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Research Article

Estimation of the Depth and Shape of the Source from Derivatives of Residual Gravity Data Using the Parametric Curves Technique: A Case Study from Erzincan-Çayırlı Region, Turkey

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Abstract
In this study, the parametric curves technique that estimates the shape and depth of a buried structure simultaneously, was applied to derivatives of residual gravity data. This method uses the origin and characteristic points of the profile data to establish a relationship between the shape and depth of the source. The first-order derivative of residual gravity data was used for buried sphere, horizontal cylinder, vertical cylinder and semi-infinite vertical dyke models, whereas second-order derivative of residual gravity data was used for vertical fault model. Besides, a software was developed to apply the method on synthetic and field data by using the .NET Framework 4.5 and C# language. This method was applied to five synthetic models and the shape factors were determined for each models. In addition to synthetic examples, a residual gravity map from Turkey was used to test the validity of the method on real data. Both proposed method and power spectrum method were applied on three profile data obtained from the study area and estimated depths were compared with each other. Finally, a 3D model of the Erzincan-Çayırlı Basin was created using the estimated depths.

Keywords: C#.NET, Depth estimation, Erzincan-Çayırlı Basin, Parametric curves, Residual gravity data, Shape factor

Parametrik Eğriler Tekniği Kullanılarak Rezidüel Gravite Verilerinin Türevlerinden Kaynağın Şekil ve Derinliğinin Belirlenmesi: Türkiye'de Erzincan-Çayırlı Bölgesi'nden Örnek Bir Çalışma

Öz
Bu çalışmada, gömülü bir yapının şekil ve derinliğini eş zamanlı olarak kestiren bir teknik olan parametrik eğriler tekniği, rezidüel gravite verilerinin türevlerine uygulandı. Bu metot, kaynağın şekil ve derinliği arasında bir ilişki kurmak için profil verilerinin karakteristik noktalarını ve orijinini kullanır. Düşey fay modeli için rezidüel gravite verisinin ikinci dereceden türevi kullanırken, gömülü küre, yatay silindir, düşey silindir ve yarı sonsuz düşey dayk modelleri için rezidüel gravite verisinin birinci dereceden türevleri kullanıldı. Ayrıca, C# dili ve .NET Framework 4.5 kullanılarak bir yazılım geliştirildi. Yöntem beş sentetik modele uygulandı ve her bir model için şekil faktörleri belirlendi. Sentetik örneklere ilave olarak, yöntemin geçerliliğini test etmek için Türkiye'den bir rezidüel gravite haritası kullanıldı. Çalışma alanından elde edilen üç profil verisine hem önerilen yöntem hem de güç spektrumu yöntemi uygulandı ve hesaplanan derinlikler birbiri ile karşılaştırıldı. Son olarak, hesaplanan derinlikler kullanılarak Erzincan-Çayırlı Baseni'nin üç boyutlu bir modeli oluşturuldu.

Anahtar Kelimeler: C#.NET, Derinlik kestirimi, Erzincan-Çayırlı Baseni, Parametrik eğriler, Rezidüel gravite verisi, Şekil faktörü

1. Introduction

One of the most important aims of the potential field geophysicists is to determine the depths and shapes of the source bodies that caused potential field anomalies. For this purpose, many numerical and graphical methods have been developed in the literature. Werner deconvolution (Werner, 1953), Kelvin transformation (Nedelkov and Burnev, 1962), Fourier transform (Odegard and Berg, 1965), power spectrum (Bhattacharyya, 1966; Spector and Bhattacharyya, 1966; Spector and Grant, 1970), Euler deconvolution (Thompson, 1982; Reid et al., 1990), Mellin transform (Mohan et. al.,1986), Local wavenumber (Thurston and Smith, 1997; Salem et al., 2005) and Tilt-depth (Salem et al., 2007)

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techniques are some of the traditional interpretation techniques.The parametric curves method was first developed by Abdelrahman and Hassanein (2000) to interpret the magnetic anomalies. Then, different methods derived from this technique were applied to potential field anomalies by many scientists (Abdelrahman et al., 2001; Essa, 2007, Abdelrahman et al., 2009; Babaee et al., 2011; Kara and Hoskan, 2016; Ekinci, 2016). Most of the techniques developed to interpret the potential field data are model-dependent methods and the accuracy of the obtained results depends upon the choice of the model that can best represent the subsurface structure. The parametric curves technique is a model-independent technique and simultaneously estimates the depths and shapes of the source bodies. In this study, parametric curves method was applied to derivatives of residual gravity data. Five synthetic models (sphere, horizontal cylinder, vertical cylinder, vertical fault and semi-infinite vertical dyke) were used to evaluate the performance of this method and, shape factors for each source models were determined. A code was written by using the .NET Framework 4.5 and C# language to develop both synthetic and field examples. In addition to residual gravity data, interpretation of magnetic anomalies can be done using this software. This method can be directly applied to anomaly in magnetic interpretation, whereas it can be applied to first or second-order derivative of the anomaly depending on the source model in gravity interpretation.

2. Materials and Methods

It was used the first or second-order derivatives of anomalies to interpret the residual gravity anomalies in this study. The first and second-order derivatives of the anomaly can be calculated using with the following central difference formulas:

$$\frac{\partial g}{\partial x} = g_x(x) \approx \frac{g(x+\Delta x) - g(x-\Delta x)}{2\Delta x} \quad (1)$$

$$\frac{\partial^2 g}{\partial x^2} = g_{xx}(x) \approx \frac{g(x+\Delta x) - 2g(x) + g(x-\Delta x)}{(\Delta x)^2} \quad (2)$$

where Δx is the sampling interval of the residual gravity anomaly. In the same way, the first-order differences can be calculated using the following equation for successive window lengths (s=1, 2, …, 5):

$$G_x(x,s) = \frac{G(x+s\Delta x) - G(x-s\Delta x)}{2s\Delta x} \quad (3)$$

In Fig. 1a, the black solid line (g) demonstrates the gravity anomalies belong to source models that give peak over the source center such as buried sphere, horizontal cylinder, vertical cylinder and semi-infinite vertical dyke. The blue solid line (g) shows the gravity anomaly of the vertical fault model. First-order derivative of the vertical fault model gives peak over the center of source. The dashed red line (G) is first or second-order derivatives of gravity anomalies depending on the source model. The differences calculated for successive window lengths are shown in Fig. 1b.

