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Structure of the Büyük Menderes Graben systems from gravity anomalies

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Abstract: The Büyük Menderes Graben (BMG) of western Turkey is bounded by E–W oriented normal faults and has been a depositional center for thick sedimentary layers since the Miocene. Four Mio-Pliocene depressions (from west to east, the Çine, Bozdoğan, Karacasu, and Denizli basins) having overall N–S trends are situated just south of the BMG. In this study, we focused on the structural characteristics of the BMG using Bouguer gravity data covering the area between 37°N and 39°N and 26°30′E and 30°E and gravity data along 4 profiles to estimate the discontinuous basement relief of the BMG. Our main objectives were to investigate the geometry of the faults bounding the BMG and surrounding faults, and to describe the extent of the cross-graben structures. Boundary analysis, analytical signals, and second derivative methods were applied to Bouguer gravity data in order to determine tectonic border lines. The 2D inversion of gravity data together with the analysis of the power spectrum for each profile exposed an image of the subsurface. As a result of both methods, the thickness of the sedimentary cover was determined to be 1.44–2.3 km in the BMG. According to model geometry, the thickness of the sedimentary deposits decreases to the south of the graben.

Key words: Boundary analysis, Büyük Menderes Graben, inversion, gravity, sedimentary thickness, western Turkey

1. Introduction

Western Turkey is tectonically one of the most active and rapidly deforming regions of continental crust in the world. The most pronounced structural and morphological features of this region are defined by normal faulting in an E–W direction, which creates the boundaries of the Büyük Menderes, Küçük Menderes, and Gediz grabens. There have been many geological and geophysical studies to estimate the sedimentary thickness of the Büyük Menderes Graben (BMG). According to Cohen et al. (1995), the depth of the basin was measured as 1.5 km at Aydın. Işık (1997) measured 2.0–2.2 km depth between Aydın and Sultanhisar and 2.2–2.3 km depth between Sultanhisar and Nazilli. Şenel (1997) determined the depth of the basin to be 2.5 km between Sultanhisar and Nazilli. Işık and Şenel (2009) determined the maximum depth of the sedimentary basin to be 3.9 km at Nazilli. Sarı and Şalk (2006) measured 2.0 km depth between Aydın and Sultanhisar and 3.5 km depth between Nazilli and Sarayköy. Altınoğlu et al. (2018) determined that the maximum sedimentary thickness of the Büyük Menderes graben is about 4 km, and the sedimentary thickness of the Karacasu and Bozdoğan graben is 2 km.

Magnetotelluric (MT) and direct current resistivity surveys were conducted to identify conductive zones inside the metamorphic complex in the easternmost part of the BMG by Bayrak et al. (2011). The results of their studies showed the presence of wide conductive regions with very low resistivity, which were imaged at depths of ~100 m, extending to a maximum depth of ~2000 m. These conductive regions signify a potential geothermal resource in the area. The presence of deep conductive regions at depths from ~15 km to 35 km, which reflects the shallow asthenosphere, could be correlated with the presence of a high enthalpy geothermal system and its heat source. MT resistivity models indicate the presence of surface conductive zones extending to a maximum of ~2000 m in depth in the middle region of the BMG, where the thicker upper layers belong to Miocene sedimentary formations overlying Paleozoic metamorphic series (Bayrak et al., 2011). The structural evolution of the BMG has been studied by several researchers (Seyitoğlu et al., 2000, 2002; Catlos and Çemen, 2005; Çemen et al., 2006; Çiftçi and Bozkurt, 2009, 2010). Some of the earlier researchers focused on the relationship between the BMG and its surroundings rather than the BMG itself (Ekinci

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et al., 2013; Oruç, 2014; Silva et al., 2010). However, the structural evolution of the BMG remains relatively unresolved.

In this study, in order to better understand the structural elements of the BMG, boundary analysis, analytical signals, and second derivative methods were applied to gravity data digitized from the Bouguer anomaly map in order to determine tectonic lines. The aim was to determine the sedimentary thickness of the BMG and to determine the structural features of the intersecting grabens in the Nazilli region. Gravity data were measured along four selected profiles across Nazilli–Arpaz, Sultanhisar–Kuyucak, Söke–Akbük, and Priene–Milet in the graben area. These data were evaluated using the 2D inversion and power spectrum methods in order to estimate the thickness of the sedimentary fill of the BMG. Along with the other studies, the MTA Bouguer gravity anomaly map and data from the four gravity profiles measured on-site were interpreted together.

2. Geology and tectonics of the Büyük Menderes Graben

The BMG is bounded to the north and to the south by metamorphic rocks of the Menderes Massif (Figure 1). The most prominent fault is the Büyük Menderes detachment fault along the northern boundary of the graben (Emre and Sözbilir, 1997; Lips et al., 2001; Okay, 2001). This fault distinguishes high-grade metamorphic gneisses and a lower Miocene sedimentary rock sequence in its hanging wall from the marble-intercalated mylonitized schists in its footwall (Göğüs, 2004; Çemen et al., 2006; Çifçi et al., 2011). The basin is surrounded by the E–W trending Küçük Menderes Graben in the north and four Mio-Pliocene depressions (from west to east, the Çine, Bozdoğan, Karacasu, and Denizli basins) with approximate N–S trends located in the south of the BMG (Paton, 1992; Ocakoğlu et al., 2014). The BMG is about 140 km long and 2.5–14 km wide and forms an arc-shaped structural pattern. The graben trends approximately E–W from Nazilli to Ortaklar westward, and the trend changes to the SW direction near Söke. The width of the graben increases from east to west, so it is defined as an asymmetrical graben (Gürer et al., 2009). The graben is bordered by well-developed normal fault systems along its length. The rock units exposed in the vicinity of the BMG can be classified into two groups as basement and basin fill units, or Pre-Neogene basement units and basin fill units. The geological units of the graben are shown in Figure 1.

3. Methods used for analyzing the gravity data

As the first step of the analysis, the inversion method suggested by Murthy and Rao (1989) was applied to the gravity data in order to estimate the thickness of the sediments through 2D inversion. The method divides the basement topography into a model of juxtaposing prisms and estimates the thicknesses of the prisms through an iterative scheme employing Marquardt's algorithm (1963).

In the second step of the application, in order to estimate average depths of the basement rock (or thicknesses of the sedimentary covers) in the study area, the power spectrum analyses were applied to the gravity data that were gathered along the four profiles (Nazilli–Arpaz, Söke–Akbük, Priene–Milet, and Sultanhisar–Kuyucak) using the method of Spector and Grant (1970) (Figure 2).

