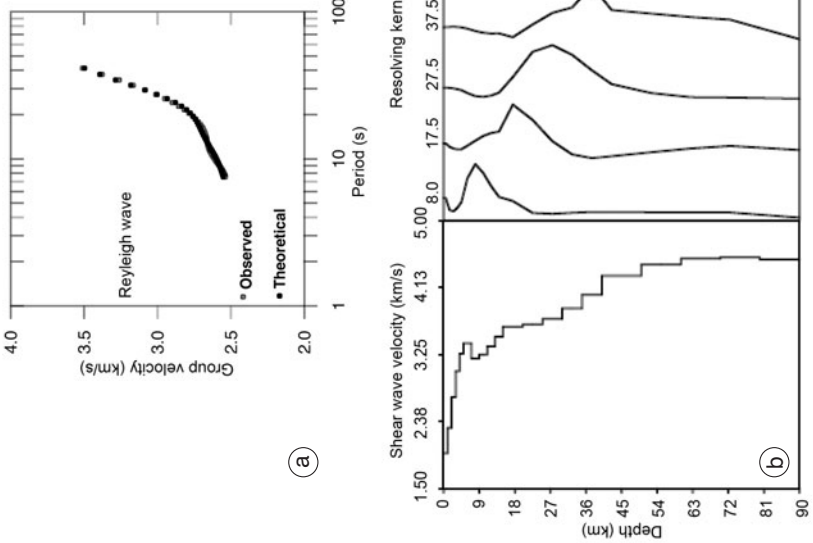
Our inversion starts with an initial model, which is constituted, based on the half-space Earth model and has 5 km/s velocity for all layers. The feasibility of using a half-space as the initial model was tested by Hwang and Mitchell (1987) using data from the Indian Shield. For the first 5 km of the model, layers as thin as 1 km were used and the layers thickness increased downwards. The total thickness of the model is taken to be 90 km and is represented by as many as 20 layers. Method uses a non-linear iterative procedure to arrive at a model that satisfies the data. The differential inversion method that we use minimizes both the magnitude of the error vector between the observed and computed velocities and differences between adjacent layers, thereby minimizing large velocity changes between adjacent layers. In this study we assumed that Poisson's ratio is 0.25 for all layers. After the inversion if successful convergence has been achieved between the observed and computed curves, theoretical group velocities should agree with observed values within the data uncertainties. In the inversion, shear velocities are only adjusted, *i.e.* compressional velocities, densities and layer thicknesses remain fixed. The reliability of the estimated models is shown by resolution kernels obtained from the rows of the resolution matrix (Jackson, 1972; Wiggins, 1972). The inverted model is obtained through a non-linear iterative process in which velocity partial derivatives are recomputed for each iteration. If successful convergence has been achieved, theoretical group velocities should agree with observed values within the data uncertainities. We obtain resolving lengths and values for model parameter uncertainities at all depths.

Examples of the results from the inversion process are presented in figs. 5a,b and 6a,b. Theoretical and observed group velocities for Rayleigh wave are shown in fig. 5a. The match between theoretical and inverted dispersion is almost perfect. The group velocities were inverted to obtain the shear wave velocity model shown in fig. 5b. Between approximately 7 and 20 km below the surface, the shear velocities observed in the model are low, varying between 3.2 and 4 km/s. The resolution kernels also plotted in fig. 5b correspond to the velocity model. The maxima of the curves coincide with the layer depths up to about 80 km below the surface. The width of the resolving kernels at shallow depths (< 18 km) and at great depth is wider (> 54 km) than the layer thicknesses at the same depths, implying that the resolution of layer structure at those depths is poor. Thus the results obtained here are most reliable for the Moho velocity structure. Similarly, we also inverted the Love wave data in fig. 6a,b.

Surface waves are effected from the phase uncertainties at the source. Therefore, the inversion results of surface waves show some scattering and may differ for each earthquake. Thus, in using the single station technique to determine the crust and upper mantle structure from surface waves, it is convenient to have a statistical average by using the data from more than one earthquake. So, we calculated average group velocity curves from the calculated group velocity curve, and then we inverted average group velocity curves for the determining the *S*-wave velocity structures.

