Turkish Journal of Earth Sciences (Turkish J. Earth Sci.), Vol. 18, 2009, pp. 383–392.
doi:10.3906/yer-0803-7 First published online 02 March 2009

Crustal Thermal Properties of the Central Pontides (Northern Turkey) Deduced from Spectral Analysis of Magnetic Data

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Received 14 March 2008; revised typescript received 21 July 2008; accepted 28 February 2009

Abstract: The Pontides can be divided tectonically into three main sectors: Eastern, Central, and Western Pontides. Each of these represents an amalgamated tectonic mosaic consisting of remnants of oceanic, continental, and island arc segments. The Eastern and the Western Pontides meet in the Central Pontides, where they are structurally mixed and form a tectonic knot. The Central Pontides of northern Turkey is one of the best exposed segments of the southern margin of Eurasia adjacent to the Tethys Ocean. The study area also extends to parts of the Sakarya and Kırşehir continents.

Magnetic spectral analysis, which has been used to estimate the Curie point depths and heat flow values, is employed to identify the thermal regime of the Central Pontides. The magnetic data of the region are separated into five subregions and the power spectra of each region is achieved by using 2D Fourier transform method to attain the average curie depth. The curie depth values changes across the studied region from 14.8 km in the south to 21.8 km in the north. The obtained results imply a high thermal gradient (39.2 °Ckm^{-1}) and corresponding heat flow values (94.1 mWm^{-2}) in the south of the research area. The northern part of the study area displays a low thermal gradient (26.6 °Ckm^{-1}) and low heat flow value (63.9 mWm^{-2}), corresponding to the Central Pontides consisting of accreted oceanic crustal material. The determined values show the heat flow decrease within the accretionary prism toward the island arc-like Pontides.

Key Words: heat flow, Curie point depth, spectral analysis, Central Pontides

Orta Pontidlerin (Kuzey Türkiye) Kabuksal Isıl Özelliklerinin Manyetik Verilerin Spektral Analizi ile Belirlenmesi

Özet: Pontidler tektonik olarak Doğu, Batı ve Orta Pontidler olmak üzere üç ana bölgeye ayrılabilir. Bu birimlerin her biri okyanusal, kıtasal ve ada yayı parçalarından oluşan birleşik bir tektonik mozayiği göstermektedir. Doğu ve Batı Pontid tektonostratigrafik birimleri Orta Pontidlerde birleşmekte olup burada yapısal olarak kaynaşmakta ve tektonik bir düğüm oluşturmaktadır. Türkiye'nin kuzeyinde yer alan Orta Pontidler Tetis Okyanusuna bitişik Avrasya'nın güney kenarına ait parçaların en iyi görüldüğü yerdir. Çalışma alanı ayrıca Sakarya ve Kırşehir kıtalarını da içermektedir.

Curie noktası derinliği ve ısı akısı değerlerini belirlemek için kullanılan Manyetik Spektral Analiz yöntemi Orta Pontidlerin termal rejimini tanımlamak için değerlendirilmiştir. Manyetik veri beş alt bölgeye ayrılmış ve her alt bölgenin ortalama Curie derinliğini belirlemek için 2B Fourier dönüşümü yöntemiyle güç spektrumları hesaplanmıştır. Çalışma alanında, Curie noktası derinlik değerleri güneyde 14.8 km'den kuzeyde 21.8 km'ye değişmektedir. Elde edilen değerler inceleme alanının güneyinde yüksek termal gradienti (39.2 °Ckm^{-1}) ve buna karşılık gelen yüksek ısı akısını (94.1 mWm^{-2}) göstermektedir. Çalışma alanının kuzeyinde yer alan yığışmış okyanusal kabuk malzemesinden oluşan Orta Pontidler düşük termal gradient (26.6 °Ckm^{-1}) ve düşük ısı akısı (63.9 mWm^{-2}) değerlerini göstermektedir. Belirlenen ısı akısı değerlerinin Pontidler gibi ada yaylarına doğru yığışım prizması içinde azaldığını ortaya koymuştur.

Anahtar Sözcükler: ısı akısı, Curie noktası derinliği, spektral analiz, Orta Pontidler

Introduction

The Central Pontides, which lie between the İzmir-Ankara suture in the south and the Black Sea in the north, include parts of the İstanbul and Sakarya zones, which were tectonically juxtaposed during the Early–Late Cretaceous (Figure 1) (Tüysüz 1999). The Central Pontides consist of the following main tectonic zones, from north to south: (i) the northern zone, (ii) the Araç-Daday shear zone, (iii) the Kastamonu-Boyabat basin fill, (iv) the Kargı Massif, and (v) the ophiolite belt (Figure 2). The northern zone comprises a magmatic belt formed during the Late–Early Cretaceous on the passive continental margin succession. The ophiolite belt is represented by disrupted ophiolite and the upper Cretaceous ophiolitic mélange association, which developed because of progressive northward subduction and obduction of the Neotethyan ocean floor (Şengör *et al*. 1985; Ustaömer & Robertson 1997; Yılmaz *et al*. 1997).

