Investigating edge detection, Curie point depth, and heat flow using EMAG2 magnetic and EGM08 gravity data in the northern part of Eastern Anatolia, Turkey

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1. Introduction

The detection of a source body’s edges is widely used in gravimetry and magnetometry because it gives properties of the potential fields. There are many commonly used methods for determining the edges of structures, such as total horizontal derivative (THDR), analytic signal, 3D Euler deconvolution, tilt angle (TA), theta map (TM), normalized horizontal derivative (NTHD), and normalized total horizontal gradient (TDX) (Pamuk, 2018). These methods have been applied in various studies. Oruç (2011) applied an edge detection technique based on a TA map derivated from the first vertical gradient to gravity data in the Kozakli region, Central Anatolia, Turkey. Oruç et al. (2013) used tilt derivatives of gravity anomalies in the Erzurum Basin (Turkey). Alvandi and Asil (2014) employed a hyperbolic TA for detecting gravity source edges in the Qom salt dome in central Iran. Altınoğlu et al. (2015) used horizontal gradient, analytic signal, and TA methods to detect the edges of the Denizli Basin and surroundings on the Bouguer gravity map. Ghosh (2016) carried out horizontal gradient analysis, 3D Euler deconvolution, TA, and TDX analysis using gravity data in northwest Himalaya.

The Curie point is known as the temperature at which a material loses its ability to gain permanent magnetism. In various tectonic settings, the CPD (Curie point depth) values obtained from magnetic data are extensively used to derive the thermal structure of the crust. Okubo et al. (1985) developed a method to determine CPD values. The method was used to estimate CPD values in our study area and has been employed in many other studies as well. Ateş et al. (2005) obtained CPD values, ranging from 7.9 km to 22.6 km, from total field magnetic intensity anomalies in Central Anatolia. Dolmaz et al. (2005) studied thermal structures based on CPD values for Western Anatolia. Aydın et al. (2005) estimated CPD values on a country-wide scale and mapped the obtained values. Bilim (2007), in Western Anatolia, calculated CPD values from the total field magnetic intensity anomalies. Bektaş et al. (2007) obtained CPD values from residual aeromagnetic data in Eastern Anatolia, finding that CPDs varied from 12.9 km to 22.6 km. For CPD variation and Moho depth maps of the Eastern Pontide Orogenic, Maden et al. (2009a) utilized the power spectral method of the radial wavenumber. Maden et al. (2009b) investigated Moho depth from observed gravity value using three different methods (relationship between Bouguer anomaly and Moho depth, spectral analysis of the radial wave number and inversion method). Maden (2009) estimated the CPDs and heat flow values using Magnetic spectral analysis to

Abstract: The edge detection, the Curie point depths (CPDs), and the heat flow in the northern part of Eastern Anatolia were examined using EMAG2 magnetic and EGM08 Bouguer gravity data. Edge detection methods are extensively employed to delineate the edges of sources using potential field data. In the study area, the tilt angle, total horizontal derivative, theta map, and 3D Euler deconvolution methods were used to delineate the subsurface geology and heterogeneity. The 3D Euler deconvolution method was carried out to determine the depth of the subsurface magnetic and gravity anomalies. The Euler depth solutions show that the depths range from 0 to 15 km for the Bouguer gravity anomalies, while the depths vary from 0 to 16 km for the magnetic anomalies. In this study area, the CPD values vary between 15.7 km and 18.6 km. For a thermal conductivity of 2.5 W m\(^{-1}\) K\(^{-1}\), the heat flow values were determined to be between 75 and 95 mW m\(^{-2}\). A plot of CPDs versus heat flow values revealed an exponential correlation between heat flow and CPD values. A good relationship was detected between the CPDs and the heat flow values.

Key words: Edge detection, Curie point depth, heat flow, EMAG2, EGM08.

