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SOFTWARE ARTICLE

CURVGRAV-GUI: a graphical user interface to interpret gravity data using curvature technique

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Abstract CURVGRAV-GUI is an open source software that was developed to interpret gridded gravity data by using curvature technique. It was developed using C# language with Microsoft.NET Framework 4.0. This program calculates the critical and extreme points, and estimates the depths of source bodies at this points. Besides, CURVGRAV-GUI processes gravity data by using minimum curvature, one of the attributes of curvature, and detects the subsurface lineaments. It is a user-friendly application that can display obtained solutions and gravity data thanks to image and scatter maps. CURVGRAV-GUI was designed to develop both synthetic and field applications. Additionally, the β constant, a parameter related to the source geometry, was examined for different source types such as sphere, horizontal and vertical cylinder and thin vertical fault. This program was tested by using two synthetic model applications. In the first synthetic model application, it was used a complex synthetic model consisting of three sphere and a horizontal cylinder located at the different depths. In the second synthetic model application, a graben model consisting of two thin vertical fault was used. Finally, the performance of the CURVGRAV-GUI was tested with using a real gravity data belonging to Kozakli-Central Anatolia region, Turkey. Very successful results were obtained for both synthetic and field data. Earth scientist can use CURVGRAV-GUI for educational experiments.

Keywords C#.Net · Curvature technique · Edge detection · Depth estimation · Interpretation · Gravity anomaly

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Introduction

The main objective in the interpretation of potential field data is to determine the locations and depths of source bodies caused the potential field data. For this purpose, many techniques were developed such as horizontal gradient magnitude (Grauch and Cordell 1987), total horizontal derivative (Cordell 1979), local wavenumber (Thurston and Smith 1997; Salem et al. 2005), tilt angle (Miller and Singh 1994; Verduzco et al. 2004) and Euler deconvolution (Thompson 1982). The techniques are based on horizontal and vertical gradient of potential field data. Curvature technique also uses the second order partial derivatives of potential field data. Hansen and deRidder (2006) first applied this approach for linear feature analysis on aeromagnetic data. This method was applied on gravity data using special functions by Phillips et al. (2007). In addition, Barraud (2013) used this method for geometrical analysis and depth estimation by using gravity gradient data.

In this paper, a visual program CURVGRAV-GUI was developed by using C# language and. NET Framework 4.0. Microsoft.NET was designed by a team led by Microsoft to create a specific language for the. NET Framework. C# language was derived from C and C++ languages. It is an application development platform with important features such as object-oriented programming, strings, properties and graphics, graphical user interface components, exception handling, multithreading, ASP.NET web pages, web services, file processing and database processing.. NET Framework is a good environment to solve problems related to the earth sciences and supports the development and execution of highly distributed component based applications. Scientist can use all the features of C# and. NET Framework to solve different types of scientific problems.

CURVGRAV-GUI calculates the second order partial derivatives of gravity data, and generates the curvature matrix for each data points, then calculates the eigenvalues and eigenvectors of curvature matrices. It calculates the critical and extreme points, and estimates the depths of source bodies at this points by using the eigenvalues and eigenvectors. CURVGRAV-GUI can display the anomalies and obtained solutions utilizing the image and scatter maps. These maps were drawn with using Oxyplot that is an open source cross platform. NET plotting library and has the MIT license.

Theory

Anomalies that give directly peak over the source bodies causing the potential field data is ideal for curvature-based depth estimation. Gravity anomalies of the sphere, horizontal cylinder and vertical cylinder are such kind of anomalies. The 3D potential field anomaly of some underground structures that gives directly peak over the sources, is expressed by a special function as follows:

$$F(x,y,z) = \frac{A}{r^{\beta}} \tag{1}$$

where A and β are positive constants. The β is a parameter related to the characteristic of the source geometry called as structural index (Reid et al. 1990; Smith et al. 1998). The relation between the structural index and β parameter was examined by Phillips et al. (2007) for various anomaly types. The parameter r is the distance between the center of mass and the observation points and expressed by $r = (x-x_0)^2 + (y-y_0)^2 + (z-z_0)^2$. The parameters x, y and z are the observation points and zero-subscripted parameters (x_0, y_0 and z_0) are source location parameters.

Curvature is a two dimensional property of a curve and describes how bent a curve is at a particular point on the curve i.e. how much the curve deviates from a straight line at this point (Roberts 2001). The view of the curvature in a three-dimensional surface is shown in Fig. 1. A curve can be defined by mathematically cutting surface with a plane. In Fig. 1, X and Y represent horizontal axes and Z represents the depth axis. The intersection of two orthogonal planes drawn with blue lines describes the maximum K_{max} and minimum K_{min} curvatures. The red arrows represent vectors which are normal to the surface. If these vectors are parallel on flat or dipping surface, the curvature is zero. If these vectors deviate over anticlines, the curvature is positive. If they converge over synclines, the curvature is negative.

The curvature of a 1-D special function is expressed as follows (Thomas 1972):

$$K(x) = \frac{\partial^2 F/\partial x^2}{\left(1 + (\partial F/\partial x)^2\right)^{3/2}} \tag{2}$$

The curvature is formulated as follows at $x = x_0$ point and the point is the peak of the special function.

$$K(x_0) = -\frac{2\beta F(x_0)}{z^2} \tag{3}$$

For 2-D case, the following relationship can be used.

$$K_{-}(x_0,y_0) = -\frac{2\beta F(x_0,y_0)}{z^2} \tag{4}$$

where K_{-} is the most negative curvature (Roberts 2001). The depth of the source is calculated by using the following equation obtained by rearrangement of Eq. 4.

$$z = \sqrt{-\frac{2\beta F(x_0,y_0)}{K_{-}(x_0,y_0)}} \tag{5}$$

Critical points (ridge and trough) and extreme points (high, low and saddle) in the gravity data can be estimated by using an approach developed by Hansen and deRidder (2006). The general aim of this approach is to find the appropriate critical points near the 3 × 3 windows on the gridded potential field data and to calculate the depths at this points. Schematic representation of the grid points is given by Fig. 2. The critical points indicate the source locations and they locate within a box of size Δx by Δy around the center of the window. In order to estimate the source depths, the amplitudes at this critical points are used. A local quadratic surface is expressed as follows:

$$a + bx + cy + dx^2 + exy + fy^2 \approx F(x,y) \tag{6}$$

where a, b, c, d, e and f are the coefficients of the quadratic surface. The flow diagram used to estimation of critical points,

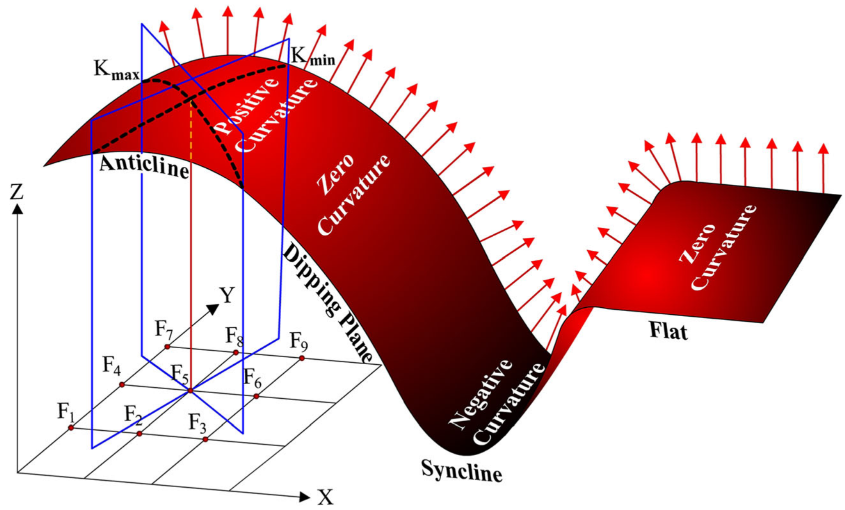


Fig. 1 Three-dimensional presentation of curvature and sign convention for curvature attributes (Modified from Roberts 2001)

extreme points and depths is shown in Fig. 3. The first step to apply the method is to compute the coefficients of the quadratic surface by using following equations along the 3 × 3 grid points.

