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Determination of the Curie Point Depth and Heat Flow From Magsat Data of Western Anatolia

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Abstract: *Temperature in the earth is one of the most important parameters in models for the constitution and active tectonics of the crust. However this subject is most poorly known.*

A boundary condition on temperature at depth in the continental crust can be principle to obtained by mapping the curie isotherm where it forms the base of magnetic crust. At the Curie temperature, a substance loses cause to magnetic polarization. Consequently, it may be possible to locate a point on the isothermal surface by determining the depth to the bottom of a polarized rock mass. If enough depths can be determined, an isothermal surface at the Curie temperature can be defined. An approach to map the magnetic crustal thickness using satellite magnetic anomaly data could be described.

In this study, the moving windows power spectrum and other power spectrum methods based on spectrum analysis have been applied to the total component Magsat data of the Western Anatolian Region and Curie depths were determined. Then, heat flow values were determined with regard to the region by using the depths and taking into consideration of heat conductivity (2 W/m^{0}C).

In conclusion, the results of both methods were compared and interpreted for the aforementioned region. Moreover, the heat flow values derived from the Curie depths, which has found through the application spectral analysis were interpreted with the tectonic structure whether are in association. Additionally, prominent geothermal fields in the region were investigated together with their computed heat flow values.

Keywords: *Curie depth, Magsat, Heat flow, Western Anatolia.*

Introduction

Geocentric X (North), Y (East) and Z (Radial inward) components of geomagnetic field and total intensity together with the geocentric latitude, longitude and radial distance are measured from the Magsat spacecraft. Magsat maps were prepared by subtracting the external and main field from Magsat data. Total component Magsat maps of western Turkey were prepared using Magsat data obtained from the British Geological Survey covering the area between 25° - 32° E longitudes and 36° - 41° N latitudes.

Magnetic anomalies at the satellite altitude can be explained by a thick magnetic layer with relatively lower susceptibility contrast or by a thin layer with higher susceptibility contrast. Furthermore, a given magnetic anomaly can be interpreted in terms of different models. For example, the anomaly can be interpreted due to lateral variations in temperature inside on an otherwise uniform layer, suggesting that the magnetic anomalies are due to variations in depth to the Curie isotherm within the layer (Mayhew, 1982). The anomalies can also be interpreted as being due to lateral variations in the magnetic mineral content and in the rock type of the magnetic layer or by a combination of these factors.

In a total component Magsat magnetic anomaly map, magnetic anomalies are irregularly distributed over western Turkey (Şalk, 1994). Positive magnetic anomalies are observed along the Izmir-Ankara ophiolite zone, in the North Aegean and in the Massifs of western Turkey. These anomalies can be related to the intrusives of magmatic and granitic masses.

In this study, total component Magsat maps were used to compute the Curie depth using the moving power spectrum (Spector and Grant, 1970) and the spectrum analysis (Tanaka et al., 1999).

Theoretical studies about the Curie depth have been conducted by several researchers (e.g. Vacquier and Affleck, 1941; Serson and Honnoford, 1957; Alldredge and Van Voorhis, 1961; Battacharrya and Morley, 1965; Hisarlı, 1996; Tsokas et al., 1998; Tanaka et al., 1999; Stampolidis and Tsokas, 2002; Pamukçu, 2004; Dolmaz et al., 2005; Cathrine Fox Maule et al., 2005; Aydın et al., 2005)

The results of both methods applied to total component Magsat data that have a sampling distance of 2 km are parallel to tectonic activity, volcanics and geothermal fields in the region.

However, when the moving window power spectrum was compared to the spectrum analysis, the obtained Curie depths were shallower and the heat flow values were higher. When these results were compared to the heat flow values formed by Tezcan and Turgay (1989), the results of the spectrum analysis seem to be more consistent. The reason is that the average depth of structure is found by using the moving window power spectrum, but the basal depths of the magnetic sources were estimated from the spectrum analysis.

The obtained results are consistent with the previous studies regarding the region (e.g. Aydın et al., 2005)

Geology of Western Turkey

The tectonic gross feature of Turkey is shown in Fig 1.

