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Analysis of gravity anomalies with hyperbolic density contrast: An application to the gravity data of Western Anatolia

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Abstract: *The primary objective of a gravity survey over a sedimentary basin is to delineate the shape of the basin. To fulfill this objective, information is needed about the densities within the sedimentary section. Densities of sedimentary rocks increase with depth (mainly due to compaction), approaching that of the basement in deep basins. Sedimentary basins are generally associated with low gravity values due to lower density of the sedimentary infill..Further, gravity modelling of a basin requires the use of expressions with hyperbolic density contrast concerning the anomaly produced by the model. The variation of the density of sediments with depth can be represented by a hyperbolic function. In this study, synthetic examples are presented to show the use of the closed form expression for the gravity anomaly of a two-dimensional arbitrarily shaped body with a hyperbolic density contrast*

Tthe most pronounced structural and morphological features of western Anatolia are caused by E-W trending normal faulting which creates the boundaries of Büyük Menderes, Küçük Menderes and Gediz grabens. These grabens which have negative Bouguer gravity anomalies are filled with Neogen sediments. These anomalies, were interpreted using a hyperbolic density function, in order to determine the depths to the metamorphic basement. The approximate depth to the metamorphic basement at each observation point is calculated using the gravity formula on an infinite slab with hyperbolic density contrast. The maximum depth of Gediz graben are determined as 2 km and 1.8 km along two almost parallel profiles.Concerning the Büyük Menderes graben, The maximum depth was found 2.5 km.

Key Words: *Gravity Anomalies, Hyperbolic Density Contrast,Western Anatolia.*

INTRODUCTION

The main purpose of a gravity survey over a sedimentary basin is to delineate the configuration of the basin. Sedimentary basins are generally associated with low gravity values due to the low density sediments in them. In general the density of sedimentary rocks in a basin increases with depth (Athy, 1930; Howell *et al*., 1966). Thus, the contrast in densities of the sediments and the basement decreases. Gravity modelling of such sedimentary basins requires the use of anomaly expressions of a model with variable density contrast. In some basins the sediment density varies with depth and this variation depends on several factors. In such situations, the gravity modelling can be carried out assuming variable density which plays an important role in accurate determination of basement depths under the sedimentary cover. A few methods exist for modelling gravity anomalies using variable density contrast. For instance, if used a quadratic density function while Bhaskara Rao (1986, 1990), Cordell (1973) and Chai and Hinze (1988) used an exponential one. The quadratic representation make use of the first three terms of the infinite series expansion of the exponential function.

Bhaskara Rao (1986) showed that the density contrast decreases in many sedimentary basins and used the quadratic density function to simulate the density variation in sedimentary basins. This function is obtained by truncating the series expansion of the exponential function. Litinsky (1989) introduced a hyperbolic density-depth function and claimedthat in certain cases this function could provide a better fit for density-depth data than did the exponential function. An important feature of the hyperbolic density function is that the gravity anomalies of bodies exhibiting hyperbolic density distribution can be derived in a closed form, a facility not available with an exponential function. When the density contrast is assumed to vary with depth in a hyperbolic manner, the response of models can be derived in a closed form and simple modelling or inversion schemes were developed. Litinsky (1989) suggested a method of interpreting gravity anomalies using the simple formula of the gravity anomaly of an infinite slab with effective hyperbolic density contrast to calculate the thickness of sediments at the different gravity stations. Litinsky's formula creates errors in the final basement depth values; the smaller the width of the basin, the more pronounced the errors in the depth values. Visweswara Rao *et al*.

(1994) derived a closed form expression for the gravity anomaly of a vertical juxtaposing prisms using a hyperbolic density function to determine the depth of the interface at different gravity stations. Information about the depth of the basin and the densities of the sedimentary rocks in the basin is needed at least at one point.

In this work, the inverse gravity modelling method using hyperbolic density contrast is applied both of the wide and narrow basin theoretical models which are layered horizontally. Then, the method is applied to gravity profiles across Gediz Graben and Büyük Menderes Graben in western Anatolia to estimate sediment-basement interface.

ANALYSIS OF GRAVITY ANOMALIES WITH HYPERBOLIC DENSITY CONTRAST

Density measurements and seismic surveys conducted in sedimentary basin (Athy, 1930; Hedberg, 1936; Maxant, 1980), show that the density-depth relationship of sedimentary rocks does not obey a deterministic mathematical formulation due to the effects of stratigraphic layering, facies variations, diagenesis, tectonic history, cementation and compaction. For the analysis of gravity data over sedimentary basins, the density variation with depth can be approximated by a hyperbolic function (Litinsky, 1989) as below;

$$\rho(z) = \Delta\rho_0 \frac{\beta^2}{(z+\beta)^2} + \rho_{max}, \tag{1}$$

where $\rho(z)$ is the density of the layer at depth z, $\Delta\rho_0$ is the density contrast at the surface, ρ_{max} is the the density of the basement, and β is a constant having a unit of length and is the decrement of density contrast with increasing depth. At depth z=0,

$$\rho(0) = \Delta\rho_0 + \rho_{max} \tag{2}$$

The variable density contrast of sediments in a basin can be approximated by the following formula

$$\Delta\rho(z) = \frac{\Delta\rho_0\beta^2}{(\beta+z)^2}, \tag{3}$$

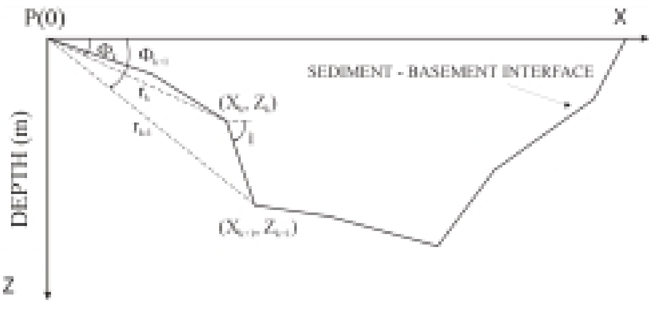

FIG. 1. A polygonal model simulating a sedimentary basin.