The study region also includes parts of the Sakarya and Kırşehir zones in addition to the western rim of the Eastern Pontides. The Sakarya zone has a basement of Permo–Triassic subduction-accretion complexes, unconformably overlain by a Jurassic and younger sedimentary cover (Okay & Tüysüz 1999). A major part of the Central Pontides consists of the metamorphic rocks of the Kargı Massif, generally regarded as part of the Sakarya zone. The Kargı Massif is considered to be a Palaeo-Tethyan subduction complex consisting of accreted pre-Jurassic ophiolite, mélange, and magmatic arc sequences (Okay *et al*. 2006). The Tokat Massif represents the metamorphic complex of the Eastern Pontide range (Yılmaz *et al*. 1997). The Kırşehir Massif, which is in contact along the controversial Inner Tauride suture with the Anatolide-Tauride Block, consists mainly of metamorphic and granitic rocks of Cretaceous age (Okay & Tüysüz 1999).

The spectral analysis method has widely been used to compute the Curie point depth from magnetic anomaly data (Bhattacharyya & Leu 1975, 1977; Gerard & Debaglia 1975; Byerly & Stolt 1977; Shuey *et al*. 1977; Bhattacharyya 1978; Connard *et al*. 1983; Okubo *et al*. 1985, 1989, 1991; Blakely 1988, 1995; Pilkington *et al*. 1994; Maus & Dimri 1995, 1996; Tsokas *et al*. 1998; Tanaka *et al*. 1999; Stampolidis & Tsokas 2002; Bansal & Dimri 2005; Stampolidis *et al*. 2005; Bansel *et al*. 2006). The Curie point is the depth at which the dominant magnetic minerals reach a crustal temperature (≈580 °C) at which rocks lose their magnetic properties. The Curie point depth, based on spectrum analysis of magnetic anomaly data, can be used to determine the crustal thermal structure of the region.

In Turkey, many researchers (Ateş *et al*. 2005; Aydın *et al*. 2005; Dolmaz *et al*. 2005; Bektaş *et al*. 2007; Bilim 2007) have carried out studies on the Curie point depth using magnetic data. The Curie-point isotherm map of Turkey, prepared from aeromagnetic data using a spectral analysis technique (Aydın *et al*. 2005), shows that the maximum Curie point depths are found to be between 20–29 km in the Eastern Pontides and Western Taurus belt, while the minimum Curie point depths in the Aegean region are as shallow as 6–10 km. In Central Anatolia, Curie depth values are revealed to change from 7.9 km and 22.6 km (Ateş *et al*. 2005), unlike Western Anatolia where the Curie point depth varies from 8.2 to 19.9 km (Dolmaz *et al*. 2005). In Eastern Anatolia, Bektaş *et al*. (2007) analyzed the magnetic anomaly data and found the Curie point depth varied between 12.9 and 22.6 km.

In this paper, the magnetic data from the Central Pontides are analyzed to estimate the Curie point depths, thermal gradients, and heat flow values of the Central Pontides by using the method of Okubo *et al*. (1985, 1989) and Tanaka *et al*. (1999). This area of extremely complex tectonics has been poorly sampled for heat flow data. The heat flow value is estimated by using the Curie point depth in order to understand the thermal regime of the study area. The correlation between the obtained Curie point and the heat flow data indicates that the Curie point depth is a useful indicator of the thermal structure in the region.

Data and Methodology

The aeromagnetic data of Turkey were measured between 1978 and 1989 by the General Directorate of Mineral Research and Exploration (MTA) of Turkey. Flight lines, oriented perpendicular to the regional geologic formations and tectonic structures, vary between 1 km and 5 km and the flight altitude is

