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INVESTIGATION OF THE SEISMIC VELOCITY DISTRIBUTION AND CRUSTAL STRUCTURE OF TURKEY BY MEANS OF GRAVITY DATA

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Review Article

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ABSTRACT

In this study, the apparent gravity density data was measured for Turkey using apparent density filter, and the seismic velocity distribution map was generated from this data cluster. By interpreting these two measured data clusters, three dimensional structure of the Conrad discontinuity was investigated. The apparent gravity filter is a kind of filter which is used in the apparent gravity measurements for different depth levels different than gravity data. In this study, considering previously measured distribution of the continental crustal thickness of the Anatolia, the density maps for different depth levels were formed and interpreted. The lowest and highest densities in different levels of Turkey are 2.23 gr/cm^3, and 3 gr/cm^3, respectively; and the mean density is 2.698 gr/cm^3. The lowest and highest seismic velocities for different thicknesses were measured as 3.20 km/sec and 6.83 km/sec, respectively. However; the mean seismic velocity of Turkey for depths increasing up to 10 km until MOHO discontinuity was estimated as 5.66 km/sec. The density and seismic velocity in the first 20 km of the continental crust have reached its highest values as 2.74 gr/cm^3 and 5.86 km/sec, respectively. This zone is also the Conrad discontinuity between the lower and upper crusts, and its average depth is 16 km in Turkey. The Conrad discontinuity boundary, which developed between SIAL-SIMA, not to be observed in the East Anatolian High Plateau made us consider that SIMA had disappeared as a result of the geological evolution, and the available crust could only be SIAL in origin.

1. Introduction

Studies of seismic velocity distribution have been carried out by various investigators for different regions of the Anatolia. Zor et al. (2003) measured seismic velocities of the crustal structure of the East Anatolian Plateau by receiver function and determined the shearing velocity in between 3.5-3.8 km/sec. Canbaz and Karabulut (2010, 2011) used environmental seismic noises to measure the regional group velocity changes in Turkey. They obtained high resolution velocity structure of Turkey by passive monitoring techniques and interpreted group velocity maps with known tectonic structures and geology. They defined the East Anatolia as low velocity, the Pontide, Bitlis and Pötürge massif as high velocity, the Central Anatolia as homogenous velocity, Isparta angle as low velocity, and the Aegean region, where the crust thins out, as the high velocity region. Karabulut et al (2013) studied velocity changes (Vp/Vs) for the western Turkey (Thrace, Sea of Marmara, Sakarya Zone, Bornova Flysch zone, Menderes massif, Lycian nappes). Ersan and Erduran (2010) used P wave receiver function analysis in order to determine the structure of crust and upper mantle velocity beneath the Central Anatolia. Warren et al. (2013) generated the maps of shear wave velocity for the Central and East Anatolia at different depths (10, 20, 30 and 40 km). In these maps, the East and Central Anatolia regions were presented as in low and high velocities, respectively. Vanacore et al. (2013) estimated the velocity ratio map of Turkey (Vp/Vs). They indicated that volcanisms in tectonically active regions in Eocene and post Eocene times in East and the Central Anatolia had shown variations in (Vp/Vs) ratios. Ozacar et al. (2008) investigated discontinuities in the upper mantle beneath the East Anatolian Plateau and measured Vp velocity as 6.30 km/sec between 0-40 km's in the crust. Çıvgın and Kaypak (2012) produced (1D) one dimensional seismic wave velocity model belonging to the upper mantle beneath Ankara and its vicinity using local earthquake data. They detected that; while the P-wave velocity of the first 8 km thick layer is 5.25 km/sec, the P-wave velocities of the underlying layers increase with depth and reached the velocity of 6.47 km/sec at a depth of 30 km.

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Toksöz et al. (2003) measured the crustal thickness nearly as 36 km in the vicinity of Kırıkkale. They stated that the crust in the region formed in two layers, the mean P-wave velocity in the upper mantle, which is 5-10 km thick, was 5 km/sec, and the velocity in the lower thick layer was 6.4 km/sec. They also specified that the velocity increased with depth and reached around 7.8-7.9 km/sec in upper mantle. The crustal thickness of Turkey, as well as seismic velocities, has been the point of interest of several investigators, and studies have been carried out in different disciplines such as; seismology, seismic and gravity. Özelçi (1973) assessed that there had been a linear relationship between gravity values and topographical elevations along the lines taken in the Anatolia. Akçığ (1988) obtained that there had been an approximate crustal thickness of 30 km in the Aegean Sea, and this thickness reached 35-40 km in West Anatolia using the power spectrum. Maden et al. (2005) applied experimental relations to gravity data and measured that the crustal thickness in the Anatolia had changed in between 26.4-49.5 km Maden et al. (2009), in other studies, measured the maximum crustal thickness of the Eastern Pontides as 43.8 km using back analysis method. Bekler et al. (2005) have used in-well explosions in stone quarries as artificial seismic source and measured the crustal thickness in the Central Anatolia as 36-40 km Arslan et al. (2010) measured the crustal thickness of Turkey as 31.4 km (shallowest) and as 50 km (deepest) using the gravity data. Karabulut et al. (2013) estimated the MOHO depth as 31 km in Thrace basin, as 25 km in the Sea of Marmara, as 32 km in İzmir-Ankara Suture Zone, as 25 km in the Menderes Massif using receiver function. Vanocore et al. (2013) measured the MOHO depth as 55 km for the East Anatolia, as 37-47 km for the Central Anatolia and much thinner for the West Anatolia using receiver function. Kahraman et al. (2015) have shown lithological and structural variations in lower, middle and upper crusts by means of the receiver function. Pamukçu et al. (2007) in their studies determined the crustal thickness nearly 45 km. Pamukçu et al. (2011) determined low density level approximately 10 km thick below the ductile zone in the Eastern Anatolia. Pamukçu et al (2015) applied the 2nd Trend Method to gravity data, and derivations in both vertical and horizontal directions in order to investigate the structure of lithosphere. According to the results of derivative, which they obtained within scope of the study, they determined that structure transitions with Bitlis-Zagros Thrust Fault increased much.

Simeoni and Brückle (2009) applied the power spectrum to gravity Bouguer anomalies, and distinguished the components consisting of low and high wavelengths in gravity data from each other. They assessed in the power spectrometer analysis that the effects consisting of relatively high wave numbers had originated from structures in the upper mantle. In addition; they also observed that the density variations with long wavelength originating from the upper mantle were rather affective. They defined the main tectonic elements of geology of the region and MOHO depth using gravity density and seismic data together. They also determined the density difference between the lower and upper crusts as 0.3 gr/cm^3.

However; in this study, the seismic velocities corresponding to the apparent density data estimated from the gravity Bouguer data were measured using the equivalence given by Barton (1986). Thus; the seismic velocity distribution in both vertical and horizontal directions of Turkey and the Conrad discontinuity boundary were studied. Besides; considering the geological units of the country, 7 seismic velocity depth sections in different directions, the crustal thickness and Conrad discontinuity were interpreted with earthquakes having magnitudes greater than 4; and as a result, the crustal model was generated using the result obtained.

2. Geology of Turkey

The geological structure of Turkey is located within the Alpine-Himalayan Orogeny system. It was shaped by the continental zones formed by the evolution of the Pan-African basement and Tethys Ocean (Paleo and Neo Tethys) exposing in a couple of regions, and by paleotectonic zones which was formed by the oceanic suture belts located among them. The shape, location, distribution, contact relationships, regional correlations and tectonic evolutions of the tectonic units extending generally in E-W directions, shown in Figure 1, have been studied by different investigators (Ketin, 1966; Özgül, 1976, 1984; Şengör and Yılmaz, 1981; Şengör 1985; Görür, 1987, 1988, 1991; Okay 1989; Koçyiğit et al., 1991; Tüysüz, 1993; Görür et al., 1983; Yılmaz et al., 1994, 1995; Okay et al., 1996; Okay and Tüysüz, 1999).

