

Sediment thicknesses of the western Anatolia graben structures determined by 2D and 3D analysis using gravity data

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Received 18 August 2003; revised 17 August 2004; accepted 17 September 2004

Abstract

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. The graben systems may have become active between 11–7 Ma and are now deeper than the surrounding topography. The Gediz and Büyük Menderes grabens exhibit negative Bouguer gravity anomalies. The Bouguer gravity anomalies increase towards the center of the Aegean Sea in a regional sense. The grabens are filled with recent sediments giving rise to relative negative gravity anomalies. These anomalies were interpreted using 2D and 3D gravity inversion techniques in order to determine the depth to the metamorphic basement. Inversion of geophysical anomalies implies fitting the observed data to theoretical anomalies possibly produced by subsurface bodies. Inversion of gravity anomalies is a non-linear problem in the sense that body parameters are not linearly related to the anomalies. Gravity anomalies caused by structures are mostly determined by a 2D model, which has an n -sided polygonal cross-section. For non-linear problems, theoretically it is more suitable to determine the parameters of the structure by a series of juxtaposing prisms or vertical dykes extending to infinity, rather than using a single n -side polygonal model. The depths to the top surfaces of a rectangular prisms with infinite depth represent the relief of the basement. The basement relief can be computed on the basis of density contrast if the reference depth is assessed. As a result of 3D analysis of the Bouguer gravity map, the maximum thickness of sedimentary cover appears to be more than 2.0 and 1.5 km for the Gediz and Büyük Menderes grabens, respectively. Towards the Sarayköy-Kızılder area, the sedimentary thickness cover thickens to more than 2.0 km. 2D analysis of the Bouguer gravity profiles indicate that the maximum thickness of the sedimentary cover is between 2.5 and 3.5 km in the Büyük Menderes graben, and between 0.5 and 2.0 km in the Gediz Graben.

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Keywords: Inversion; Gravity; Graben; Density contrast; Basement; Sediment cover; 2D and 3D gravity analysis

1. Introduction

The objective of this paper is to determine the structure of specific basins in western Turkey using their negative Bouguer anomalies. Various algorithms have been reported by several authors (Talwani et al., 1959; Bott, 1960; Cordell and Henderson, 1968; Murthy, 1988; Murthy and Rao, 1989; Murthy et al., 1990; Rao and Babu, 1991) in order to produce synthetic data that simulate the response of subsurface structures or to directly invert the gravity

anomalies for the same purpose. The 2D and 3D inversion methods developed by Murthy and Rao (1989) and Rao (1986) were used in this work.

Gravity profiles are often characterized by higher frequency information superimposed on the smooth regional trend, which is usually referred to as the ‘gravitational anomaly’. It is of interested to invert these data to determine the nature of the mass distribution that would give rise to such an anomalous field. Unfortunately, as with other problems in potential theory, the solution is not unique. Different mass distributions can produce the same gravitational field. Even the very strong constraint that the gravity anomaly is caused by a single 2D mass of uniform density does not lead to an unambiguous interpretation.

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Nevertheless, a meaningful interpretation may be obtained if seismic data, and perhaps geologic data from boreholes or wells, are used to constrain sufficiently the range of possible models.

2. Structure of the grabens in western Turkey

Western Turkey is a structurally complex region exhibiting all the superimposed imprints of extensional, compressional and strike-slip tectonics. Generally, the active deformation of western Turkey is governed by interaction of three major plates (Eurasia, Arabia and Africa), as well as other small plates (blocks). The bulk deformation in the region appears to have originated from subduction and collision-related processes, i.e. the forces applied at the plate boundaries (Şengör et al., 1985).

Extension in this region has been attributed to:

1. Westward escape of the Anatolian block along the North Anatolian Transform Fault.
2. Neogene to recent subduction in the Hellenic Trench.
3. Gravitational collapse of thickened crust following Paleogene Alpine–Himalayan compression.

East–West grabens (e.g. Edremit, Bakırçay, Kütahya, Simav, Gediz, Küçük Menderes, Büyük Menderes and Gökova grabens) and their basin-bounding active normal faults are the most prominent neotectonic features of western Turkey (Dumont, 1979; Duvarci, 2001).

Other, less dominant structural elements of western Turkey are the NNE–trending basins and their intervening horsts (e.g. Gördes, Demirci, Selendi and Uşak–Güre basins) (Yılmaz et al., 2000; Sengör, 1987; Fuenzelida et al., 1997) (Fig. 1).

Extension continues today and major earthquakes have occurred in the Gediz and Büyük Menderes grabens. In western Turkey, the north–south extension inferred from major earthquakes is about 13.5 mm/year (Eyidoğan, 1988). Regional uplift across western Turkey has been no more than 700–800 m in the past 7–8 My, as estimated from the elevation of Miocene marine sediments to the east of the Büyük Menderes graben (Westaway, 1993). GPS data show that the westernmost part of the Anatolian plate is rapidly escaping to the SW at a rate of 30 ± 1 mm/year motion (Oral, 1994; Şalk et al., 1999; McClusky et al., 2000).