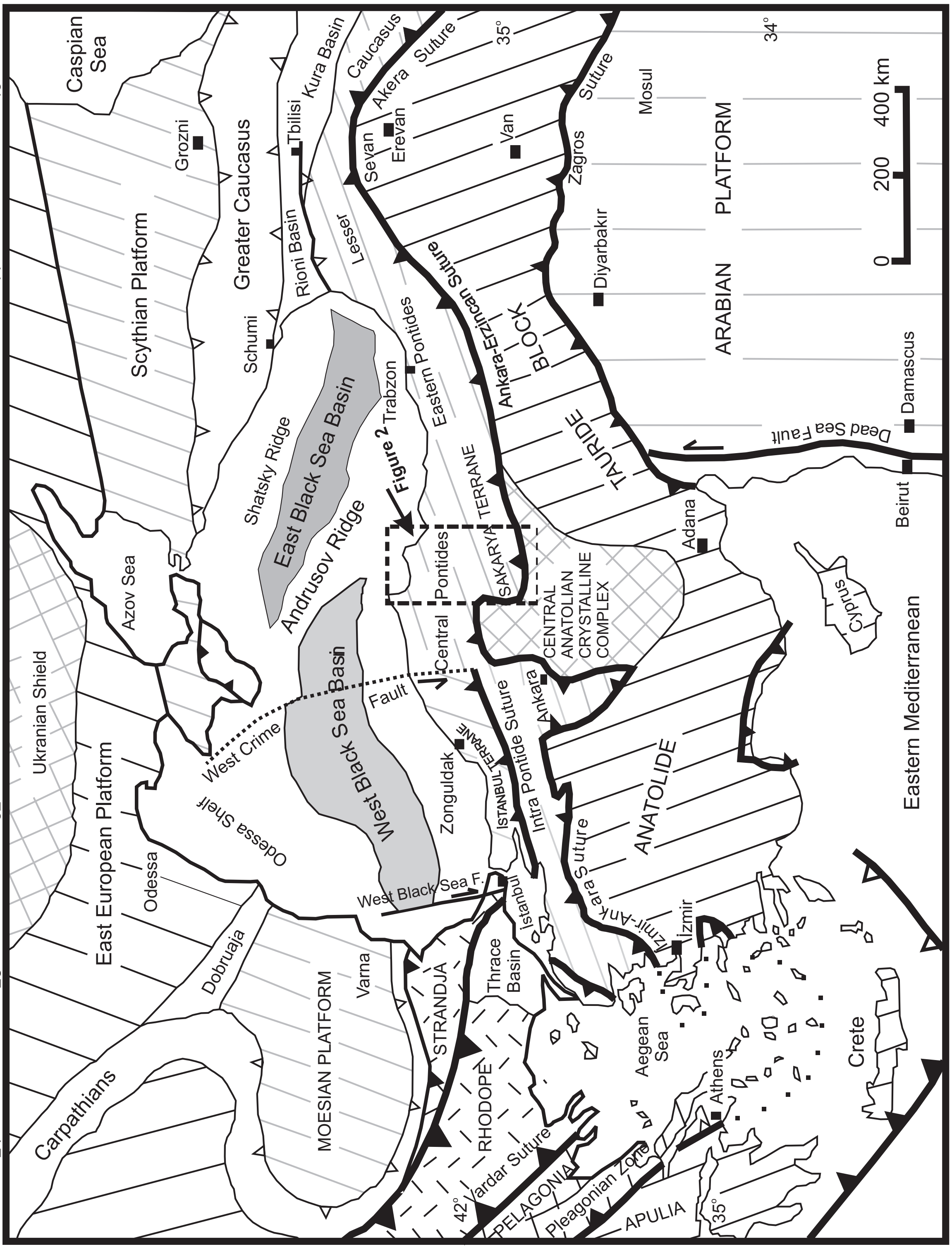

Figure 1. Tectonic map of the Turkey and surrounding region showing the major sutures and continental blocks (Okay & Tüysüz 1999; Okay *et al.* 2006). Dashed-line box shows location of study area shown in Figure 2.