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obtain the thermal regime of the Central Pontides. Using aeromagnetic data, Bilim et al. (2016) prepared radiogenic heat production, heat flow, and CPD maps for the Menderes Massif and the Aegean Region, Turkey. Bilim et al. (2017) investigated CPD, geothermal gradient, and heat flow using magnetic anomaly data of the Gulf of Iskenderun. Using power spectral analysis, Elbarbary et al. (2018) estimated the CPD values and heat flow in Egypt. Mono et al. (2018) estimated CPD values, heat flow, and geothermal gradient from spectral analysis of magnetic anomalies in the Loum-Minta region, Cameroun. Using aeromagnetic maps, Chukwu et al. (2018) determined CPD and heat flow values for the Niger Delta Basin of Nigeria. Özer and Polat (2017a, 2017b) investigated the relation among seismic velocity, Curie depth, heat flow, and geothermal resources. Özer et al. (2018) claimed that the Curie depth has good harmony with tomographic findings, especially in Aydın and the SW part of İzmir. Furthermore, Özer et al. (2019) reported that Curie depth of 29 km, which can be associated with the crustal magma chambers, is found to be 5–7 km above the Moho depth in Eastern Anatolia.

The aims of the present study are to obtain the CPD and heat flow values of subsurface structures in the northern part of Eastern Anatolia, Turkey, using spectral analysis of the EMAG2 magnetic data. In addition, using EMAG2 magnetic and EGM08 Bouguer gravity data, we determined the source body’s edges using the TA, TM, and THDR methods. Lastly, the top depth of the anomaly source was determined using the 3D Euler deconvolution method on the magnetic and gravity anomalies.

2. The tectonic and geology of the study area
There are several major fault systems located in the Alpine–Himalayan orogenic belt in Turkey, such as the Aegean Graben System, the East Anatolian Fault zone (EAFZ), and the North Anatolian Fault Zone (NAFZ). The NAFZ is one of the world's largest strike-slip fault zones, and this zone consists of a cross-continental plate (Tatar et al., 2013). The NAFZ has an approximate length of 1200 km and extends to the Saroz bay in the northern part of the Aegean Sea (Şengör et al., 2005). The destructive earthquakes occurred on the NAFZ as follows: Kocaeli earthquake (1999), Mudurnu Valley earthquake (1967), Erbaa-Niksar earthquake (1942), Tosya earthquake (1943), Bolu-Gerede earthquake (1944), Abant earthquake (1957), and Erzincan (1939) earthquake (Tatar et al., 2013) (Figure 1).

The northern region of the study area located in the northeast of Turkey generally shows an irregular terrain morphology due to geologic and tectonic characteristics. The Eastern Pontide Orogenic Belt is an important metallogenetic area on the eastern coast of the Black Sea and forms a mountain chain of approximately 500 km long and 100 km wide on the southeast coast of the Black Sea. According to Arslan et al. (1997), the Northeastern Pontides has experienced extensive volcanic activity from the Liassic to the Tertiary and is tectonically a paleo-island arc. According to lithological and structural differences, the Eastern Pontides is divided into the north and east (Gedikoglu et al., 1979; Bektaş et al., 1995). Plio-Quaternary sediments cover the southern part of the study area (Erzincan Basin). These sediments include deposits, clastics, and basin-margin conglomerates. The conglomerates are composed of carbonates and ophiolite melange rocks. In the center of the basin; sand, silt, and gravels are mostly observed (Barka and Gülen, 1989). Along the eastern half of the North Anatolian Fault, the Niksar and Taşova-Erbaa Basins located in the western part of the study area were formed. The Paleozoic metamorphics, which are the main units around the Taşova-Erbaa Basin, are Eocene and Mesozoic volcanics (Barka et al., 2000). The Sivas Basin was formed on the basis of metamorphic-ophiolitic rocks and pre-Maastrichtian platform carbonates. The Maastrichtian-Paleocene aged limestones unconformably overlie the basement in the Sivas Basin. This unit moves upward inside the Eocene clastic rocks and the Paleocene basaltic lavas. Fluvial deposits, Plio-Quaternary, and Quaternary alluvium units overlie the clastic rocks unconformably (Yılmaz and Yılmaz, 2006). Figure 2 shows the geological map of the northern part of Eastern Anatolia, Turkey.