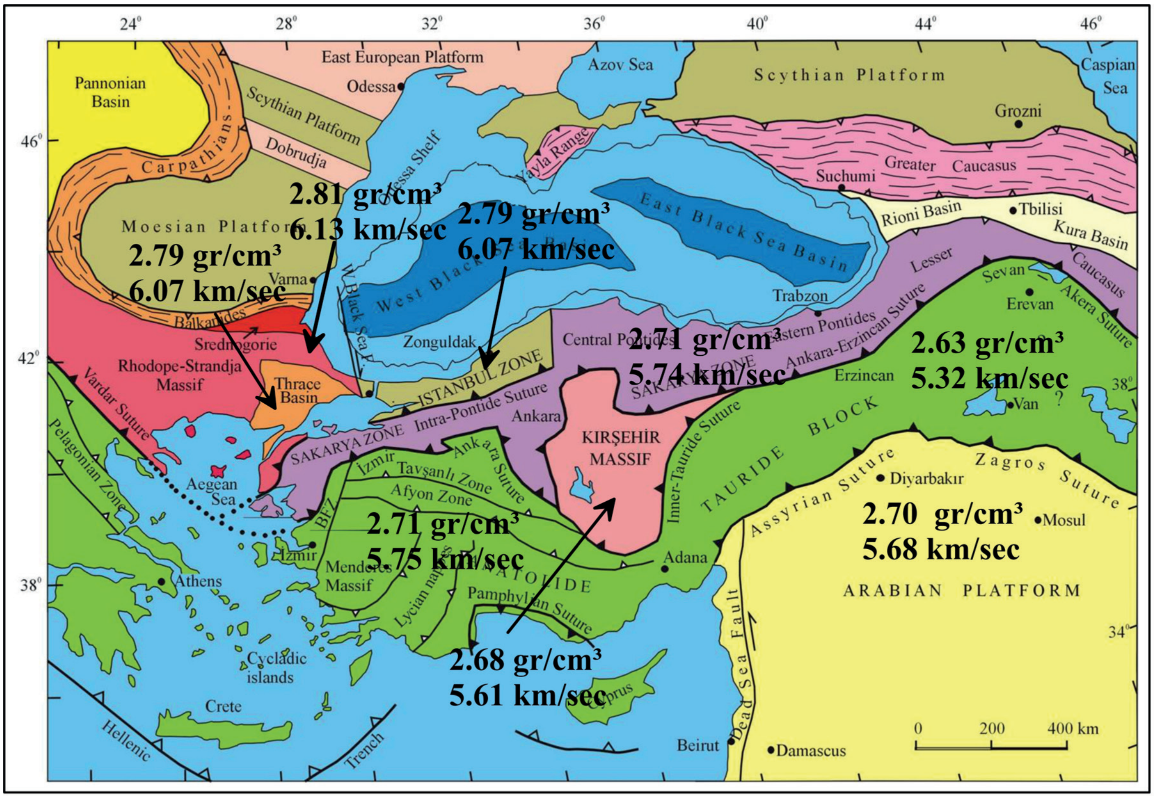

Figure 1- Tectonic units and structural zones of Turkey (modified from Okan and Tüysüz, 1999).

When the continental zones, which are tectonically in contact with each other, and suture belts are studied from north to south, the Strandja zone is located in northwest of Turkey. Gneiss and metagranitoids are observed at the basement of Strandja zone, which is formed by the Strandja massif and Thrace basin. These lithologies are overlain by Triassic-Early Jurassic clastic and carbonate rocks which metamorphosed in Late Jurassic. These metamorphic rocks were then unconformably overlain by the succession of Thrace Basin which was formed by carbonate and clastic rocks deposited between Middle Eocene to recent (Aydın, 1974; Kasar and Okay, 1992; Okay et al., 2001). The Strandja zone separates from the İstanbul Zone with a strike slip tectonic contact in East (Okan and Tüysüz, 1999). At the bottom of the İstanbul Zone, the Pan-African basement rocks composed of Precambrian gneiss, metagranite and amphibolite exist. This basement is then overlain by a sedimentary deposit which is composed of an unmetamorphosed Ordovician-Carboniferous clastic and carbonate rocks (Kozur and Göncüoğlu, 1999; Özgül, 2011). Triassic clastic and carbonate rocks unconformably overlie the underlying succession (Şengör and Yılmaz, 1981; Yılmaz et al., 1995). Late Cretaceous-Eocene volcanoclastic and carbonate rocks constitute cover rocks of the İstanbul-Zonguldak zone (Okay et al., 1994; Görür and okay, 1996). The Inner Pontide suture separates the İstanbul Zone from the Sakarya Zone in south (Şengör and Yılmaz, 1981). Late Cretaceous-Paleocene ophiolitic mélange and Late Cretaceous-Eocene blocky flysch are observed in the Inner Pontide Suture (Okay and Görür, 1995; Görür and Okay, 1996). In the southern part of the Inner Pontide Suture, the continental rock assemblage extending from the Biga Peninsula to Eastern Black Sea constitutes the Sakarya Zone. Metamorphic massifs composed of gneiss, marble and metaperidotites at the basement of the Sakarya zone (Kazdağ, Uludağ and Pulur massifs) were influenced by Hercynian orogeny. These massifs are tectonically overlain by Late Paleozoic-Triassic volcanosedimentary rock assemblages (Karakaya Complex). This complex is highly deformed and consists of limestone blocks and was influenced from the low grade metamorphism, (Bingöl et al., 1973; Okay et al., 1996; Duru et al., 2004). These rocks are then transgressively overlain by Early Jurassic-Eocene carbonate and flysch deposits in which the volcanic products especially in the Black Sea are widely observed starting from Late Cretaceous.

Besides; dense granitic intrusions are observed in the Sakarya Zone between Late Paleozoic-Miocene intervals. İzmir-Ankara-Erzincan suture in the southern part of the Sakarya Zone presents northerly dipping subduction zone of the Neo-Tethys Ocean (Şengör and Yılmaz, 1981). These ophiolitic rocks are accompanied by Triassic-Cretaceous aged, densely sheared ophiolitic rocks, Late Cretaceous blocky flysch in western Anatolia (Bornova Flysch Zone) and by blueschists in Tavşanlı Zone (Okay, 1984; Okay, 1986; Erdoğan et al, 1990). In the southern part of İzmir-Ankara-Erzincan Suture, the Central Anatolian Massif consisting of high graded metamorphic rocks are observed. This crystalline massif, which is cut by the Late Cretaceous granitic intrusions, is unconformably overlain by clastic and carbonate rocks deposited between Late Maastrichtian to recent (Erkan, 1975; Göncüoğlu, 1981; Seymen, 1982; Gökten, 1986). The Central Anatolian Massif separates from Tauride platform in south by the Inner Tauride Suture which is composed of Late Cretaceous-Eocene ophiolitic rocks (Şengör and Yılmaz, 1981). The Menderes Massif and Taurus platform take place towards the south of the İzmir-Ankara Suture and Inner Tauride Suture. The Menderes Massif consists of a core and surrounding cover units (Dürr et al., 1978; Şengör and Sungurlu, 1984; Konak, 2003). The core is formed by lensoidal gneiss and migmatites representing the Pan-African metamorphic basement. However; the cover units are composed of Late Paleozoic-Eocene carbonate and clastic deposits which were affected from the regional metamorphism in Paleocene-Eocene. The Taurus Platform is composed of different tectono-stratigraphical units and nappes in Paleocene-Eocene. These units and nappes, which consist of the platform, the continental margin and oceanic lithologies deposited in between Paleozoic-Tertiary times thrusted on each other by Late Cretaceous-Eocene movements and occasionally affected from metamorphism (Özgül, 1976; Özgül, 1984). The Bitlis Suture forms the boundary of Taurus Platform and the Arabian Platform, and it represents the southern branch of the Neo-Tethys Ocean which existed from Late Triassic to Early Miocene. Extensive ophiolitic nappes in the Eastern and Southern Anatolia are the remnants of this ocean (Şengör and Yılmaz, 1981; Dewey et al., 1986). The Arabian platform located at the southern part of the Bitlis Suture is represented by highly deformed basement consisting of Precambrian oceanic and continental fragments and by overlying clastic rocks deposited in pre Late Permian. These units are then transgressively overlain by Late Permian-Tertiary carbonate deposit on and around the Arabian Platform (Perinçek, 1980; Perinçek et al., 1991; Şengör and Natal, 1996).