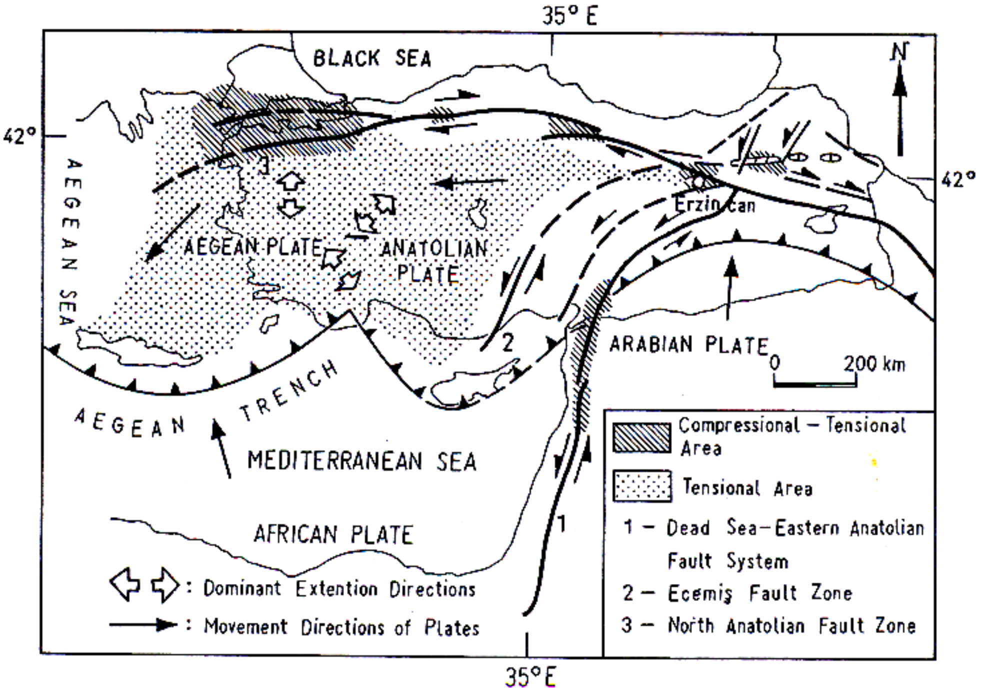

Figure 1. Main tectonic structures of Turkey (Koçyiğit, 1984).

The Aegean and Anatolian plates cover the western and central parts of the country.

Many of the natural phenomena, which lie within the scope of geophysics, are related with the earth's heat. Some of these can be described as follows: all physical properties of rocks, the existence of many minerals, geothermal areas, internal mantle movements as a result of plate tectonics and geomagnetic field of the earth due to the induce electrokinematic currents produced within the melted outer core. All these cause increase of temperature with depth. Turkey is within an area of high heat flow.

Western Turkey is one of the most seismically active and rapidly extending regions in the world. As a result, it has a long history of large earthquakes, magmatic and volcanic activity and high heat flow. The Neogene geological evolution of Western Turkey involves a widespread magmatism producing intrusive as well as extrusive rocks.

Three main types of magmatic rock groups can be readily distinguished in the region. The first group is an intermediate to the felsic variety of the volcanic series were referred as andesitic suite. The second group consists predominantly of the felsic varieties were referred as the granitic suite. The third group is represented by the locally developed basic lavas. The basic rocks were referred as the basaltic suite (Yılmaz, 1989).

The volcanics in western Turkey contain both calc-alkaline and alkaline. In the region of western Turkey and the Aegean, volcanism has been active since the Eocene with varying intensity and distribution in both space and time. Lava flows and pyroclastics cover extensive areas from the present Hellenic Arc in the south towards the Black Sea in the north. Domes, lava flows and agglomerates with minor tuffs and ignimbrite sheets cover extensive areas in western Turkey as well as in the northern and central islands. These volcanics are essentially calc-alkaline in nature, although volumetrically minor shoshonitic-alkaline volcanics overlap with the calc-alkaline ones in both space and time. Calc-alkaline volcanics range in composition from basaltic andesite to rhyolite. However, they are dominated by andesites and dasites. Shoshonitic volcanics (Afyon, Denizli, Bodrum, Kos, Patmos) and the alkaline volcanics with sodic nature (Ezine, Urla) are upper Miocene and younger in age and are comprised of dominantly basaltic compositions (Innocenti et al., 1982; Keller, 1983; Fytikas et al., 1984; Ercan et al., 1985; Savaşçın and Güleç, 1990). In western Turkey, Quaternary volcanics are observed in Kula and are represented by lava flows, cones and craters.