$$
\begin{aligned}
a &= \frac{1}{9}\left[5F_{i,j} + 2\left(F_{i+1,j} + F_{i-1,j} + F_{i,j+1} + F_{i,j-1}\right) - \left(F_{i+1,j+1} + F_{i+1,j-1} + F_{i-1,j+1} + F_{i-1,j-1}\right)\right] \\
b &= \frac{1}{6\Delta x}\left[F_{i+1,j+1} + F_{i+1,j} + F_{i+1,j-1} - \left(F_{i-1,j+1} + F_{i-1,j} + F_{i-1,j-1}\right)\right] \\
c &= \frac{1}{6\Delta y}\left[F_{i+1,j+1} + F_{i,j+1} + F_{i-1,j+1} - \left(F_{i+1,j-1} + F_{i,j-1} + F_{i-1,j-1}\right)\right] \\
d &= \frac{1}{6\Delta x^2}\left[F_{i+1,j+1} + F_{i+1,j} + F_{i+1,j-1} + F_{i-1,j+1} + F_{i-1,j} + F_{i-1,j-1} - 2\left(F_{i,j+1} + F_{i,j} + F_{i,j-1}\right)\right] \\
e &= \frac{1}{4\Delta x\Delta y}\left[F_{i+1,j+1} + F_{i-1,j-1} - F_{i+1,j-1} - F_{i-1,j+1}\right] \\
f &= \frac{1}{6\Delta y^2}\left[F_{i+1,j+1} + F_{i,j+1} + F_{i-1,j+1} + F_{i+1,j-1} + F_{i,j-1} + F_{i-1,j-1} - 2\left(F_{i+1,j} + F_{i,j} + F_{i-1,j}\right)\right]
\end{aligned}
\tag{7}
$$

where Δx and Δy are grid intervals in x and y directions.

The orthogonal curvature matrix are created by using the coefficients of quadratic surface:

$$
\begin{pmatrix} \frac{\partial^2 F}{\partial x^2} & \frac{\partial^2 F}{\partial x \partial y} \\ \frac{\partial^2 F}{\partial x \partial y} & \frac{\partial^2 F}{\partial y^2} \end{pmatrix} = \begin{pmatrix} 2d & e \\ e & 2f \end{pmatrix} \tag{8}
$$

The eigenvalues of the curvature matrix are calculated by using the following equations:

$$
\lambda_+ = (d+f) + \sqrt{(d-f)^2 + e^2}, \lambda_- = (d+f) - \sqrt{(d-f)^2 + e^2} \tag{9}
$$

The eigenvalues are separated into two classes that are negative and positive. The negative eigenvalue λ_- is useful to estimate the source depth by using Eq. 5 and it is called as most negative curvature by Roberts (2001). Besides, the largest eigenvalues obtained from

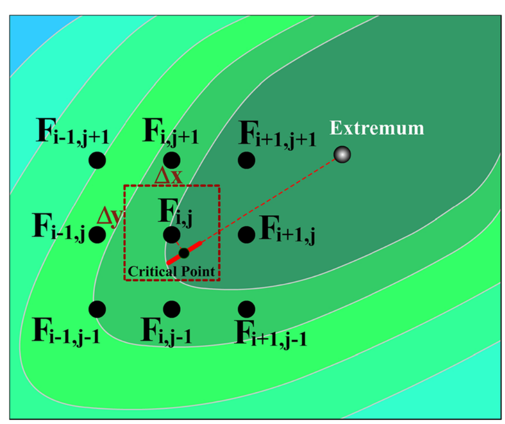
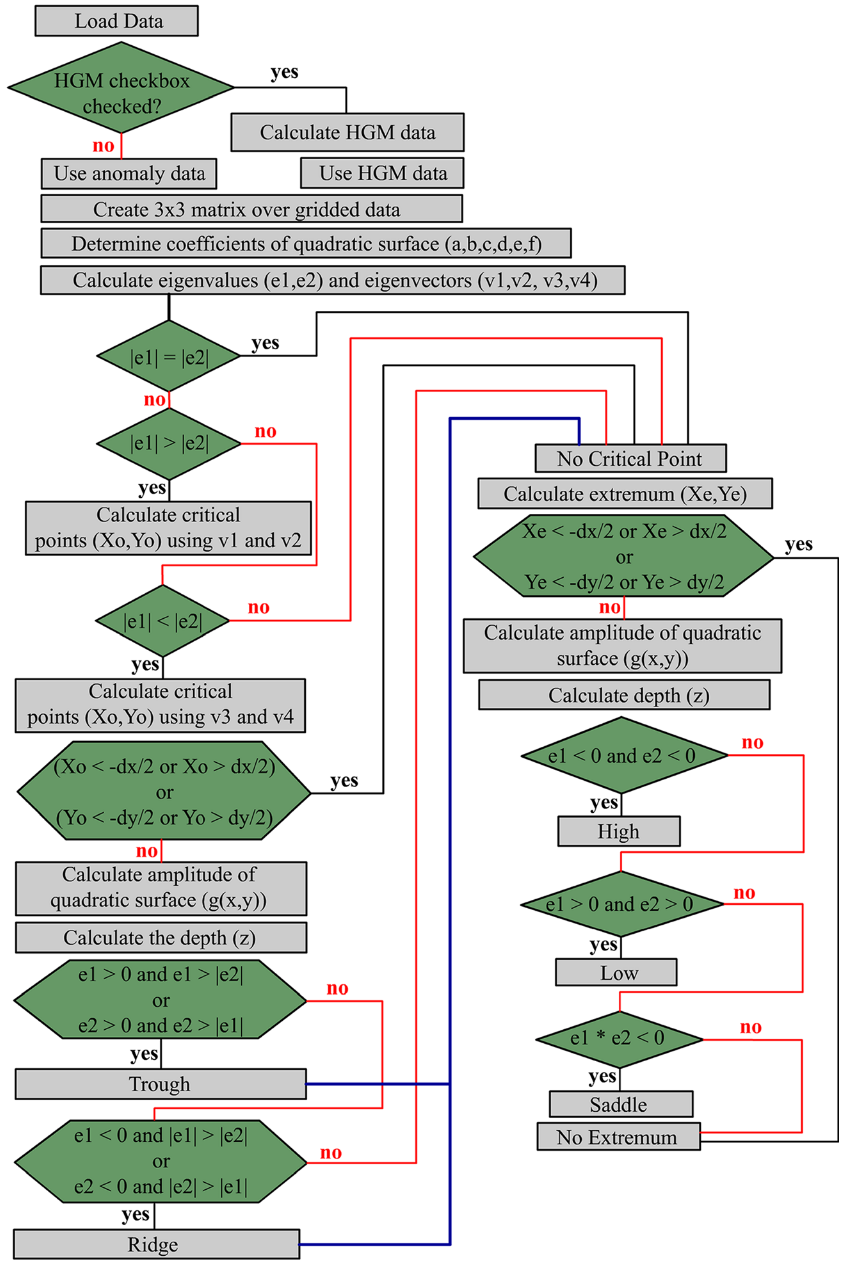


Fig. 2 Schematic representation of locations of grid points used to test a ridge crest in the special function F(x,y) near F(i,j) (Modified from Roberts 2001)

Fig. 3 Flow diagram of CURVGRAV-GUI for curvature based depth estimation



the calculated curvature matrices for the each grid points represent the edge of the source bodies caused by potential field data (Sertcelik and Kafadar 2012).