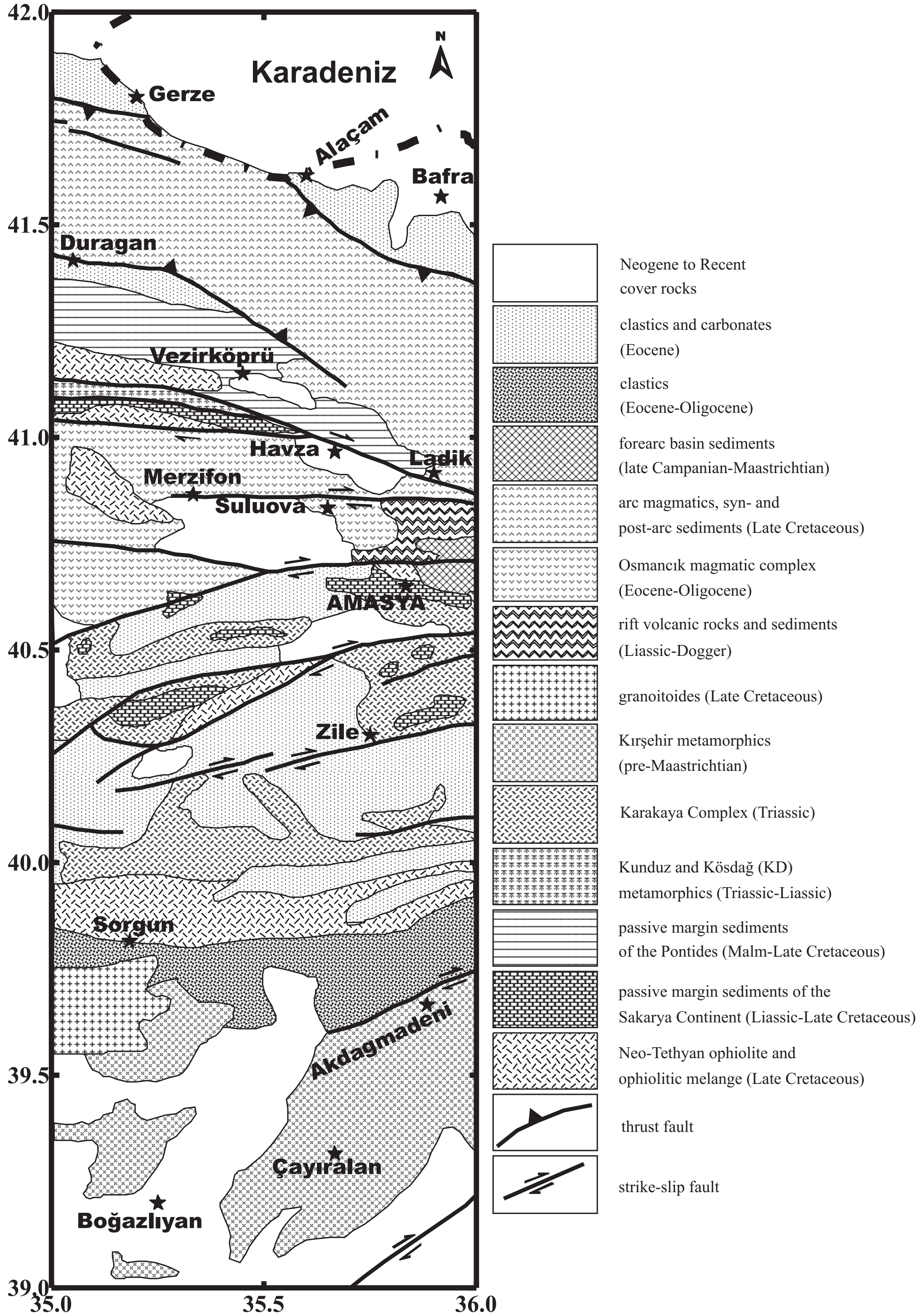

Figure 2. Geological map of the Central Pontides (modified from Yılmaz *et al.* 1997).

about 600 m above the ground surface. The IGRF (1982.5) was removed from the data to prepare the aeromagnetic anomaly map of Turkey. The aeromagnetic data of the study region (Figure 3) was obtained from the MTA with grid interval of 2.5 km (Aydın & Karat 1995; Aydın *et al.* 2005).

Okubo *et al.* (1985, 1989) provided a two-step method to estimate the bottom depth (Z_b) of the deepest magnetic sources using the spectral analysis method formulated by Spector & Grant (1970).

In this method initial computation of the depth to centroid of a magnetic body (Z_o) is followed by the estimation of the top bound (Z_t) of the magnetized source. These depth values are determined by fitting a straight line through the high and low-wave number parts of the radially averaged power spectrum of

$$\ln\left[\Phi_{\Delta T}(|k|)^{1/2}\right] \text{ and } \ln\left\{\left[\Phi_{\Delta T}(|k|)^{1/2}\right]/|k|\right\},$$

where $\Phi_{\Delta T}$ is the power spectra of the magnetic anomaly data and k is the wave number (Figure 4). Then, the Curie point depth (Z_b) is calculated from these two depths as follows.

$$Z_b = 2Z_o - Z_t \quad (1)$$

The depth of the anomaly sources causing the magnetic anomaly is given by,

$$Z_i = \frac{\ln \Phi_{\Delta T}(k_{i+1}) - \ln \Phi_{\Delta T}(k_i)}{2(k_{i+1} - k_i)} \quad (2)$$

relationships from the radial wavenumber curves, where $\Phi_{\Delta T}$ is the power spectrum of the magnetic data, k is wave-number and Z is the depth of the anomaly sources (Cianciara & Marcak 1976). The heat flow value is expressed by Fourier's law with the following formula,

$$q = \lambda \frac{dT}{dZ} \quad (3)$$

where q is the heat flow and λ is the coefficient of thermal conductivity. In this equation, it is assumed that the direction of the temperature variation is vertical and the temperature gradient dT/dZ is constant. According to Tanaka *et al.* (1999), the Curie temperature (θ) can be obtained from the Curie point depth (Z_b) and the thermal gradient dT/dZ using the following equation;

$$\theta = \left[\frac{dT}{dZ}\right] Z_b \quad (4)$$

In this equation, it is assumed that the surface temperature is 0 °C and no heat sources exist between the Earth's surface and the Curie point depth. In addition, from Equation (3) and Equation (4) a relationship can be determined between the Curie point depth (Z_b) and the heat flow (q) as follows.

$$q = \lambda \left[\frac{\theta}{Z_b}\right] \quad (5)$$

In this equation the Curie point depth is inversely proportional to the heat flow (Turcotte & Schubert 1982; Tanaka *et al.* 1999; Stampolidis *et al.* 2005).