Kaya (1982) reported that the older Miocene structure in western Turkey consists of a N to NE-trending graben-horst system and the ENE-trending Büyük Menderes full-graben. The superimposed late Miocene structure is represented by WNW and ENE-trending half grabens (the Gediz, Simav and Kütahya grabens). In this context, the Büyük Menderes graben would have been influenced by the late Miocene-Pliocene half-graben tectonics, and

half-grabens characterized by the older N to NE-trending normal faults.

The most continuous topographic escarpments in western Turkey are oriented E–W and appear to be the footwalls of major active normal faults. These escarpments are seen in satellite images, topographic maps and in the field (Yılmaz et al., 2000). In terms of total displacements and extent of strike, the Gediz and Büyük Menderes fault zones are the most important and have been described in detail. Each has a Neogene basin in its hanging-wall, visible as low-lying sediment up to 2 km thick in its uplifted footwall.

According to borehole data obtained for geothermic purposes (Erisen, 1996), the thickness of the sediments is 1224 m in Ömerbeyli-Aydın (ÖB-8), 1241 m in Kızıldere-Denizli (KD-9), 350 m in Salavatlı-Nazilli (AS-2), 762 m in Caferbeyli-Salihli (SC-1). Both the Büyük Menderes and Gediz basins are asymmetric, with their dominant active extensional fault traces on their southern and northern margins, respectively (Roberts, 1988; Paton, 1992). These faults separate the recent basin from belts of exhumed Neogene sediments in faulted and depositional contact with the basement. In addition, Neogene sediments are uplifted along the northern margin of the Gediz graben, and within isolated sub-basins on the southern margin of the Büyük Menderes graben. In each graben, one margin is characterized by steeper topography, and more extensive and thicker exposures of Neogene sediments; and has been associated with surface breaks during earthquakes in historic times. The depositional systems in the Gediz and Büyük Menderes grabens are syn-tectonic. Locally, major structures have been modified by antithetic faulting. These basins, while being mainly half-grabens, exhibit synthetic and antithetic faulting on their hanging wall margins which created topographic relief and generated locally derived coarse detritus (Cohen et al., 1995).

3. Gravity anomalies in western Turkey

The Bouguer gravity map of Turkey was published by the General Directorate of Mining Research and Exploration Company of Turkey (MTA), in 1979 on the 1/500000 scale. The Bouguer gravity map was digitized using 5 km grid spacing in order to calculate the sediment thicknesses of western Turkey grabens. The grabens are characterized by lower gravity anomaly values due to their thick sedimentary deposits. The horsts that consist of high grade metamorphic rocks of the Menderes massif show the higher gravity values. Generally, regional negative Bouguer gravity anomalies are present in western Turkey. Regional negative gravity anomalies in the continental stress field are created as a result of the joint effect of a zone of low density and thin oceanic crust (Darracott et al., 1972; Condie, 1976). The Gediz and Büyük Menderes grabens, which have generally E–W trends, are the large areas identified with negative Bouguer gravity anomalies (Fig. 2). The positive