3. Geophysical Data and Applied Data Process

The gravity method, which is one of the potential areal methods of the geophysics, provides significant information in investigating the locations, depths and geometries of buried structures in small, medium and large scale fields with the help of geological data. The General Directorate of Mineral Research and Exploration (MTA) has taken gravity measurements in 60648 stations in 3-5 km intervals in the country. The measurement points, as 1st, 2nd and 3rd degree triangulations being the first, were taken at certain points such as; school, mosque, crossroads, bridges and river junctions in 1/25 000 scale topographical maps. The collection of regional gravity data cluster of Turkey began in 1973 and has continued 15 years by several geophysical teams. The Turkish Petroleum Corporation (TPAO) and the General Command of Mapping (HGK) have made significant contributions in collecting these data. MTA has spread the international base value, which it had been taken by HGK from postdam and carried out airports, across the country and formed the Turkish National Gravity Base Network. Worden Master, LaCoste Romberg 344 and 347 gravimeters were used during the collection of regional gravity data.

In this study, the gravity apparent density filter was applied to Bouguer data of Turkey and the apparent density map was generated (Figure 4).

The apparent density filter and lateral distribution of the density in a horizontally layered environment can be estimated by the gravity area. The main assumption here is that the density in vertical axis does not show any variation. The apparent density filter is expressed by the formula of Gupto and Grant, (1985).

Here, the apparent density: $(\rho(x,y))$

$$\rho(x,y) = \rho_o + (1/2\pi G)\, F^{-1}\{(\omega / 1\text{-}e^{-\omega h}) \,.\, \Delta g(u,v)\}$$

where;

ρ_o : estimated background density,

G: gravitational constant,

ω: total wave number

h : thickness,

u : number of waves in x direction,

v : number of waves in y direction,

F^{-1}: inverse Fourier Transformation.

As it is understood from the equation; the apparent density wave filter is a linear filter expressed in wave number medium.

The velocity and density data generated by Barton (1986) were used in each grid cells of the apparent density map (Table 1). So; linearly, a transition into the seismic velocities were made and the seismic velocity map of Turkey was generated (Figure 6).

The tectonic units of Turkey stated in the study of Okan and Tüysüz (1999) were plotted on all the maps generated. In addition, there are several fault systems in Anatolia, and two of the most important fault among them (the North Anatolian Fault Zone (NAFZ) and the East Anatolian Fault Zone (EAFZ)) was plotted on generated maps.

While the gravity Bouguer signature of the general tectonic structures like; the Sakarya Zone, İstanbul, Anatolide-Tauride Block, Kırşehir and Menderes Massifs are clearly observed for some geological structures, the gravity response of some tectonic structures shows some differences (Figure 2). The eastern boundary of the İstanbul Zone and Sakarya Zone cannot be discriminated clearly from each other, and the diversity of the Bornova Flysch Zone with its surround is not clearly observed in the Bouguer map. Besides; while the eastern part of the Anatolide-Tauride Block is represented by low amplitude Bouguer values, it distinctively separates from the Arabian Platform in south and from the Sakarya Zone in north. NW-SE orientation of Tavşanlı and Afyon Zones were also observed in the gravity map (Figure 2). In this study, the relationship of tectonic structures with gravity apparent density and seismic velocity distributions were also investigated.

The map was reproduced by using data of the crustal thickness map of Turkey given by Arslan et al. (2010). The regressional equivalence, Y=-72.2E+7.77, found for the Bouguer anomaly type

Table 1- Seismic velocities measured for different densities (Barton, 1986).

Density (gr/cm^3)	Velocity (km/sec)	Density (gr/cm^3)	Velocity (km/sec)	Density (gr/cm^3)	Velocity (km/sec)
1.47	1.5	2.36	3.8	2.80	6.1
1.66	1.6	2.38	3.9	2.83	6.2
1.73	1.7	2.39	4.0	2.85	6.3
1.80	1.8	2.41	4.1	2.87	6.4
1.86	1.9	2.43	4.2	2.90	6.5
1.92	2.0	2.44	4.3	2.93	6.6
1.98	2.1	2.46	4.4	2.95	6.7
2.01	2.2	2.48	4.5	2.98	6.8
2.03	2.3	2.50	4.6	3.01	6.9
2.06	2.4	2.52	4.7	3.04	7.0
2.09	2.5	2.53	4.8	3.07	7.1
2.11	2.6	2.55	4.9	3.10	7.2
2.13	2.7	2.57	5.0	3.13	7.3
2.15	2.8	2.59	5.1	3.16	7.4
2.18	2.9	2.61	5.2	3.19	7.5
2.21	3.0	2.62	5.3	3.22	7.6
2.23	3.1	2.64	5.4	3.25	7.7
2.24	3.2	2.66	5.5	3.28	7.8
2.26	3.3	2.68	5.6	3.31	7.9
2.28	3.4	2.70	5.7	3.34	8.0
2.30	3.5	2.72	5.8	3.38	8.1
2.32	3.6	2.74	5.9	3.42	8.2
2.34	3.7	2.77	6.0		

was used in Woollard (1959) equation and equation T=32-0.08(-72.2E+7.77)=31.38+5.77E was obtained, thus the crustal thickness map of Turkey was prepared. In the crustal thickness map in Figure 3, the shallowest and the deepest crustal structures were measured as 29.54 km and 50.62 km, respectively. The difference between the shallowest and the deepest crustal structures is 21 km across Turkey. The thinnest parts of the continental crust have been the Thrace Basin and seasides. The continental crust in the west of the country thins out until Denizli. This area overlaps with the SE boundary of the Menderes Massif at the same time. Areas, where the continental crust thins out, have clearly revealed graben regions in which the geothermal activity is the most. Another area, where the continental crust thins out, is the Isparta Bend in south. The separations of İstanbul and Sakarya Zones, which cannot be observed between Karabük and Kastamonu in the Gravity Bouguer map, have become distinctive in the crustal thickness map (Figure 3). The crustal thinning in the İstanbul Zone has differed from the Sakarya Zone by crustal thickening. The crustal thickness of NW-SE extending Tavşanlı and Afyon Zones have increased towards west. The crustal thickness between the eastern and western parts of the Kırşehir Massif to display a difference is remarkable. The crustal thickness of the Lake Tuz and its surround is observed as one of the shallowest regions of the massif. The deepest region of Turkey in crustal thickness is the East Anatolian Plateau with 40-50 km. The Arabian Platform with a depth of 35 km has separated from the deeper Anatolide-Tauride Block by the Bitlis Suture Belt (Figure 3).