where $\Delta\rho(z)$ is the density contrast at depth z, $\Delta\rho_0$ is the density contrast extrapolated to the ground surface, and β is the rate of variation of density contrast expressed in units of length. The gravity anomaly $\Delta g(0)$ at any point $P(0)$ on the principle profile of a 2-D body of irregular cross section (Fig. 1) can be calculated using the equation (Visweswara Rao *et al*., 1994)

$$\Delta g(0) = 2G\Delta\rho_0\beta^2 \sum_{k=1}^{n} P_1 \left[\frac{\sin\cdot i}{P_2} \ln\frac{r_{k+1}Q_1}{r_kQ_2} \cdot - \frac{\beta - P_1\cos\cdot i}{P_1P_2}(\phi'_{k+1} - \phi'_k) \right], \tag{4}$$

where

$$P_1 = x_k \sin\cdot i - z_k \cos\cdot i$$
$$P_2 = \beta^2 - 2\beta P_1 \cos\cdot i + P_1^2$$
$$Q_1 = \beta + z_k$$
$$Q_2 = \beta + z_{k+1}$$
$$r_k = (x_k^{\,2} + z_{k+1}^{\,2})^{1/2}$$
$$r_{k+1} = (x_{k+1}^{\,2} + z_{k+1}^{\,2})^{1/2}$$
$$\phi'_k = \pi/2 - \phi_k$$
$$\phi'_{k+1} = \pi/2 - \phi'_{k+1}$$
$$\sin\cdot i = (z_{k+1} - z_k)/R$$
$$\cos\cdot i = (x_{k+1} - x_k)/R$$
$$R = \left[(x_{k+1} - x_k)^2 + (z_{k+1} - z_k)^2\right]^{1/2}$$

and G is the gravitational constant.

The quantities x_k, x_{k+1}, z_k, z_{k+1}, ϕ_k, ϕ_{k+1} and i are explained in Fig.1. In general, the values of β and $\Delta\rho_0$ are unknown and can be estimated by least squares fitting to the density-depth values which are observed by borehole data in the field.

If the formation lithology, thicknesses of the formations and their density information are known from borehole data for a basin with n sedimentary layers with different thicknesses h_i and different density contrasts $\Delta\rho_i$, the weighted density constant (or average density constant) $\overline{\Delta\rho}$ can be determined by

$$\overline{\Delta\rho} = \frac{\Delta\rho_1h_1 + \Delta\rho_2h_2 + \cdots + \Delta\rho_nh_n}{h_1 + h_2 + \cdots + h_n} = \frac{\sum\Delta\rho_ih_i}{\sum h_i} = \frac{\sum\Delta\rho_ih_i}{H} \tag{5}$$

where, H, denotes the total thickness of the sediments or the depths to the basement of the basin. According to Litinsky(1989), the parameter β can be estimated by two methods. If a density cross section of the basin and the values of $\Delta\rho_0$ and $\overline{\Delta\rho}$ are known, β can be calculated from the equation

$$\beta = \overline{\Delta\rho}H/(\Delta\rho_0 - \overline{\Delta\rho}) \tag{6}$$