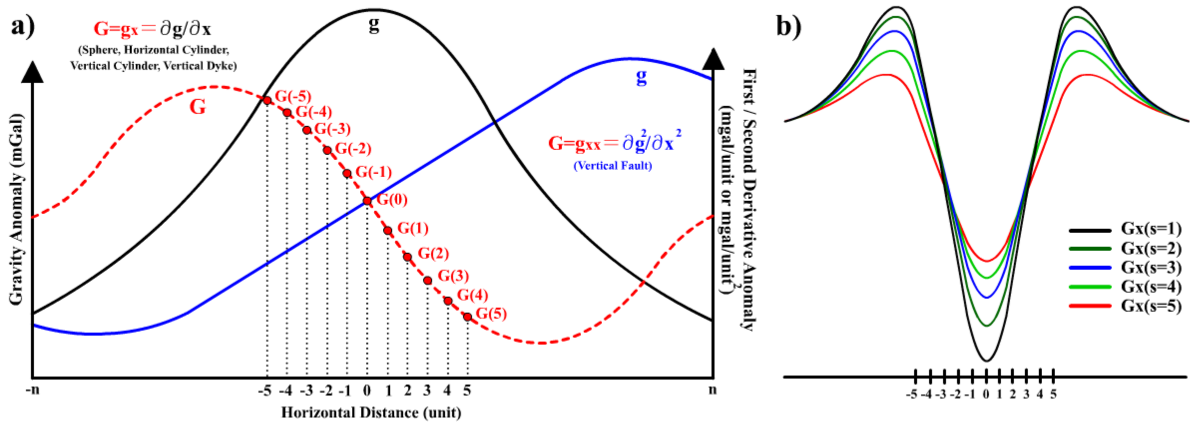

Fig. 1 a) Gravity anomalies and their first or second-order derivatives b) Differences for successive window lengths s=1, 2, …, 5.

Abdelrahman and Hassanein (2000) obtained the following simple equation to calculate the depths of source bodies:

$$z(s,q) = s\sqrt{\frac{1-4[F(s)]^{1/q}}{[F(s)]^{1/q}-1}} \qquad (4)$$

where

$$F(s) = \frac{G_x(-s)+G_x(+s)}{2G_x(0)} \qquad (5)$$

Finally, the depths can be calculated for each shape factor (q=0, 0.1, 0.2, …,3) using the Eq. (4). If the calculated depths are plotted against the shape factors, the intersection point of the parametric curves simultaneously gives the depth and shape of the source. The parametric curves may not intersect at any point for field data because it contains noise. In this case, the depth and shape factor are determined by using the closed area created by the parametric curves. In the synthetic applications, two parametric curves are enough to determine the depth and shape factor. In the case of use of the field data, more than two parametric curves should be used to accuracy of the parameter estimation because the field data contains noise. Besides, anomaly data should be filtered carefully and removed the noise before this method is applied. In particular, this filtering process is necessary in gravity interpretation because this method is used the first or second-order derivatives of the residual gravity data.

3. PRMCURV Graphical User Interface

PRMCURV-GUI is an open source software developed by using the Microsoft .NET Framework 4.5 and C# language. It was developed to interpret residual gravity data and magnetic data. C#.NET is an application development platform with important features such as object-oriented programming, file and database processing, graphical user interface components, ASP.NET web pages, multithreading, web services and many more. C# and .NET Framework can be used to solve problems in different engineering fields. PRMCURV-GUI allows to develop both synthetic and field applications. Its main menu, synthetic application and field application windows are shown in Fig. 2, Fig 3 and Fig. 4, respectively.

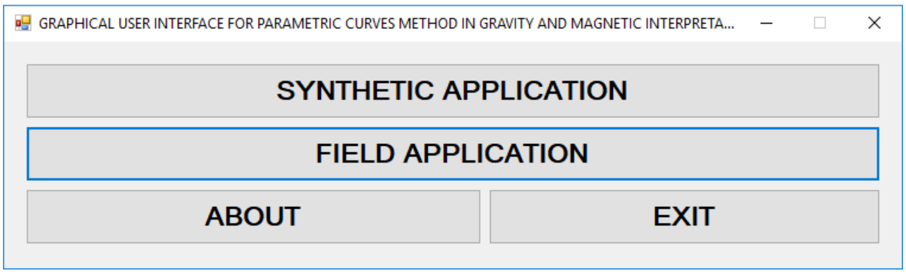

Fig. 2. Screenshot of PRMCURV-GUI main menu window.

In the “Synthetic Application Window", a source type should be selected and entered the number of observation points, sampling interval, density difference, origin point (observation point number in the source center), depth and radius or thickness parameters to generate a synthetic model. PRMCURV-GUI calculates and plots the residual gravity anomaly, its first or second-order derivative, differences and parametric curves.In the field application window, the field data should be loaded by clicking the “Load Data” button. If the residual gravity anomaly of vertical fault is used, it should be selected the “second-order derivative” radio button in the “use for interpretation” panel. For residual gravity data of sphere, horizontal cylinder, vertical cylinder and semi-infinite vertical dyke, it should be selected the “first-order derivative” radio button. The “anomaly” radio button can also be used to magnetic interpretation.