Spectral Analysis of Magnetic Data

The high frequency magnetic anomalies near Merzifon, Amasya, Akdağmadeni, Sorgun and Zile appear to be associated with volcanic and sedimentary rocks and granitoids. In the south of the study region, high frequency magnetic anomalies may originate from the Upper Cretaceous ophiolitic melange between the Pontides and Kırşehir Massif. Across the Çankırı Basin the magnetic anomalies do not exceed 1700 nT. Magnetic anomaly patterns were observed to run parallel to the main tectonic elements of the study region.

To discover the Curie depth of the region, the power spectrum method is applied to the magnetic anomaly data of the region. In this method the magnetic data must be reduced-to-the-pole before low pass filtering to remove the effects of topography (Tanaka *et al.* 1999). The power spectrum curve (Figure 4) is computed in the Fourier domain. The values on the graphs show the depth of the top bounds (Z_t = 13.2 km), and centroids (Z_o = 16.8 km) of magnetic sources, respectively. The average Curie point depth (Z_b = 20.4 km) is then computed by using these two depth values for this region.

In this study, the Curie point temperature is assumed to be 580 °C in order to compute the thermal gradient of the region. Thus, the thermal gradient is calculated as (580 °C/20.4 km) 28.4 °Ckm^{-1}. To fix the heat flow value of the region,

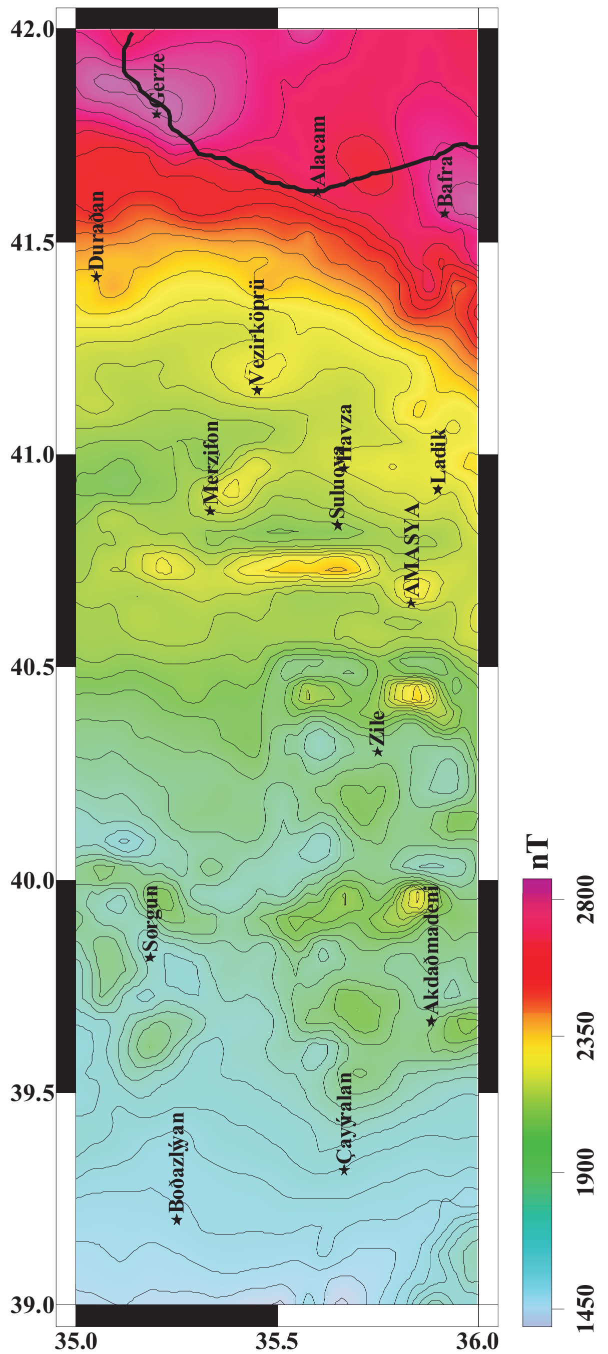

Figure 3. Magnetic anomaly map of the study region. Contour interval is 50 nT. Colour bar indicates interval values. Colour levels point out anomaly intensity from magenta (highest) to blue (lowest).

Equation 3 is used and the thermal conductivity value is taken as 2.1 $Wm^{-1}°C^{-1}$, as suggested by Tezcan (1979). The average heat flow value for the whole area is estimated at 59.6 mWm^{-2}.