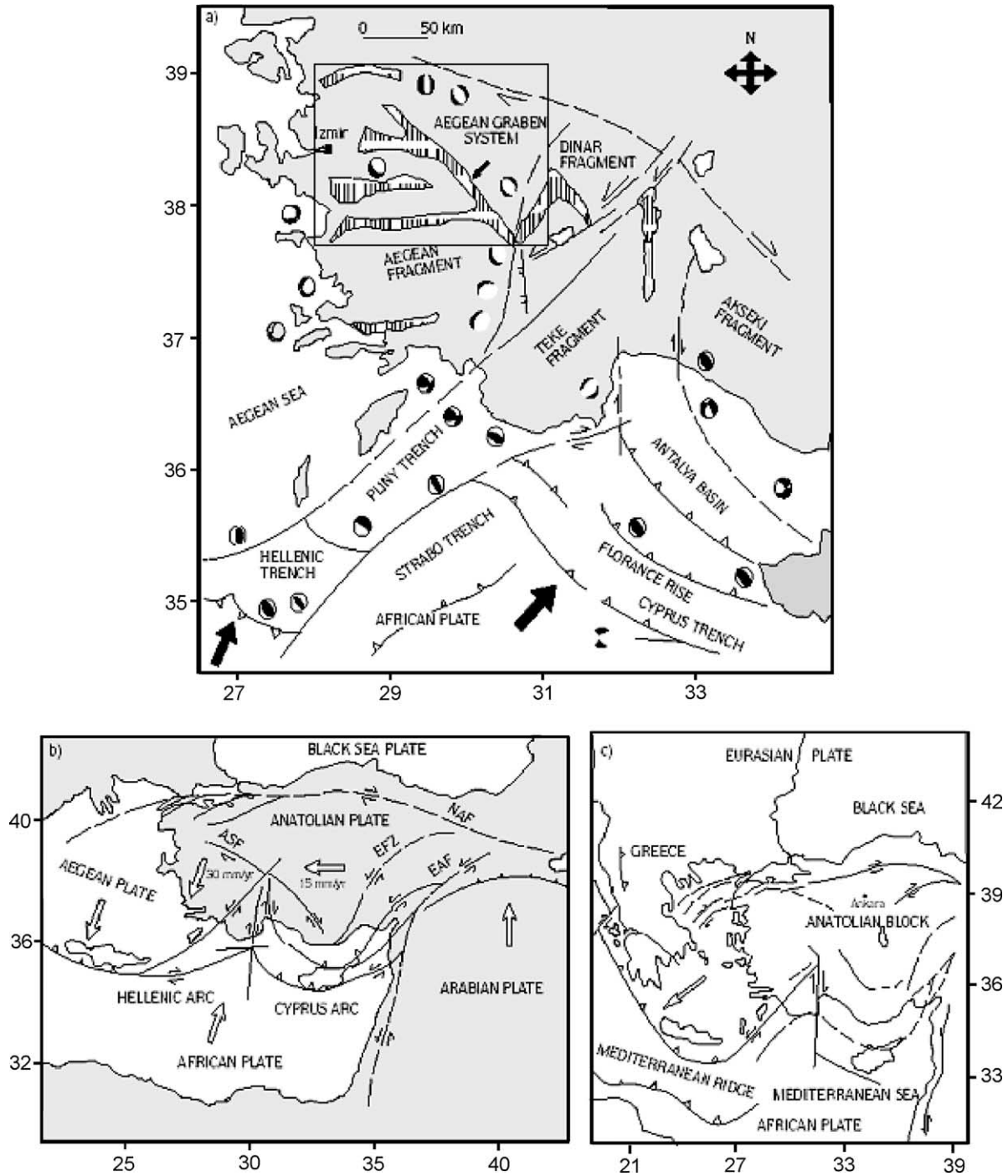


Fig. 1. Main tectonic features SW Turkey and adjacent areas showing relation the between Hellenic and Cyprus arcs (Savaşın and Oyman, 1998; modified from Yağmurlu et al. (1997)). Inset corresponds to the study area.

Bouguer gravity anomaly observed to the west of Menderes massif is interpreted as a continuation of a positive anomaly belt identified as the concave side of an island arc (Rabinowitz and Ryan, 1970; Öznelçi, 1973). Similarly, the negative anomaly belt towards central Anatolia from the Denizli area is defined as the continuation of Crete's relatively negative anomaly belt. It is also identified as the convex side of an island arc. Gravity values increase from E

to W towards the Aegean Sea. The anomalies related to regional structures have N–S, NE–SW and NW–SE trends, and the anomalies related to residual structures have broadly E–W and NW–SE trends.

The profiles (A–A'), (B–B') and (C–C'), which were taken from the Bouguer gravity anomaly map, were digitized at 5 km intervals. Before the application of the two and 3D inversions on the data, the regional effect

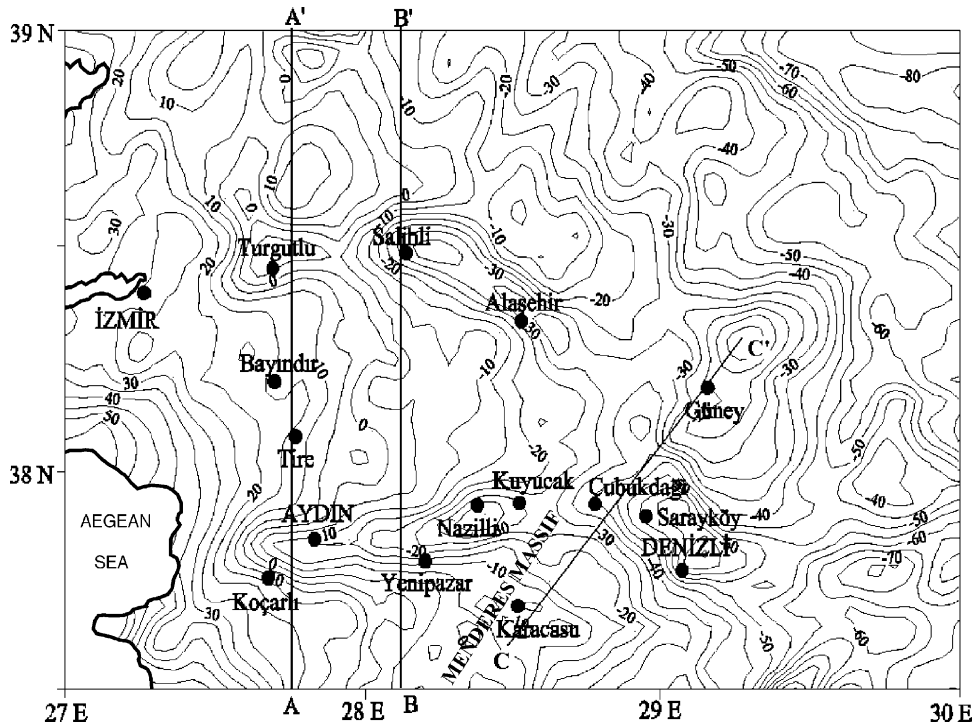


Fig. 2. Bouguer gravity anomaly map of the Aegean region (MTA (Directorate of Mineral Research and Exploration, 1979) (contour interval 5 mGal).