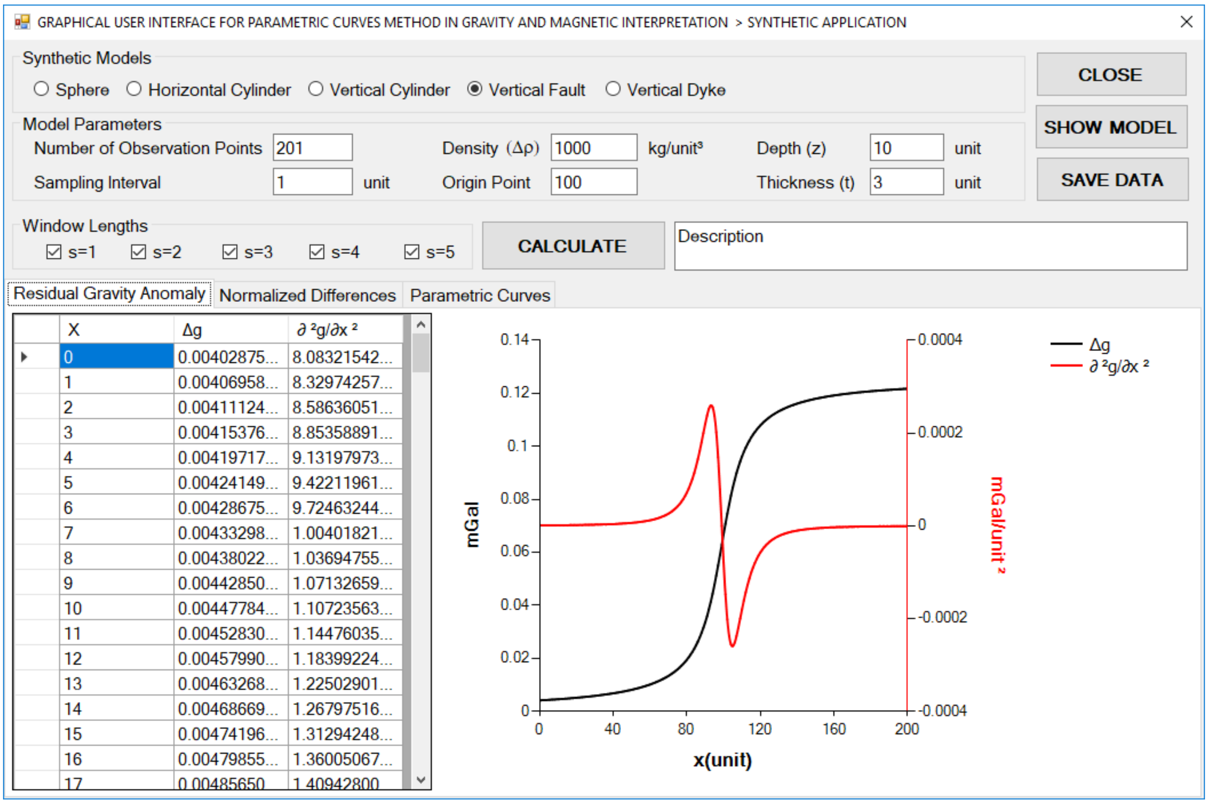

Fig. 3. Screenshot of synthetic application window.