Method

Moving Windows Power Spectrum

The application of the power spectrum to potential field data and the identification of anomalies by this method has been studied by Bhattacharyya (1965-1966), Spector and Bhattacharyya (1966). The depths relating to these anomalies have been determined by Spector and Grant (1970) and these consequently have been used by many researchers afterwards.

The relation between the power spectrum and the structure causing anomaly was expressed using equation 1.

$$S(w)=\sum_{p=1}^{p} f^{p}(w,\alpha_1^{p},\alpha_2^{p},......,\alpha_n^{p})\exp(-2wh) \qquad (1)$$

where S(w) is the power spectrum, α is the structure parameter, h is the depth, f is an anomalous function. The accuracy of the spectrum estimation, which is a statistical approach, is possible with the smallest values of variance and mean square errors. In this practice, the data were divided equally with the help of a window function, the values at the same frequency were added and the arithmetical average was found. This operation is defined by the following equation (Jenkis and Watts, 1968);

$$\overline{S}(w) = \frac{1}{R}\sum_{r=1}^{R} S_r(w) \tag{2}$$

Here, S_r (w), is the power spectrum belonging to each section and R is the number of sections. The first spectrum was obtained by Cianciara and Marcak (1976). If the approach given in equation (2) was substituted in equation (1), the equation (3) is obtained.

$$\overline{S}(w) = \frac{1}{R}\sum_{r=1}^{R}\sum_{p=1}^{P} f_r^{\,p}(w, \alpha_1^{\,pr}, \alpha_2^{\,pr}, \ldots\ldots, \alpha_n^{\,pr}) \exp(-2wh) \tag{3}$$

In the equation (3)

$$f_r^{\,p}(w, \alpha_1^{\,pr}, \alpha_2^{\,pr}, \ldots\ldots, \alpha_n^{\,pr}) = c^{pr} = constant$$

$$C = \sum_{r=1}^{R}\frac{1}{R}\sum_{p=1}^{P} c^{pr}$$

neccessary transforms are achieved, the relation could be given by equation 4.

$$S = C.\exp(-2wh) \tag{4}$$

If the logarithm is taken on both sides in equation (4), the average depth depending to the structures causing anomaly is found with equation (5).

$$\overline{h}_i = \frac{\ln(w_{i+1}) - \ln(w_i)}{2(w_{i+1} - w_i)} \qquad i = 1, 2,\ldots\ldots \tag{5}$$

Benefiting from equation (5), structural depth is determined for every window of the anomaly, which was separated into windows. The structural depths computed by means of moving windows spectrum method are assigned to the mid-point of the x-axis, which they belong to. Thus, structural depth is obtained more in-to-depth along a profile.

Theoretical Model Based on Spectrum Analysis

The heat flow is the primary observable quantity to determine temperature variations. Many heat flow observations are derived from drillings on land and probes underwater. (Pollack et al., 1993). The measurements show geographically irregular distribution, they remain insufficient to define the regional thermal structures since the measured heat flow values reflect local thermal anomalies. Therefore, Curie point determination based on the spectrum analysis of magnetic anomaly data is significantly important. By this method, the depth at which is the magnetite passes from a ferromagnetic state to paramagnetic state under the effect of increasing temperature, is determined. The lower limit depth of such a magnetic source is taken as the Curie point depth.