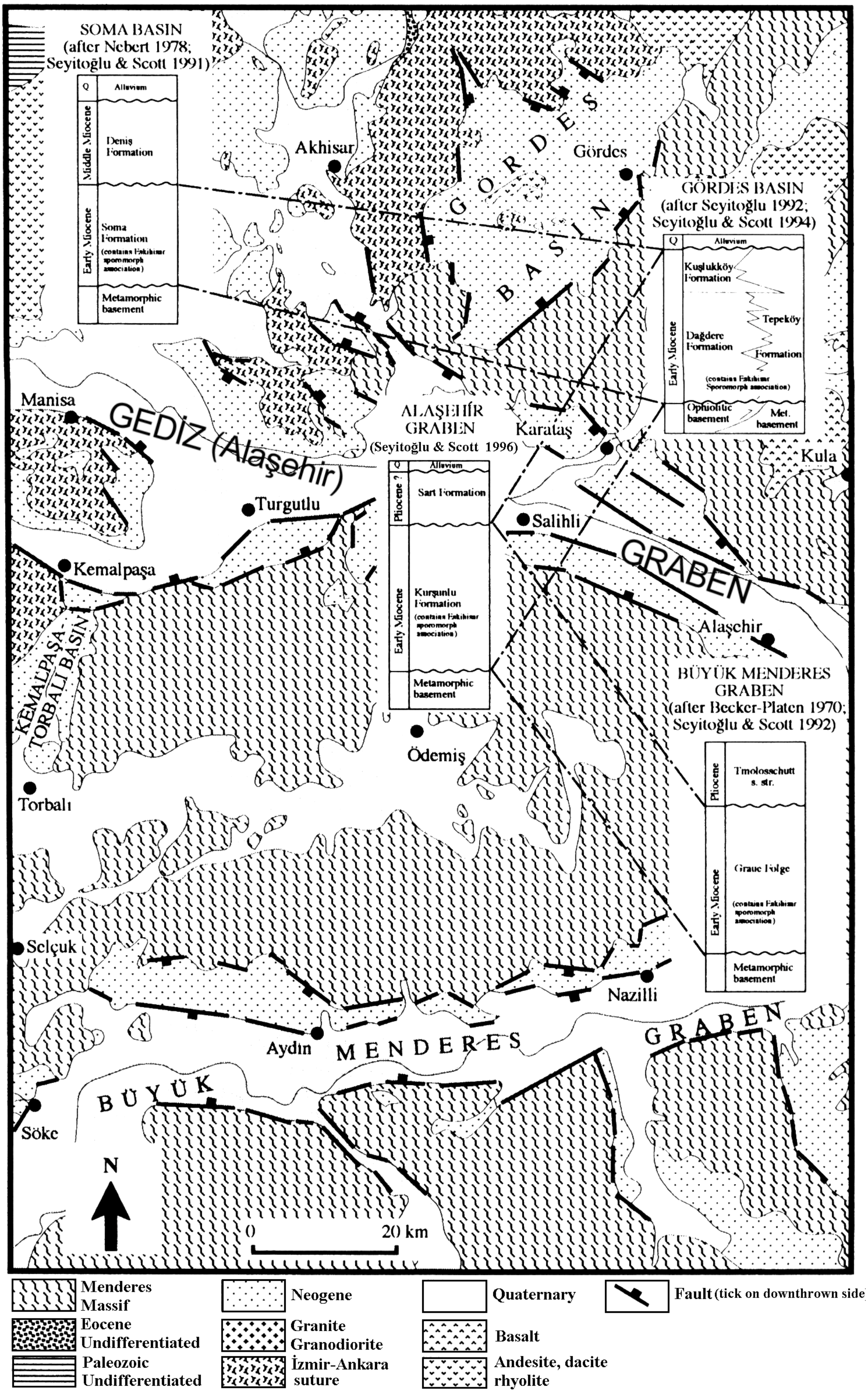

FIG. 2. Geology and tectonics of the Gediz and Büyük Menderes Grabens (Western Turkey) (Seyitoğlu and Scott, 1996).

The density contrast $\Delta\rho_0$ of surface sediments can be found from density measurements of rock samples, from borehole gravity, density logging, or from gravity data (e.g. Nettleton's method). If the values of weighted density contrast and the density contrast of the near surface sediments have been assessed, it is easy to find the parameters for the density-depth functions. On the other hand, if the depth of a sedimentary basin and the surface density are known, β can be found by using the equation

$$\beta = \Delta g H / (41.85 \Delta\rho_0 H - \Delta g) \tag{7}$$

At any gravity station the initial depth of the interface, *H* can be calculated using the infinite slab formula for the case of a hyperbolic density constant (Litinsky, 1989) as

$$\mathrm{H} = -\Delta g_k \beta / (\Delta g_k - 41.85 \Delta\rho_0 \beta) \tag{8}$$

Δgk is the residuel anomaly value at the kth station on the profile. The difference (E_k) between the residual and the calculated anomalies at any stations is attributed to the error in the depth of the interface at that station. This difference is used to correct the depth using the formula

$$H_k = H_k + \frac{\beta E_k}{41.85 \cdot \Delta\rho_0 - E_k} \tag{9}$$

The relationship between the near surface density contrast $\Delta\rho_0$ and the weighted density constant $\overline{\Delta\rho}$ of a basin determines the behavior of the curve describing the density in a basin.

GEOLOGY AND TECTONICS OF WESTERN TURKEY

Western Turkey is part of a zone of distributed extensional deformation which includes Greece, Yugoslavia, Bulgaria and Albania. It is one of the most rapidly extending areas on the continents and, as such, has high seismicity and a landscape which is controlled to a large degree by the active normal faulting. Extension in the Aegean area is thought to have started sometime in the middle Miocene (Mercier *et al*. 1979, 1987, 1989) related to the development of the Hellenic arc. However seismic evidence (Jackson and McKenzie, 1988) and an interpretation of paleomagnetic data (Kissel and Laj, 1988) suggest that most of the extension has occurred in the last 5 Ma. The geomorphology of western Turkey is dominated by a series of approximately E-W trending grabens. In some cases they lie entirely onshore, while elsewhere the hanging wall is now underwater. The Gediz and Büyük Menderes graben are two of the major onshore graben in western Turkey while the Gulf of Kerme, which is bounded on the north side by a normal fault, is now underwater.

The Gediz valley comprises one of the major E-W trending graben in western Turkey. It is about 150 km long and is bounded by a normal fault system, part of which moved in a major earthquake in 1969, near Alaşehir (Eyidoğan and Jackson, 1985). There is a large sedimentary cover between the two faults. Further, it seems that the southern fault system must have been the important fault in the past. The Gediz graben becomes generally narrower towards the east and the valley floor rises gradually. These features are consistent with the overall structure of western Turkey which suggests that the greatest stretching is towards the west and so the eastern end of the graben is probably relatively poorly developed. As the sediments are continental it is difficult to correlate between different sections along the graben.

The valley of Büyük Menderes river, like that of the Gediz, is one of the major E-W trending graben in western Turkey. The structure of the Büyük Menderes is like that of the Gediz graben. It is about 150 km long, about 10-20 km wide, bounded by a normal fault system which has broken along some part of its length in recent earthquakes. In another part of the graben, there are two sets of faults. Many of the features observed in the Gediz graben are also present in the Büyük Menderes. These two grabens pose some differences. The main fault bounding the Büyük Menderes graben is on the north side of the valley whereas that in the Gediz graben is on the south side. Further, the Büyük Menderes has a distinct subsidiary graben which joins the main valley (Fig.2).