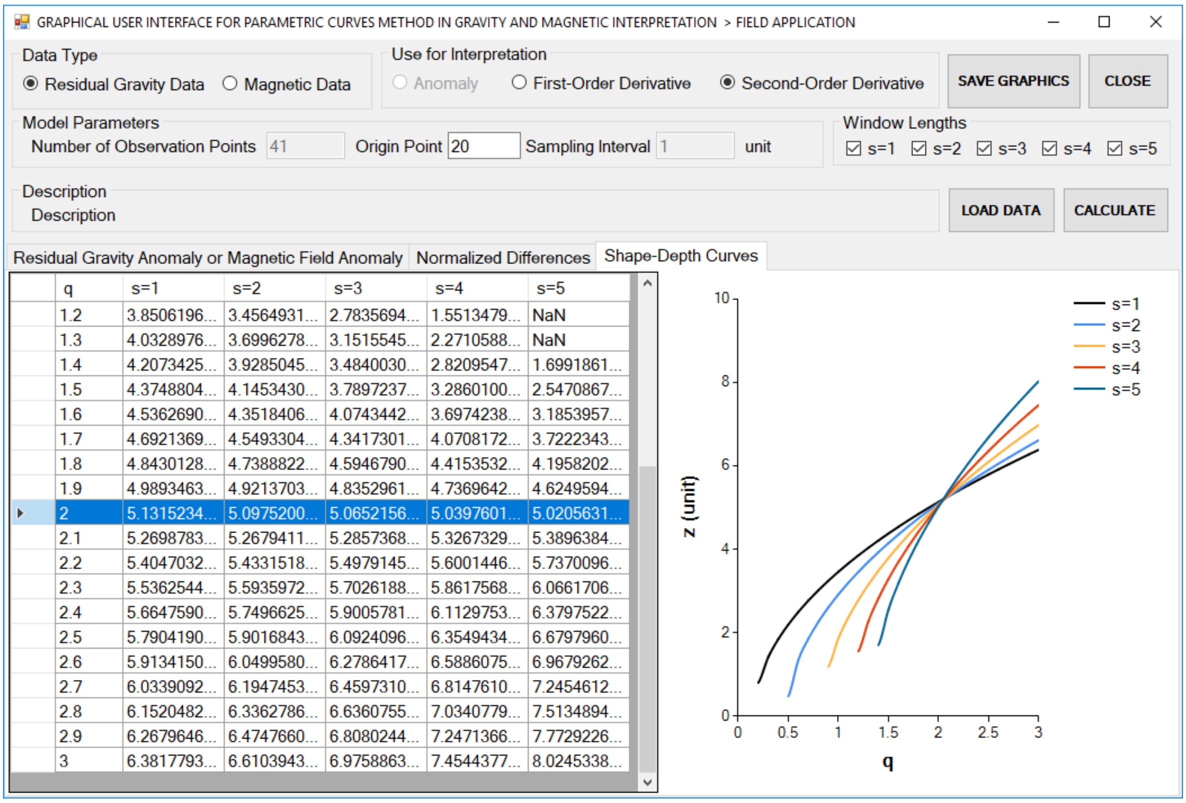

Fig. 4. Screenshot of field application window.

4. Synthetic Model Experiments

It was computed five synthetic residual gravity anomalies for buried sphere, horizontal cylinder, vertical cylinder, vertical fault and semi-infinite vertical dyke models, and the shape factors were determined for each models. The synthetic model parameters are shown in Fig. 5a, Fig. 6a, Fig. 7a, Fig. 8a and Fig. 9a. Residual gravity anomalies and its first or second-order derivatives are shown in Fig. 5b, Fig. 6b, Fig. 7b, Fig. 8b and Fig. 9b. The theoretical derivation formulas are used to calculate the first and second-order derivatives of residual gravity profile data in the synthetic applications. The parametric curves calculated for successive window lengths are shown in Fig. 5c, Fig. 6c, Fig. 7c, Fig. 8c and Fig. 9c. When the intersection points of the parametric curves are examined, it can be easily seen that the calculated source depths are compatible with the model depths.

Table 1. Shape factors for some source models. FHD and SHD are the first-order and second-order horizontal derivatives of residual gravity anomaly, respectively.

Source Models	Shape Factors
Semi-infinite vertical dyke (FHD)	1.0
Vertical cylinder (FHD)	1.5
Horizontal cylinder (FHD)	2.0
Vertical fault (SHD)	2.0
Sphere (FHD)	2.5

Table 1 summarizes the calculated shape factors for five source models. In addition, the method was applied to vertical fault anomaly shown in Fig. 8b, using the numerical derivation formula given by Eq. 2. The average depth and shape factor were estimated 5.071 and 2.0, respectively. The calculated depths versus the shape factors (q=0, 0.1, …, 3) for successive window lengths (s=1, 2, …, 5) are shown in Fig. 10.

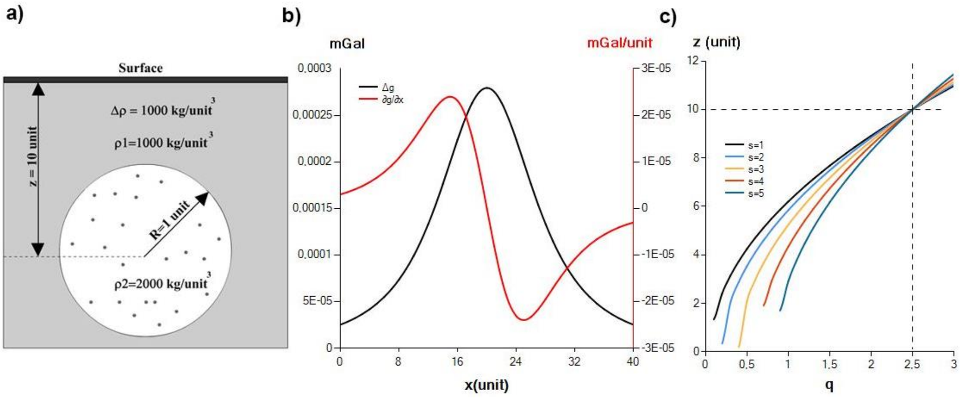

Fig. 5. a) Buried sphere model b) Gravity anomaly of model in (a) and its first-order derivative c) Parametric curves.

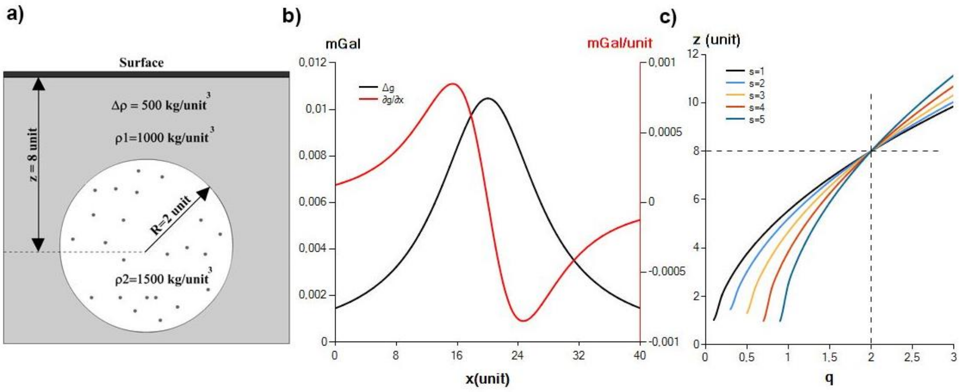

Fig. 6. a) Horizontal cylinder model b) Gravity anomaly of model in (a) and its first-order derivative c) Parametric curves.