3. The magnetic and gravity data
3.1. EGM08 Bouguer gravity data
In this study, EGM08 Bouguer gravity data were used, which were obtained within the scope of the WGM (World Gravity Map) project arranged at the beginning of 2008 in cooperation with UNESCO and the Commission for the Geological Map of the World (CGMW) (Figure 3). In this project, the archives of the Bouguer and free-air gravity data, the land, airborne, and sea measurements, and the global regional measurements of recent years have been compiled. A Bouguer anomaly grid with spherical harmonics (with ellipsoidal harmonic degree 2159) was determined with a sensitivity of 1 mGal by benefiting from the topography and bathymetry database of the earth, which was in 5' × 5' ranges (Pavlis et al., 2008; Pavlis et al., 2012). In the examination of the Bouguer gravity map, it has been observed that the gravity values range from −210 to 50 mGal. The northern part of the study area has relatively greater gravity values, while the lowest gravity values are observed in the Erzincan Basin (Figure 3).

3.2. EMAG2 magnetic data
EMAG2 (the global Earth Magnetic Anomaly Grid 2) used in this study consists of ship and airborne magnetic measurements and satellite data. EMAG2 is an important update of the grid for the World Digital Magnetic Anomaly Map. The magnetic grid was determined 4 km above the geoid with 2' resolution (Maus et al., 2009). In addition,
the resolution was increased from 3′ to 2′, and the altitude was reduced from 5 to 4 km above the geoid (Maus et al., 2009).

The total magnetic intensity (Figure 4a) was reduced to the pole (RTP) to overcome the bipolarity phenomena of the magnetic data (Figure 4b). The magnetic values ranged between –750 and 750 nT in the RTP magnetic anomaly map of the study area. The lowest magnetic values have been observed in the Erzincan Basin while the highest values have been obtained around Ordu. High magnetic anomaly values have been observed generally, except the basins (Figure 4b).

4. Edge detection and depth estimation

With gravity and magnetic methods, it is very important to introduce the edges of the mass, as edges can cause anomalies in modeling and mapping. There are many commonly used methods for determining the edges of structures. Some of the commonly used methods include THDR, analytic signal, 3D Euler deconvolution, TA, TM, NTHD, and TDX. The TA, THDR, and TM methods have been successfully utilized in revealing the edges of lapped structures, and these methods were also used to determine the structural edges in the study area. The THDR is a commonly used edge detection filter, as given by Cordell and Grauch (1985) as:

\[ THDR = \sqrt{\left(\frac{\partial G}{\partial x}\right)^2 + \left(\frac{\partial G}{\partial y}\right)^2} \]

where \( G \) is the gravity anomaly (or magnetic anomaly) and \( \frac{\partial G}{\partial x} \) and \( \frac{\partial G}{\partial y} \) are the horizontal derivatives of the gravity anomaly (or magnetic anomaly). The TA method...
Figure 2. The geological map of the study area on shaded relief together with tectonic structure and the epicenter distribution of earthquakes (M ≥ 3) ((The earthquake data from AFAD (Prime Ministry Disaster and Emergency Management Authority in Turkey), the geological map simplified from MTA, 2002; active faults from Emre et al. (2013)).

Figure 3. EGM08 Bouguer gravity anomaly map with major tectonic structures in the study area (compiled from Pavlis et al. (2008)).
was developed by Miller and Singh (1994). This method uses the ratio of the vertical derivative to the absolute value of the horizontal derivative of the potential field data:

$$\text{TA} = \tan^{-1}\left(\frac{\partial G/\partial z}{|\partial G/\partial z|}\right)$$

(2)

where TA is tilt angle, $\partial G/\partial z$ are the vertical derivative of the gravity anomaly (or magnetic anomaly). Theta map (TM, θ) method was developed by Wijns et al. (2005):

$$TM = \sqrt{\frac{(\partial G/\partial x)^2 + (\partial G/\partial y)^2}{(\partial G/\partial x)^2 + (\partial G/\partial y)^2 + (\partial G/\partial z)^2}}$$

(3)

These edge detection methods were applied to the magnetic anomaly and the Bouguer gravity anomaly maps. In addition, the results of the methods were compared with each other and with the geology of the region along with two sections taken on the map. The three methods produced good results in the field studies (Figures 5–10). In addition, a tilt angle value of 0° gives the edges of the source, as shown in Figures 6 and 9. Tilt angle values range between 1.570 and –1.570 (–π/2 to +π/2). The tilt angle value at the boundary location of the vertically positioned source is zero, and this value is negative outside the source. In this case, the tilt angle is used to determine the direction of the structure. In addition, for estimating the depth to top of the magnetic source, the half distance between the –π/4 and +π/4 contours can be used. In this study, the top depths of the structures were calculated by using the tilt angle map at 15 points chosen near the block centers (Figure 9).