If the eigenvalues (λ_- and λ_+) are negative, the extreme point is a maximum, otherwise; it is minimum. If they have opposite signs, the extreme point is a saddle. The eigenvectors (v_x, v_y) associated with eigenvalues can be calculated by using the following equation:

$$\begin{pmatrix} 2d & e \\ e & 2f \end{pmatrix}\begin{pmatrix} v_x \\ v_y \end{pmatrix} = \lambda\begin{pmatrix} v_x \\ v_y \end{pmatrix} \tag{10}$$

The eigenvectors providing the following conditions are used to calculate the critical points:

$$\begin{pmatrix} v_x \\ v_y \end{pmatrix} = \left\{ \begin{matrix} \begin{pmatrix} 1 \\ (\lambda-2d)/e \end{pmatrix} or \begin{pmatrix} (\lambda-2f)/e \\ 1 \end{pmatrix} & if \quad e\neq 0 \\ \begin{pmatrix} 1 \\ e/(\lambda-2f) \end{pmatrix} & if \quad \lambda\neq 2f \\ \begin{pmatrix} e/(\lambda-2d) \\ 1 \end{pmatrix} & if \quad \lambda\neq 2d \end{matrix} \right\} \tag{11}$$

The coordinates of critical points (x_0, y_0) can be calculated using the eigenvectors and coefficients of quadratic surface:

$$x_0 = \frac{bv^2_{>x} + cv_{>x}v_{>y}}{2\left(dv^2_{>x} + ev_{>x}v_{>y} + fv^2_{>y}\right)},\quad y_0 = \frac{cv^2_{>y} + bv_{>x}v_{>y}}{2\left(dv^2_{>x} + ev_{>x}v_{>y} + fv^2_{>y}\right)} \tag{12}$$

The eigenvalue having the smallest magnitude (λ_+ in the ridge case) has an associated eigenvector $v_< = (v_{<x}, v_{<y})$ pointing in the direction of elongation of the quadratic surface. The eigenvalue having the largest magnitude (λ_- in the ridge case) has an associated eigenvector $v_> = (v_{>x}, v_{>y})$ pointing in the direction perpendicular to elongation of the quadratic surface (Phillips et al. 2007).

The coordinates of extreme points can be calculated using the coefficients of quadratic surface:

$$x_e = \frac{2fb-ce}{e^2-4df},\quad y_e = \frac{2cd-be}{e^2-4df} \tag{13}$$

The curvature technique uses Eq. (5) to estimate the depths at the critical and extreme points. The β constant must be known to estimate the depths. Sphere, horizontal cylinder and vertical cylinder give peak directly over the source. The same thing is not valid for fault anomalies (Fig. 4). In this study, the horizontal gradient magnitude of fault anomaly was used to apply the approach, because the HGM gives peak over the faults. The HGM data were calculated using difference approximation as follows:

$$\begin{gathered}
\frac{\partial F(i,j)}{\partial x} = \frac{F(i+1,j-1) + F(i+1,j) + F(i+1,j+1) - F(i-1,j-1) - F(i-1,j) - F(i-1,j+1)}{6\Delta x}\\
\frac{\partial F(i,j)}{\partial y} = \frac{F(i+1,j-1) + F(i+1,j) + F(i+1,j+1) - F(i-1,j-1) - F(i-1,j) - F(i-1,j+1)}{6\Delta y}\\
HGM(i,j) = \sqrt{\left(\frac{\partial F(i,j)}{\partial x}\right)^2 + \left(\frac{\partial F(i,j)}{\partial y}\right)^2}
\end{gathered} \tag{14}$$

The horizontal gradient magnitude is also useful to detect of edges of source bodies caused by potential field data (Grauch and Cordell 1987). As presented in "Appendix", the values of β constant for some source bodies are between 0.5 and 1, and given in Table 1.

The eigenvalues can be used to determine the nature of the dominant elongation of quadratic surface. If the two eigenvalues are of equal magnitude, the surface does not have a dominant elongation. If the eigenvalue having the greater magnitude is negative, the dominant elongation is a ridge. If

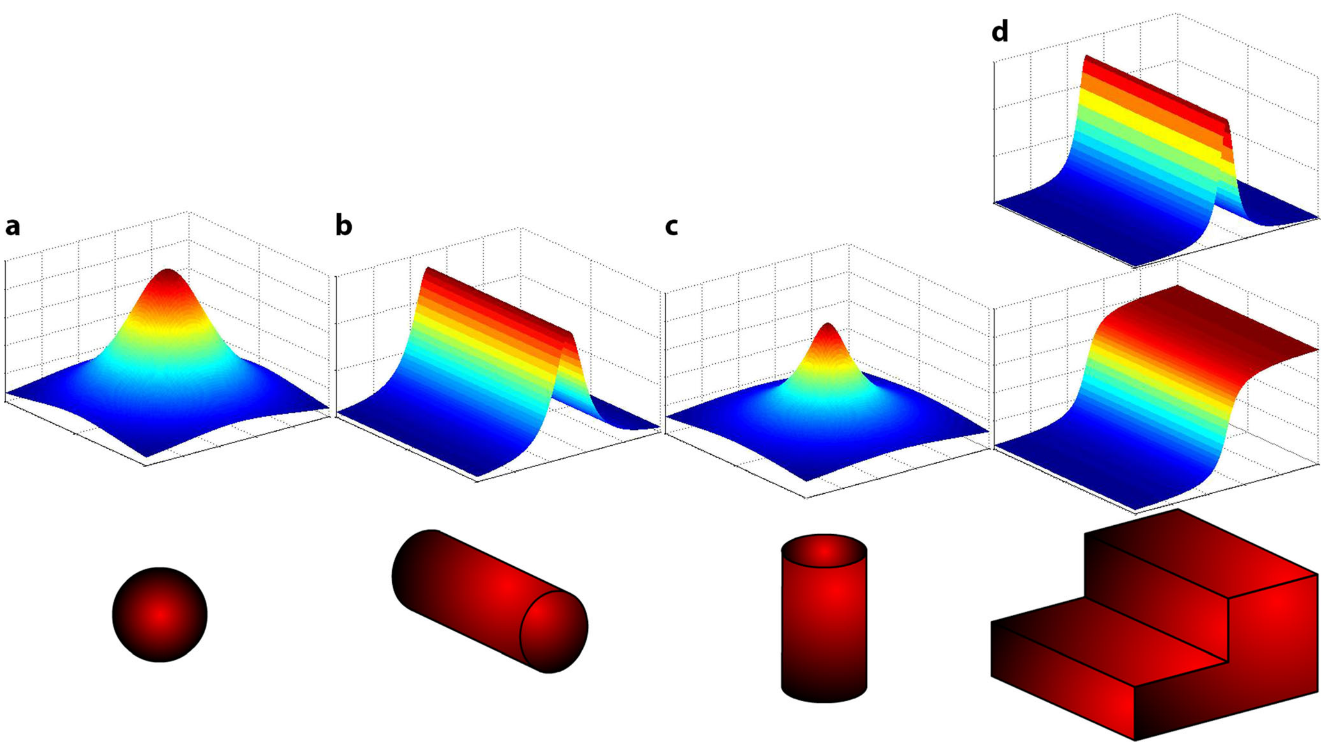


Fig. 4 Gravity anomaly of **a**) Sphere **b**) Horizontal cylinder **c**) Vertical cylinder **d**) Thin vertical fault and its first order horizontal derivative

Table 1 Relation between source model and β constant, and theoretical gravity equations of some source bodies (Nettleton 1976)

Model	Formula	β	
		Anomaly	HGM
Sphere	$g(x,z)=\frac{4\pi G\rho R^3 z}{3(x^2+z^2)^{3/2}}$	1.5	-
Horizontal cylinder	$g(x,z)=\frac{2\pi G\rho R^2 z}{x^2+z^2}$	1	-
Vertical cylinder	$g(x,z)=\frac{\pi G\rho R^2}{(x^2+z^2)^{1/2}}$	0.5	-
Thin vertical fault	$g(x,z)=2\pi G\rho R^2 t\left(\frac{\pi}{2}+tan^{-1}\left(\frac{x}{z}\right)\right)$	-	1

the eigenvalue having the greater magnitude is positive, the dominant elongation is a trough (Phillips et al. 2007). In this study, it was seen that the dominant elongation used to determine the source edge is ridge for gravity anomalies such as sphere, horizontal and vertical cylinder and fault.