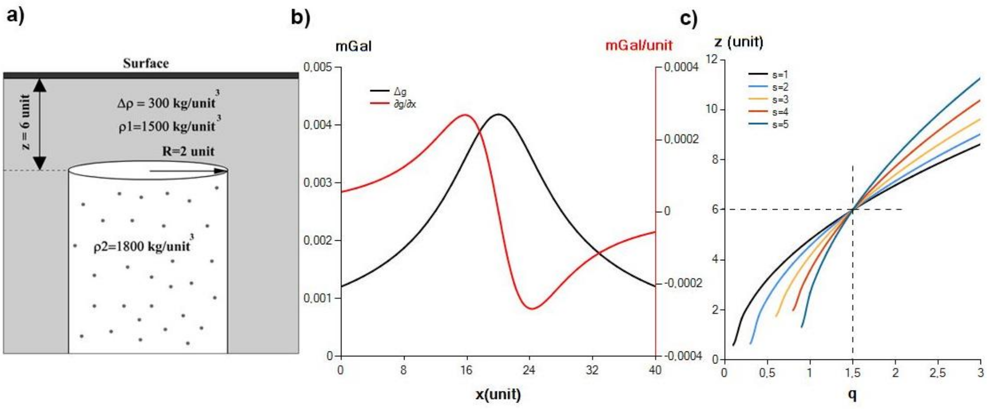

Fig. 7. a) Vertical cylinder model b) Gravity anomaly of model in (a) and its first-order derivative c) Parametric curves.

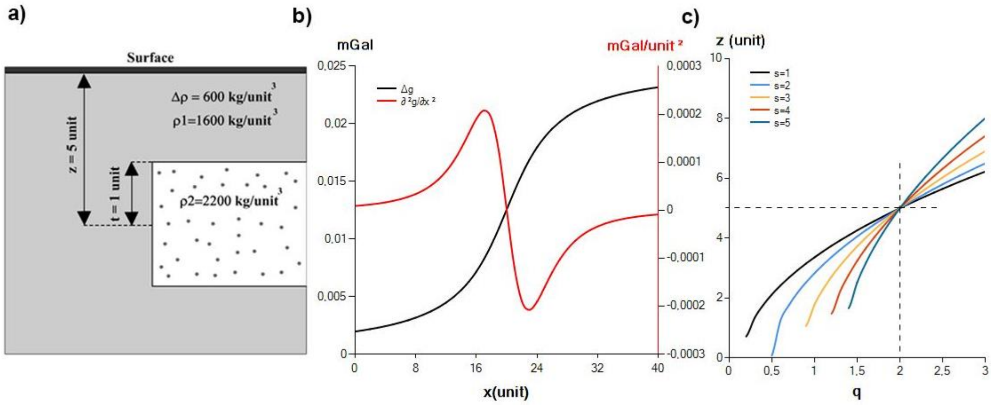

Fig. 8. a) Vertical fault model b) Gravity anomaly of model in (a) and its second-order derivative c) Parametric curves.

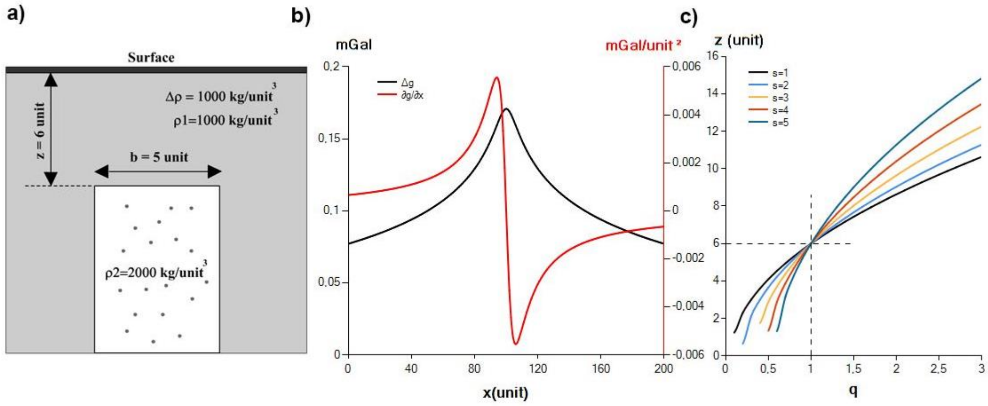

Fig. 9. a) Semi-infinite vertical dyke model b) Gravity anomaly of model in (a) and its first-order derivative c) Parametric curves.

q	s=1	s=2	s=3	s=4	s=5
1,2	3,8506196...	3,4564931...	2,7835694...	1,5513479...	NaN
1,3	4,0328976...	3,6996278...	3,1515545...	2,2710588...	NaN
1,4	4,2073425...	3,9285045...	3,4840030...	2,8209547...	1,6991861...
1,5	4,3748804...	4,1453430...	3,7897237...	3,2860100...	2,5470867...
1,6	4,5362690...	4,3518406...	4,0743442...	3,6974238...	3,1853957...
1,7	4,6921369...	4,5493304...	4,3417301...	4,0708172...	3,7222343...
1,8	4,8430128...	4,7388822...	4,5946790...	4,4153532...	4,1958202...
1,9	4,9893463...	4,9213703...	4,8352961...	4,7369642...	4,6249594...
2	5,1315234...	5,0975200...	5,0652156...	5,0397601...	5,0205631...
2,1	5,2698783...	5,2679411...	5,2857368...	5,3267329...	5,3896384...
2,2	5,4047032...	5,4331518...	5,4979145...	5,6001446...	5,7370096...
2,3	5,5362544...	5,5935972...	5,7026188...	5,8617568...	6,0661706...
2,4	5,6647590...	5,7496625...	5,9005781...	6,1129753...	6,3797522...
2,5	5,7904190...	5,9016843...	6,0924096...	6,3549434...	6,6797960...
2,6	5,9134150...	6,0499580...	6,2786417...	6,5886075...	6,9679262...
2,7	6,0339092...	6,1947453...	6,4597310...	6,8147610...	7,2454612...
2,8	6,1520482...	6,3362786...	6,6360755...	7,0340779...	7,5134894...
2,9	6,2679646...	6,4747660...	6,8080244...	7,2471366...	7,7729226...
3	6,3817793...	6,6103943...	6,9758863...	7,4544377...	8,0245338...