3. Results and discussions

The wave paths are divided into two groups as Western and Eastern Turkey. Then in Western Turkey, we constituted three groups according to the similarities of dispersion curves and in Eastern Turkey two groups of Rayleigh and Love waves. Western Turkey's first group includes 10 paths which traverse Eastern Marmara and Crete. The second group includes 3 Rayleigh wave and 2 Love wave paths which traverse the Aegean Sea and Western and Central Anatolia. The third group includes 4 crossing the whole of Turkey (fig. 2). Eastern Turkey includes 4 Rayleigh and 6 Love wave paths which traverse Turkey (fig. 2). An average *S*-wave velocity structure under each group of wave path is obtained from the inversion of the group velocity dispersion data of surface waves. Detailed descriptions of individual path groups are given below.



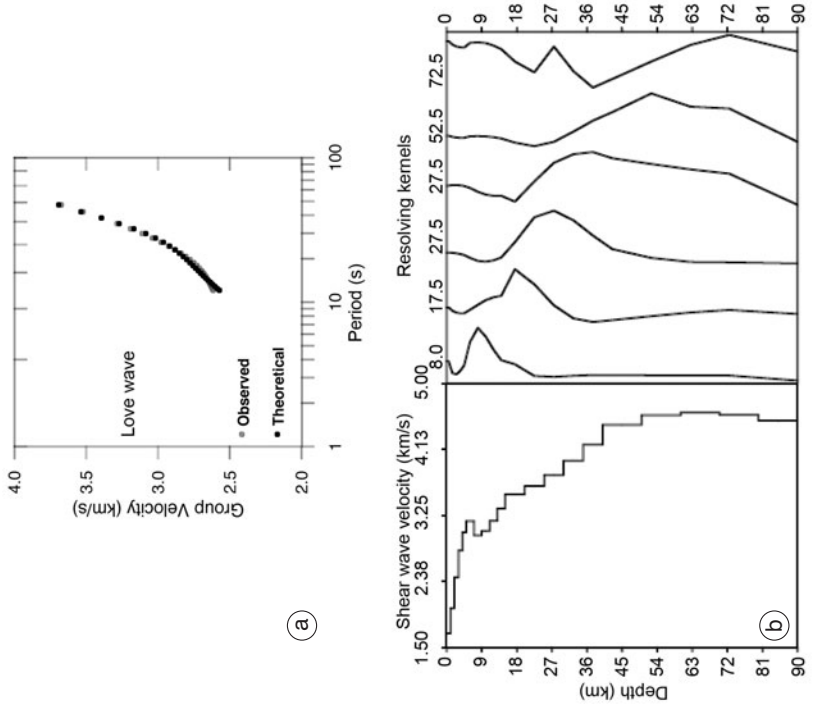


Fig. 5a,b. a) Theoretical and observed group velocities for the best-fitting model from Rayleigh waves. b) Resolving kernels (right side) for the best-fitting model (left side) for region traversed by path in western group.

Fig. 6a,b. a) Theoretical and observed group velocities for the best-fitting model from Love waves. b) Resolving kernels (right side) for the best-fitting model (left side) for region traversed by path in western group.

3.1. *Western Turkey*

Group 1 – The group velocity dispersion curves of fundamental-mode Rayleigh waves are shown in fig. 7a for the 10 paths in group 1 which traverse Eastern Marmara and Crete. The figure shows that the group velocity dispersion curves of Rayleigh waves for all paths follow each other closely for periods longer than about 12 s. The Rayleigh group velocity increases from 2.65 km s^{-1} at period 15 s to about 3.5 km s^{-1} at period 50 s.

Figure 7b shows the individual and average *S*-wave velocity models for group 1 paths. From the figure we can see a Low Velocity Zone (LVZ) at depths 7-15 km with *Vs* of 3.2 km s^{-1}. These paths have an average crustal thickness of 35 km. The shear wave velocity, *Vs*, in the upper mantle reaches 4.4 km s^{-1} at depth 50-60 km.

Group 2 – The group velocity dispersion curves of fundamental-mode Rayleigh and Love waves are shown in fig. 8a for the 3 Rayleigh wave and 2 Love wave paths in group 2 which traverse the Aegean Sea and Western and Central Anatolia. The figure shows that the group velocity dispersion curves of Rayleigh and Love waves for all paths follow each other closely for periods longer than about 20 s. The Rayleigh wave group velocity increases from 2.7 km s^{-1} at period 15 s to about 3.45 km s^{-1} at period 50 s and the Love wave group velocity increases from 2.9 km s^{-1} at period 8 to about 3.75 km s^{-1} at period 50 s.