(25 mGal) was eliminated by subtraction of the first degree polynomial. The average values density differences, which were used for the two and 3D solutions, were inferred from boreholes drilled in the area (Büyük Menderes and Gediz grabens), for the geothermal purposes by the MTA.

In the 2D case (see Appendix A), the gravity profile (A–A') is in the N–S direction along Longitude of 27°45' E, crossing the Büyük Menderes and Gediz basins at the westernmost parts of these basins (Fig. 3). The Büyük

Menderes and Gediz basins are dominated by negative gravity anomalies. The Küçük Menderes basin doesn't show a significant gravity anomaly. According to the modelling studies (Sarı and Şalk, 2002; Göktürkler et al., 2003), this is probably due to a very thin sedimentary cover on the Küçük Menderes massif metamorphic rocks. The negative gravity anomalies are due to the thick Neogene sediments within the Gediz and Büyük Menderes grabens. According to geological data, the faults on the northern side of Gediz basin are

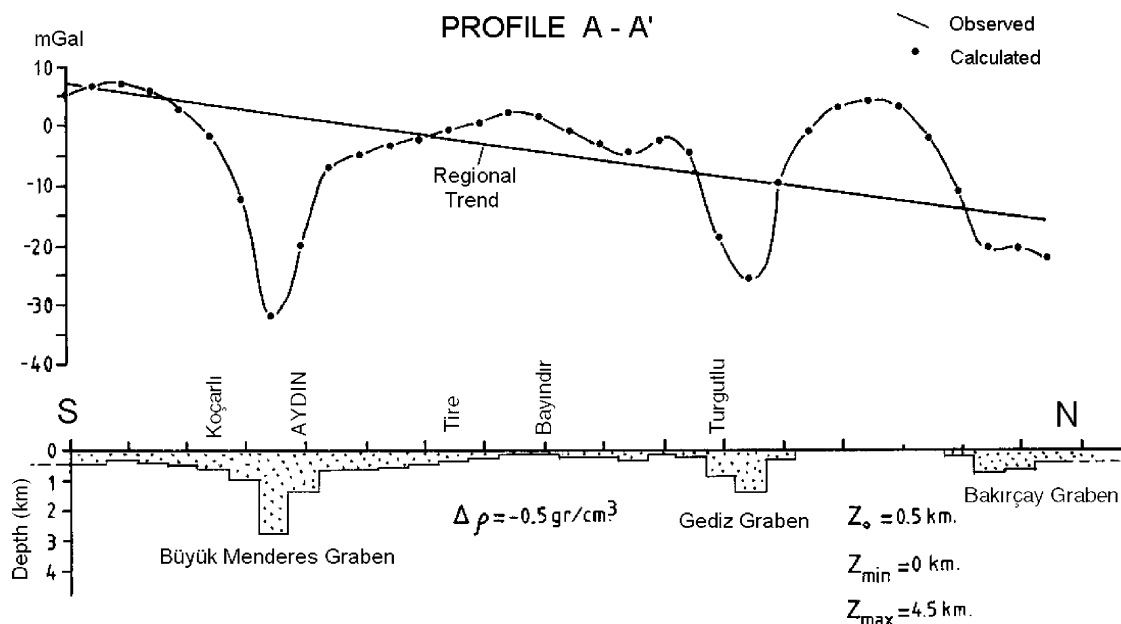


Fig. 3. Interpreted Bouguer gravity profile AA' in accordance with the 2D inversion technique (see Fig. 2 for the location).