Applying the apparent density filter to gravity Bouguer data, the gravity apparent density map was obtained (Figure 4). The apparent density values range in between 2.55 gr/cm^3 and 2.98 gr/cm^3 and the difference is 0.43 gr/cm^3. The continental crust to be thick in the East Anatolian Plateau causes the density of the region to decrease. However, the continental crust to thin out at seasides as well has caused an increase in apparent densities in these areas (Figures 3 and 4). The NS boundary of the İstanbul Zone and the Sakarya Zone separation, which is not clear between Karabük and Kastamonu settlement areas in the gravity Bouguer map, were not well observed also in the density map. The mean density distributions of each tectonic units of the Anatolia in figure 1 were measured, and these were given in table 3.

The thickest value of the crustal thickness map of Turkey is nearly 50 km. Therefore; the apparent density values and seismic wave velocities were measured in 10 km increments until the depth of 50 km (Figure 5). The mean seismic velocity and densities have the lowest values between 0-10 km. However, the densities and velocities show an increase in between 10-20 km. The mean velocities of levels located in deeper parts show a relative decrease with respect to this level. However, the numerical values of the information observed in figure 5 were given in table 2.

The wave velocity map of Turkey was obtained by using the apparent density map of Turkey generated from gravity data. Also; an assessment was made between the seismic velocities of the rocks and their densities by means of the relationship between

Table 2- Density and seismic velocity data measured for different depth levels.

	0-10 km			10-20 km			20-30 km			30-40 km			40-50 km		
	Min.	Max.	Ort.	Min.	Max.	Ort.	Min.	Max.	Ort.	Min.	Max.	Ort.	Min.	Max.	Ort.
Density (gr/cm³)	2.23	2.95	2.60	2.55	2.98	2.74	2.58	2.96	2.71	2.62	2.98	2.72	2.63	2.99	2.72
Seismic velocity (km/sec)	3.20	6.7	5.13	4.90	6.83	5.86	5.05	6.73	5.72	5.30	6.80	5.79	5.35	6.83	5.78

Table 3- Mean density and seismic velocities of the structural elements.

	Anatolide Tauride Block	Thrace Basin	Arabian Platform	Istanbul Zone	Strandja Massif	Kırşehir Massif	Sakarya Zone
Density (gr/cm³)	2.67	2.79	2.7	2.79	2.81	2.68	2.71
Seismic Velocity (km/sec)	5.52	6.07	5.68	6.07	6.13	5.61	5.74

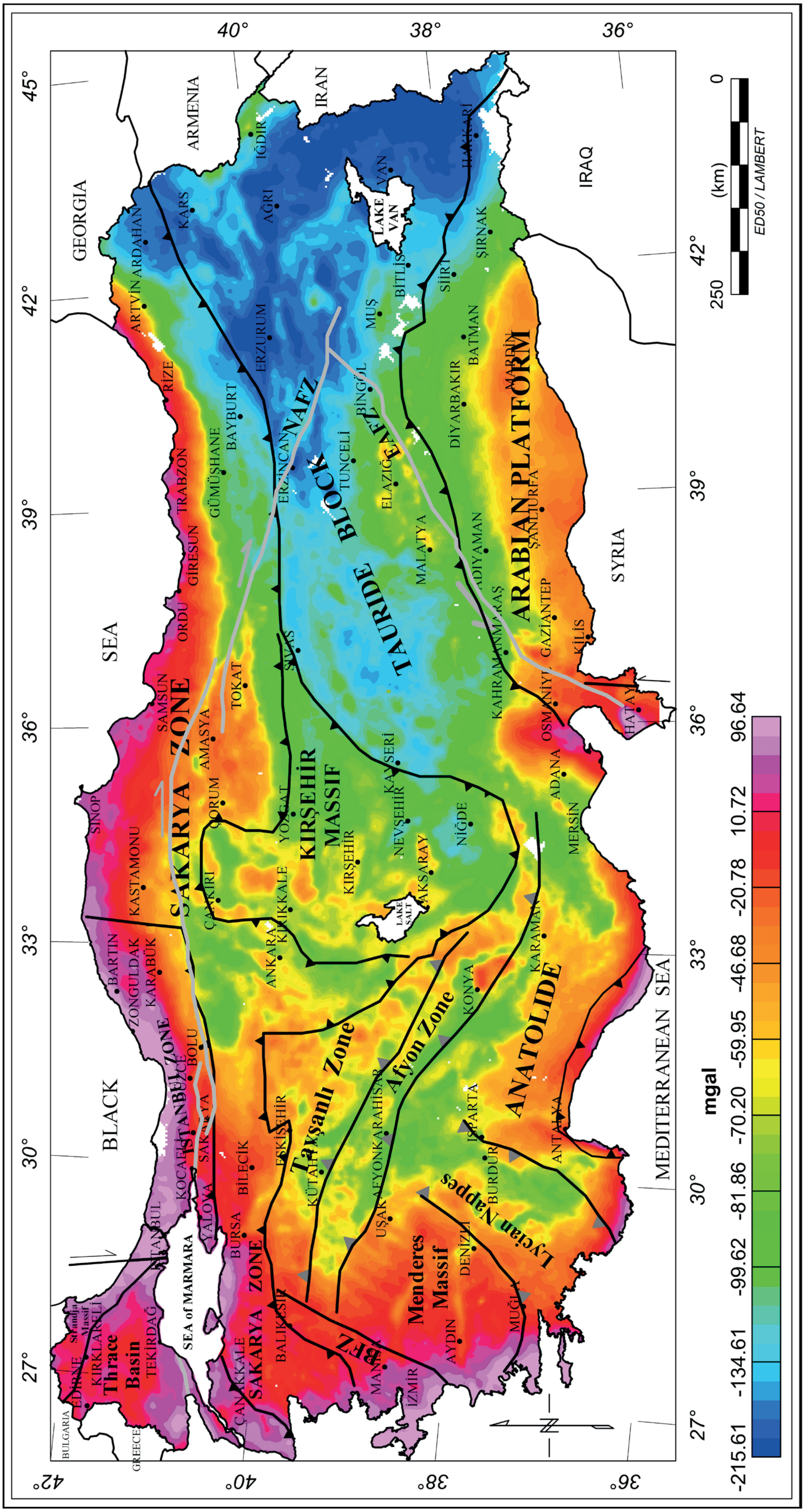

Figure 2- Gravity Bouguer map of Turkey.