In the third step of the application, in order to estimate the tectonic lines related to the subsurface structures, the boundary analysis method was used on the gravity data, which were digitized from the MTA Bouguer anomaly map (1979) (Figure 3). In this map, the Bouguer density correction value is taken as 2.67 g/cm^3. The method was first used by Cordell and Grauch (1982, 1985) to determine lateral changes in mass density of upper crustal blocks. Blakey and Simpson (1986) developed a method for identifying maximum values on a horizontal gradient map produced from 3D gridded potential field data. Their method is based on automated procedures to determine the locations of horizontal gradient amplitudes over the contoured map plane. There are 7 options in the algorithm for detecting boundaries, such as only vertical edges or only horizontal edges. Option 3 was selected for calculation of maximum gradients for each station, which includes adjacent points in vertical, horizontal, and diagonal directions simultaneously.

In the fourth step of the application, the analytical signal method was performed with a combination of the horizontal and vertical gradients of the gravity anomaly data. The analytical signal has a form over causative bodies that depends on the locations of the bodies (Nabighian, 1982). This was also adopted by Green (1976) and Hansen et al. (1987), who discussed and demonstrated the properties of the analytical signal for 2D gravity data analysis. The locations of the maxima of the amplitudes were calculated by using the method of Blakely and Simpson (1986).

In the fifth step, the second vertical derivative method was used on the Bouguer gravity data. One of the problems inherent within the interpretation of Bouguer anomaly maps is that it is difficult to resolve the effects of shallow structures from those due to more deeply seated ones. The removal of the effect of the regional field from the Bouguer anomaly data results in an intermediate and nonunique set of residuals. It is possible to separate the probable effects of shallow and deeper structures by using second vertical derivatives (SVDs) (Kearey et al, 2002). SVD calculations have been widely used to enhance local anomalies obscured

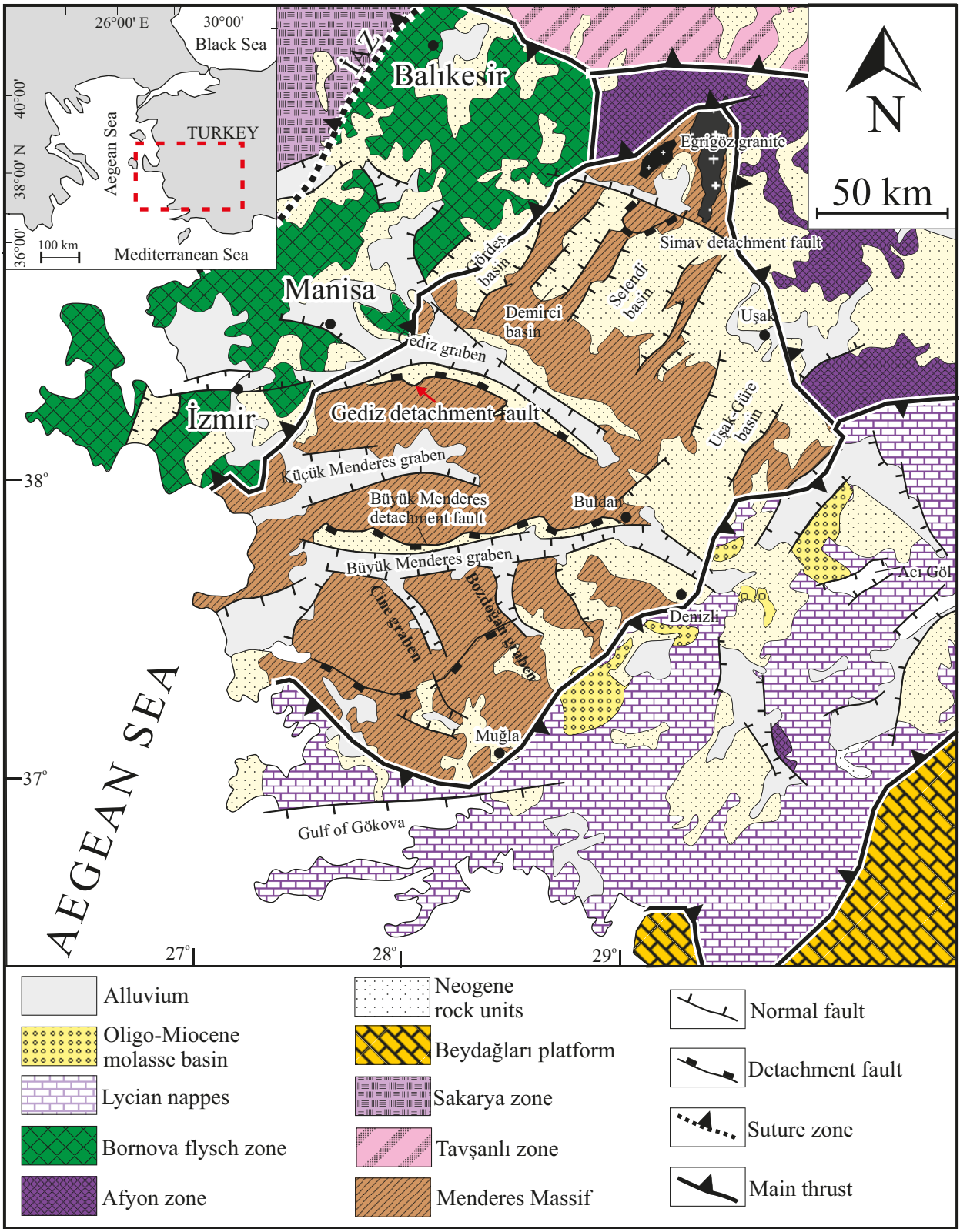


Figure 1. General and structural features of the Aegean region (geological map of western Anatolian basins compiled from Bozkurt and Park, 1994; Bozkurt, 2001; Sözbilir, 2001, 2005; Işık et al., 2003; Özer and Sözbilir, 2003; Bozkurt and Sözbilir, 2004; Çifçi et al., 2011).