The method is similar to the practical work performed by Spector and Grant (1970), depending on the determination by lower limit using the middle and upper depths. Blakely (1995), noted that in the case that a layer is presumed to extend infinitely in the horizontal direction, the depth of the magnetic source from the surface remains very minor when compared to the horizontal scale. In this situation, he described the magnetization M (x, y) as a random function of x and y axes. The power-density spectra of the total field anomaly are introduced as follows:

$$\mathbf{\Phi}_{\Delta T}(k_x, k_y) = \mathbf{\Phi}_M(k_x, k_y).F(k_x, k_y)$$

$$F(k_x, k_y) = 4\pi^2 C_m^2 |\Theta_m|^2 |\Theta_f|^2 e^{-2|k|d}(1 - e^{-|k|t})^2 \tag{6}$$

where, d is the depth of the upper surface and t is the thickness of the structure. Here, the Φ_M is the power-density spectra, C_M is the proportionality constant. Θ_M and Θ_f stand for the direction of magnetization and geomagnetic field, respectively. As

$|\Theta_M|^2$ and $|\Theta_f|^2$ are radially symmetrical, the relation between them can be simplified. Equation (6) was investigated by many authors (e.g. Tanaka et al., 1999) in diverse forms and basal depth of the magnetic source was found.

In this study, one dimensional spectrum analysis of a vertical magnetic sheet is investigated and using the approaches of Tanaka et al. (1999), the basal depth of the magnetic source was found theoretically.

The vertical component of the vertical finite magnetic sheet is given with the equation (7): (Grant and West, 1965).

$$\Delta Z = A\left\{\frac{x\sin\theta - h_2\cos\theta}{x^2+h_2^2} - \frac{x\sin\theta - h_1\cos\theta}{x^2+h_1^2}\right\} \qquad (7)$$

If the polarization angle of the magnet is at a position of $\theta = 90^0$, the vertical component will be equal to the total component (ΔZ=F). So, the equation (7) turns to the equation (8):

$$\Delta F = A\left\{\frac{x}{x^2+h_2^2} - \frac{x}{x^2+h_1^2}\right\} \qquad (8)$$

where the upper and the lower depths of vertical magnetic sheet are h_1 and h_2, respectively. The amplitude spectrum is explained by equation 9:

$$\Phi(k) = B\left(e^{-kh_1} - e^{-kh_2}\right) \qquad (9)$$

where B is a constant. If a similar approach to the study of Tanaka et al. (1999) is applied, the power spectrum is derived as follows:

$$G(k) = Be^{-2kh_1}\left(1 - e^{-k(h_2-h_1)}\right)^2 \qquad (10)$$

If the equation is arranged for short wavelengths; equation 11 was obtained:

$$\mathrm{Ln}(G(k)^{1/2}) = \ln C - kh_1 \qquad (11)$$

where C is a constant. From the upper depth of the structure is computed from equation (11). Additionally, assuming that h_0 is the mid-point of the structure, equation (10) is rearranged into the form given below:

$$G(k)^{1/2} = De^{-kh_0}\left(e^{-k(h_1-h_0)} - e^{-k(h_2-h_0)}\right) \qquad (12)$$

where D is a constant. The expression of equation (12) at long wavelengths could be expressed as follows:

$$G(k)^{1/2} = De^{-kh_0}\left(e^{-k(-d)} - e^{-k(d)}\right) \approx De^{-kh_0}\,2kd \qquad (13)$$

where 2d is the thickness of the magnetic source. In order to determine the mid-point of the structure, the equation given below is rearranged:

$$\ln(G(k)^{1/2}/k) = \ln E - kh_0 \qquad (14)$$

Benefiting from the mid-point and upper limit depths of the source, the lower depth (base depth) is found from the following equation (Tanaka et al., 1999):

$$h_2 = 2h_0 - h_1 \qquad (15)$$

As a result, by using the approaches of Blakely (1995) and Tanaka et al. (1999), the same results were obtained with one-dimensional power spectrum.

In order to exemplify this situation; the power spectra applied to the vertical magnetic sheet with upper depth of h_1 = 6 km and a lower depth of h_2 = 16 km through equations (11) and (14), are depicted in Fig. 2.