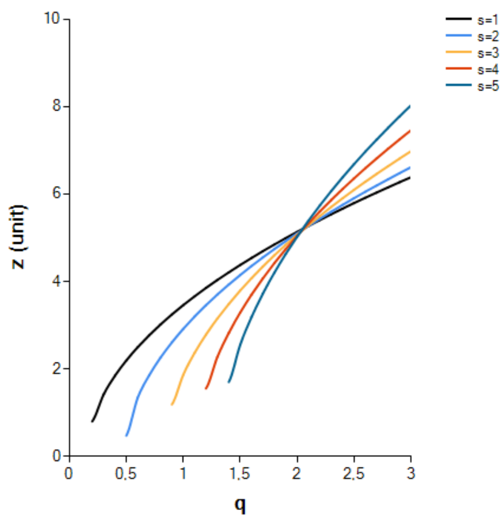

Fig. 10. For model in Fig. 8, computed parametric curves using the numerical derivation, and their numerical values.

5. Real Data Example

The study area is northeast of Erzincan city in Turkey and there are very important fault zones and basins in this area (Fig.11). The Erzincan Basin extending in the northwest-southeast direction is one of the most important basins in the region. It has been evaluated in detail by Akpınar et al. (2016). The other important tectonic structure in the area is Erzincan-Çayırlı Basin located at northeast of the Erzincan Basin. North

Anatolian Fault Zone (NAFZ) and North-East Anatolian Fault Zone (NEAFZ) are located in the south and north of this basin, respectively (Fig. 11).

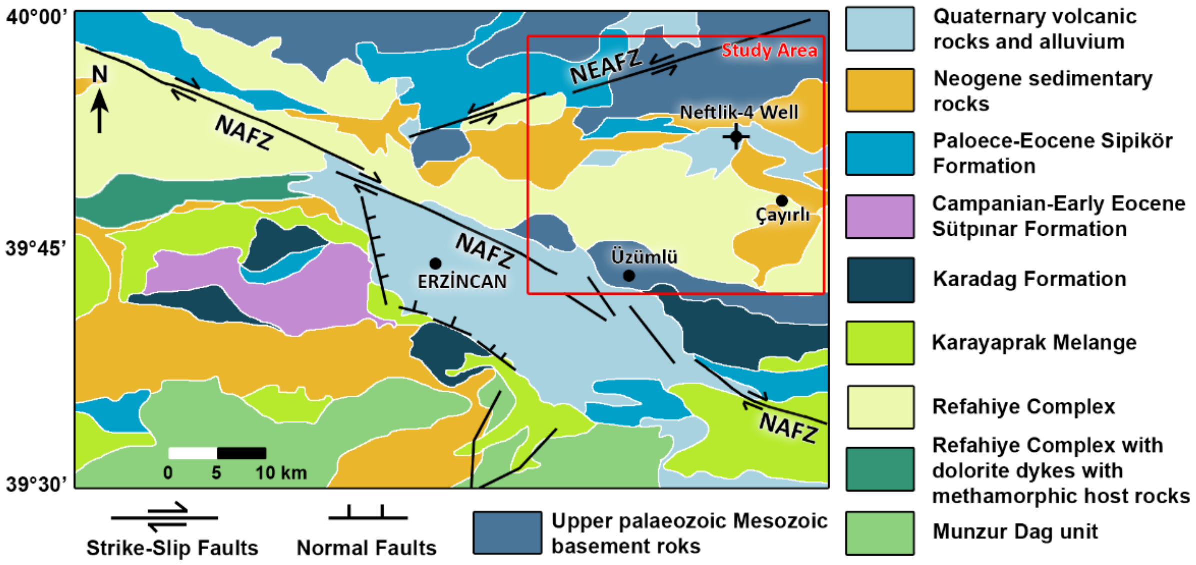

Fig. 11. Simplified geological map of the study area and its surroundings (modified from Rice et al., 2009).

The residual gravity data in Fig. 12 was collected by General Directorate of Mineral Research and Exploration. The AA', BB' and CC' profiles, sampled at intervals of 0.5 km and obtained from the residual gravity anomaly map belong to Erzincan-Çayırlı area, are 20 km, 21 km and 23 km lengths, respectively (Fig. 13a, 14a and 15a). There is a well of 2050 m length, called as Neftlik-4, drilled by General Directorate of Mineral Research and Exploration, in the region. The drilling data obtained from Neftlik-4 well show that it could not be reached the basement rock at 2050 m (Demirmen, 1965).

Table 2. The estimated depths for AA', BB' and CC' profiles.

Profile	Proposed method	Power spectrum method
AA'	1.291 km	1.246 km
BB'	2.262 km	2.278 km
CC'	2.299 km	2.312 km

As shown in Fig. 12, there are positive and negative anomalies in the southwest and northeast of the study area. In a previous study in the region, the maximum depth of the basin causing the negative anomaly in the northeast of the study area was estimated to be 2261 m using the quadratic density function (Tan, 2008).