Figure 8b,c shows the individual and average *S*-wave velocity models for group 2 Rayleigh wave and Love wave paths, respectively. From the figure we can see an LVZ at depths 13-20 km with *Vs* of 3.5 km s^{-1} according to the Rayleigh wave paths, and for Love wave paths we can see an LVZ at depths 11-20 km with *Vs* of 3.37 km s^{-1}. These paths have an average crustal thickness of 25 km for both of Rayleigh and Love waves. The shear wave velocity, *Vs*, in the upper mantle reaches 4.4 km s^{-1} at depth 60 km.

Group 3 – The group velocity dispersion curves of fundamental-mode Rayleigh waves are shown in fig. 9a for the 4 Rayleigh wave paths in group 3 which traverse the Aegean Sea and Central Anatolia and Armenia. The figure shows that the group velocity dispersion curves of Rayleigh waves for all paths follow each other closely for periods longer than about 20 s. The Rayleigh wave group velocity increases from 2.6 kms^{-1} at period 20 s to about 3.5 kms^{-1} at period 50 s.

Figure 9b shows the individual and average *S*-wave velocity models for group 3 Rayleigh wave paths. From the figure we can see an LVZ

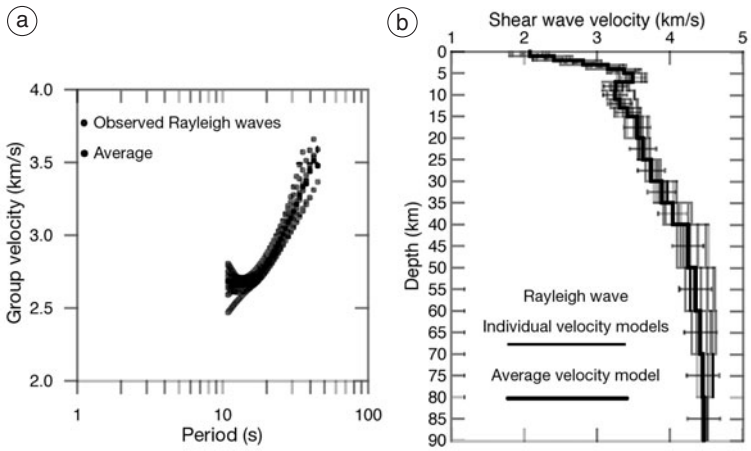


Fig. 7a,b. a) Group velocity curves for Rayleigh waves and b) shear wave velocity structures for group of 1 of Western Turkey.

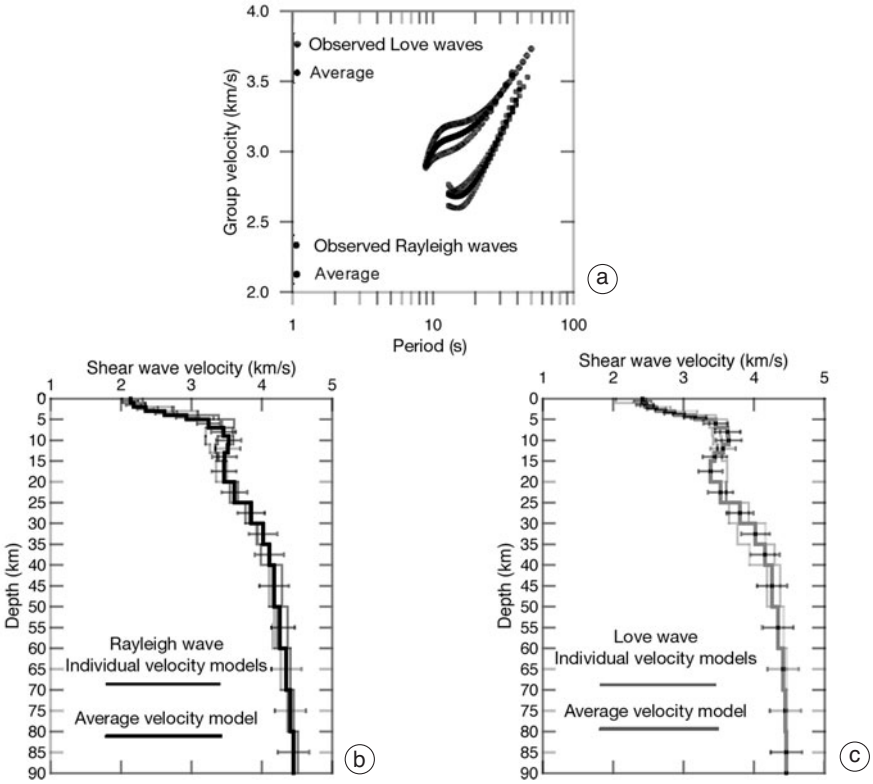


Fig. 8a-c. a) Group velocity curves for Rayleigh and Love waves and b) shear wave velocity structures and c) for group of 2 of Western Turkey.