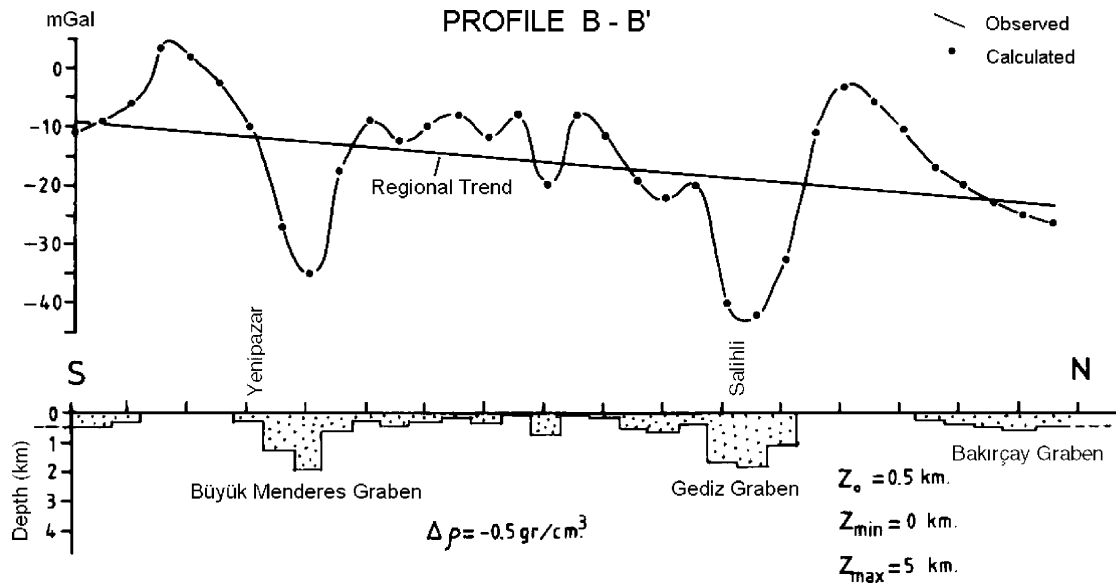


Fig. 4. Interpreted Bouguer gravity profile BB' in accordance with the 2D inversion technique (see Fig. 2 for the location).

antithetic to the main fault system along the south side of the graben. The faults on the south side control the topography and asymmetry of the graben. The profile B-B' crosses the Büyük Menderes and Gediz grabens in a N–S direction from Nazilli to Salihli (Fig. 4). The sedimentary fills are thicker at the southern side compared to the northern side in both grabens. The average sedimentary thicknesses are almost the same as along profile A–A'. In both profiles, the Küçük Menderes graben is not recognizable, probably because of the very thin sedimentary cover.

The profile C–C', in the Sarayköy geothermal area, is in the SW–NE direction (Fig. 5). The average sedimentary thickness is 3.5 km and becomes thicker towards the SW. Asymmetric graben features are also prevalent.

In the 3D case (see Appendix B), a variable density difference was assumed in order to estimate the sedimentary

cover thickness in the region. On the bases of variable density contrasts (-0.4 , -0.5 , $-0.5 \exp(0.15z)$, $-0.5 \exp(-0.1609z)$ gr/cm^3) along the E–W striking Büyük Menderes graben, the sedimentary thicknesses are found to be in the range of 1.5 and 2.0 km (Figs. 6–9). The maximum sedimentary thicknesses (2.0–2.5 km) are obtained in the Kızıldere-Sarayköy geothermal region towards Denizli. However, the Gediz graben is wider and trends ESE to WNW with sedimentary thicknesses of 1.5–2.5 km. The contours in Figs. 6–9 identify sedimentary thicknesses corresponding to the boundaries of the grabens. Overall, a sedimentary cover density of 0.5 g/cm^3 can be assumed. Geoelectric studies, which were made by M.T.A, indicate a maximum depth of about 2 km for the basement in the Germencik-Aydın and Sarayköy-Denizli areas (Turgay et al., 1980; Şahin and Üney, 1981). On the other hand,

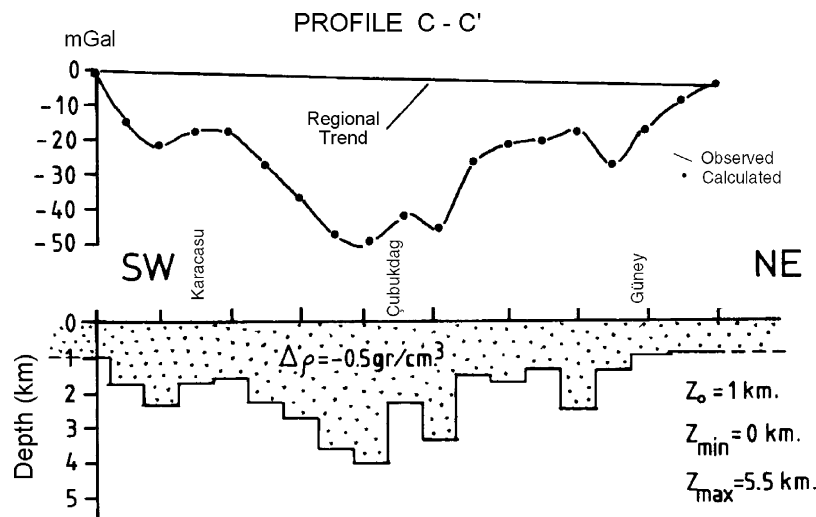


Fig. 5. Interpreted Bouguer gravity profile CC' in accordance with the 2D inversion technique (see Fig. 2 for the location).