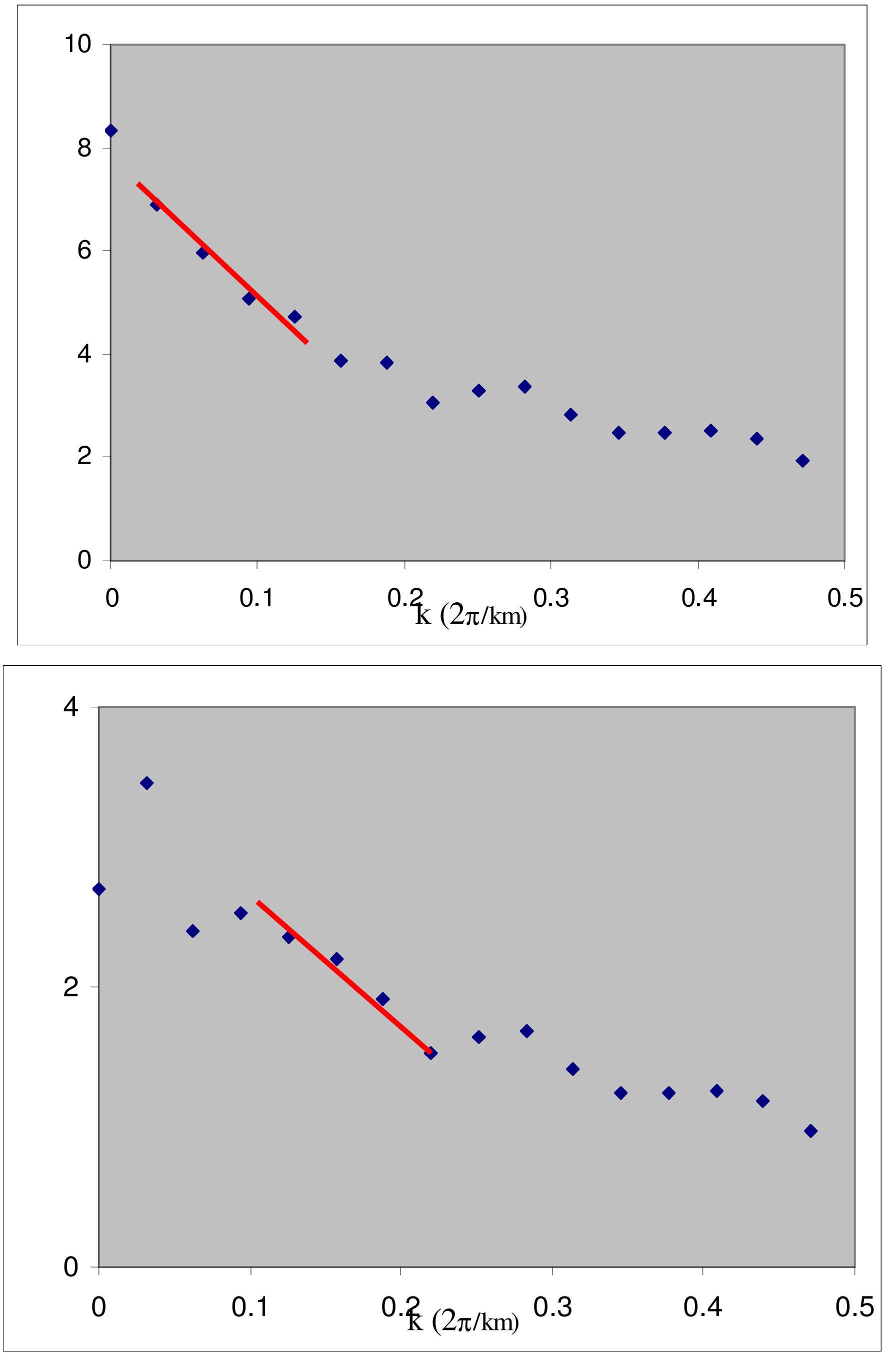

Figure 2. Power spectra belonging theoretical data and estimated depths.

From this figure it was found that the upper depth is approximately 5 km while the mid-point depth was 10 km. By using the approach given in equation (10), the lower depth was determined as 15 km.