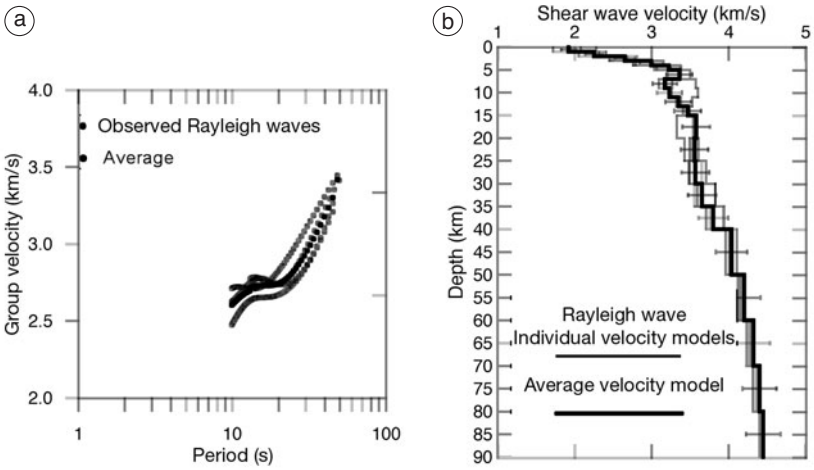


Fig. 9a,b. a) Group velocity curves for Rayleigh waves and b) shear wave velocity structures for group of 3 of Western Turkey.

at depths 7-15 km with *Vs* of 3.2 km s^{-1}. These paths have an average crustal thickness of 40 km. The shear wave velociy, *Vs*, in the upper mantle reach 4.3 km s^{-1} at depth 60 km.

The average *Pn* velocity for the entire Aegean region is approximately 7.9 km/s (Panagiotopoulos and Papazachos, 1985), which is lower than the worldwide average continental uppermantle *Pn* velocity of 8.1 km/s (Mooney and Braile, 1989). *Pn* velocity for Western Turkey was suggested to be 7.8 and 7.85 km/s by Kalafat *et al.* (1987) and Horasan *et al.* (2002), respectively. Al-Lazki *et al.* (2004) suggested that the very low *Pn* velocity (~7.5 km/s) and thinned crust (26-32 km) beneath the Aegean (Makris and Vees, 1977; Akyol *et al*., 2006) may reflect a very thin to absent mantle lid, where *Pn* propagation is actually sampling asthenospheric rather than lithospheric mantle. Mindevalli and Mitchell (1989), using surface waves, gave an average crustal thickness of about 34 km for the western part of Turkey. Horasan *et al*. (2002) suggest a crustal thickness of 33 km in the region. Zhu *et al*. (2006) showed that Moho depth