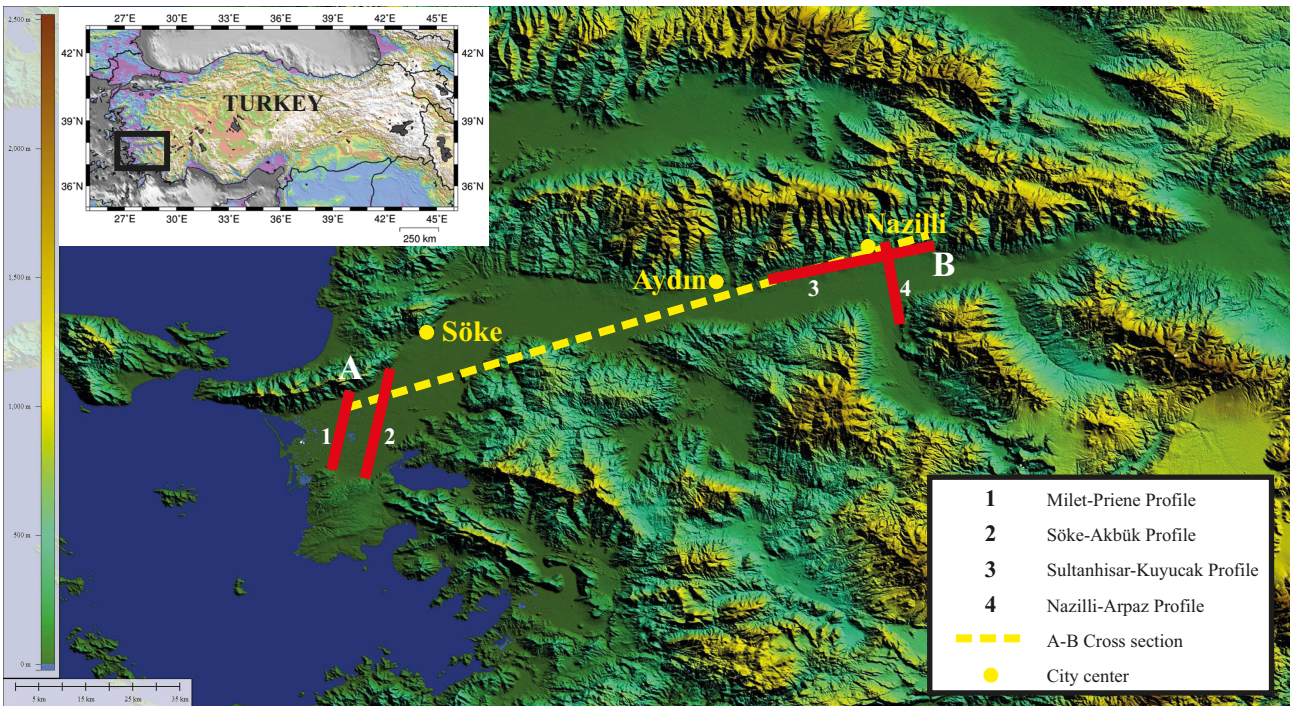


Figure 2. Locations of the gravity profiles in the study area.

by broader regional trends and to aid in the definition of the edges of source bodies. A shallow geological feature of limited lateral extent will typically have a gravity anomaly with greater curvature than the regional field on which it is superimposed (Dobrin and Savit, 1988).

4. Interpretation of the Bouguer gravity data

The Bouguer gravity anomaly data used in this study consist of data digitized with a sampling interval of 1 km from a 1/500,000 scale map prepared by the MTA (1979). Generally, regional negative gravity anomalies are present in western Turkey. The BMG is one of the large areas identified as having negative Bouguer gravity anomalies. These negative anomalies (between –15 and –70 mGal) correspond to the Quaternary alluvium and Neogene sediments (Figure 3).

The Bouguer gravity map does not effectively indicate whole structural features associated with the BMG. The main purpose is to locate major boundaries in the BMG by finding the steepest parts of regional gradients seen in the gravity data. The results of the boundary analysis, analytical signal, and second derivative methods indicated that the regional structures mainly trended in an E–W direction (Figures 4a–4c). The boundary analysis method was used to determine the structural boundaries in the horizontal direction. Maximum gradient values show great coherence with the structural borders of the BMG (Figure 4a). The E–W trending BMG and approximately SE–NW trending Çine and Bozdoğan cross-grabens are shown in Figure 4a.

Similarly, the signs of both grabens are also not clearly observed in the analytical signal anomaly map (Figure 4b). Therefore, both of these graben formations are thought to contain shallow features. Furthermore, after the removal of the effects of the shallow features (near the surface) in the second vertical derivative anomaly map, the Çine and Bozdoğan cross-grabens could not be observed clearly in Figure 4c.

Milet–Priene, Söke–Akbük, Sultanhisar–Kuyucak, and Nazilli–Arpaz gravity profile data were collected using a Scintrex Autograv CG-5 gravity instrument with a reading resolution of 1 μGal (standard field repeatability: <5 μGal) at 100 m intervals (Yeraltı Aramacılık Ltd. Co., İstanbul, Turkey) and assessed within the scope of this study. Bouguer correction was performed on the measured data using a density value of 2.67 gr/cm^3. After the correction process, the data were evaluated by the 2D inversion and power spectrum techniques.

The density difference values used for 2D inversion were chosen by taking into account the density ranges of sedimentary, magmatic, and metamorphic rocks in the literature, as well as the lithological information in the wells drilled for the purpose of geothermal exploration. Since there is insufficient well lithology information in the study

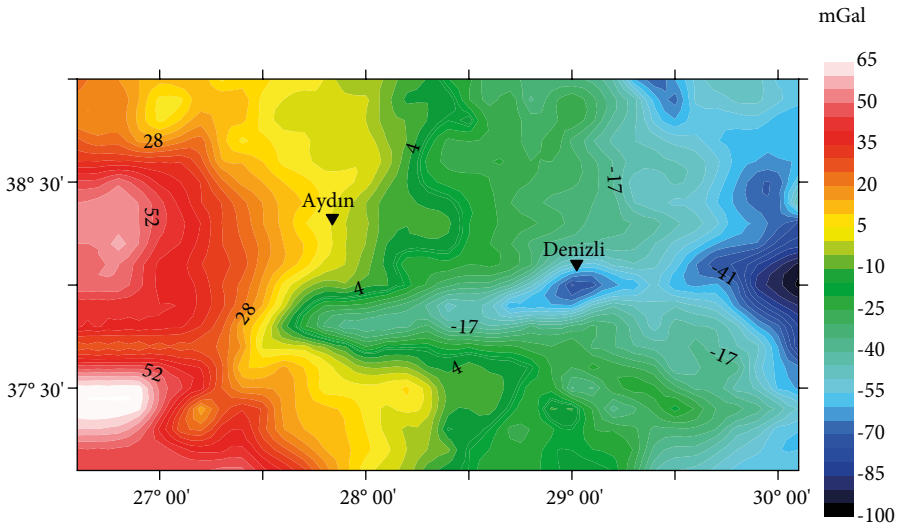


Figure 3. Bouguer gravity map of the study area (contour interval: 3 mGal).

area, a wide range of density difference values were chosen. Based on this information, the used density difference values between –0.45 and –0.5 gr/cm^3 were selected. In the initial model used in 2D inversion, the vertical prism block widths were chosen as 500 m and the initial depth was 0.5 km. The mean square error was calculated as the square root of the mean of the sum of squares of the difference between the observed and calculated values.