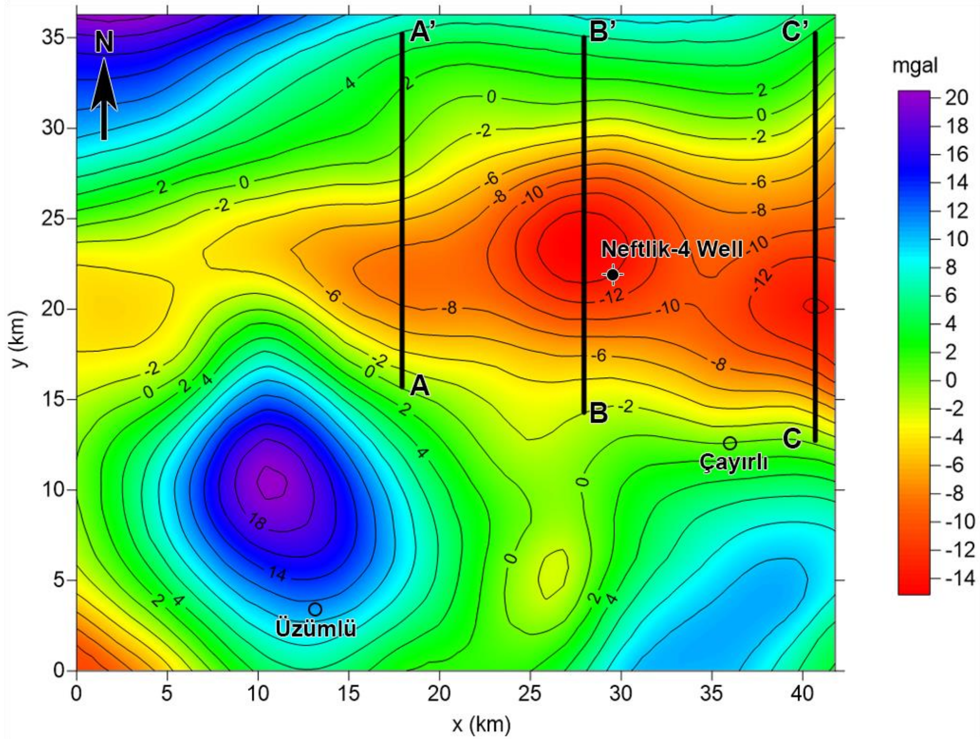

Fig. 12. Residual gravity anomaly map of Erzincan-Çayırlı Region in Turkey and AA', BB' and CC' profiles.

As shown in Fig. 13b, 14b and 15b, the depths estimated from AA', BB' and CC' profiles are 1291 m, 2262 m and 2299 m, respectively. In field applications, the parametric curves may not always intersect at single point. In such cases, the center of the closed area between the parametric curves is used to determine the depth and shape of the source (Fig. 13b). In addition, the power spectrum technique was applied on each profile and obtained depths were presented in Table 2. The Matlab code written by Oruç (2013) was used to obtain the power spectrums of profile data (Fig. 13c, 14c and 15c). Finally, the 3D model of Erzincan-Çayırlı Basin was created based on the depths obtained for each profiles (Fig. 16).

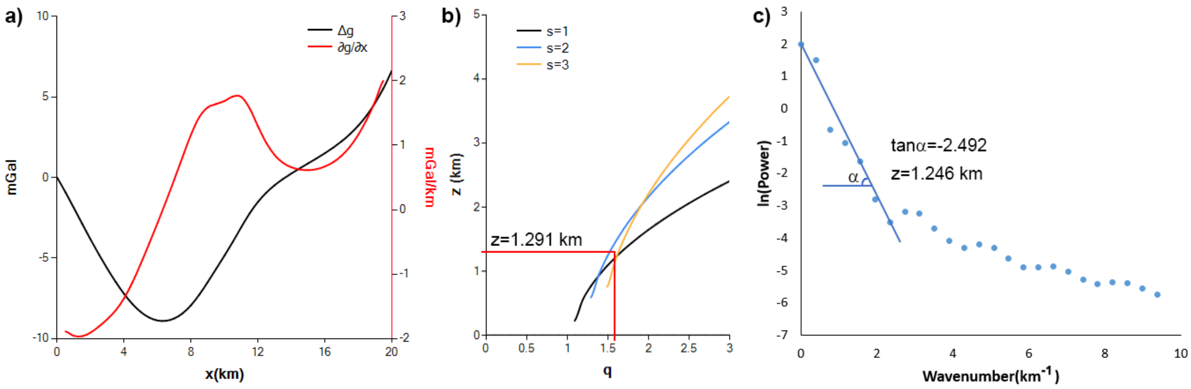

Fig. 13. a) AA' profile data (black line) and its second-order derivative (red line) b) Parametric curves. c) Power spectrum of AA' profile

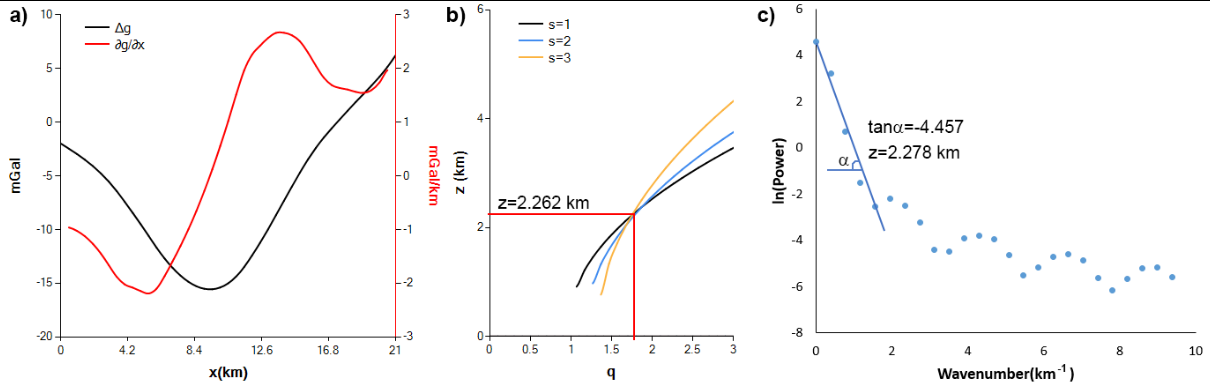

Fig. 14. a) BB' profile data (black line) and its second-order derivative (red line) b) Parametric curves. c) Power spectrum of BB' profile