Figure 6 shows that the tilt angle of the Bouguer gravity data shows an NW–SE trend toward the northwest.
of the study area. This trend is in line with the direction of the North Anatolian Fault Zone. In the northern part of the study area, N–S-oriented structures attract attention; however, NE–SW-oriented structures are seen in the western part. In general, there is a good conformity between the fault zone and zero contours (Figure 6). Figure 9 illustrates that the tilt angle of the magnetic data shows an SW–NE trend toward the southwest from the middle of the study area.

The position of the anomaly source in the vertical and horizontal directions was estimated by the 3D Euler deconvolution (ED) method, which is a function of the potential field data in the x, y, and z directions. The method was derived by Thomson (1982), and it was used on the magnetic data throughout the profiles. Subsequently, Reid et al. (1990) developed an equivalent method and applied it to the gridded magnetic data.

The 3D Euler deconvolution equation (Reid et al., 1990) is

\[
(x - x_0) \frac{dg}{dx} + (y - y_0) \frac{dg}{dy} + (z - z_0) \frac{dg}{dz} = \eta(\beta - g)
\]

which can be rewritten into

Figure 5. THDR of the Bouguer gravity anomaly.

Figure 6. TA of the Bouguer gravity anomaly.
where $x_0$, $y_0$, $z_0$ are the coordinates of the source whose total gravity is detected at $x$, $y$, $z$; $\eta$ is the structural index; and $\beta$ is the regional value of gravity.

The structural index (SI) characterizes the source geometry (Table 1). In this study, the procedure is carried out with a depth tolerance of 15%, a window size of 10 grid cells, and structural indices 1 and 0 for magnetic and gravity data, respectively (Figures 11 and 12).

5. The calculation method of Curie point depth (CPD)

The method of Okubo et al. (1985) was utilized to calculate the CPD. In this method, $z_t$ is the depth to the top of the structure, and $z_0$ is the depth of the center of the structure; a correct and reliable calculation of $z_0$ is required in order to calculate $z_t$ (CPD). Firstly, the depth of the centroid ($z_0$) of the magnetic source can be calculated using Eq. (6);

$$\ln \left[ \frac{p(s)^{1/2}}{|s|} \right] = \ln A - 2\pi |s| z_0$$
where $z_0$ is the depth to centroid of magnetic body, $P(s)$ is the radially averaged power spectrum of the magnetic anomaly, $A$ is the constant, and $k$ is the wave number.

The second step is obtaining of the $z_t$ (depth to top) using the second method of Okubo et al. (1985), and $z_t$ was obtained with the help of Eq. (7).

$$\ln [P(s)^{1/2}] = \ln B - 2\pi |s| z_t$$

(7)

**Table 1. Structural index (SI).**

<table>
<thead>
<tr>
<th>Source</th>
<th>Magnetic SI</th>
<th>Gravity SI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal cylinder</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Contact</td>
<td>0</td>
<td>-1</td>
</tr>
<tr>
<td>Sphere</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Fault (small step)</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

Figure 9. TA of the magnetic anomaly.

Figure 10. TM of the magnetic anomaly.
where $B$ is a sum of constants independent of the wave number. The depth to the top boundary $z_t$ was obtained from the slope of the second longest wavelength of the spectral segment of the second spectrum. After calculating $z_t$ and $z_0$, we can easily calculate $z_b$ using Eq. (8):

$$z_b = 2 \cdot z_0 - z_t.$$  

(8)

The magnetic anomaly map for the calculation of the CPD was divided into 15 blocks with a size of $110 \times 110$ km. All blocks overlapped with adjacent blocks by 50%, meaning that the distance between the centers of two
blocks was 55 km. The center of the blocks was indicated with a plus sign (Figure 13). The power spectrum method (Spector and Grant, 1970) was used for each block. The steepest slope was used to calculate $z_t$, which was the upper depth of the magnetic source. For the calculation of $z_0$, the depth of the center of the source, the power spectrum was separated by $s$ and plotted against the number of waves. The least-squares method was used to determine the line that best matched the data points, and the slopes were obtained (Figure 14). The calculated depths are shown in Table 2.