MODELLING OF SEDIMENTARY BASINS

Sedimentary basins, with a density contrast varying with depth, can be modelled from their gravity anomalies using the concept of hyperbolic density contrast using the method of Bott (1960). At first, the inversion method was applied to the gravity anomalies over models of five layers for the broad and narrow basin types (Fig. 3-4). A seven layers model for an asymmetrical trapezoidal basin model is shown in figure 5. The results, which were obtained at the end of the inversion procedure using the parameter values as β, $\Delta\rho_0$ and H for the related basin models are shown in figures. 6, 7 and 8. The results, i.e. the depths to the basement for the model basins, show that they were determined very accurately. Then, the method is applied to the gravity profiles crossing the Gediz and Büyük Menderes grabens.

GRAVITY DATA OF WESTERN TURKEY AND ITS ANALYSIS

Bouguer Gravity Data of Western Turkey

Generally, negative regional Bouguer gravity anomalies are present in western Turkey. It is pointed out that

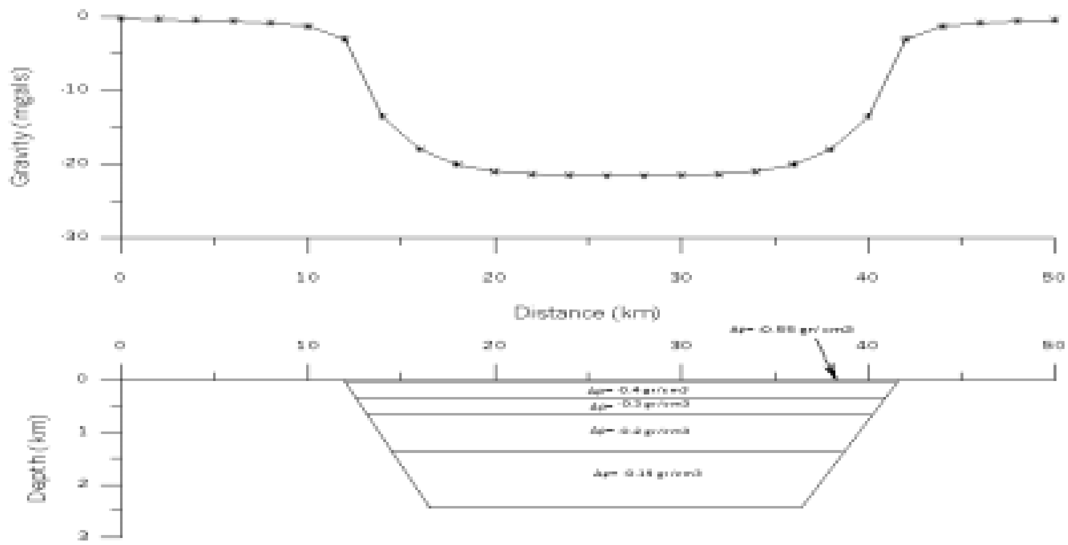

FIG. 3. The broad basin model and the gravity anomaly which is produced.

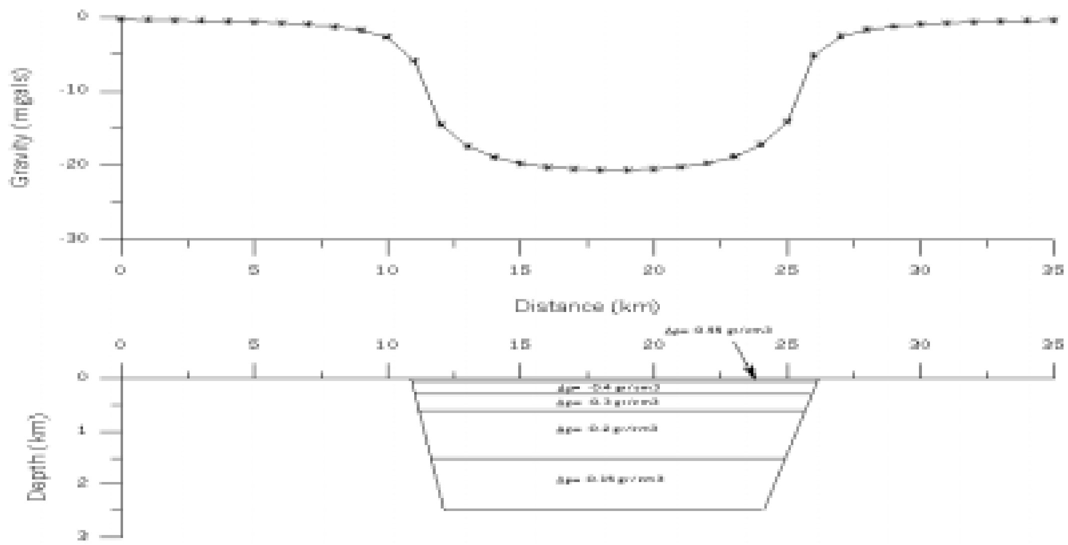

FIG. 4. The narrow basin model and the gravity anomaly which is produced.