The best fit between observed and calculated gravity data was determined for –0.45 gr/cm^3 density contrast value for both profiles (Priene–Milet and Söke–Akbük) (Figures 5 and 6). The maximum depth of the basement for the Priene–Milet profile was about 2.3 km. The interpreted faults were marked on the subsurface model and these faults were interpreted as Ağaçlı faults for the Priene–Milet profile and as a Priene fault for the Söke–Akbük profile (Sümer et al., 2013).

The Sultanhisar–Kuyucak profile is 25 km long and extends in a W–E direction. The gravity data were collected in the northern margin of the BMG, which has a south-dipping low-angle normal fault. This profile is in the W–E direction and is located within the BMG. The profile cuts NE–SW in the eastern section of the graben. The depth of the basement was determined at about 1.8 km for –0.5 gr/cm^3 density contrast value (Figure 7). The interpreted faults were marked on the subsurface model and were interpreted as cross-graben borders.

The Nazilli–Arpaz profile is 14 km long and extends in a N–S direction. The best fit between observed and calculated gravity data was determined for –0.5 gr/cm^3 density contrast value, and the maximum depth of the basement was about 2.3 km (Figure 8). The interpreted faults were marked on the subsurface model, and these faults were interpreted as the Nazilli fault, the Nazilli–Büyük Menderes fault, and the Nazilli–Hamidiye fault.

According to the power spectrum results, the average depth of the Priene–Milet profile was determined to be 1.82 km (Figure 9a). The maximum depth for the Söke–Akbük profile was determined to be about 1.6 km, and the average depth of the Söke–Akbük profile was 1.44 km (Figure 9b). The average depth of the Sultanhisar–Kuyucak profile was determined to be 1.65 km (Figure 9c). The average depth of the Nazilli–Arpaz profile was determined to be 1.9 km (Figure 9d).

The results of the present study and the previous studies on the BMG have been compiled on the approximately SW–NE oriented A–B cross-section starting from Milet and extending around Nazilli to a length of 110 km. As shown in Figure 10, Cohen et al. (1995) determined the sedimentary thickness to be 1.5 km for Aydın and its surroundings. Işık (1997) measured the sedimentary thickness of the region between Aydın and Sultanhisar as 2–2.2 km and that between Sultanhisar and Nazilli as 2.2–2.3 km. Şenel (1997) determined the sedimentary thickness of the region between Sultanhisar and Nazilli to be 2.5 km. Sari and Şalk (2006) reported that the sedimentary thickness could be more than 1.5 km (more than 2 km in the Sarayköy–Kızıldere region) and that the maximum sedimentary thickness for the BMG ranged between 2.5 and 3.5 km by using both 3D and 2D analysis of gravity data. Işık and Şenel (2009) determined the maximum sedimentary thickness for the BMG as 3.9 km. Kaldırım (2008) determined thickness within the basin range as being from 3.8 to 4.8 km by evaluating 3 gravity cross-