To reveal a 2D Curie depth profile, the study area was separated into 5 different subregions with dimensions of 1°×1° and step intervals of 0.5°. The magnetic anomaly data of the subregions are transformed into the frequency domain using the 2D Fourier method. The magnetic data was reduced-to-pole before low pass filtering to remove the effects of topography and regional features, thus avoiding erratic estimates of the Curie point depth (Tanaka *et al.* 1999). Figure 5 shows the example graph of the power spectra curve to find the depth of the Curie point by using 2D magnetic anomaly data covering the area 35°E, 41°N to 36°E, 42°N. The depth to the top (Z_t), centroid (Z_o) and basal depth (Z_b) of the magnetic source are computed by the least squares method. The basal depth is interpreted as the bottom depth of the magnetized source causing the magnetic anomaly. The 2D Curie depth profile beneath the study region was determined from a spectral analysis technique, which showed that the Curie point surface is undulating and deepens from 14.8 km in the south to 21.8 km in the north (Figure 6). The heat flow values obtained from Curie point depth and thermal gradient values varie from 94.1 mWm^{-2} in the south to 63.8 mWm^{-2} in the north. The graph of heat flow (q) versus Curie point depth (Z_b) values (Table 1), shows that they are proportional with a relationship of $q = 1392\ Z_b^{-1}$ (Figure 7), as given in Equation (5).

Discussion and Conclusions

In Turkey, estimates of the Curie point depth using magnetic anomaly data undertaken by various researchers (Ateş *et al.* 2005; Aydın *et al.* 2005; Bektaş *et al.* 2007; Bilim 2007). Ateş *et al.* (2005) computed that the Curie depth values vary between 7.9 km and 22.6 km in Central Anatolia. Aydın *et al.* (2005) used the spectral analysis method to evaluate a Curie-point isotherm map of Turkey. They found the maximum and minimum Curie point depths in this area are 12 km and 24 km, respectively.

Previous studies showed that the Curie point depth is linked to the geological context. Tanaka *et al.* (1999) pointed out that the Curie point depths are about 10 km or less in volcanic and geothermal areas, 15–25 km on island arcs and ridges, deeper than 20

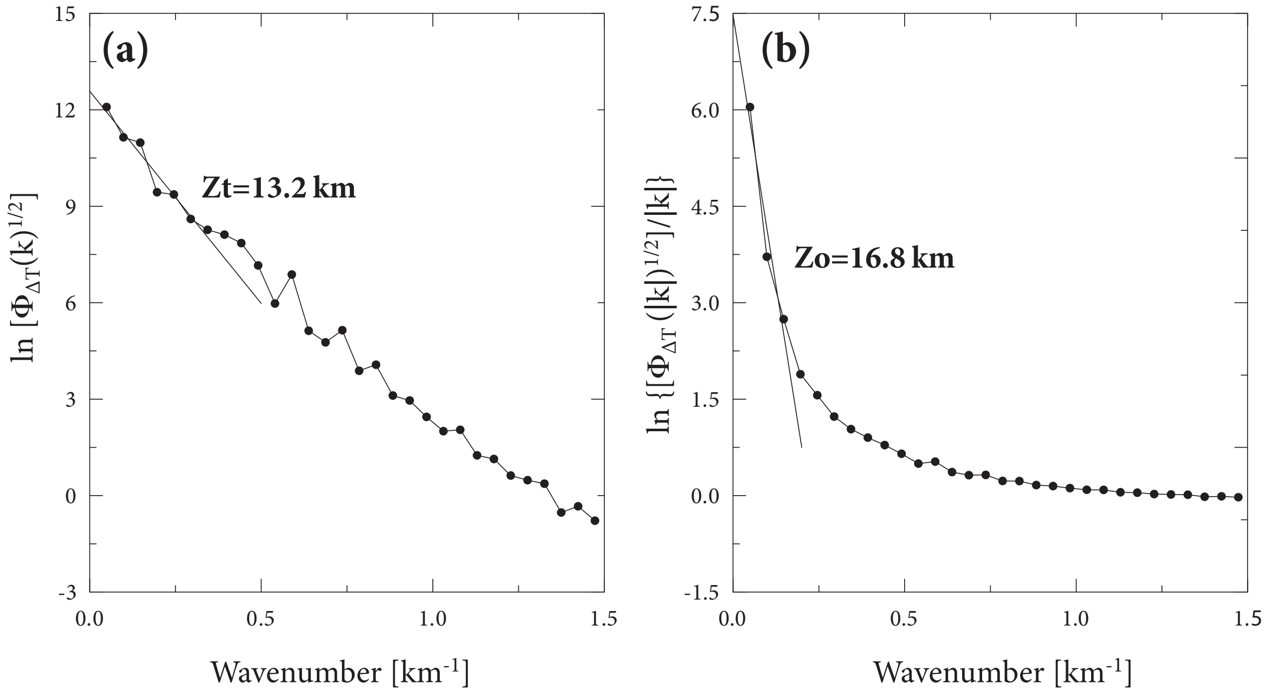

Figure 4. The Power spectrum curves of the reduced to pole magnetic data of the study region. The values over the linear segments are the depths to the upper bound (Z_t = 13.2 km), and centroid (Z_o = 16.8 km) estimated by least squares method.