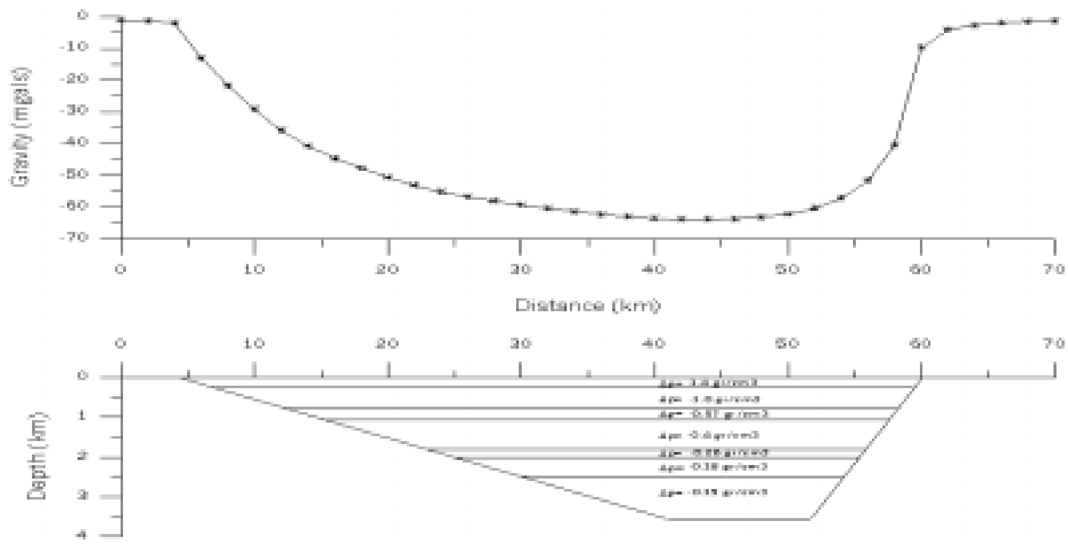

FIG. 5. The asymetrical trapezoidal basin model along its gravity anomaly.

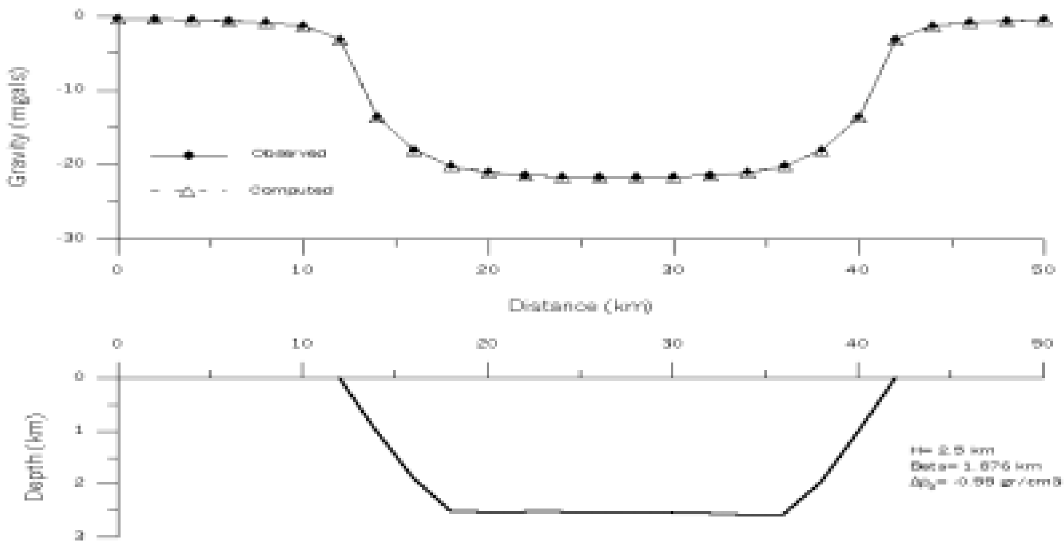

FIG. 6. The inversion result for the broad basin model.

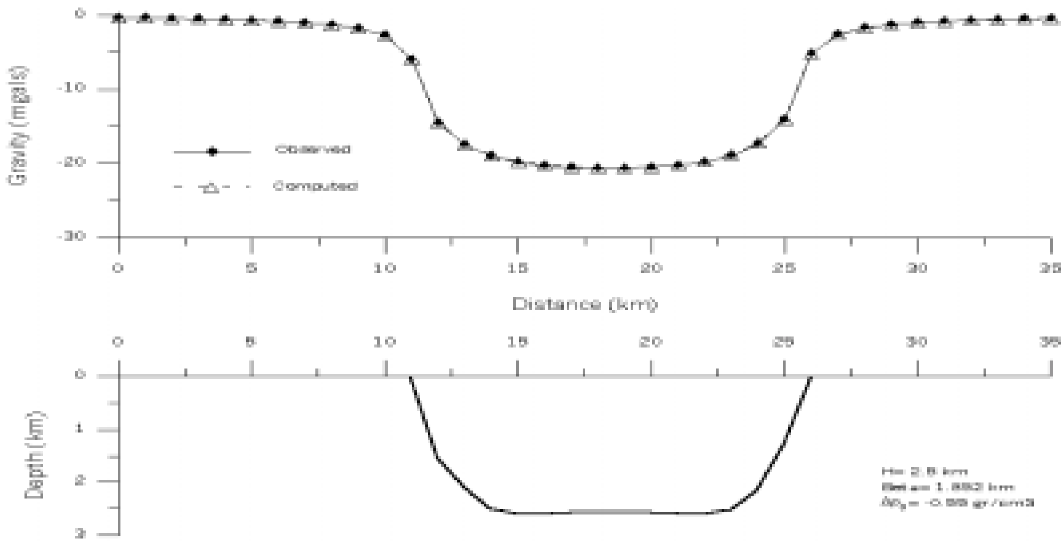

FIG. 7. The inversion result for the narrow basin model.