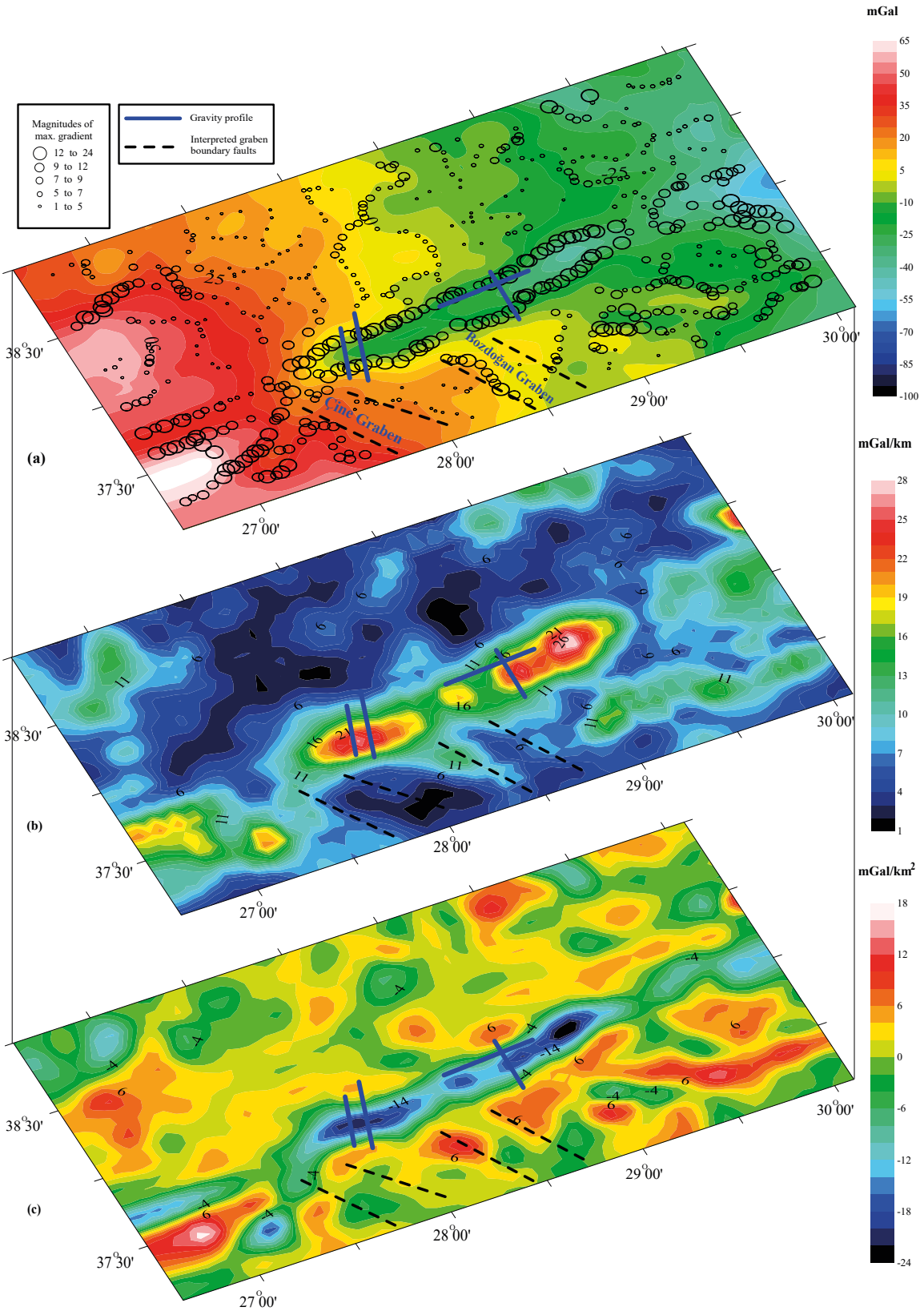


Figure 4. (a) Calculated maximum horizontal gradient values for boundary analysis overlaid on the Bouguer gravity map; (b) analytical signal map; (c) second vertical derivation map of the gravity data.

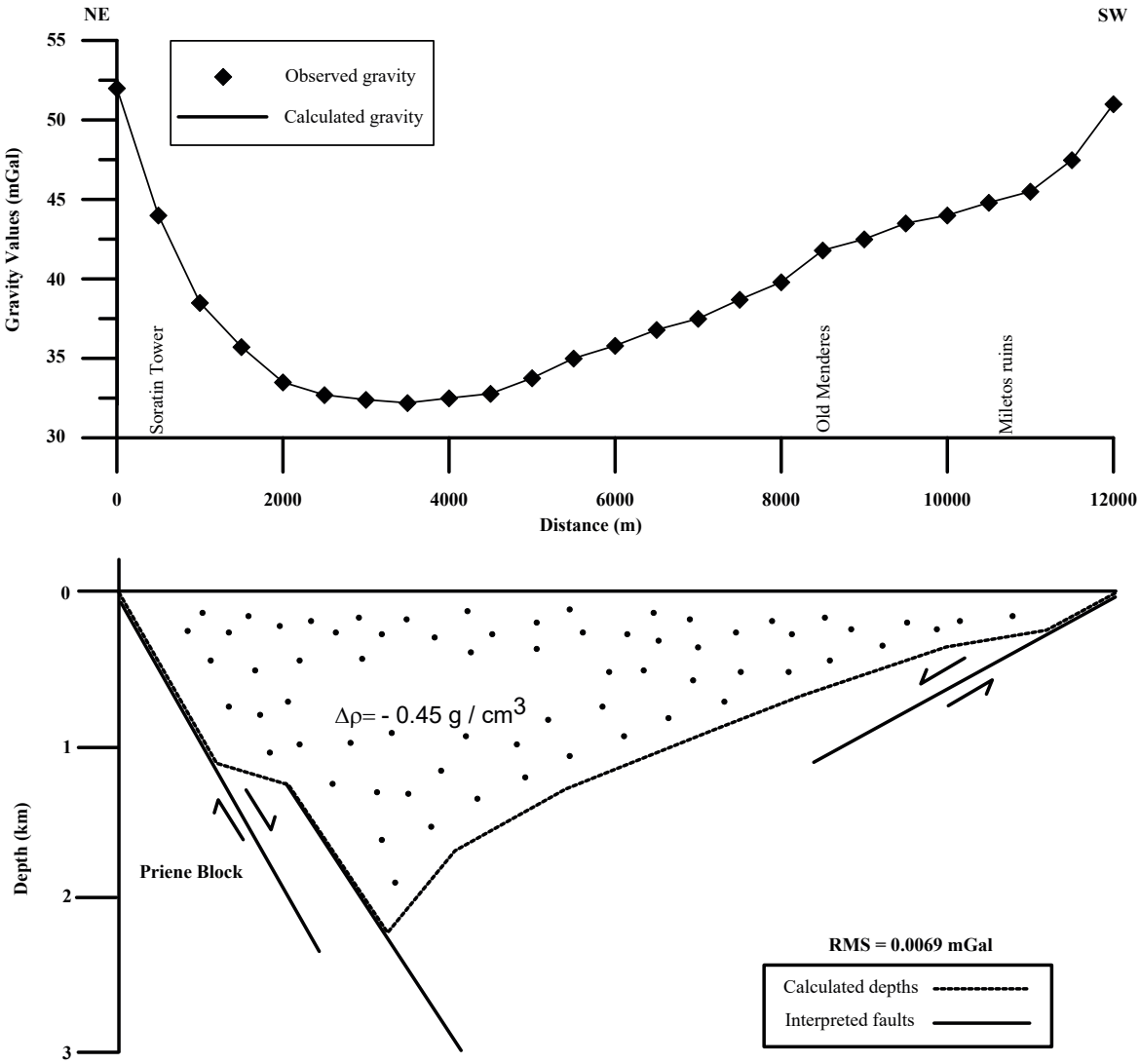


Figure 5. Interpreted gravity profile of Priene–Milet in accordance with 2D inversion technique (maximum iterations = 50).

sections. In the present study, the maximum sedimentary thickness of the graben was determined to be 2.3 km for Milet–Priene, 1.6 km for Söke–Akbük, 1.8–4 km for Sultanhisar–Kuyucak, and 2.3 km for Nazilli–Arpaz.

5. Results and conclusions

This study aims to provide a better understanding of the boundary faults, the thickness of the sedimentary cover, and the basement topography of the BMG. For this purpose, the boundary analysis, second vertical derivative, and analytical signal methods were applied to Bouguer gravity anomaly map data to determine the structural boundaries. It was evaluated and interpreted by 2D inverse solution and power spectrum processes to determine the topography of the BMG.

The boundary faults related to the E–W trending Büyük Menderes main graben and approximately SE–NW trending Çine and Bozdoğan cross-grabens were clearly observed on the boundary analysis map, but neither of these grabens appears on the maps of second derivatives and analytical signals. This is in accordance with previous research, which stated that the cross-grabens are shallow.