CURVGRAV-GUI not only calculates the depths at the critical and extreme points but also detects the edges of sources in the gravity data using the minimum curvature attribute (Peet and Sahota 1985). The maximum and minimum curvatures are attributes associated with the dominant elongation and represent the ridges and troughs, respectively. Therefore, the minimum curvature attribute is very important to detect the source edges for gravity anomalies such as sphere, horizontal and vertical cylinder and fault. The mean curvature is similar to the maximum curvature visually and it is average of the minimum and maximum curvatures. The multiplication of minimum curvature with maximum curvature gives the Gaussian curvature exhibiting rapid sign changes. The use of the Gaussian and mean curvature attributes are not preferred by oneself to get information about the surface. However, the mean curvature and Gaussian curvature are important, because they are used to derive many of the other curvature attributes such as minimum and maximum curvatures and curvedness (Phillips et al. 2007). The curvedness is a general measure of the amount of total curvature, that is, it is amplitude of the minimum and maximum curvatures. It gives all of the dominant elongations (ridge and trough). In this

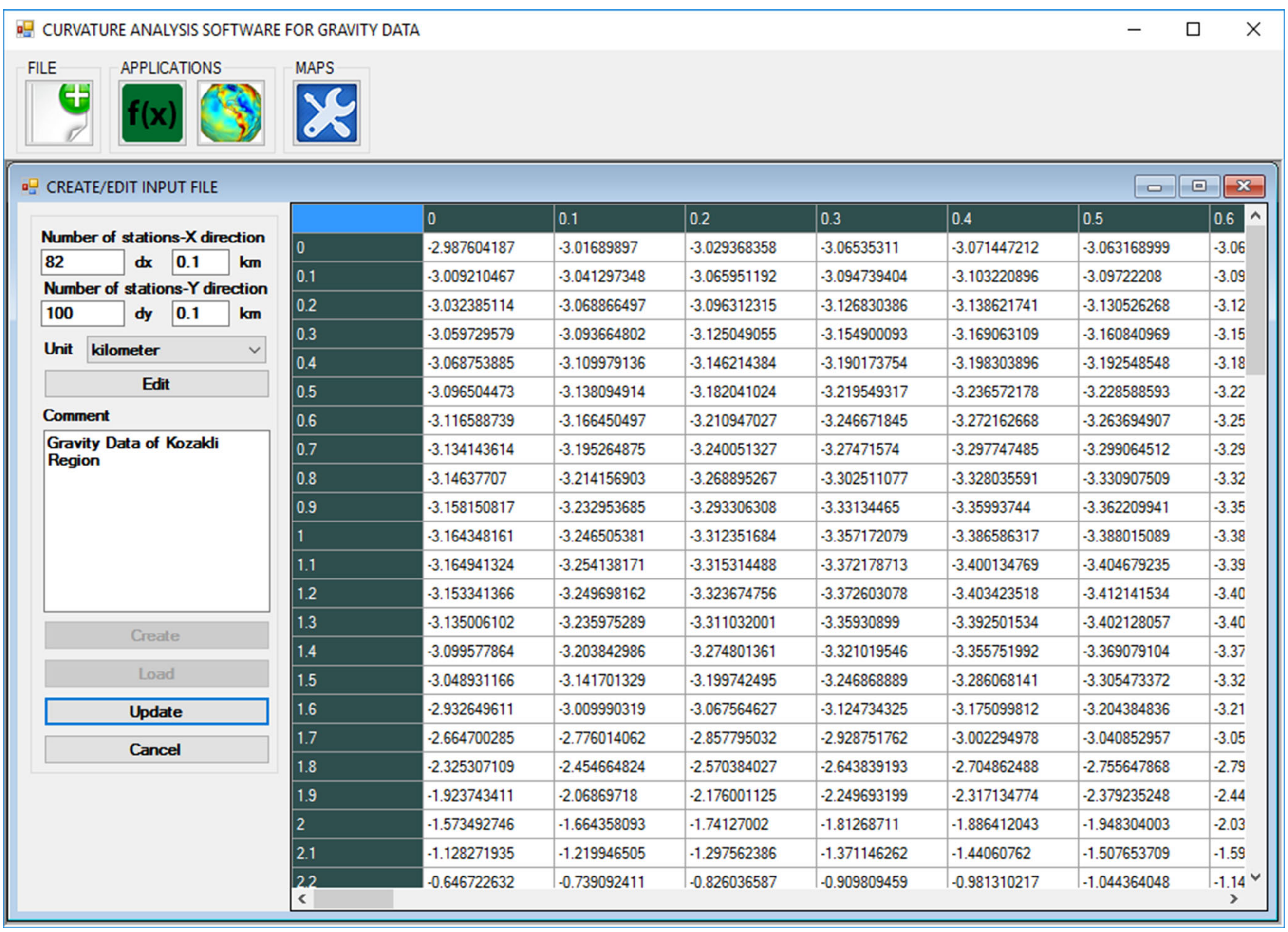


Fig. 5 Screenshot of create/edit input file window

study, the minimum curvature was used to detect the edges of sources, because the interested dominant elongation was ridge. The mean curvature K_m, Gaussian curvature K_g and minimum curvature K_{min} are expressed by following equations:

$$K_m = \frac{d(1+c^2)-ebc+f(1+b^2)}{(1+b^2+c^2)^{3/2}} \quad (15)$$

$$K_g = \frac{4df-e^2}{(1+b^2+c^2)^2} \quad (16)$$

$$K_{min} = K_m - \sqrt{{K_m}^2 - K_g} \quad (17)$$

CURVGRAV-GUI

CURVGRAV-GUI is a Windows-based program and requires Framework 4.0. The main program window has four buttons used to create or edit an input file, to develop synthetic or real data experiments and to change map settings (Fig. 5). The program uses a string file format (*.txt) that can be easily created the "create/edit input file" window. The input file contains column count, row count, sampling intervals in x and y directions, distance unit, comments, coordinates and gravity data. The existing files can be edited using the edit button.

Using the synthetic application window, it can be created complex models consisting of spheres, horizontal or vertical cylinders and thin vertical faults (Fig. 6). First, number of stations in x and y directions, station intervals, number of source bodies and β constant should be determined. After that the parameters button should be clicked. In the source parameters tab page, the source types (sphere, horizontal cylinder, vertical cylinder and vertical fault) should be selected and determined the model parameters (location-x, location-y, depth, radius, height and density contrast). Finally, the calculate button should be clicked to calculate the solutions. CURVGRAV-GUI can plot the image and scatter maps. The source locations and depths can be easily seen by clicking the solution points shown with the colored circles on the scatter map. The critical points panel allows the user to select the desired dominant elongation (ridge and/or trough).