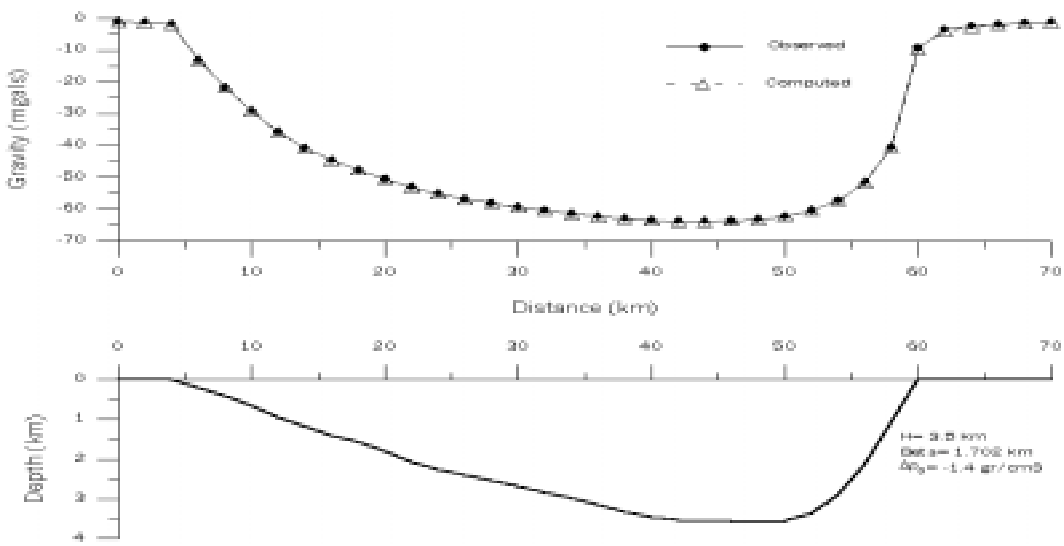

FIG. 8. The inversion result of the asymetrical trapezoidal basin model.

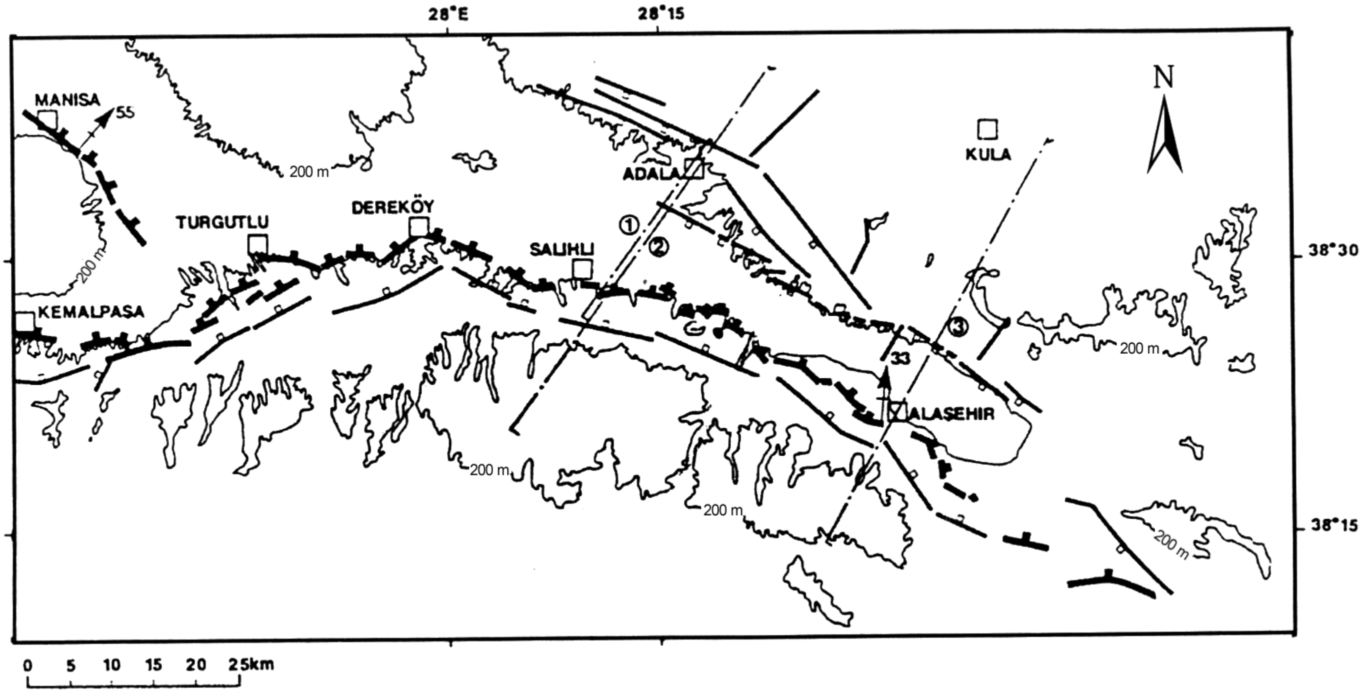

FIG. 9. The dashed lines show the profiles across the Gediz graben. The gravity anomaly along the profiles were interpreted (Paton, 1992).