As a result of the 2D gravity inversion, the maximum thickness of the sedimentary deposits was determined to be 2.3 km in Priene–Milet and Nazilli–Arpaz, and 1.8 km in Sultanhisar–Kuyucak and Söke–Akbük. The average

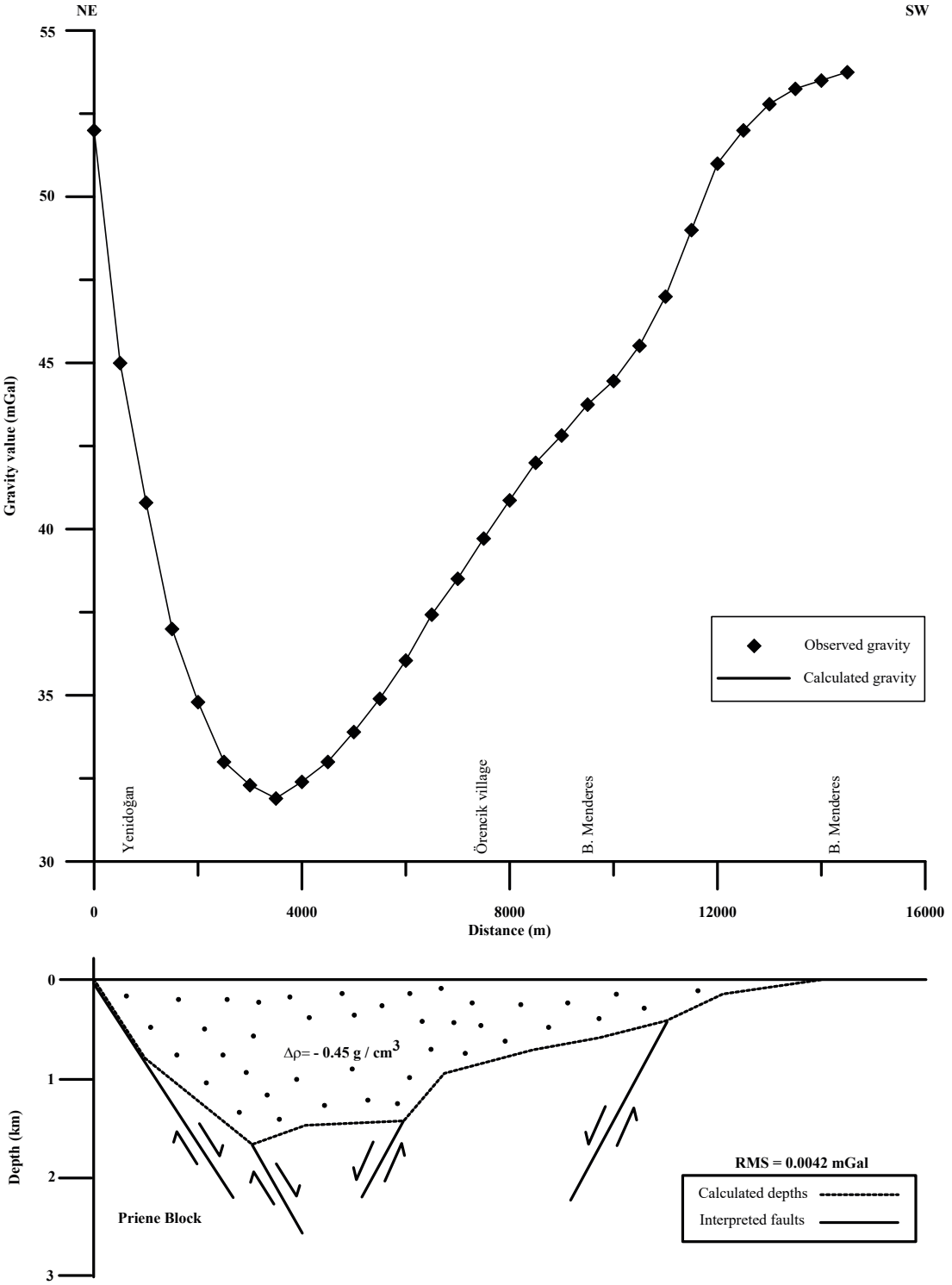


Figure 6. Interpreted gravity profile of Söke–Akbük in accordance with 2D inversion technique (maximum iterations = 50).