The program also enables to interpret real gravity data using field application window (Fig. 7). In the field

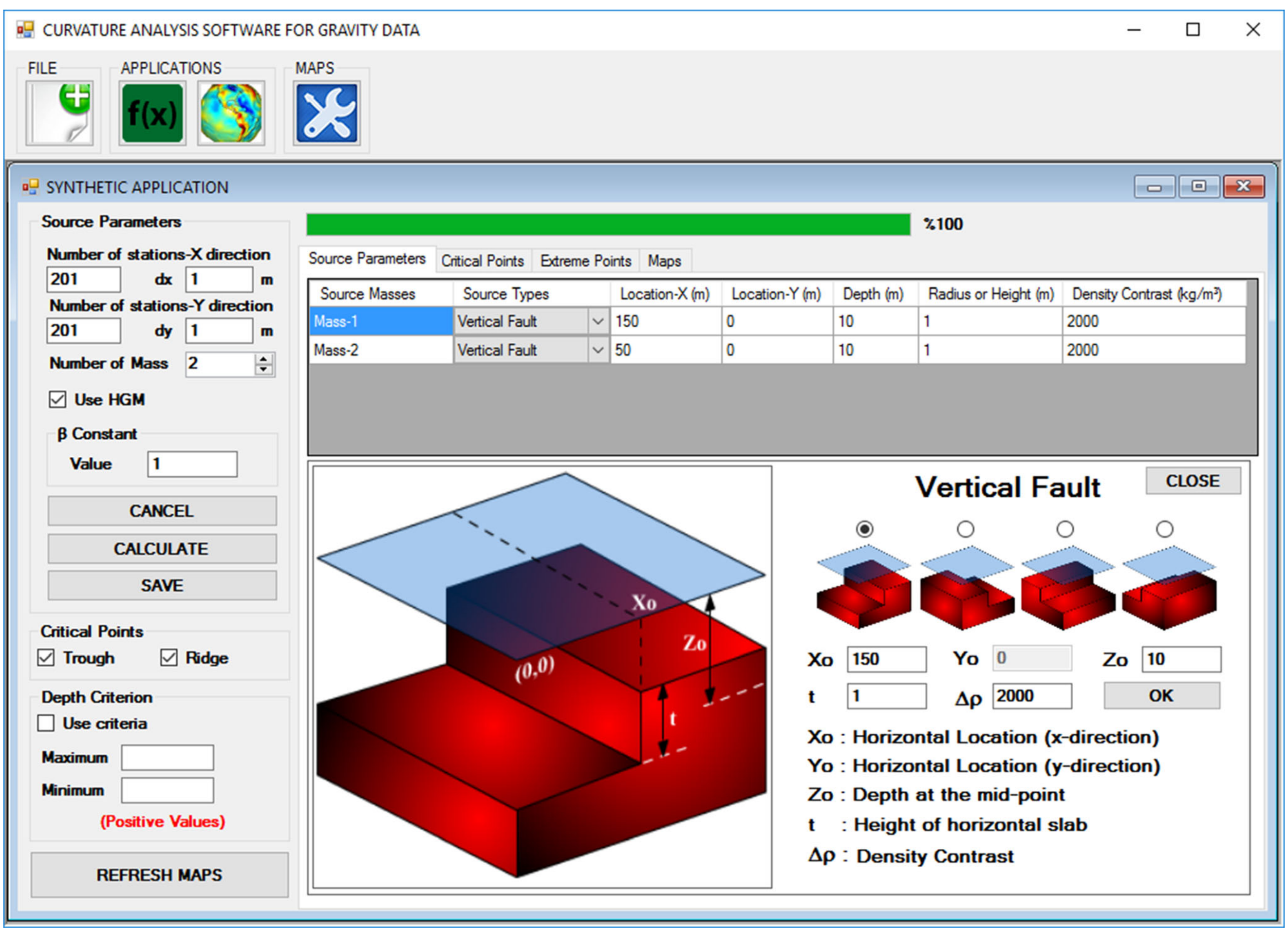


Fig. 6 Screenshot of synthetic application window

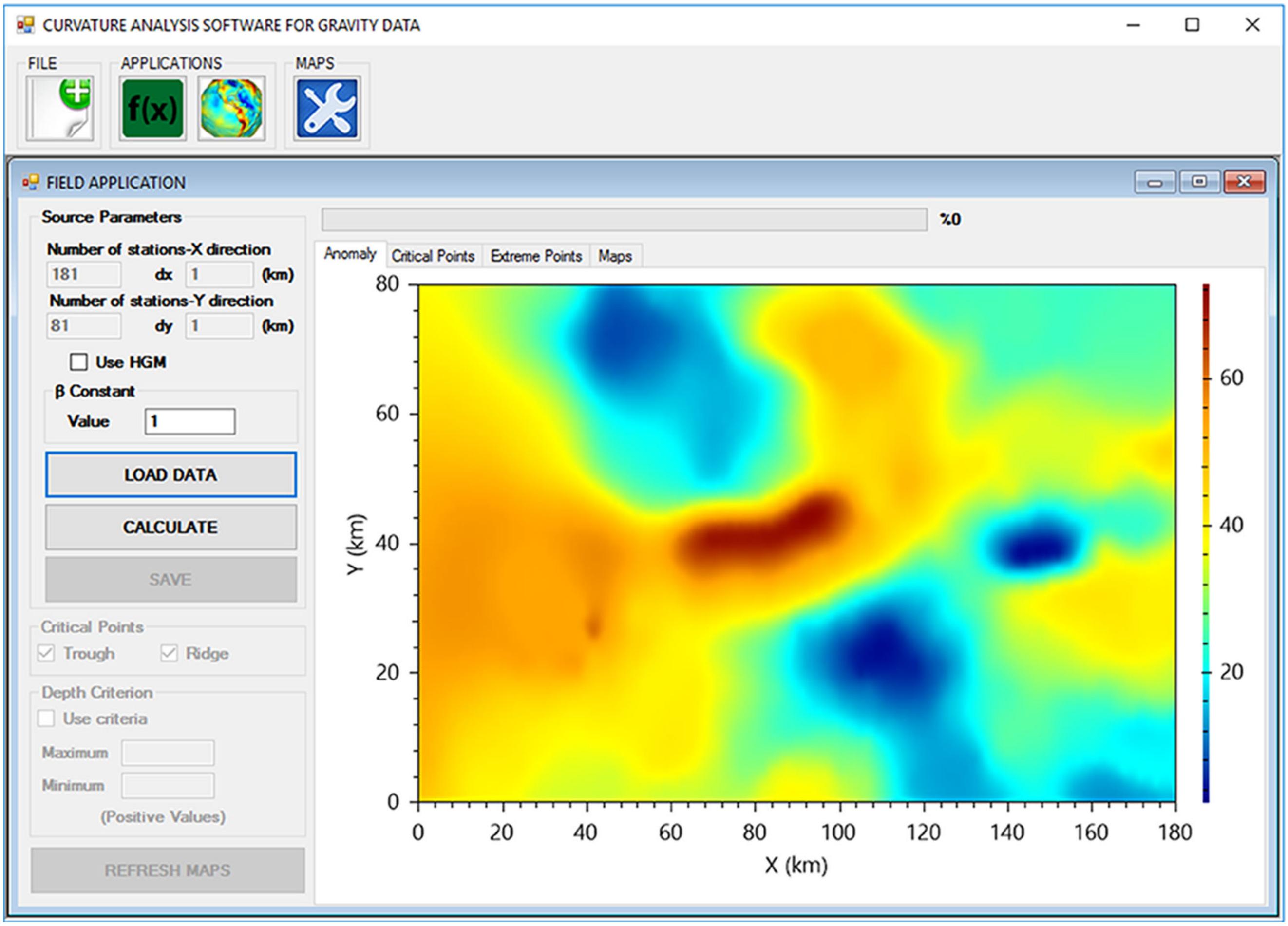


Fig. 7 Screenshot of field application window

application window, the load data button should be clicked and selected the current input file. The HGM checkbox enables to use the horizontal gradient magnitude of the gravity data to interpret the fault anomalies. Finally, clicking the calculate button, the source locations and depths can be estimated. The calculated horizontal locations, depth and dominant elongations can be shown numerically in the critical points and extreme points tab pages. Besides, the solutions can be shown visually in the maps tab page.