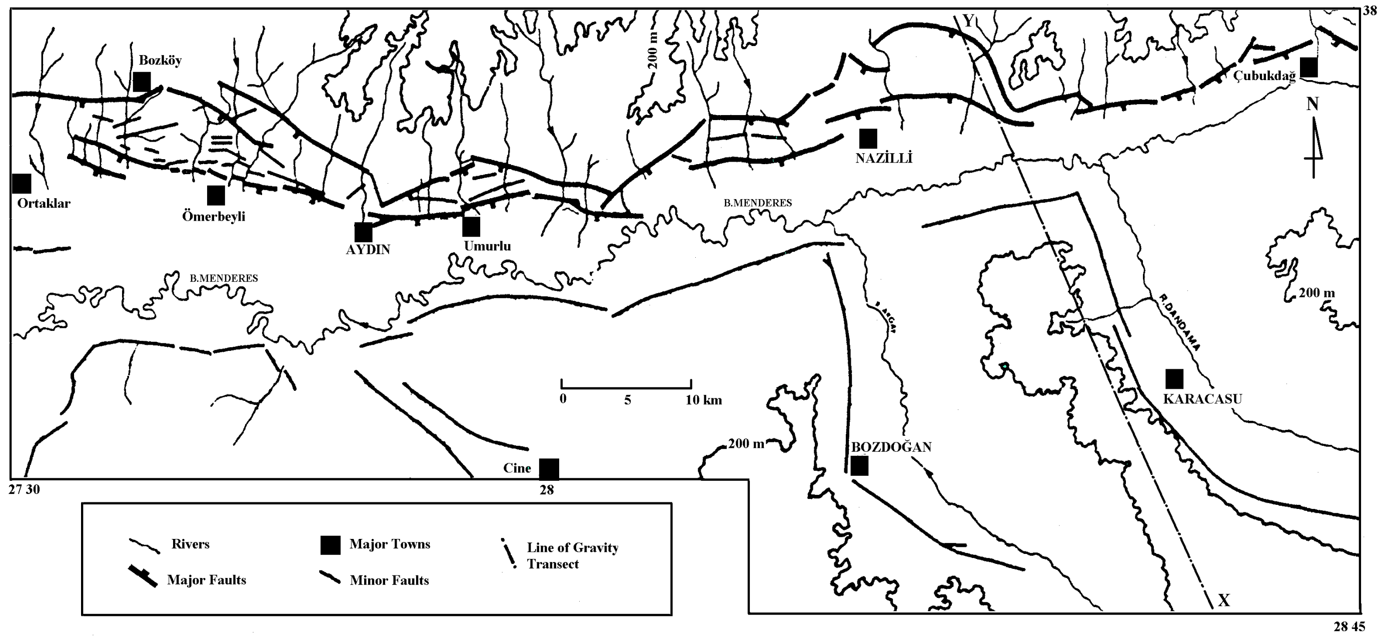

FIG. 10. The dashed line shows the profile across the Büyük Menderes graben (Paton, 1992).

regional negative gravity anomalies in continental stress field are created as a result of the common effect of a zone of low density and of thin oceanic crust (Darracott *et al.*, 1972 and Condie, 1976). The Gediz and Büyük Menderes grabens have generally E-W trends. Thus, large areas show negative Bouguer gravity anomalies. Positive Bouguer gravity anomaly observed at the west of Menderes massif is interpreted as a continuation of positive anomaly belt identified as a concave side of island arc (Rabinowitz and Ryan, 1970, Özelçi, 1973). Similary, the negative anomaly belt towards to central Anatolia from the Denizli area is defined as the continuation relative negative anomaly belt of Crete identified as a convex side of the island arc. Increase in gradient from E to W can be related to the uplifted mantle. The anomalies related to regional structures have N-S and NE-SW trends and the anomalies related to residuel structures have E-W and NW-SE trends (Kaya, 1981, 1982).

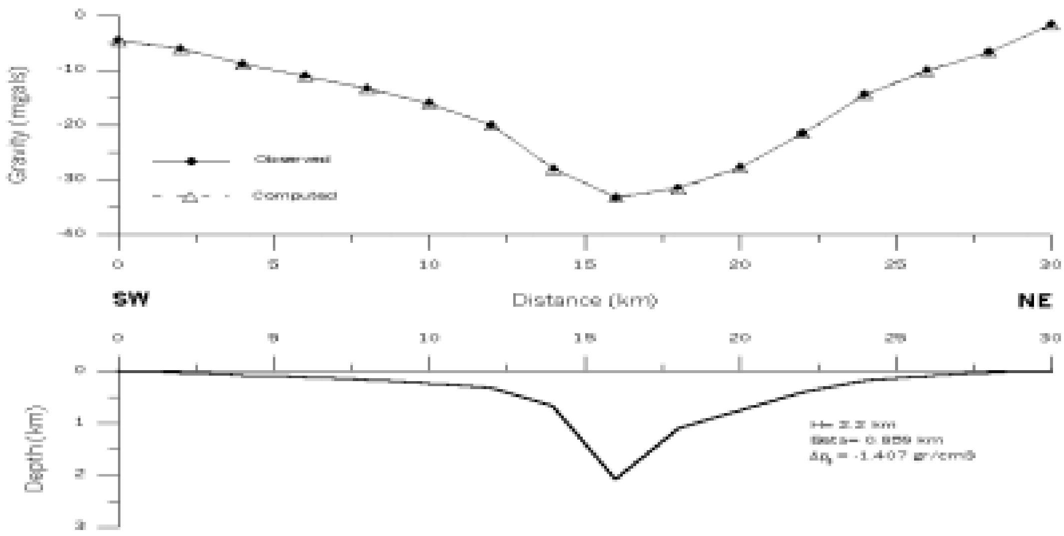

FIG. 11. The inversion result of the profile 2 ,which is seen Fig.9, in Gediz graben area.