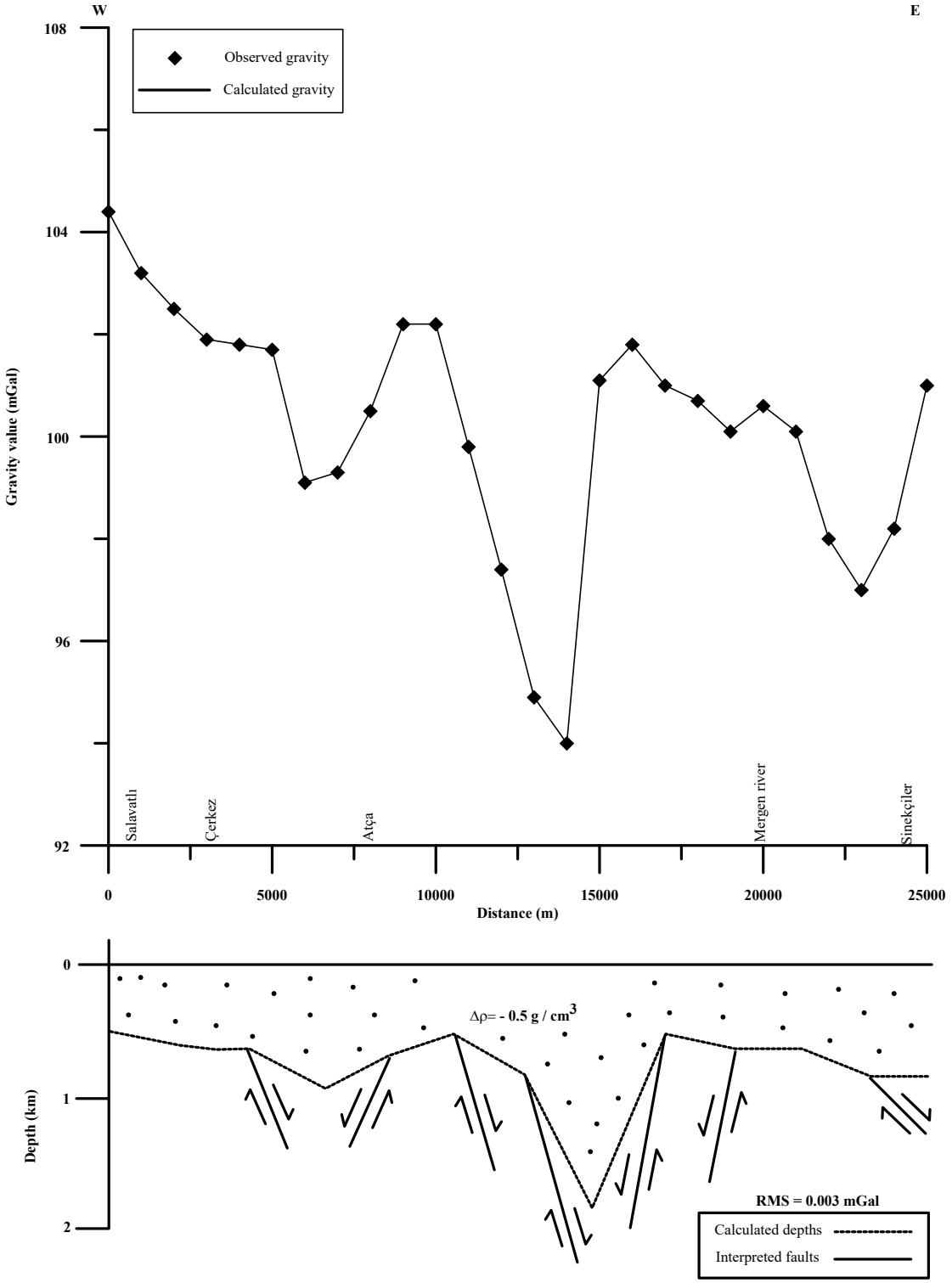


Figure 7. Interpreted gravity profile of Sultanhisar–Kuyucak in accordance with 2D inversion technique (maximum iterations = 50).

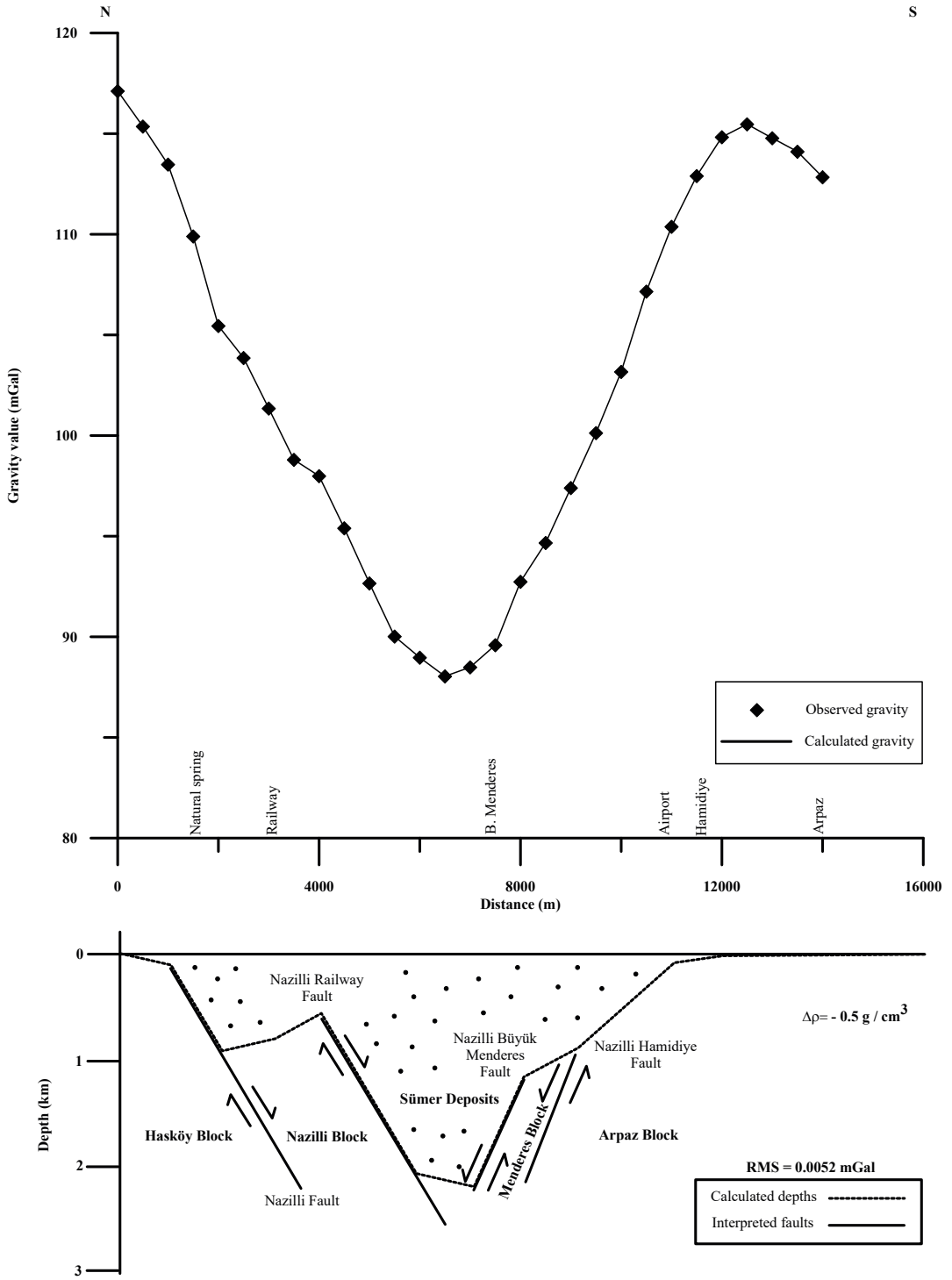


Figure 8. Interpreted gravity profile of Nazilli–Arpaz in accordance with 2D inversion technique (maximum iterations = 50).