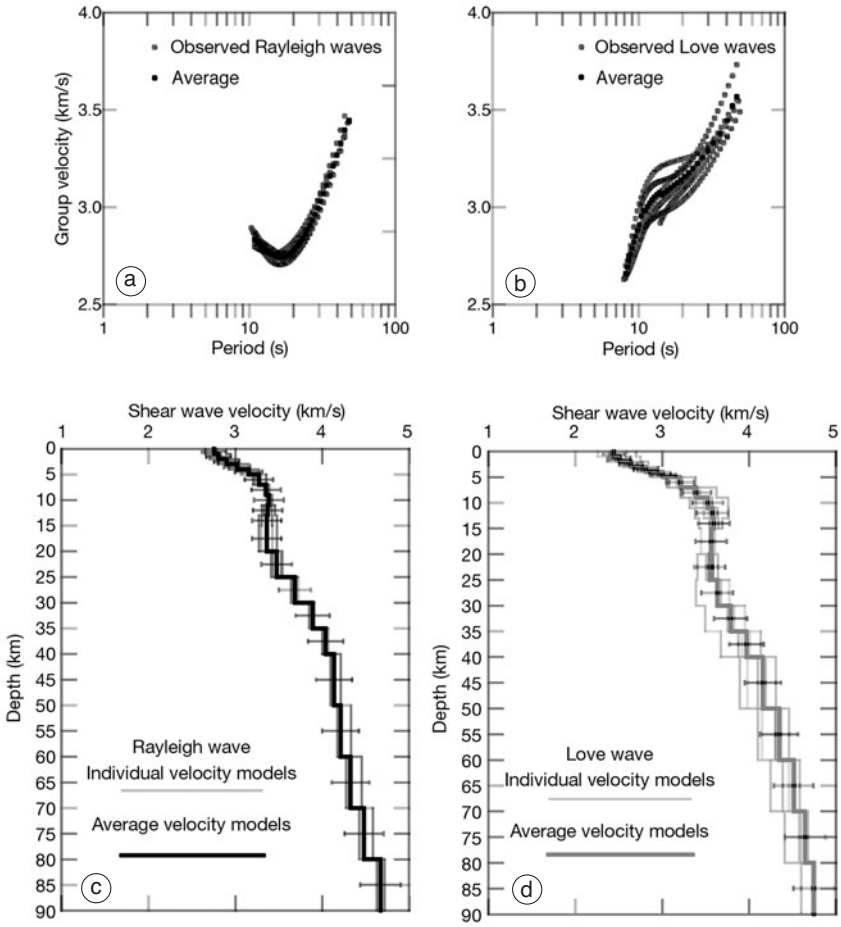


Fig. 10a-d. Group velocity curves a) for Rayleigh waves and b) for Love waves and shear wave velocity structures (c and d) for Eastern Turkey.

is ~28 and 30 km under the stations BOZ and KUL using receiver function analysis, respectively. These thicknesses are similar to values obtained in this study.

3.2. *Eastern Turkey*

The group velocity dispersion curves of fundamental-mode Rayleigh and Love waves are shown in fig. 10a,b for the 4 Rayleigh wave and 6 Love wave paths in group Eastern Turkey which traverse along Anatolia. The figure shows that the group velocity dispersion curves of Rayleigh waves for all paths follow each other closely for periods longer 15 s, and of Love waves for all paths that follow each other closely for periods longer than about 10 s. However, we can see that there is some scatter at Love wave group velocity dispersion curves. The Rayleigh wave group velocity increases from 2.8 km s^{-1} at period 15 s to about 3.5 km s^{-1} at period 50 s and the Love wave group velocity increases from 2.6 km s^{-1} at period 8 to about 3.6 km s^{-1} at period 50 s.

Figure 10c,d shows the individual and average *S*-wave velocity models for Eastern Anatolia Rayleigh wave and Love wave paths, respectively. From the figure we can see an LVZ at depths 12.5-20 km with a shear wave velocity of 3.3 km s^{-1} according to the Rayleigh wave paths. From the Love wave paths we can not see an LVZ clearly. Love wave paths have an average crustal thickness of 40 km. If we accept the mantle *Vs* velocity as 4.2 km s^{-1}, the Rayleigh wave and Love wave paths have a crust-mantle transition between at 40 and 50 km depths. The shear wave velocity, *Vs*, in the upper mantle reaches 4.5 km s^{-1} at depth 60 km.

4. Conclusions

We have presented the results of a study of Rayleigh and Love wave dispersion in the Turkey plate. The shear wave velocity crustal structures under western and eastern groups from surface to a depth of 90 km can be seen clearly. The results are compared in fig. 11a,b. The models for Western Turkey and Eastern Turkey are similar to one another throughout the uppermost crust and lower crust. Our inversion results indicate that the Anatolia region has a Low Velocity Zone (LVZ) at 7-20 km depths. In this depth range, shear velocities are faster in Eastern Turkey than in Western Turkey. The

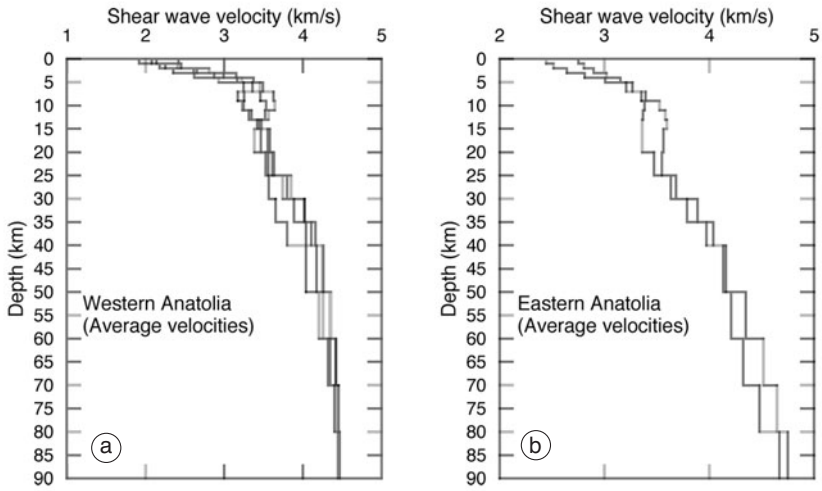


Fig. 11a,b. Average shear wave velocity models for a) Western and b) Eastern Turkey.