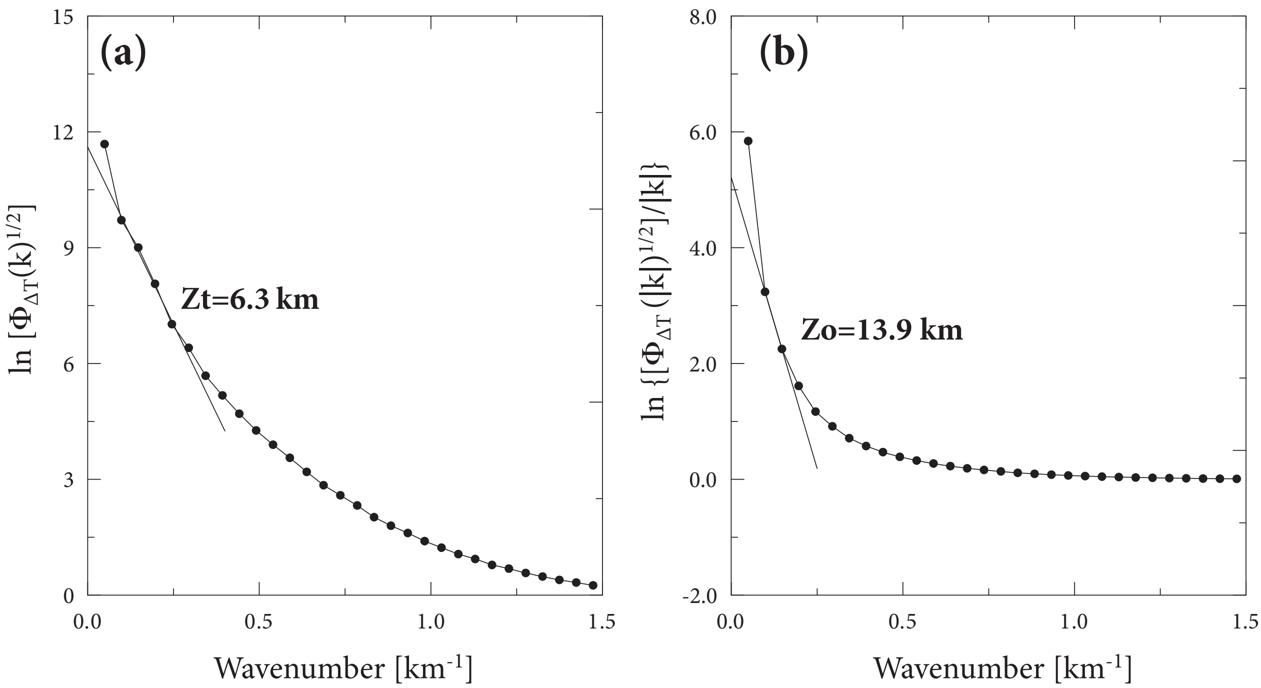

Figure 5. Examples of spectra for the estimation of the depth to Curie point using the 2D magnetic anomaly data covering a region of (35°E, 41°N)–(36°E, 42°N). The values over the linear segments are the depths to the upper limit (Z_t = 6.3 km) and centroid (Z_o = 13.9 km) estimated by the least squares method.