Figure 14 indicates the power spectrum of the magnetic source of block 1. The slope of the longest wavelength portion of the spectrum divided by the radial frequency ($z_0$) was used to obtain the central depth of the deepest magnetic source (Figure 14a). The slope of the second longest wavelength portion of the spectrum was utilized to determine the upper limit depth ($z_t$) of the magnetic source (Figure 14b). $z_0$ and $z_t$ were 9.33 and 1.86 km, respectively, for block 1. CPD was calculated to be 16.8 km by using Eq. (8) for block 1.

The other CPD values are shown in Table 2 and Figure 15. CPD values range from 15.73 to 18.61 km for the study area. In most parts of the study area, the CPD values are between 16 and 17 km. The highest CPD value was obtained at the point of B6, B7, and B14. In the regions close to Sivas, the CPD value is generally between 17 and 18 km. On the NAFZ at points B10 and B12, the CPD values vary between 17 and 18 km. The values from previous studies and those obtained in this study are compared in Table 2, showing that this study is in line with the previous studies. It can be seen that blocks B6, B7, B8, B9, B10, and B8 had relatively lower values compared with what was found in previous studies.

In addition, in this study, the depths from different methods ($z_t$ values, the minimum depths in the blocks obtained using Euler Deconvolution method and the depths obtained from the TA map) were compared with each other (Table 3).

6. The calculation of heat flow

Empirical relation which is a one-dimensional heat conductive transport model to estimate heat flow based on Fourier’s law (Fourier, 1955) can be used. In a one-dimensional case under assumptions that the direction of the temperature variation is vertical and the temperature gradient $dT/dz$ is constant, Fourier’s law takes the following form:

$$ q = k \frac{dT}{dz} $$

where $q$ is heat flow, $k$ is the coefficient of thermal conductivity, $\theta$ is thermal gradient. According to Tanaka et al. (1999), the Curie temperature ($\theta$) can then be defined as:

$$ \theta = \frac{[dT]}{[dz]} z_b $$

where $z_b$ is CPD. The heat flow values were calculated by combining Eqs. (9) and (10):

$$ q = k \frac{\theta}{z_b} $$

where $q$ is heat flow, $k$ is the coefficient of thermal conductivity, $z_b$ is CPD. In heat flow process, it is assumed that thermal conductivity is 2.5 Wm$^{-1}$K$^{-1}$, Curie point temperature of 580 °C (Bektaş et al., 2007; Nwankwo et al.)

Figure 13. The magnetic anomaly map of the study area. The squares indicate three blocks (B1, B6, and B2). Block sizes are 110 × 110 km$^2$. Plus sign shows the blocks’ centers and numbers utilized for the CPD regions.
Table 2. Comparison of the obtained CPD values with those of the previous studies.

<table>
<thead>
<tr>
<th>Block no.</th>
<th>Block center-X</th>
<th>Block center-y</th>
<th>Maden et al. (2009a)</th>
<th>Bektas et al. (2007)</th>
<th>Aydin et al. (2005)</th>
<th>This Study</th>
</tr>
</thead>
<tbody>
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<td>b1</td>
<td>36.606</td>
<td>39.428</td>
<td>17</td>
<td>18</td>
<td>14</td>
<td>16.8</td>
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<tr>
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<td>20.5</td>
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<tr>
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<td>18.61</td>
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<tr>
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<td>39.165</td>
<td>40.443</td>
<td>22.5</td>
<td>16</td>
<td>22</td>
<td>17.61</td>
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</tbody>
</table>

Figure 14. Examples of power spectrum of the block 1 for estimation of the CPD, a) the determining of the centroid depth, $z_c$ b) the determining of the top depth, $z_t$. 