low crustal velocities may be associated with high crustal temperatures, a high degree of fracture, or the presence of fluids at high pore pressure in the crust (Akyol *et al*., 2006). The thickness of this low velocity zone varies beneath Anatolia. The average crustal thickness changes from 25 to 40 km from western to eastern region. Upper mantle maximum shear wave velocities range between 4.3-4.5 km s^{-1} at 50-60 km depths for Turkey. Low near surface shear wave velocities change between 3.5-3.8 km s^{-1}. Both the crustal velocities and upper mantle velocities obtained for Turkey are lower than those obtained throughout most of Europe.

Other similar studies in the Anatolian plate have estimated the *Sn* velocity at around 4.5 km/s (Saunders *et al*., 1998; Sandvol *et al*., 1998). The findings by Kadinsky-Cade *et al*. (1981), Rodgers *et al*. (1997) and Gök *et al*. (2000) on inefficient *Sn* propagation in the Turkey are important. Rodgers *et al*. (1997) pointed out that inefficient *Sn* propagation (high attenuation), low *Pn* velocity and volcanism may indicate partial melt in the upper mantle. In fact, the low *Sn* velocity (~4.5 km/s) and the low *Pn* velocity (~7.8 km/s) estimated in this study also indicate a probable sub-Moho partial melt. Necioglu *et al*. (1981) found the crust in Western Turkey is 25-32 km thick from travel time analysis of local and regional earthquake arrival times. Saunders *et al*. (1998) also indicated a possible low velocity zone in the upper mantle beneath station ANTO. They found ~37.5 km crustal thickness beneath station ANTO. Shear velocities were between 3.3 km/s and 3.5 km/s in the lower crust and 4.5 km in the uppermost mantle. Hearn and Ni (1994) used a tomographic technique to obtain *Pn* velocities in the region and found that *Pn* velocity is approximately 7.8 km/s in the Anatolian plate. Sandvol *et al*. (1998) found crustal thickness value of 37 km in the Anatolian plate using receiver function inversion method and average crustal shear velocity of 3.6 km/s. Mindevalli and Mitchell (1989) measured fundamental mode Rayleigh and Love wave group velocities in the 8-50 s period range for the ANTO seismic station. Similarly, they found the shear wave velocity to be 4.2 km/s and an average crustal thickness of 40 km. Receiver function studies in Eastern Turkey (Zor *et al*., 2003) found an average crustal thickness of 45 km. Maggi and Priestly (2005) found that the Turkish-Iranian plateau was underlain by a strong low-velocity anomaly at least down to 150 km depth. There are low velocity anomalies also under the Turkish peninsula and the Aegean sea. They showed that the strongest portion of the low velocity anomaly was located under the easternmost Turkish plateau and extended down to 200 km depth.

Thus our obtained values are similar to previous geophysical studies in the region. Final 1D shear wave velocity models found in this study represent the most acceptable model for future geophysical and geological investigations in the Turkish plate. These average velocity structures are important for many disciplines of seismology that use a preliminary initial velocity structure. For example, it is important for seismic hazard studies that use a deterministic approach based upon complete waveform modeling. Especially important is the role of the upper crustal layers.

REFERENCES

Akyol, N., L. Zhu, B. J. Mitchell, H. Sozbilir and K. Kekovali (2006): Crustal structure and local seismicity in Western Anatolia, *Geophys. J. Int.*, **166** (3), 1259-1269, doi: 10.1111/ j.1365-246X.2006.03053.x.

Al-Lazki, A., D. Seber, E. Sandvol, N. Turkelli, R. Mohamad and M. Barazangi (2003): Tomographic *Pn* velocity and anisotropy structure beneath the Anatolian plateau (Eastern Turkey) and the surrounding regions, *Geophys. Res. Lett.*, **30** (24), 8043, doi: 10.1029/ 2003GL017391.

Al-Lazki, A., E. Sandvol, D. Seber, M. Barazangi, N. Turkelli and R. Mohamed (2004): *Pn* tomographic imaging of mantle lid velocity and anisotropy at the junction of the Arabian, Eurasian and African plates, *Geophys. J. Int.*, **158**, 1024-1040.