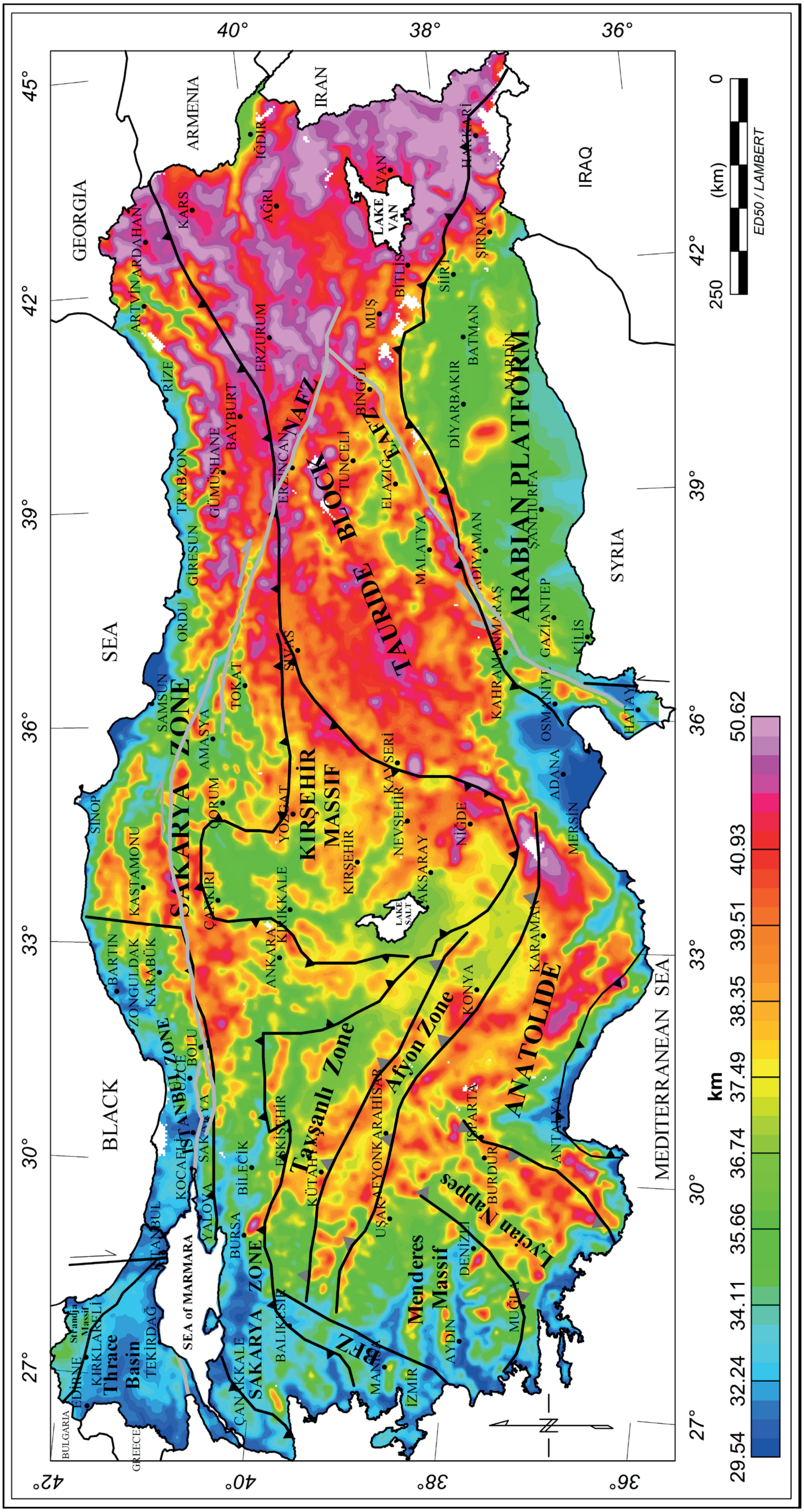

Figure 3- Continental crustal thickness map of Turkey.

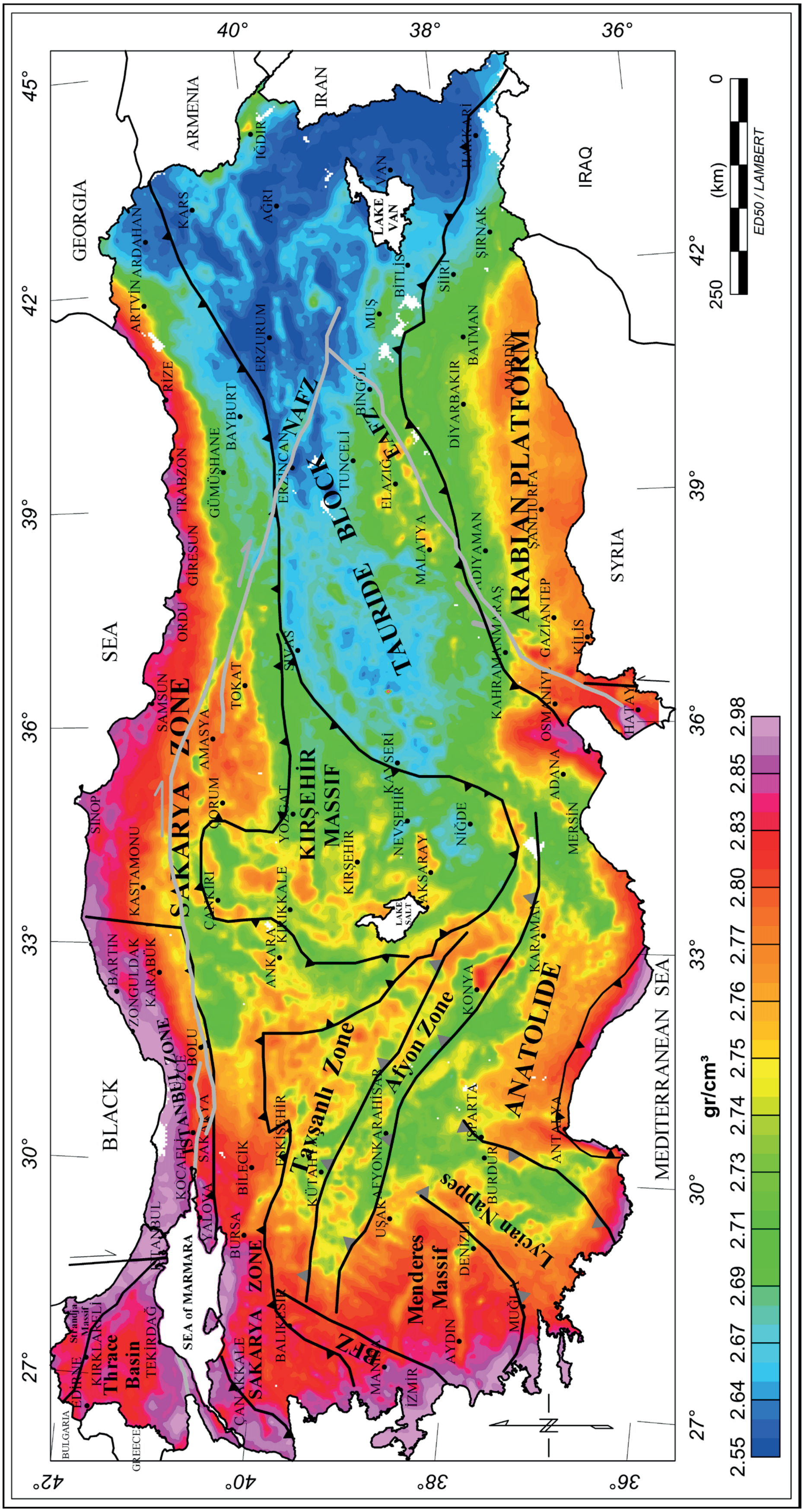

Figure 4- Gravity apparent density map of Turkey (measured 20 km thickness).