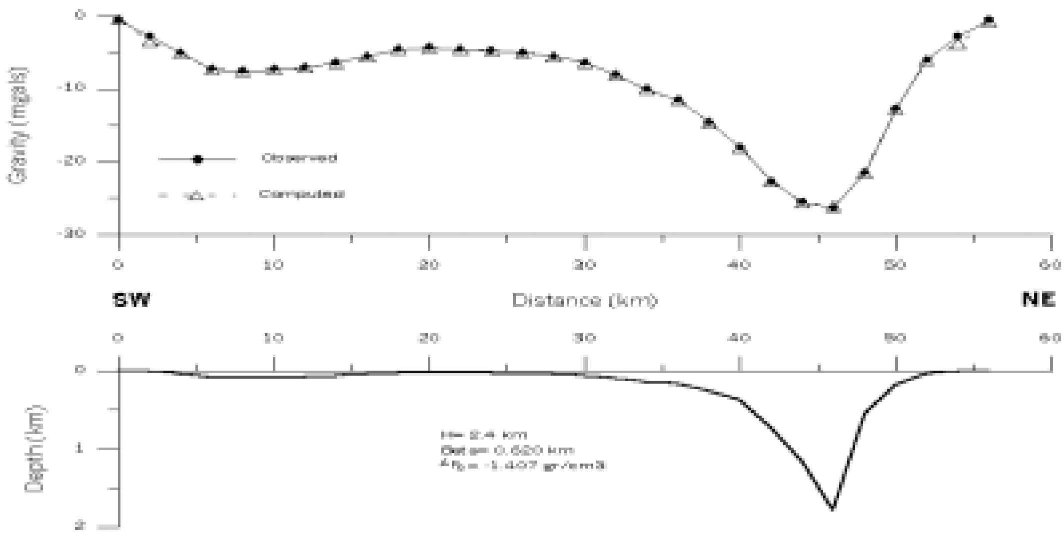

FIG. 12. The inversion result of the profile 3 ,which is seen Fig.9, in Gediz graben area.

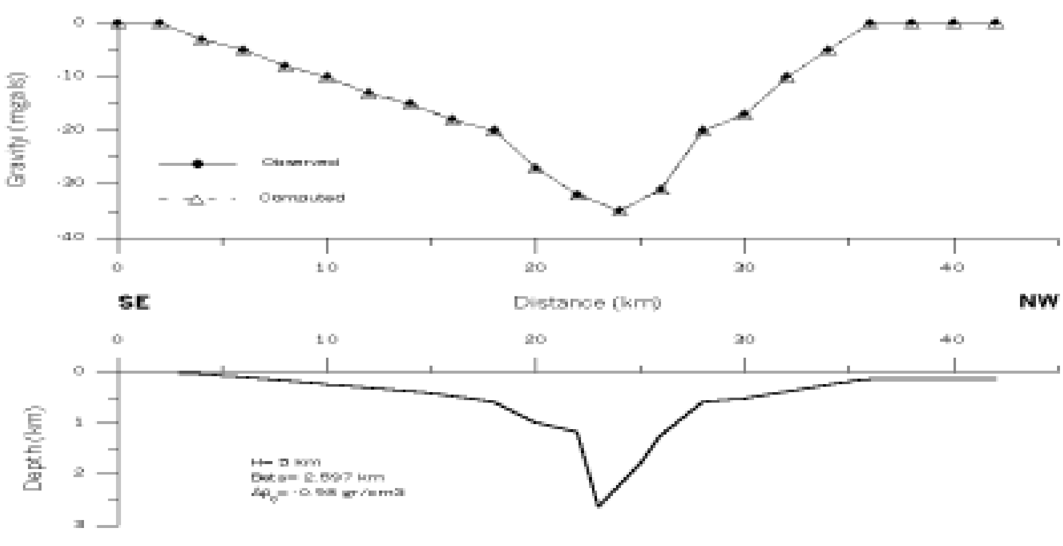

FIG. 13. The inversion result of the profile X-Y in Büyük Menderes graben area.

Analysis for the profiles of Gediz and Büyük Menderes Grabens

In the second stage of the application, the inversion method was applied to three gravity profiles which are taken from Paton (1992). The locations of the profiles are shown in Fig. 9 and Fig. 10. The values of β and $\Delta\rho_0$ were estimated by least squares fitting to the density-depth values. The information about the depths of the Gediz and Büyük Menderes grabens and the densities of the sedimentary fillings were obtained by the borehole data. The results of the study are given Fig. 11-12 and 13. The obtained results are compatible with the geological setting. The maximum depths of Gediz graben were inferred as 2 km for the profile 2 and 1.8 km for the profile 3. In the Büyük Menderes graben, The maximum depth obtained was 2.5 km along the x-y profile.

CONCLUSIONS

If a density cross-section of a basin is known from independent data such as density logs, core samples, or gravimetric logs, the effective density can be calculated. If the depth of a basin is known only at one point and no other information is available regarding the true density section, the effective density can be obtained from a basic formula. Determining the sedimentary thickness from gravity data, using the hyperbolic density function, is more realistic than other density functions. If the lithology and thicknesses of the formation, as well as densities, are known from borehole or other geophysical dataat any point in a sedimentary basin, the determination of basement depths under sedimentary cover can be made more accurate. The accuracy of the depth determination of basins from gravity data is quite adequate for the preliminary evaluation of oil and gas potential of an area and for the planning of seismic and borehole exploration programs.

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