Table 2. Comparison of the obtained CPD values with those of the previous studies.
The heat flow values change from 75 mW m\(^{-2}\) to 95 mW m\(^{-2}\) (Figure 16, Table 4).

In this study, an empirical exponential relationship was developed between CPD values and the heat flow. This equation can be used to determine the heat flow on the basis of CPD values. For the study area, Eq. (12) gives the correlation between the heat flow and CPD (Figure 17):

\[ HF = 1450 \times \text{CPD}^{-1} \]  

(12)

where CPD is the CPD (km) and HF is the heat flow.

7. Discussion and conclusions

The RTP magnetic intensity of the study area shows the range of magnetic anomalies which vary from 750 nT to –750 nT. Some of the higher magnetic anomalies are also related to ophiolitic rocks, the volcanic rocks along the northern and eastern parts of the study area.

In interpreting potential field data, edge detection methods play an important role. In this study, various edge detection methods were applied to potential field data (Bouguer gravity and magnetic) to detect the edges of subsurface structures. THDR, TA, and TM methods were used for this purpose. The source boundaries are obtained from the zero contours of TA.

TA, TM, THDR, and Euler deconvolution methods were applied to the magnetic anomaly successfully. Hence, the edges of sources were obtained clearly. The predominant structural edges were obtained from the edge detection analysis of TA map. These edges are at NE–SW and NW–SE directions in magnetic data, generally. The trends correspond to the well-known geological contact, tectonic, and earthquake distribution. In the TA map of magnetic anomaly, the boundaries of the structure can be easily determined using 3 different contours (0, +\(\pi/4\), –\(\pi/4\)). Furthermore, half of the distance between the contours +\(\pi/4\) and –\(\pi/4\) gives the top depth of source causing the anomaly in the TA map. In this study, the upper depths of the structures were calculated using the TA map at 15 points chosen near the block centers. The calculated depths range from 2.05 km (close to the block 6) to 4.44 km (close to the block 14). In addition, the edges and top depths of the magnetic source obtained from 3D Euler deconvolution ranged from a mean value of 0 to 16 km with SI = 1.

The boundaries obtained from the TA map and the Euler deconvolution were compared in order to clearly reveal the magnetic source geometry by superimposing ED results and zero contours of TA. It is seen that the structure boundaries obtained using these two different methods were found to be substantially consistent with each other. In addition, in this study, the depths from different methods (\(z_1\) values, the minimum depths in the blocks by Euler Deconvolution method and the depths from the TA map) were compared with each other.

The depths obtained for the blocks b11–b15 located at the north of the study area are as follows: 2.27, 2.55, 3.16, 4.44, 2.94 km by TA map, respectively. Considering the minimum depths in all blocks by Euler Deconvolution method, 0–3 km and the depths of \(z_1\) were obtained as 1.91, 1.82, 1.91, 1.67, 1.39 km, respectively. The depths obtained using the tilt angle method for the blocks b1–b5 located at the south of the study area are as follows 3.05, 2.11, 3.22, 3.27, 2.61 km, respectively. Considering the minimum depths in all blocks by Euler Deconvolution method, 0–3 km, \(z_1\) depths were estimated as 1.86, 2.13, 1.95, 1.80, 2.11 km.
km, respectively. In general, it can be said that the depths obtained using different methods are compatible with each other. It can be said that known magmatic geological units are related with dominant lineaments in the northern region of the study area.

The gravity values range from –210 to 50 mGal in the Bouguer gravity map of the study area. The northern part of the study area has relatively greater positive gravity values (10–50 mGal). The lowest negative gravity values (~170 mGal to ~210 mGal) are observed in the Erzincan Basin. Moreover, possible structural boundaries were detected applying edge detection methods to Bouguer gravity data. The tectonic map has been compared with dominant lineaments and new lineaments have been obtained using the edge detection methods. There is a good agreement between the geophysical results and the boundaries of