The depth value obtained here is also called as the Curie point depth. From the Curie point depths, the heat flow could be obtained by taking into consideration the area:

$$q = k\left(\frac{dT}{dz}\right)$$

(16)

The unit is µkal/cm^{2}s (HFU) in c.g.s. system and mWm^{-2} in SI system. In equation (16); k is the heat conductivity, T is the average Curie depth and z is the Curie depth of the domain.

Applications

Magsat magnetic data was sampled at intervals of 2 km for the area in western Anatolia between the latitudes of 36^0-41^0 N and longitudes of 25^0-32^0 E (Fig. 3).

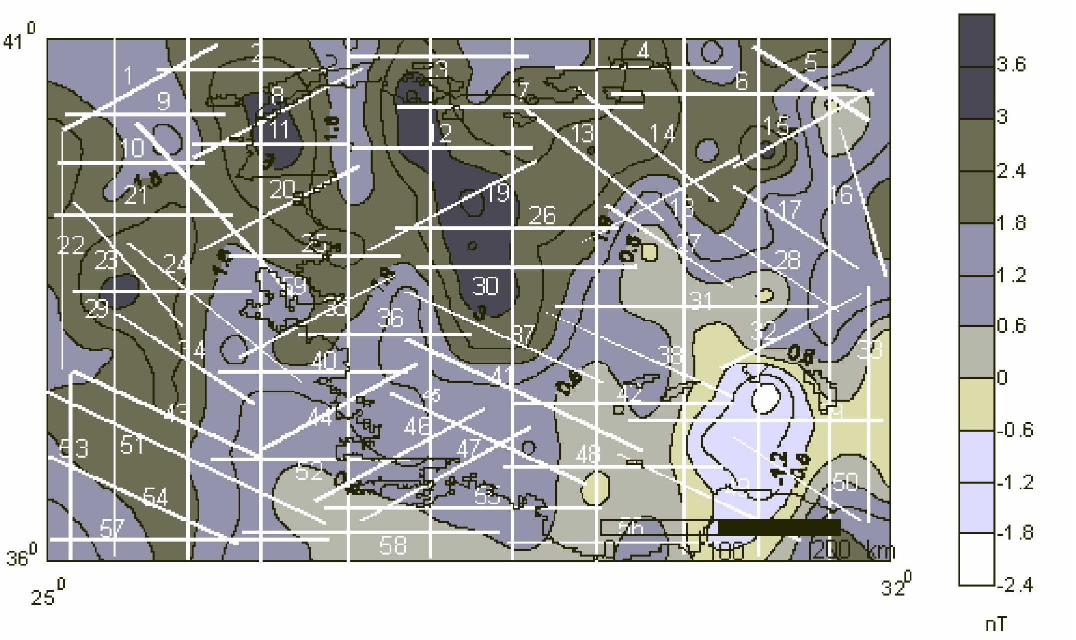

Figure 3. Map of total component Magsat magnetic data of West Anatolian (contour interval is 0.6 nT)

Ten cross-sections, which were 500 km length and taken in the direction of N-S on the anomaly map, are given in Fig. 3. Then, one dimensional moving windows power spectrum method has been applied to the each cross-section within five windows. Furthermore the average structure depths were determined. The computed depths were mapped as probable Curie depths in Fig. 4.