Ambraseys, N.N. and J.A. Jackson (1998): Faulting associated with historical and recent earthquakes in the Eastern Mediterranean region, *Geophys. J. Int.*, **133**, 390-406.

Backus, G. and F. Gilbert (1970): Uniqueness in inversion of inaccurate gross Earth data, *Philos. Trans. R. Soc. London Ser. A*, **266** (1173), 123-192.

Bozkurt, E. (2001): Neotectonics of Turkey – a synthesis, *Geodinamica Acta*, **14**, 3-30.

Çakir, Ö. and M. Erduran (2004): Constraining crustal and upper mantle structure beneath station TBZ (Trabzon, Turkey) by receiver function and dispersion analyses, *Geophys. J. Int.*, **158**, 955-971.

Canitez, N. and M.N. Toksöz (1980): Crustal Structure Beneath Turkey, *Eos Trans. Am. Geophys. Un.*, **61**, pp. 290.

Chen, C.Y. and P. Molnar (1980): The uppermost mantle *P*-wave velocities beneath Turkey and Iran, *Geophys. Res. Lett.*, **7**, 77-80.

DZIEWONSKI, A. and A.L. HALES (1972): Numerical analysis of dispersed seismic waves, in *Methods in Computational Physics*, edited by B.A. BOLT (Academic Press), 39-85.

GOFORTH, T. and E. HERRIN (1979): Phase-matched filters: application to the study of Love waves, *Bull. Seismol. Soc. Am.*, **69**, 27-44.

GOK, R., N. TURKELLI, E. SANDVOL, D. SEBER and M. BARAZANGI (2000): Regional wave propagation in Turkey and surrounding regions, *Geophys. Res. Lett.*, **27** (3), 429-432.

GOK, R., E. SANDVOL, N. TURKELLI, D. SEBER and M. BARAZANGI (2003): *Sn* attenuation in the Anatolian and Iranian plateau and surrounding regions, *Geophys. Res. Lett.*, **30** (24), 8042, doi: 10.1029/2003GL018020.

HEARN, T. and J. NI (1994): Seismic velocities beneath continental collision zones: the Turkish-Iranian plateau, *Geophys. J. Int.*, **117**, 273-283.

HERRMANN, R.B. (1973): Some aspects of band-pass filtering of surface waves, *Bull. Seismol. Soc. Am.*, **63**, 663-671.

HORASAN, G., L. GULEN, A. PINAR, D. KALAFAT, N. OZEL, H.S. KULELI and A.M. ISIKARA (2002): Lithospheric structure of the Marmara and Aegean regions, Western Turkey, *Bull. Seismol. Soc. Am.*, **92**, 322-329.

HWANG, H.J. and B.J. MITCHELL (1987): Shear velocities, *Q* in stable and tectonically active regions from surface wave observations, *Geophys. J. R. Astron. Soc.*, **90**, 575-613.

JACKSON, D.D. (1972): Interpretation of inaccurate, insufficient, and inconsistent data, *Geophys. J. R. Astron. Soc.*, **28**, 97-109.

JACKSON, J.A. and D.P. MCKENZIE (1984): Active tectonics of the Alpine – Himalayan belt between Turkey and Pakistan, *Geophys. J. R. Astron. Soc.*, **77**, 185-264.

KADINSKY-CADE, C., M. BARAZANGI, J. OLIVER and B. ISACKS (1981): Lateral variations of high-frequency seismic wave propagation at regional distances across the Turkish and Iranian plateaus, *J. Geophys. Res.*, **86**, 9377-9396.

KALAFAT, D., C. GURBUZ and B. UCER (1987): Batı Turkiye'de kabuk ve Ust Manto Yapisinin araştırılması, *Deprem Arastirma Bulteni*, **59**, 43-64 (in Turkish).

KARAGIANNI, E., D. PANAGIOTOPOULOS, G. PANZA, P. SUHADOLC, C. PAPAZACHOS, A. KIRATZI, D. HATZFELD, K. MAKROPOULOS, K. PRIESTLEY and A. VUAN (2002): Rayleigh wave group velocity tomography in the Aegean area, *Tectonophysics*, **358**, 187-209.

KASAPOĞLU, K.E. and M.N. TOKSÖZ (1983): Consequences of collision of Arabian and Eurisian plates-finite elements models, *Tectonophysics*, **100**, 71-95.

LAWSON, C.L. and R.J. HANSON (1974): *Solving Least Squares Problems* (Prentice-Hall, New Jersey), pp. 340.