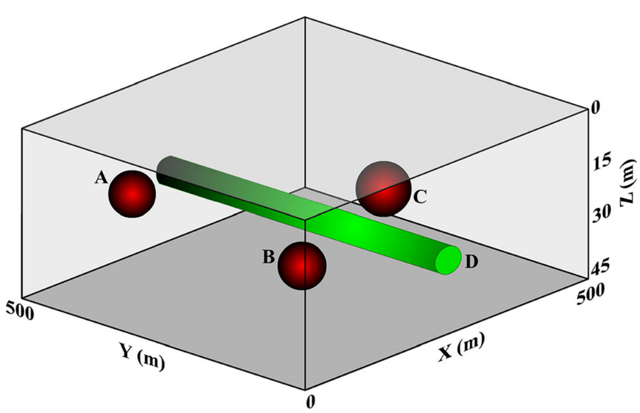


Fig. 8 3D view of synthetic model

Solutions for a specific depth range can be displayed by using the depth criterion panel. In this panel, the maximum and minimum depths should be entered positive.

A user can change the map settings such as font size, number of color for image maps (from 10 to 1000), number of color for scatter maps (from 10 to 500), marker type (circle, cross, diamond, plus, square, star and triangle), marker size (from 1 to 10) and marker stroke size (from 1 to 5).

Applications

Synthetic model experiments

First synthetic gravity data was generated using three sphere and a horizontal cylinder. The number of stations and sampling intervals in x and y directions are 500 m and 1 m, respectively. The depths of source bodies (A, B, C and D) are 20 m, 25 m, 30 m and 28 m, and the density contrasts of source bodies are 2400, 2200, 2100 and 1300 kg/m^3. 3D view of the synthetic model is shown in Fig. 8. The synthetic potential field anomaly and its horizontal gradient magnitude are shown in Fig. 9a and b, respectively. The critical and extreme points and the depths related to them are

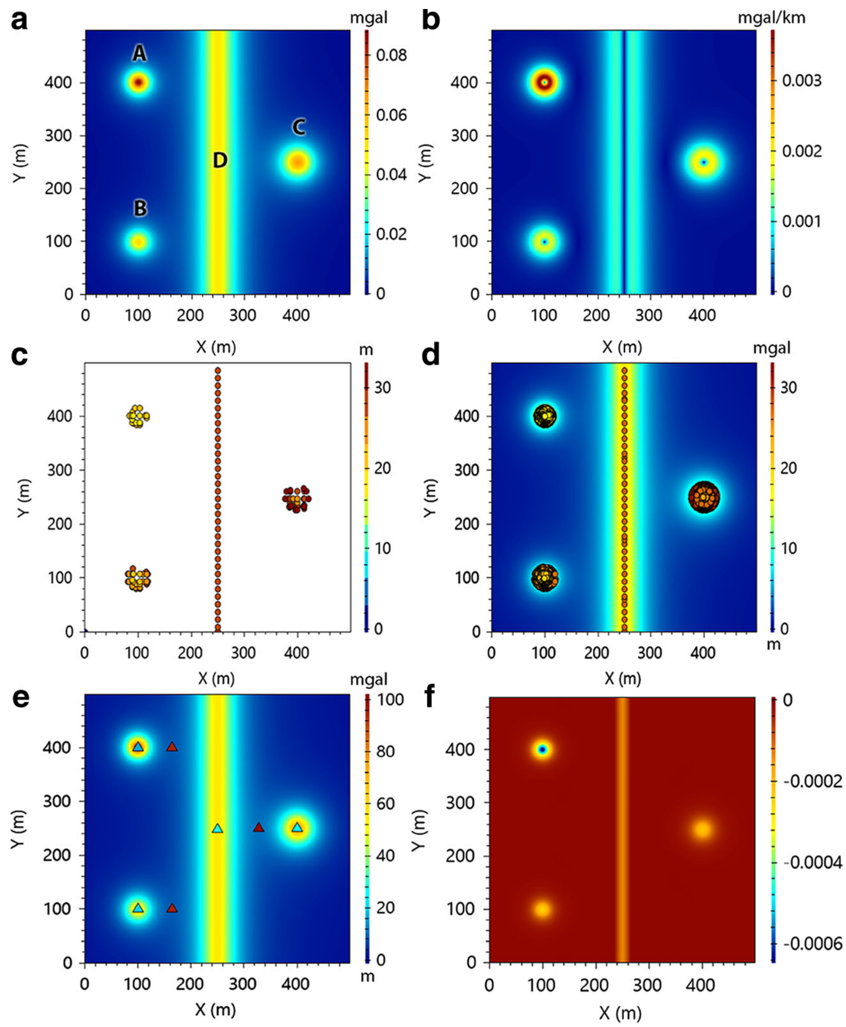


Fig. 9 **a**) Image map of theoretical gravity data **b**) HGM anomaly of data in (**a**) **c**) Calculated depths related to critical points **d**) Depth solutions in (**c**) on data in (**a**) **e**) Extreme points on data in (**a**). Turquoise and maroon triangles show high and saddle points, respectively **f**) Minimum curvature of data in (**a**)

shown in Fig. 9c and e. The obtained critical points were marked by using colored circles on the potential field anomaly (Fig. 9d). The minimum curvature map is shown in Fig. 9f.

The β constant must be selected carefully, because the curvature technique is model-depended method. In the first synthetic model experiment, β constant was selected 1 and 1.5. The calculated locations and depths for both structural indices are given in Table 2 and Table 3. The parameters in Table 2 and Table 3 show that the β constant selection is very important to obtain the correct depth solutions. The bold font parameters in Table 2 and Table 3 demonstrate the solutions calculated using correct β constants.

In the second synthetic application, a graben generated by using two thin vertical fault was used. The number of stations and sampling intervals in the x and y directions are 200 m and 1 m. The depths of mid-point, height and density contrast of faults are 10 m, 1 m and 2000 kg/m^3, respectively. 3D view of

Table 2 Comparison of initial and calculated source parameters (β = 1.5)

Source Mass	Initial Parameters			Calculated Parameters		
	X	Y	Z	X	Y	Z
A (Sphere)	**100**	**400**	**20 m**	**100**	**400**	**20.272**
B (Sphere)	**100**	**100**	**25 m**	**100**	**100**	**25.480**
C (Sphere)	**400**	**250**	**30 m**	**400**	**250**	**30.433**
D (Horizontal Cylinder)	250	-	28 m	250.064	-	34.577

The bold font parameters demonstrate the solutions calculated using correct β constants

Table 3 Comparison of initial and calculated source parameters (β = 1)

Source Mass	Initial Parameters			Calculated Parameters		
	X	Y	Z	X	Y	Z
A (Sphere)	100	400	20 m	100	400	16.552 m
B (Sphere)	100	100	25 m	100	100	20.805 m
C (Sphere)	400	250	30 m	400	250	24.848 m
D (Horizontal Cylinder)	**250**	**-**	**28 m**	**250.064**	**-**	**28.232 m**

The bold font parameters demonstrate the solutions calculated using correct β constants