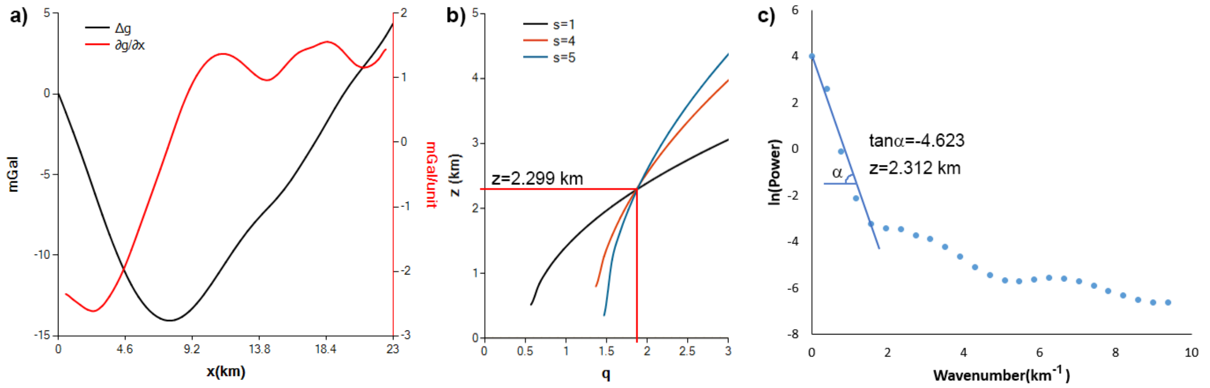

Fig. 15. a) CC' profile data (black line) and its second-order derivative (red line) b) Parametric curves. c) Power spectrum of CC' profile

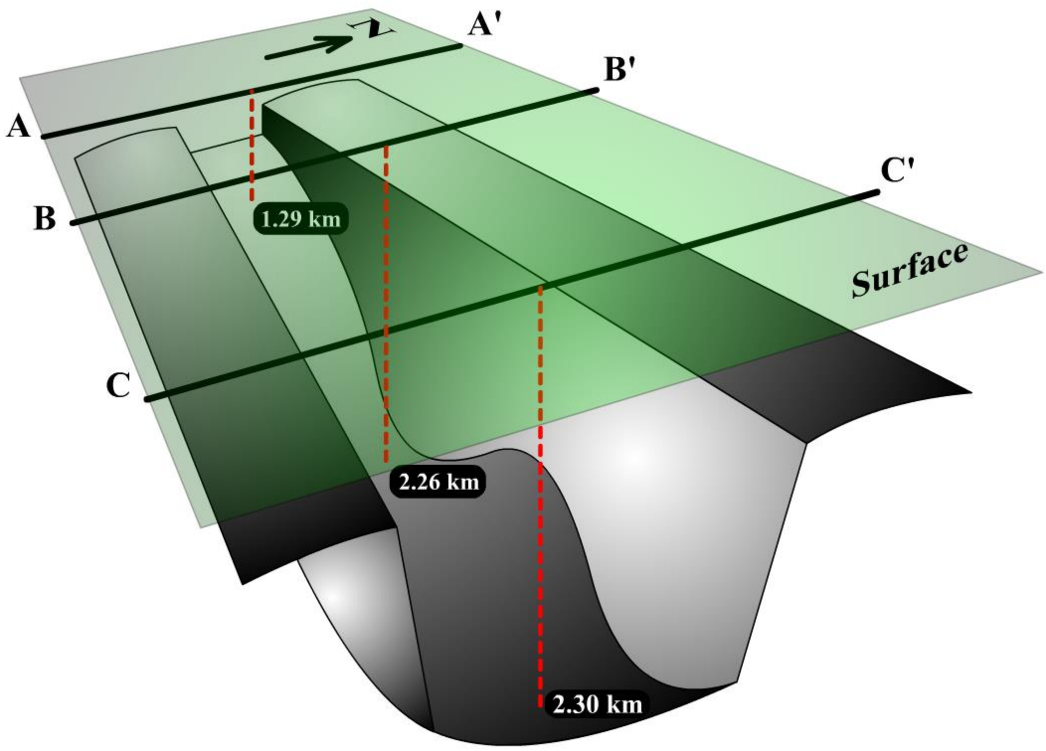

Fig. 16. a) 3D model of Erzincan-Çayırlı Basin.

6. Conclusions

The parametric curves technique was applied to derivatives of residual gravity data. The shape factors were calculated by using the synthetic residual gravity data belong to buried sphere, horizontal cylinder, vertical cylinder, vertical fault and semi-infinite vertical dyke models. It was shown that the parametric curves method performed well performance on both synthetic and field data. In the case study, this method was applied to three profile data obtained from the residual gravity data of Erzincan-Çayırlı region in Turkey and, the depths of the Erzincan-Çayırlı basin for AA’, BB’ and CC’ profile data were estimated to be 1291 m, 2262 m and 2299 m, respectively. To test the accuracy of the estimated depths, power spectrum technique was applied on each profile data and it was seen that the results were consistent with each other. Finally, the three-dimensional model of the Erzincan-Çayırlı Basin was created based on the estimated depths using the proposed method. In addition, a user-friendly graphical user interface was developed to interpret the residual gravity data and magnetic data by using this method in a practical way. The program source code and executable file can be obtained from the corresponding author.

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