LE PICHON, X. and J. ANGELIER (1979): The Hellenic Arc and trench system: a key to the neotectonic evolution of the Eastern Mediterranean area, *Tectonophysics*, **60**, 1-42.

MAGGI, A. and K. PRIESTLY (2005): Surface waveform tomography of the Turkish-Iranian Plateau, *Geophys. J. Int.*, **160**, 1068-1080.

MAKRIS, J. and R. VEES (1977): Crustal structure of Central Aegean Sea and the island of Evvia and Crete, Greece, obtained from refraction seismic experiment, *J. Geophys.*, **42**, 329-341.

MCKENZIE, D. (1972): Active tectonics of the Mediterranean region, *Geophys. J. R. Astron. Soc.*, **30**, 109-185.

MEIJDE, M., S. LEE and D. Giardini (2003): Crustal structure beneath broadband seismic stations in the Mediterranean region, *Geophys. J. Int.*, **152**, 729-739.

MINDEVALLI, O.Y. and B.J. MITCHELL (1989): Crustal structure and possible anisotropy in Turkey from seismic surface wave dispersion, *Geophys. J. Int.*, **98**, 93-106.

MOONEY, W.D. and L.W. BRAILE (1989): The seismic structure of the continental crust and upper mantle of North America, in *The Geology of North America: An Overview*, edited by A. BALLY and P. PALMER (Geol. Soc. Am., Boulder, CO), 39-52.

NECIOGLU, A., B. MADDISON and N. TURKELLI (1981): A study of crustal and upper mantle structure of northwestern Turkey, *Geophys. Res. Lett.*, **8**, 33-35.

PANAGIOTOPOULOS, D.G. and B.C. PAPAZACHOS (1985): Travel times of *Pn*-waves in the Aegean and surrounding area, *Geophys. J. R. Astron. Soc.*, **80**, 165-176.

RODGERS, A.J., J.F. NI and T.M. HEARN (1997): Propagation characteristics of short-period *Sn* and *Lg* in the Middle East, *Bull. Seismol. Soc. Am.*, **87**, 396-412.

ROTSTEIN, Y. and Z. BEN-AVRAHAM (1986): Active tectonics in the Eastern Mediterranean: the role of oceanic plateaus and accered terranes, *Israel J. Earth Sci.*, **35**, 23-39.

ROTSTEIN, Y. and A.L. KAFKA (1982): Seismotectonics of the southern boundery of Anatolia, Eastern Mediterranean region: subduction, collision, and arc jumping, *J. Geophys. Res.*, **87** (B9), 7694-7706.

RUSSELL, D.R., R.B. HERRMANN and H.J. HWANG (1984): SURF; an interactive set of surface wave dispersion programs for analyzing crustal structure, *Earthquake Notes*, **55**, pp. 13.

SANDVOL, E., D. SEBER, A. CALVERT and M. BARAZANGI (1998): Grid search modeling of receiver functions: implications for crustal structure in the Middle East and North Africa, *J. Geophys. Res.*, **103**, 26899-26917.

ŞAROĞLU, F., Ö. EMRE and I. KUŞÇU (1992): *Türkiye Diri Fay Haritası* (MTA Yayini), (in Turkish).

SAUDERS, P., K. PRIESTLEY and T. TAYMAZ (1998): Variations in the crustal structure beneath Western Turkey, *Geophys. J. Int.*, **134**, 373-389.

TAYMAZ, T., J. JACKSON and D. MCKENZIE (1991): Active tectonics of the north and Central Aegean Sea, *Geophys. J. Int.*, **108**, 422-490.

TURKELLI, N. (1985): Seismic investigation of the crustal structure in Central Anatolia, *Ph.D. Thesis* (METU, Ankara, Turkey).

WIGGINS, R.A. (1972): The general linear inverse problem: implications of surface waves and free oscillations for Earth structure, *Rev. Geophys. Space Phys.*, **10**, 251-285.

ZHU, L., B. J. MITCHELL, N. AKYOL, I. CEMEN and K. KEKOVALI (2006): Crustal thickness variations in the Aegean region and implications for the extension of continental crust, *J. Geophys. Res.*, **111**, B01301, doi:10.1029/2005JB003770.

ZOR, E., E. SANDVOL, C. GURBUZ, N. TURKELLI, D. SEBER and M. BARAZANGI (2003): The crustal structure of the East Anatolian plateau (Turkey) from receiver functions, *Geophys. Res. Lett.*, **30** (24), 8044, doi: 10.1029/2003GL018192.

(received March 16, 2006;
accepted March 2, 2007)