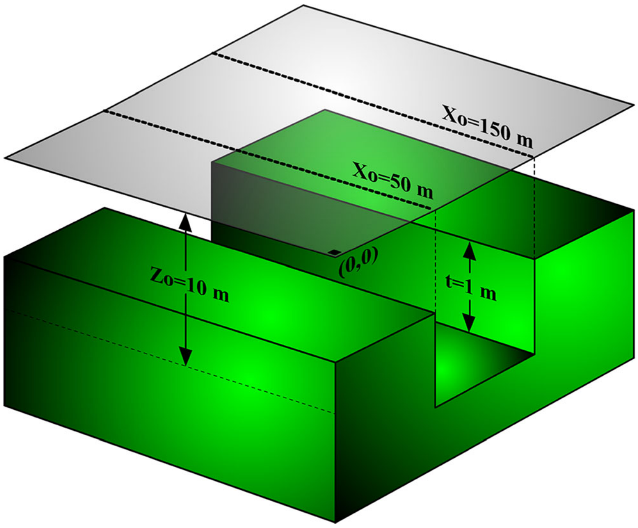


Fig. 10 3D view of synthetic model

the synthetic model is shown in Fig. 10. The synthetic gravity anomaly and its horizontal gradient magnitude are shown in Fig. 11a and b, respectively. The horizontal gradient magnitude of anomaly was used to interpret the synthetic model. The critical points and depths related to them are shown in Fig. 11c. The minimum curvature map shown in Fig. 11d. The calculated horizontal location and depth are given in Table 4.

Table 4 Comparison of initial and calculated source parameters (β = 1)

Source Mass	Initial Parameters			Calculated Parameters		
	X	Y	Z	X	Y	Z
Vertical Fault	-	50	10 m	-	48.990	10.081 m
Vertical Fault	-	150	10 m	-	150.009	10.081 m

Real data examples

The gravity data of Kozakli-Central Anatolia region in Turkey, provided by General Directorate of Mineral Research and Exploration, was used to evaluate the performance of the CURVGRAV-GUI. The Bouguer anomaly has contours with NE-SW trends, is shown in Fig. 12a. It is shown high gravity values about 20 mgal in the central and SE part of the gravity data. This gravity values are probably related to long linear NE-SE trending structural features in the basement complex beneath the sediments of the central and SE portion (Oruç 2011). This area is a geothermal region and there is a graben extending Northwestern-Southeastern direction, called as Kozakli Graben in the region. The geothermal resources exist at the edge of the Kozakli graben and a typical step faulting system is seen at the graben flanks (Ekingen 1971). In this study, the residual gravity anomaly shown in the Fig. 12b obtained by removing a first-order polynomial

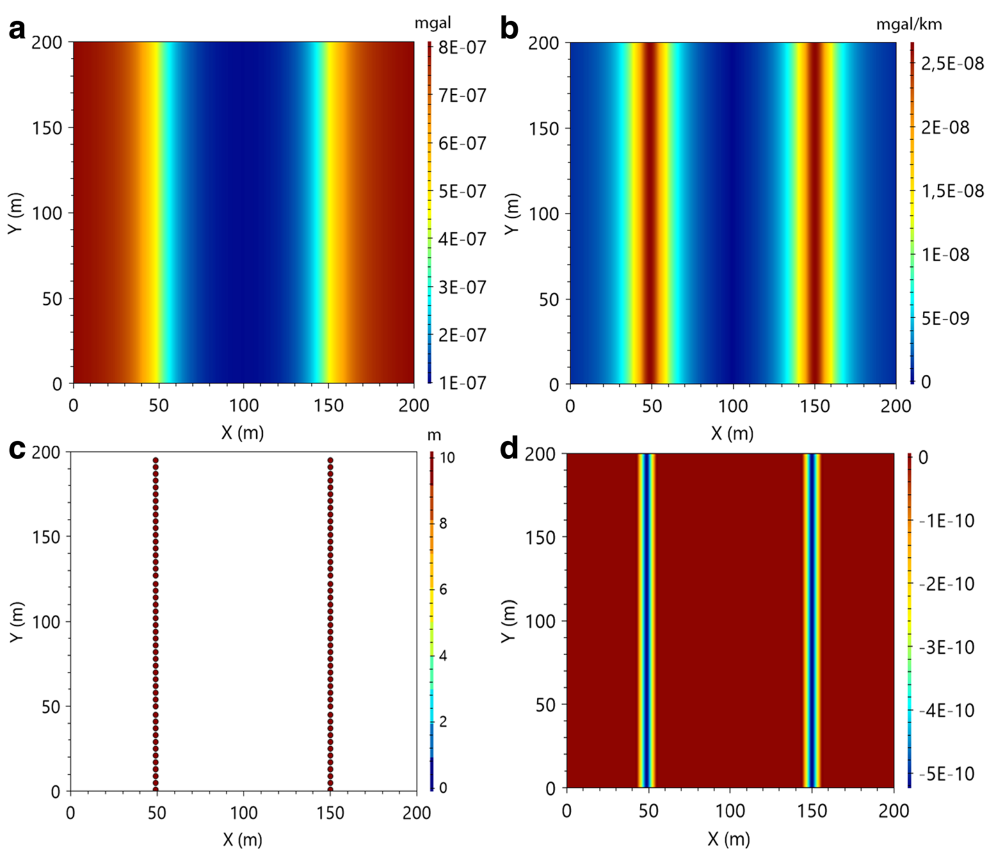


Fig. 11 **a**) Image map of theoretical gravity data **b**) HGM anomaly of data in (**a**) **c**) Calculated depths related to critical points **d**) Minimum curvature map