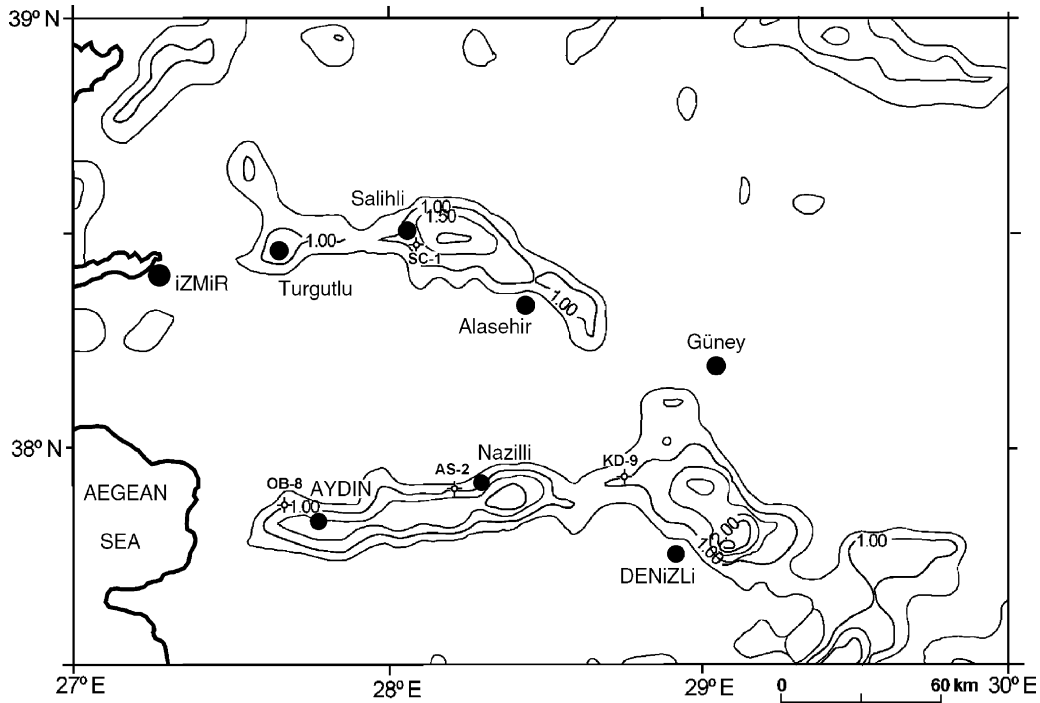


Fig. 6. Depth to the basement by gravity inversion using a constant density contrast of -0.4 gr/cm^3 (contour interval is 0.5 km).

gravity analysis presented herein and the geoelectrical studies indicate that basin the sedimentary covers between Alaşehir and Sarayköy-Denizli, and in the Küçük Menderes are very thin.

4. Discussion and conclusions

Sedimentary thicknesses in western Turkey are of great interest because there are no data from explosion

seismology and deep wells. Recently, Paton (1992) studied Bouguer gravity data over the Büyük Menderes and Gediz grabens and estimated an average depth to the basement of 1.5–2 km. Güreş et al. (2002) suggests varying sedimentary thicknesses in the range of 1–3.8 km along the Gediz graben.

The sedimentary cover on the Menderes Massif in western Turkey was determined from 3D and 2D analysis of the Bouguer gravity data (MTA, 1979). As a result of 3D analysis of the Bouguer gravity map, the maximum

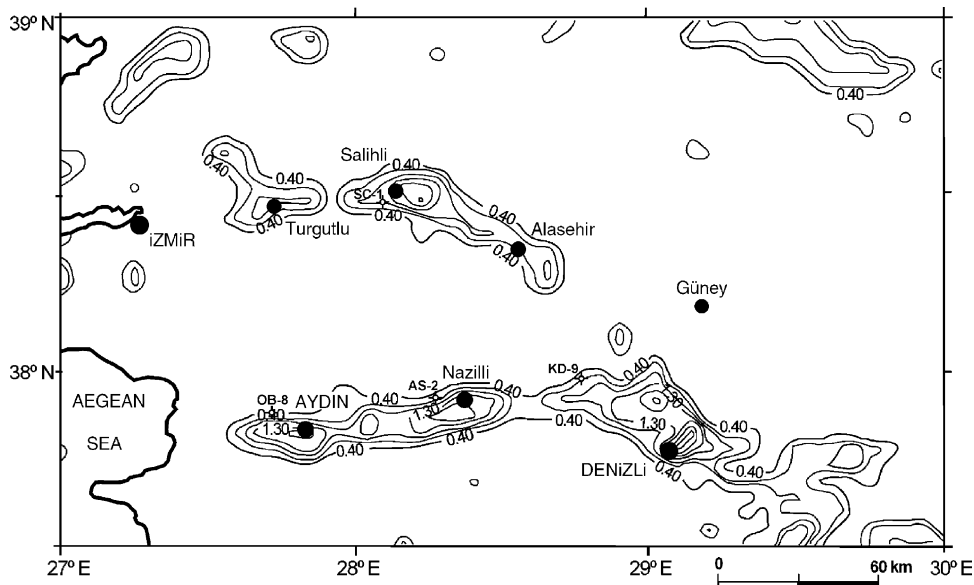


Fig. 7. Depth to the basement by gravity inversion using a constant density contrast of -0.5 gr/cm^3 (contour interval is 0.3 km).