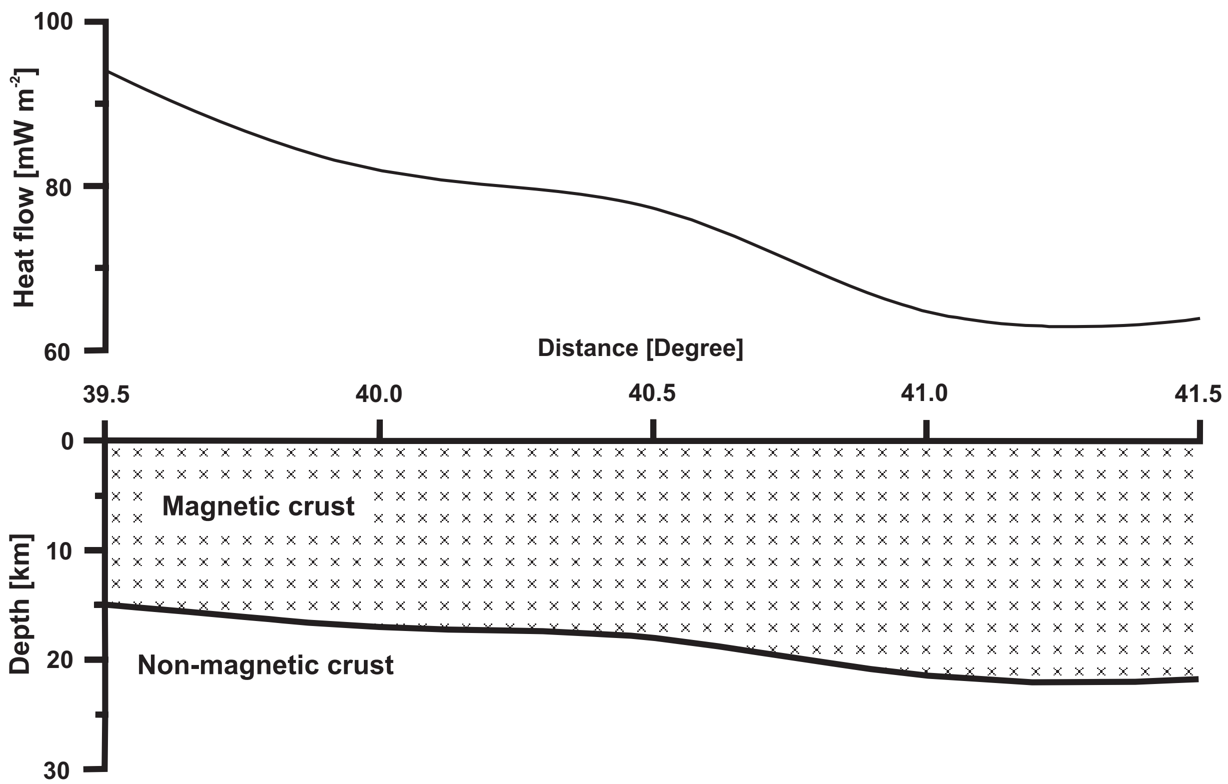

Figure 6. 2D Curie point depth and heat flow anomaly section for the study region.

Table 1. The calculated Curie point depth and Heat Flow values for the study region.

Location	Curie Point Depth [km]	Thermal Gradient [°Ckm^{-1}]	Heat Flow [mWm^{-2}]
Whole Data	20.4	28.4	59.6
(35.0°E,39.0°N)–(36.0°E,40.0°N)	14.8	39.2	94.1
(35.0°E,39.5°N)–(36.0°E,40.5°N)	17.0	34.1	81.9
(35.0°E,40.0°N)–(36.0°E,41.0°N)	18.0	32.2	77.3
(35.0°E,40.5°N)–(36.0°E,41.5°N)	21.5	26.9	64.7
(35.0°E,41.0°N)–(36.0°E,42.0°N)	21.8	26.6	63.9

km in plateaus, and over 30 km in trenches. Curie point depths in continental areas are generally deeper than those in oceanic areas. Shallow Curie point depths are consistent with high heat flow values, as seen in back-arc regions, young volcanic regions and trenches (Yamano 1995).

The average Curie point depth, determined from a spectral analysis technique applied to magnetic data, is 20.4 km for the region. The thermal gradient and heat flow values are calculated at 28.4 °Ckm^{-1}, 59.6 m Wm^{-2}, respectively. In the study area, the depth of the Curie point surface changes from 14.8

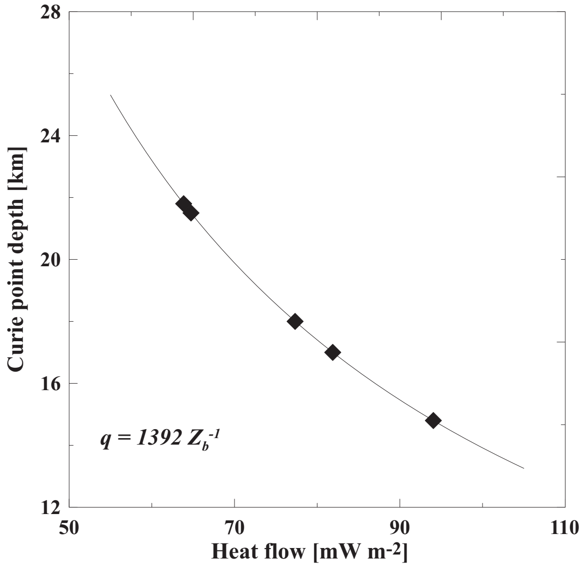

Figure 7. The Curie point depth versus heat flow data graph for the study region.

km in the south to 21.8 km in the north. The heat flow values computed from the Curie depth values vary from 94.1 mWm^{-2} in the south to 63.8 mWm^{-2} in the north. These results show that the south of the investigated area has relatively high geothermal potential compared to the northern part of the region. It is possible that partial melting of the crust caused by rising magma contributed to the present high geothermal potential in the south of the study area.

Acknowledgments

I express my thanks to General Directorate of the Mineral Research and Exploration (MTA) of Turkey for providing digital aeromagnetic data. I would like to thank Professor Ram Bansal and anonymous referees for their thorough critical and constructive comments. I am grateful to Erdin Bozkurt for his editorial advice to improve this manuscript. English of the final text is edited by John A. Winchester.

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