<table>
<thead>
<tr>
<th>Block no.</th>
<th>Block center-x</th>
<th>Block center-y</th>
<th>Magnetic source depth (km)</th>
<th>Tilt angle</th>
<th>Euler deconvolution</th>
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**Figure 16.** Heat flow map for the study area. The values were illustrated on the map with different symbols for different heat flow values.
geological formations and tectonic structures. TA and Euler Deconvolution methods have given better results in the gravity method. The edges and top depths of the gravity source were obtained from 3D Euler deconvolution method. The depths of source change from 0 to 15 km for SI = 0 as can be seen in the superimposed map consisting of the TA and ED results. The zero contours of TA map and the edges obtained by Euler Deconvolution method were found to be highly compatible with each other. The upper depth of the NE–SW-oriented structure in the south of Sivas Province is estimated between 0 and 6 km. It can be said that the depth of the boundary of Erzincan basin in the NE direction varies between 3 and 6 km. It can be said that the fault located in the south of Sivas Province continues in the SW and NE directions with the TA and Euler deconvolution applied to both gravity and magnetic data. The structure located in the south of Giresun Province in the SE and NW directions was detected with

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<th>Block no.</th>
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**Figure 17.** The relationship between CPD and surface heat flow.
the TA and Euler deconvolution applied to both gravity and magnetic data. The structure similar to the circle in the south of Sivas Province draws attention in the edge detection analysis applied to gravity data.

CPDs for the study area were estimated using EMAG2 magnetic data using spectral analysis. The CPD values change from 15.73 km to 18.61 km. The CPD of 17–19 km was observed in the northern part of study area covered by volcanic units. When the results of other researchers were examined in the northern part of the study area (blocks of 11–15); for b11 block Maden et al. (2009a), Bektas et al. (2007), and Aydın et al. (2005) obtained the CPD values as 19.5 km, 15.5 km, and 22 km, respectively. In this study, the CPD was obtained as 17.73 km for b11 block. For block b13, Maden et al. (2009a), Bektas et al. (2007), and Aydın et al. (2005) obtained the CPD values as 19 km, 17.5 km, and 22 km, respectively. In this study, the CPD was obtained as 17.17 km for b13 block. For block b15, Maden et al. (2009a), Bektas et al. (2007), and Aydın et al. (2005) obtained the CPD values as 22.5 km, 16 km, and 22 km, respectively. In this study, the CPD was obtained as 17.61 km for b15 block. CPD values were estimated from 17 km to 18 km in block 7 located near the Sivas Province and in block 10 located at the northwest of Erzincan Province. Shallow CPD values were obtained in the southern parts of the study area. Shallow CPD values which change between 15 and 17 km could be explained with crustal thinning. The shallow CDP values are suitable with earthquake distributions and the tectonic structure in depth. Seismic activity or earthquake distribution is the result of tectonic characteristics of the study area. The reason why the depths are different may be that the authors used different data and data processing methods.

In the present study, heat flow values were calculated according to Fourier’s law. In areas where CPD values increase, heat flow values decrease. Heat flow values vary between 75 mW m\(^{-2}\) and 95 mW m\(^{-2}\) for the study area. Important geothermal energy fields are characterized by high heat flow. Therefore, these areas can be associated with shallow CPD values and high heat flow values. High heat flow values (85–95 mW m\(^{-2}\)) in the study area were generally obtained in the south of the study area. The heat flow map indicated that the highest heat flow values (90–95 mW m\(^{-2}\)) were estimated in the southeast of Sivas Province and the lowest heat flow values (75–80 mW m\(^{-2}\)) were obtained in the southern part of Giresun Province. In particular, the south of the study area where high heat flow values are obtained can be said as possible geothermal potential areas. High negative Bouguer gravity anomalies are also noteworthy in these areas. A plot of CPDs versus heat flow values revealed an exponential relationship between heat flow and CPDs with correlation coefficient 1.0. A good correlation was detected between the CPDs and the heat flow values.

The epicenter of earthquakes (M ≥ 3) between 1900 and 2018 and heat flow values were compared. High seismic activity draws attention in the south-eastern parts of the study area where CPD is low and heat flow is high. This situation can be explained by the complex geological structure of this region. In the northeastern part of the study area, the seismic activity is low and the heat flow values are relatively low.

Acknowledgments

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References