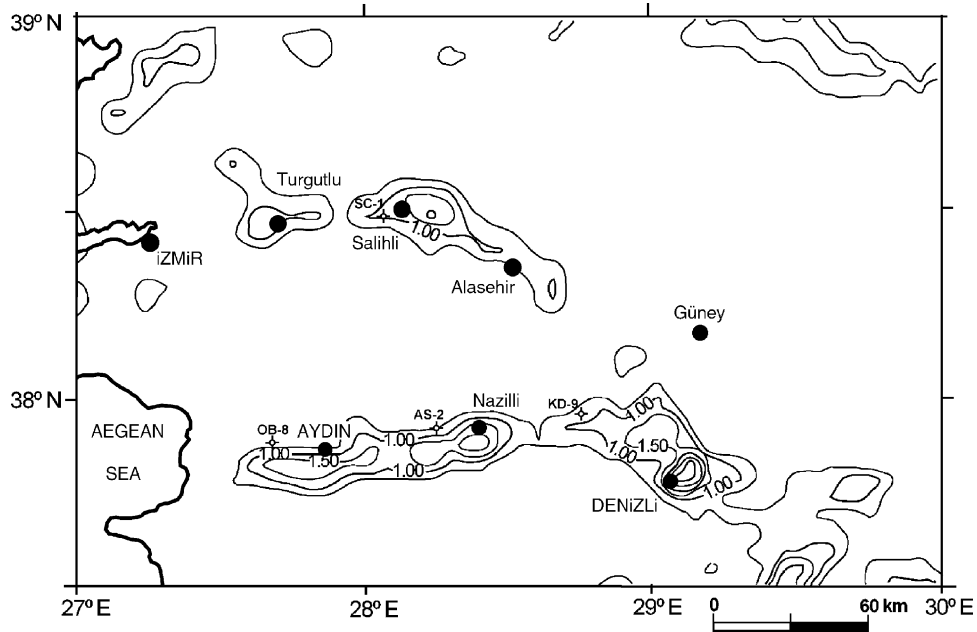


Fig. 8. Depth to basement by gravity inversion using an exponential depth-density function of $-0.5\exp(-0.15)$ gr/cm^3 (contour interval is 0.5 km).

thickness of sedimentary cover appears to be more than 2.0 km in the Gediz graben and over 1.5 km in the Büyük Menderes graben. Towards the Sarayköy-Kızıldere area, the sedimentary thickness reaches more than 2.0 km. In both grabens, the sedimentary cover is bounded by the E–W striking normal fault systems.

2D analyses of Bouguer gravity profiles indicate maximum thicknesses of the sedimentary cover to be between 2.5 and 3.0 km in the Büyük Menderes graben, and between 1.5 and 2.0 km in the Gediz Graben. Both profiles A–A' and B–B' show negative gravity anomalies over

the Büyük Menderes and Gediz grabens. In the Kızıldere-Sarayköy area, the sedimentary thickness is more than 2.0 km. The gravity profiles indicate that the Gediz and Büyük Menderes graben systems are asymmetric. However, the asymmetric setting is not seen in 3D analysis. The basement topography could be better determined using a smaller sampling interval for both 2D and 3D analysis. The gravimetric pattern appears compatible with field observations, borehole data and the results of other investigations. The results obtained are the explicit indication of multi-solution of potential data. In order to better constrain

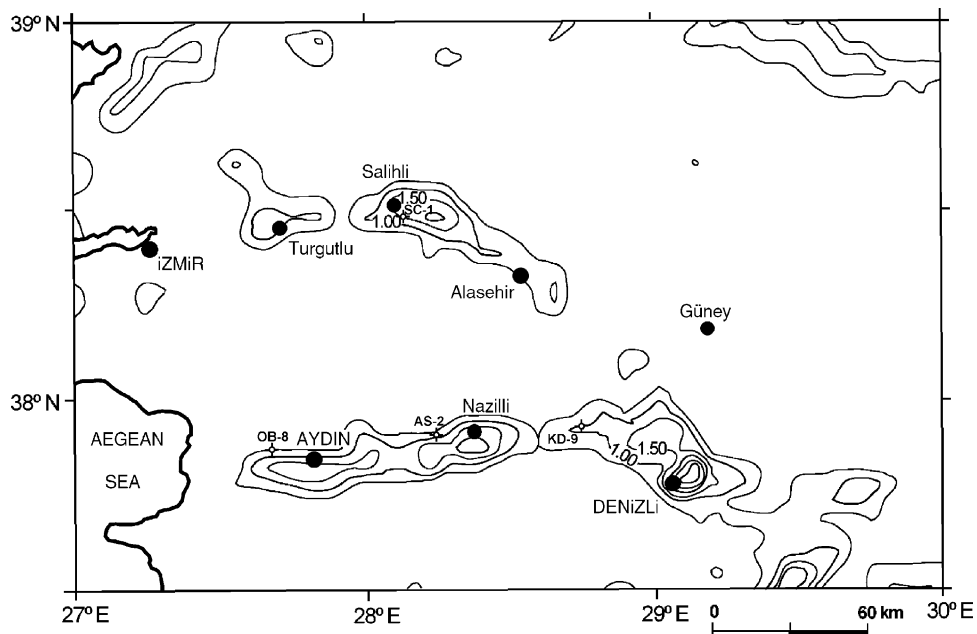


Fig. 9. Depth to basement by gravity inversion using an exponential depth-density function of $-0.5\exp(-0.1609)$ gr/cm^3 (contour interval is 0.5 km).