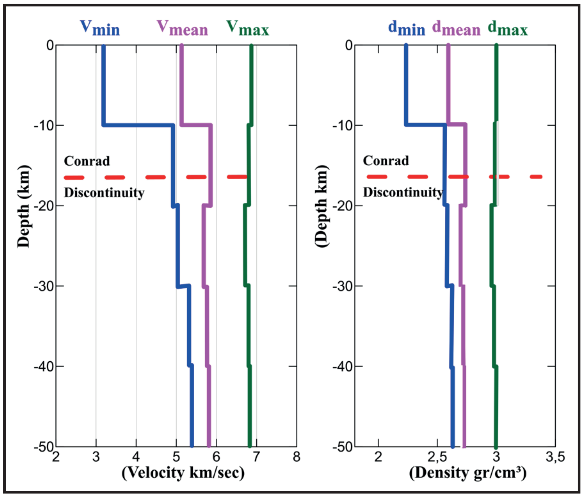

Figure 5- The variation of seismic velocity and apparent densities at depths of 0-50 km.

seismic and gravity, which are the two disciplines of the geophysics. From each density and seismic velocities, the information related to the rock type can be acquired and the structural models of the earth crust can be obtained. Nafe and Drake (1957) and Ludwig et al. (1970) carried out velocity-density measurements from several collected rock types. They also graphed density and velocity values in their measurements and acquired a mean linear function. Barton (1986), Nafe and Drake (1957) and Ludwig et al. (1970) presented a mutual density and velocity values in tabular form. The seismic velocity values of this investigation were taken from the table of density-velocity values of Barton (1986).

The seismic wave velocity map, which had been obtained from the map of gravity apparent map of Turkey, was given in figure 6. Seismic velocities vary in between 4.91-6.78 km/sec and the velocity difference across the country is 1.87 km/sec. The average of seismic wave velocities of each structural element was measured and their results were given in table 3 considering the tectonic units of Turkey. Since Anatolide and Tauride Blocks present some differences in density and velocity, their eastern and western parts were investigated separately. As the East Anatolian Plateau has a deep crustal thickness, its mean density and velocity values are 2.63 and 5.32 gr/cm^3, respectively. However; its western side reaches a much higher mean density and velocity values (2.71, 5.75 gr/cm^3) with respect to the eastern side (Figures 1 and 6).

When mean velocities given in table 3 were studied, it was seen that the Strandja Massif had the maximum seismic velocity with 6.13 km/sec among the tectonic units of Turkey. The İstanbul Zone and Thrace Basin has the same seismic velocity with 6.07 km/sec, and then the Sakarya Zone, the Arabian Platform, Kırşehir, Anatolide and Tauride Blocks follow order successively.

In order to fully investigate the depth at which high velocity and density values are observed, the thicknesses in the apparent density filter were linearly incremented as 1 km. It was revealed that the boundary, where the maximum velocity and density are observed, was nearly at a depth of 16 km for Turkey in data (Figure 5). In addition; the distribution of seismic velocities, which had been estimated from the apparent density data with 1 km increments in thickness, were investigated, and it was seen that 74% of the total data had occurred within a band of 10-20 km depth. Only a very few portion of the high velocity data (4%) occurred in 40-50 km depths (Table 4).

Table 4- The distribution of the Conrad discontinuity (measured for different depth levels).

0-10 km	10-20 km	20-30 km	30-40 km	40-50 km
% 0	% 74	% 11	% 11	% 4

Zor et al. (2003) constructed a network with 29 seismographs at an elevation of 2 km in the East Anatolian High Plateau. They measured the mean crustal thickness of the region as 45 km and (*Vp/Vs*) mean seismic velocity as 3.7 km/sec by interpreting *V* and *S* seismic wave velocities from the seismic data collected. Şengör et al (2003) explained that the closure of the Neo-Tethys Ocean occurred between Early Eocene to Late Eocene and the rigid Arabian Plate dipped into the Pontide arc and then steepened in Middle and Late Miocene. The plate was then broken and subducted into the asthenosphere and lost its mantle crust. They also emphasized that the asthenosphere had entered from this broken region and uplifted the Eastern Anatolia. They also attributed the density decrease in the crust to this high temperature effect. Keskin (2003) explains that the reason, why the region was extensively covered with volcanism in Neogene and Quaternary in Eastern Anatolia, reflects only a small portion of the melt exposing in the area and the presence of plutonic intrusions in deeper parts

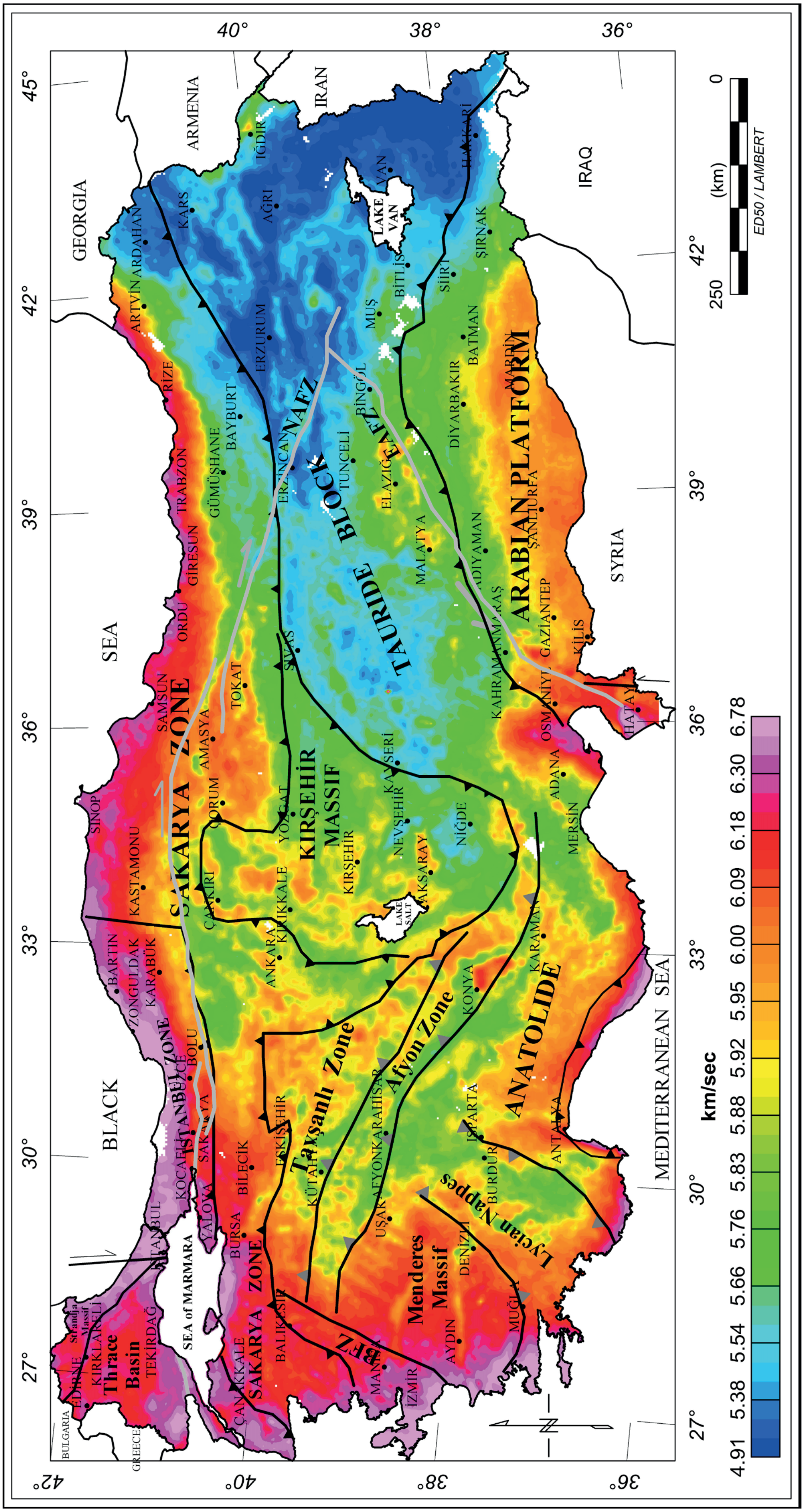

Figure 6- Seismic velocity map of Turkey (measured for 20 km depth).

of the crust. Pamukçu and Akçığ (2011) mentioned about the presence of several vertical discontinuities in the region between EAFZ and NAFZ, and the flexible region starting at a depth of 10 km within crust structure.