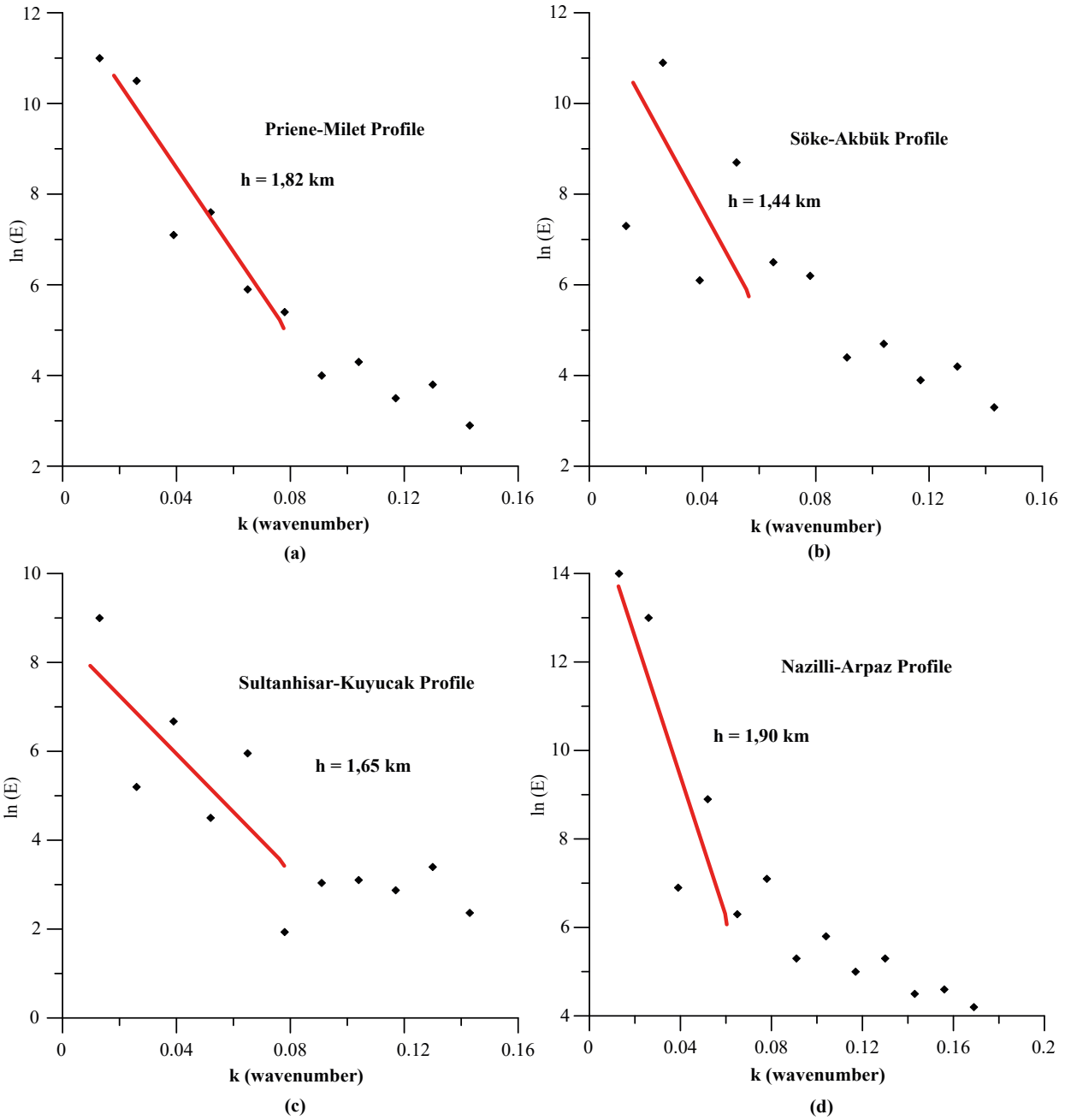


Figure 9. Power spectrum results of the measured gravity profiles: (a) Priene–Milet; (b) Söke–Akbük; (c) Sultanhisar–Kuyucak; (d) Nazilli–Arpaz.

depths of the gravity profiles were measured as 1.82 km for the Priene–Milet profile, 1.44 km for the Söke–Akbük profile, 1.65 km for the Sultanhisar–Kuyucak profile, and 1.9 km for the Nazilli–Arpaz profile according to the power spectrum method. The gravity profile indicates that the BMG system has asymmetrical graben features.

In this study, structural boundaries and sedimentary cover thicknesses and basement topography and faults have been interpreted for both the western and middle sections of the BMG. As seen in Figure 10, in the middle part of the BMG, the results of this study differ from the results obtained in other studies, due to different intensity values used in the evaluations, the different evaluation methods used, the multiresolution of the gravity method, and the data we used being more sensitive than other data. It is logical for there to be differences between the methods.

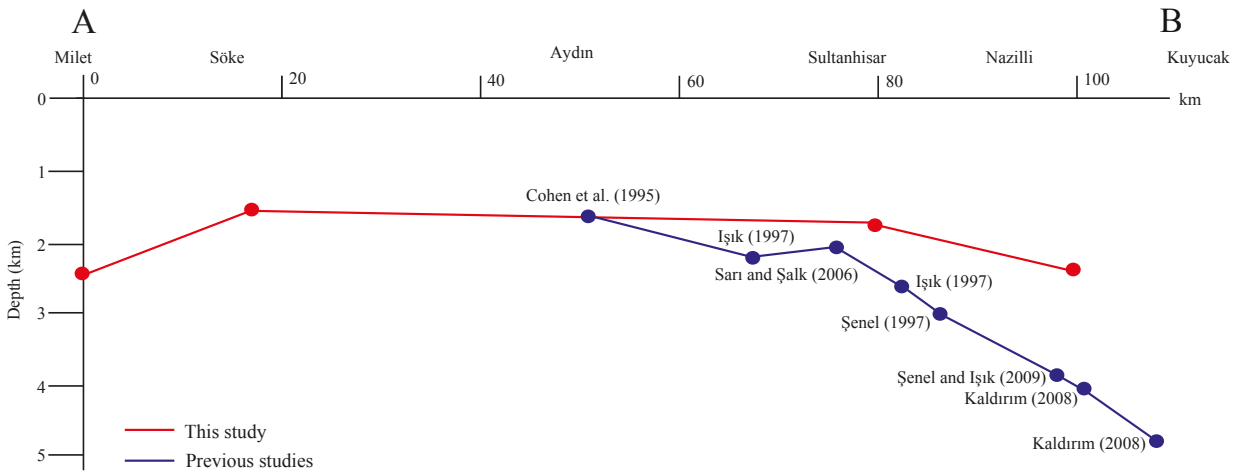


Figure 10. Results obtained in this study and previous studies for the sedimentary thickness of the Büyük Menderes Graben.

These results are compatible with geological observations and other geophysical investigations.

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