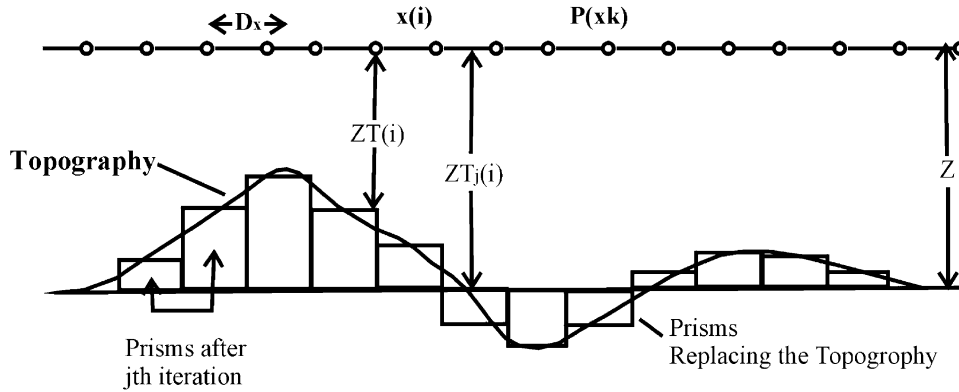


Fig. 11. 3D prismatic model (Bhaskara Rao, 1991).

Appendix B

Appendix B.1. 3D analysis of gravity anomalies variable density contrast

The decrease in values of density contrast for sedimentary rocks can be approximated by a quadratic function (Bhaskara Rao, 1986) as,

$$\Delta\rho(z) = a_0 + a_1z + a_2z^2$$

where z represents the depth measured positive in a downward direction, a_0 represents the extrapolated value of density contrast at the surface, and a_1 and a_2 are constants of the quadratic function and are solved by the least squares method from data of the given density function.

For 3D modelling of the gravity anomalies, a sedimentary basin may be viewed as a number of vertical prisms of half thickness T and half width W placed in juxtaposition at each observation point. It is assumed that each prism is placed just below the observation point and has a thickness Δx and width Δy equal to the station spacing in the x and y directions, respectively. The equation for the gravity anomaly in the prismatic model with a quadratic density function is given by

$$\begin{aligned} \Delta g(x,y) = & Ga_0 \left\| \left\| z \tan^{-1} \frac{XY}{zR} + \frac{X}{2} \ln \frac{R-Y}{R+Y} + \frac{Y}{2} \ln \frac{R-X}{R+X} \right\| \right\| \\ & + Ga_1 \left\| \left\| \frac{z^2}{2} \tan^{-1} \frac{XY}{zR} - \frac{X^2}{2} \tan^{-1} \frac{YZ}{XR} \right. \right. \\ & \left. \left. - \frac{Y^2}{2} \tan^{-1} \frac{XZ}{YR} + XY \ln(2R+2z) \right\| \right\| \\ & + Ga_2 \left\| \left\| \frac{z^3}{3} \tan^{-1} \frac{XY}{zR} - \frac{X^3}{6} \ln \frac{R-Y}{R+Y} \right. \right. \\ & \left. \left. - \frac{Y^3}{6} \ln \frac{R-X}{R+X} + \frac{2}{3} XYR \right\| \right\| \end{aligned}$$

where $X_1 = x + T$, $X_2 = x - T$, $Y_1 = y + W$, $Y_2 = y - W$ and $R = (X^2 + Y^2 + z^2)^{1/2}$ and G is the gravitational constant

(Bhaskara Rao, 1990). R represents the distance from one of the eight vertices of the prismatic model to the observation point as shown in Fig. 11.

In order to save computer time and make practical use of the programs, Bhaskara Rao (1990) developed approximate equations (which can be obtained by treating the prism as a line mass) for anomaly calculations. These equations are valid down to a small distance away from the centers of the prisms. At greater distances from the center of the prism, the calculated anomaly using approximation equation becomes closer to the exact value. These are obtained by treating the prism as a line mass in 3D space. The approximate equation in the 3D case is given by Bhaskara Rao (1990) as,

$$\begin{aligned} \Delta g(x,y) = & Ga_0 \Delta x \Delta y \left| \frac{-1}{R} \right|_{z=Z_1}^{Z_2} + Ga_1 \Delta x \Delta y \left| \frac{-z}{R} \right. \\ & \left. + \ln(z+R) \right|_{z=Z_1}^{Z_2} + Ga_2 \Delta x \Delta y \left| \frac{(2x^2 + 2y^2 + z^2)}{R} \right|_{z=Z_1}^{Z_2} \end{aligned}$$

where $R = (x^2 + y^2 + z^2)^{1/2}$ and Δx and Δy are the station spacings in the x and y direction, respectively.

After substituting the limits, the approximate equation may be written as,

$$\Delta g(x,y) = G \Delta x \Delta y (P_1 + P_2 + P_3)$$

where

$$P_1 = a_0 \left[\frac{1}{R_1} - \frac{1}{R_2} \right]$$

$$P_2 = a_1 \left[\frac{Z_1}{R_1} - \frac{Z_2}{R_2} + \ln \frac{R_2 + Z_2}{R_1 + Z_1} \right]$$

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