The Conrad discontinuity has taken its name from seismologist Victor Conrad and is the discontinuity area where the seismic wave velocity increases in horizontal direction in the continental crust. The depths of this boundary are generally in between 15-20 km, and there is not observed any Conrad discontinuity on the oceanic crust (Figure 9). The continental crust is divided into two parts; as the upper and lower crusts. While the upper crust consists of felsic rocks such as; granite etc. (silica, aluminum, SIAL), the lower crust is composed of mafic rocks such as; basalt etc. (silica, magnesium, SIMA). The average of this depth, in which there is a compositional difference between SIAL and SIMA, was found as 16 km for Turkey (Figure 7).

Considering the tectonic units of Turkey, cross sections were taken along 7 lines (Figure 8). In cross sections, which show the variation of seismic velocities with depth, the compatibility between the deep crustal structure of the Eastern Anatolia in figure 3 and high values of the Conrad discontinuity in figure 7 actually indicates an unconformity. This unconformity is also observed clearly in cross sections (Figure 8), because the high velocity zone (Conrad discontinuity), that should occur between SIAL-SIMA, does not exist in east. It is quite remarkable that the high velocity level exists in deeper most parts of the crust and sometimes at depths closer to mantle within crust. This study also brought up a question whether one of SIAL-SIMA layers might be missing in the East Anatolian continental crust.

The crustal depths, the Conrad discontinuity and earthquakes with magnitudes equal or greater than 4 were plotted on cross sections in figure 8. The majority of earthquakes have occurred along the Conrad discontinuity and at depths very close to this discontinuity. As seen in figures 8a, b and d, the Conrad discontinuity were distinctively observed along lines taken in West Anatolia and the Central Anatolia. There was not detected any Conrad discontinuity in Anatolide and Tauride Blocks in figures 8c, e and f. The high velocity zone in figure 8g have existed on the crust-mantle boundary.

The Conrad discontinuity, which is observed in west of the Anatolia, could not be traced in the Anatolide-Tauride Block in east. The reason, why the Conrad discontinuity is not observed but the high velocity zone in crust-mantle boundary in the East Anatolian High Plateau is seen, made us consider that the crust might have formed only from SIAL. If this argument is right, then there is not SIMA in the crustal structure of the East Anatolia. According to this inference the crustal model of Turkey was given in figure 9, schematically.

4. Results

With this study, the crustal thickness map generated from our previous study was updated, and the crustal thickness in related sections was taken from this map. The apparent density filter was applied to Gravity Bouguer data and "The Apparent Density Map of Turkey" was obtained. For each grid cell of the apparent density map, the corresponding seismic velocities were taken and the "Seismic Wave Velocity map of Turkey" was generated.

The graph of seismic velocity and apparent density with respect to depth was formed and the "high velocity zone" between 10-20 km intervals was determined according to this graph. This zone was determined as the "Conrad Discontinuity". In order to determine the position of the "Conrad Discontinuity" across the country, the measurements were made by incrementing thicknesses as 1 km intervals. As a result of the measurements, the "Mean Conrad Discontinuity" was estimated as 16 km's, and the "Conrad Discontinuity Map of Turkey" was obtained.

The variations of seismic velocities with depth were investigated in 7 cross sections together with crustal thickness, the Conrad discontinuity and the tectonic units of Turkey. It was seen that the Conrad discontinuity was not available in the East Anatolian High Plateau, and high velocity zone along the crust-mantle boundary.

The Conrad discontinuity boundary, which developed between SIAL-SIMA, not to be observed in the East Anatolian High Plateau made us consider that SIMA has disappeared as a result of the geological evolution, and the available crust could only be SIAL in origin. Keskin (2003) explains that the magma generation in this region is related with the subduction

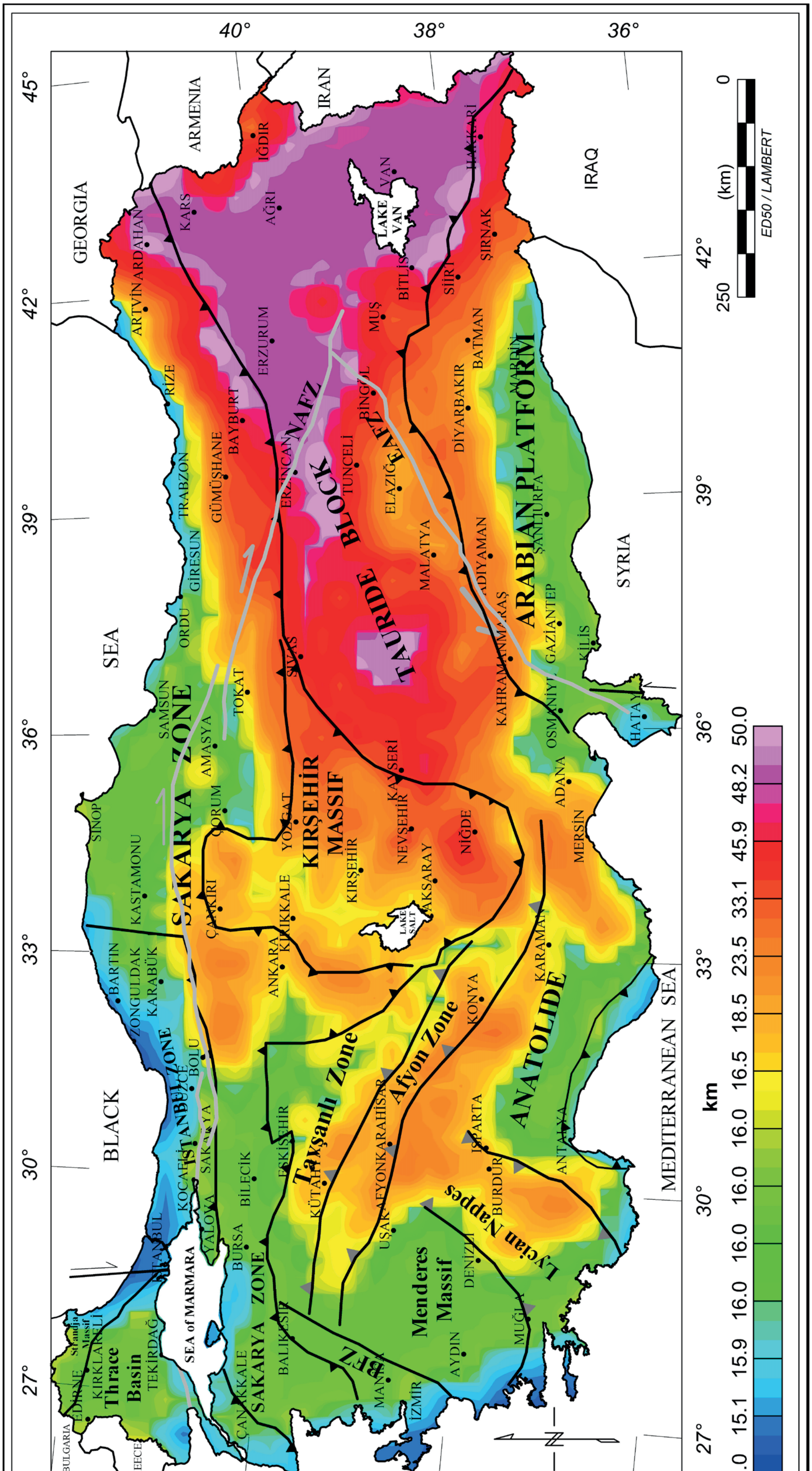

Figure 7- Conrad discontinuity depth map of Turkey.