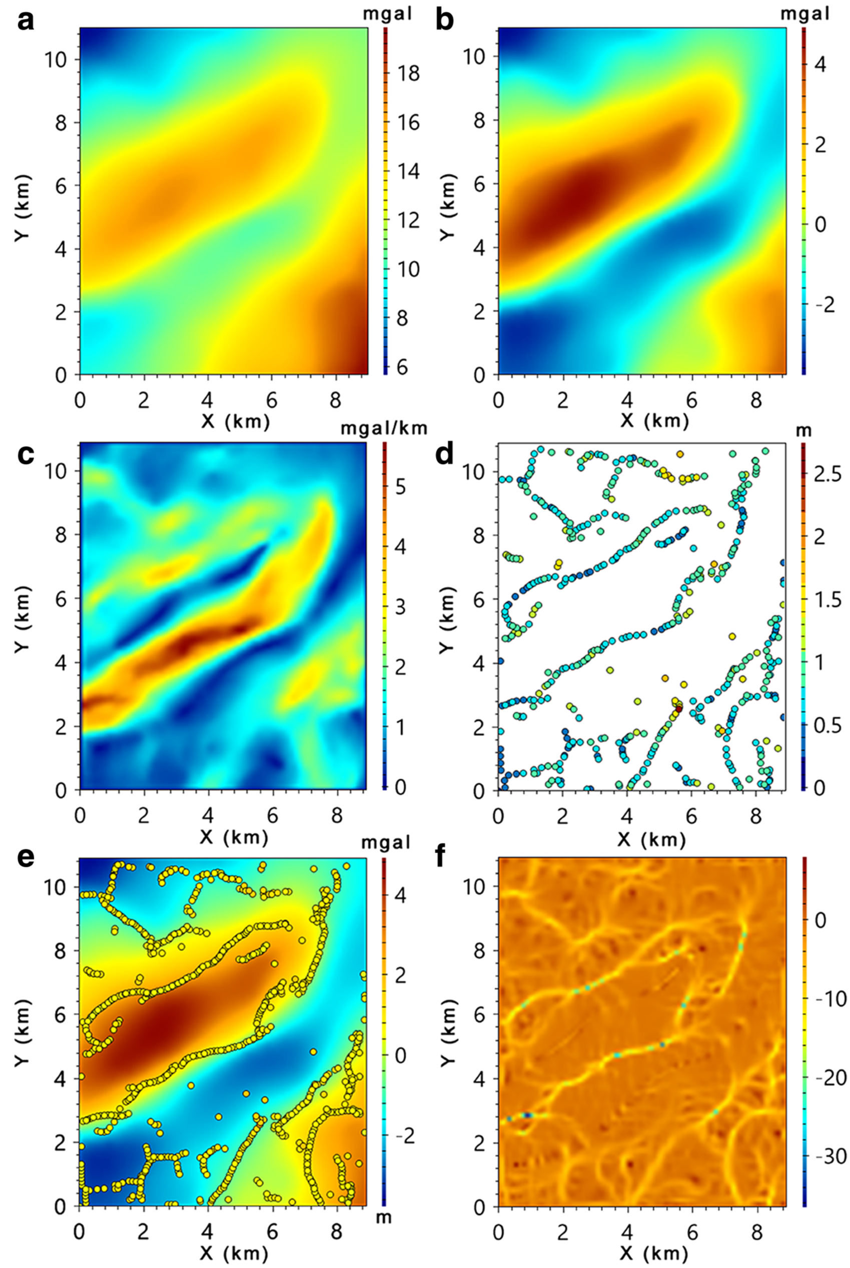


Fig. 12 **a**) Image map of Bouguer gravity anomaly of Kozakli-Central Anatolia Region, Turkey **b**) Residual gravity anomaly obtained from Bouguer gravity anomaly in (**a**) **c**) HGM anomaly of residual gravity anomaly in (**b**) **d**) Calculated depths related to critical points **e**) Depth solutions in (**d**) on anomaly in (**b**) **f**) Curvature map of anomaly in (**b**)

surface from the Bouguer anomaly in the Fig. 12a, was used to depth estimation and edge detection. It is shown in the Fig. 12b that the dominant extension of contours is Northwestern-Southeastern direction and it is clearly seen to be associated with Kozakli Graben. The area covers 9 km and 11 km in the x and y directions, respectively. The HGM of residual gravity anomaly in the Fig. 12b is shown in the Fig. 12c. The estimated depths at the critical points calculated from the HGM data is shown in the Fig. 12d. In addition, the estimated critical points were superimposed the residual gravity anomaly (Fig. 12e). The minimum curvature map is shown in Fig. 12f. The depths of the subsurface structures in the study area were calculated between 0.2 and 0.6 km by Oruç (2011) using the Euler deconvolution method. This results showed that the depths and horizontal locations calculated by using curvature technique were consistent with a previous study performed by Oruç (2011).

Conclusions

A program CURVGRAV-GUI was developed with using C#.NET language with Framework 4.0. This is a user-friendly program that has the ability both data processing and display data graphically. The horizontal locations and depths of source bodies caused gravity data can be calculated easily and accurately by using CURVGRAV-GUI. This program detects lineaments by using the minimum curvature attribute. The theoretical application results show that CURVGRAV-GUI is successful in calculating the source locations and depths, if the β constant is selected correctly. CURVGRAV-GUI was also tested by using real gravity data belonging to Kozakli-Central Anatolia region in Turkey and results were presented. It was seen that the obtained depth and location solutions were consistent with the research in the literature. The program may be useful tool to interpret data for geoscientists interested in potential fields.

Program availability and requirements

The program source code and executable file can be obtained from the corresponding author.

It is required Microsoft Windows operating system and Framework 4.0.

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Appendix: Calculation of the β values for some source bodies

Sphere

$$g(x,z)=\frac{Az}{\left(x^2+z^2\right)^{3/2}} \tag{18}$$

$$\frac{\partial g}{\partial x}=\frac{-3Axz}{\left(x^2+z^2\right)^{5/2}} \quad , \quad \frac{\partial^2 g}{\partial x^2}=\frac{15Ax^2z}{\left(x^2+z^2\right)^{7/2}}-\frac{3Az}{\left(x^2+z^2\right)^{5/2}} \tag{19}$$

$$K(x)=\frac{\frac{\partial^2 g}{\partial x^2}}{\left(1+\left(\frac{\partial g}{\partial x}\right)^2\right)^{\frac{3}{2}}} \Rightarrow \quad K(x)=\frac{\frac{15Ax^2z}{\left(x^2+z^2\right)^{7/2}}-\frac{3Az}{\left(x^2+z^2\right)^{5/2}}}{\left(1+\left(\frac{-3Axz}{\left(x^2+z^2\right)^{5/2}}\right)^2\right)^{\frac{3}{2}}}, \quad K(0)=\frac{-3A}{z^4} \tag{20}$$

$$K(0)=-\frac{2\beta g(0)}{z^2} \Rightarrow \quad \frac{-3A}{z^4}=\frac{-2\beta\frac{A}{z^2}}{z^2}, \quad \beta=\frac{3}{2} \tag{21}$$

Horizontal cylinder

$$g(x,z)=\frac{Az}{x^2+z^2} \tag{22}$$

$$\frac{\partial g}{\partial x}=\frac{-2Axz}{\left(x^2+z^2\right)^2} \quad , \quad \frac{\partial^2 g}{\partial x^2}=\frac{8Ax^2z}{\left(x^2+z^2\right)^3}-\frac{2Az}{\left(x^2+z^2\right)^2} \tag{23}$$

$$K(x)=\frac{\frac{\partial^2 g}{\partial x^2}}{\left(1+\left(\frac{\partial g}{\partial x}\right)^2\right)^{\frac{3}{2}}}, \quad K(x)=\frac{\frac{8Ax^2z}{\left(x^2+z^2\right)^3}-\frac{2Az}{\left(x^2+z^2\right)^2}}{\left(1+\left(\frac{-2Axz}{\left(x^2+z^2\right)^2}\right)^2\right)^{\frac{3}{2}}}, \quad K(0)=\frac{-2A}{z^3} \tag{24}$$

$$K(0)=-\frac{2\beta g(0)}{z^2}, \quad \frac{-2A}{z^3}=\frac{-2\beta\frac{A}{z}}{z^2}, \quad \beta=1 \tag{25}$$

Vertical cylinder

$$g(x,z)=\frac{A}{\left(x^2+z^2\right)^{1/2}} \tag{26}$$

$$\frac{\partial g}{\partial x}=\frac{-Ax}{\left(x^2+z^2\right)^{3/2}} \quad , \quad \frac{\partial^2 g}{\partial x^2}=\frac{3Ax^2}{\left(x^2+z^2\right)^{5/2}}-\frac{A}{\left(x^2+z^2\right)^{3/2}} \tag{27}$$

$$K(x)=\frac{\frac{\partial^2 g}{\partial x^2}}{\left(1+\left(\frac{\partial g}{\partial x}\right)^2\right)^{\frac{3}{2}}}, \quad K(x)=\frac{\frac{3Ax^2}{\left(x^2+z^2\right)^{5/2}}-\frac{A}{\left(x^2+z^2\right)^{3/2}}}{\left(1+\left(\frac{-Ax}{\left(x^2+z^2\right)^{3/2}}\right)^2\right)^{\frac{3}{2}}}, \quad K(0)=\frac{-A}{z^3} \tag{28}$$

$$K(0)=-\frac{2\beta g(0)}{z^2}, \quad \frac{-A}{z^3}=\frac{-2\beta\frac{A}{z}}{z^2}, \quad \beta=\frac{1}{2} \tag{29}$$

Vertical thin fault

$$g(x,z)=A\left(\frac{\pi}{2}+tan^{-1}\left(\frac{x}{z}\right)\right) \tag{30}$$

$$\frac{\partial g}{\partial x}=\frac{Az}{x^2+z^2} \tag{31}$$

The horizontal gradient of the vertical thin fault anomaly is equal to the horizontal cylinder anomaly. In this study, the curvature method was applied on horizontal gradient of vertical thin fault anomaly, therefore, the β parameter is 1.

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