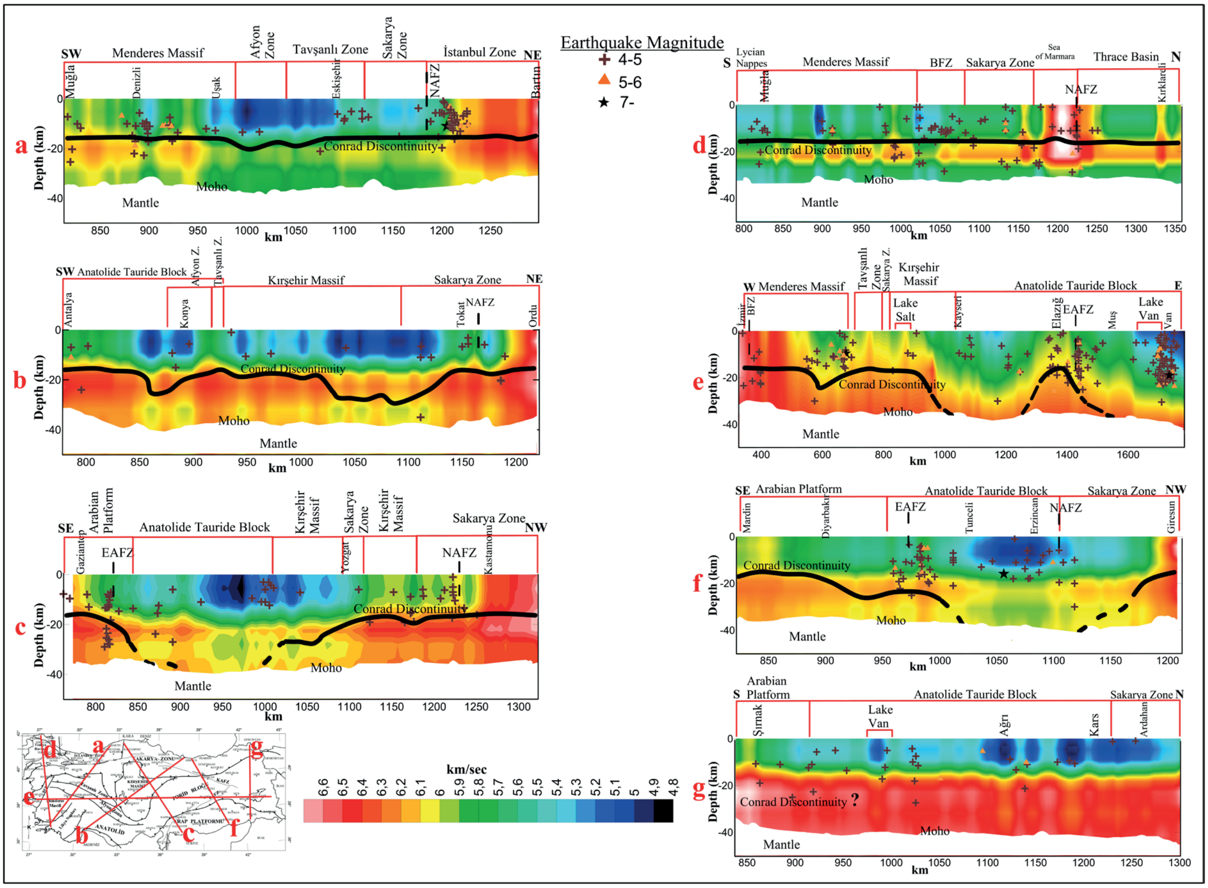

Figure 8- The variation of seismic velocities with depth.

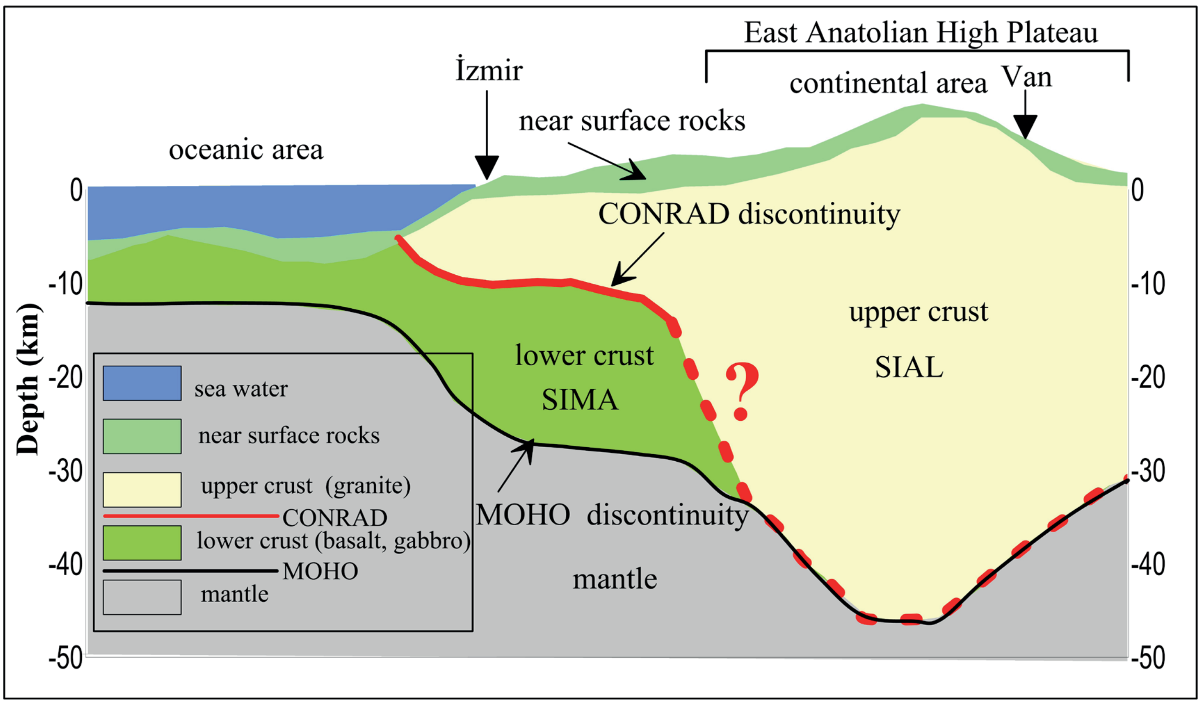

Figure 9- Crustal model (disappearance of the Conrad discontinuity and the appearance of the maximum seismic velocities between continental crust and mantle at depths (thick, dotted red line)).

between the Arabian and Eurasian plates and with the subduction related lithospheric slab breakoff in the model which he had generated for the volcanism related with the collision in East Anatolia. According to the model proposed by Keskin (2003), the Arabian Oceanic lithosphere, which subsides beneath the East Anatolian Accretion Prism, detached 11-13 million years ago, so the asthenosphere was uplifted from the detached segments and formed the volcanism in the East Anatolia ranging from 6 million years ago to recent. Another suggestion, which supports this idea, is the shallow Curie depths belonging to the East Anatolian region obtained in the study carried out by Pamukçu et al (2014). It can be interpreted that the uplifting asthenosphere material through these geodynamical processes might have melted-depleted the lower crust beneath the East Anatolian Accretion Prism (SIMA).

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