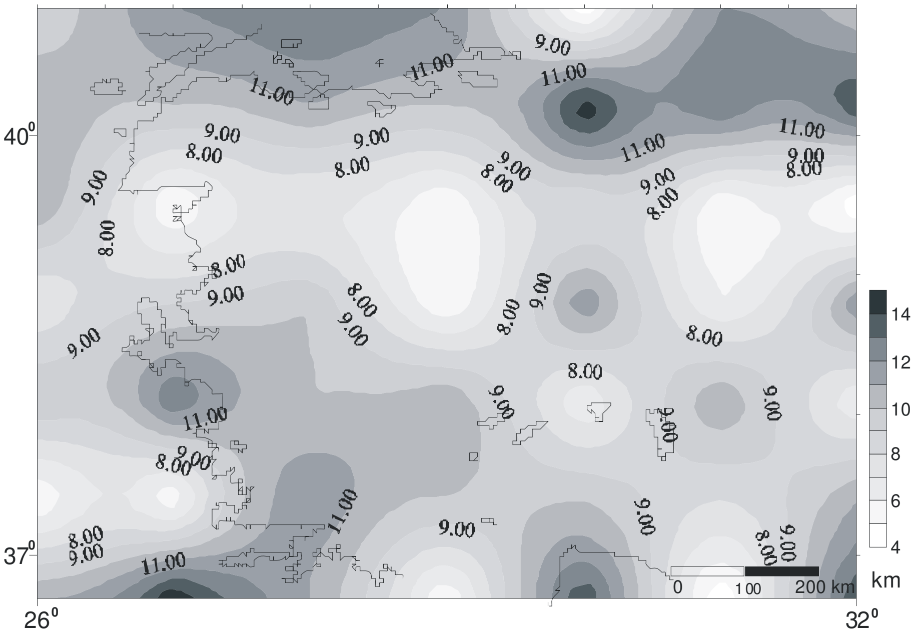

Figure 4. Map of Curie depth regarding West Anatolia by means of equation (5) (contour interval is 1 km).

Using the computed depth values, the Curie temperature was found as 560 ^{0}C for the studied domain. Provided that the heat conductivity is accepted as k=2 W/m^{0}C , the heat flow map belonging to western Anatolia has been constructed by means of equation (16) (Fig. 5)

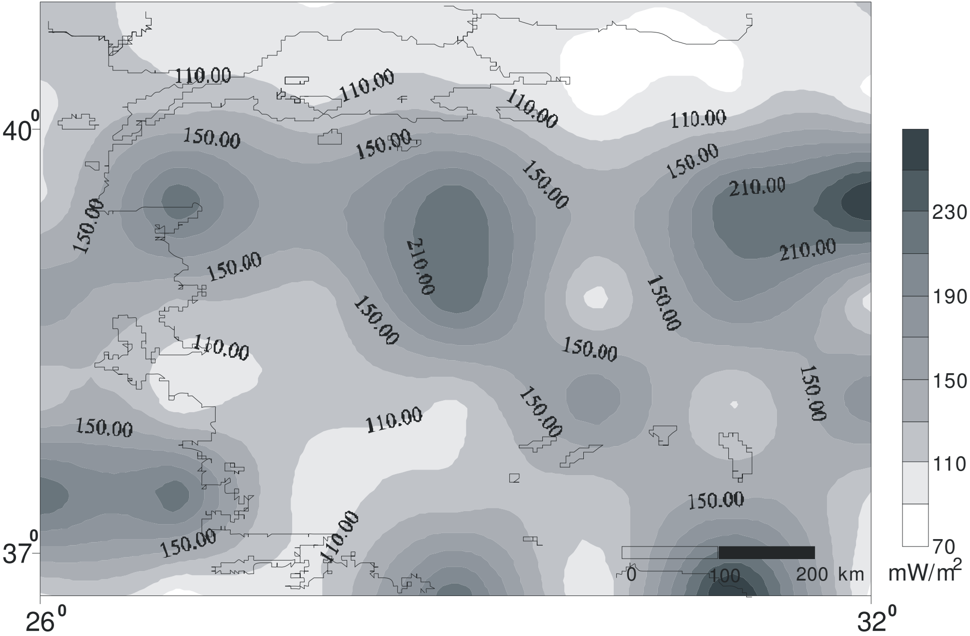

Figure 5. Heat flow map of West Anatolia computed from Curie depths in Fig. 4 (contour interval is 20 mW/m^2).

In the second stage of the study, fifty eight cross-sections taken on the anomaly map are given in Fig. 3. The depths obtained from the equations (11) and (14) were substituted in equation (15). Curie depths were calculated with spectrum analysis (Fig. 6). Additionally, the Curie temperature was found to be 560 ^{0}C and the heat flow map was plotted for the same region by using equation (16) (Fig.7).

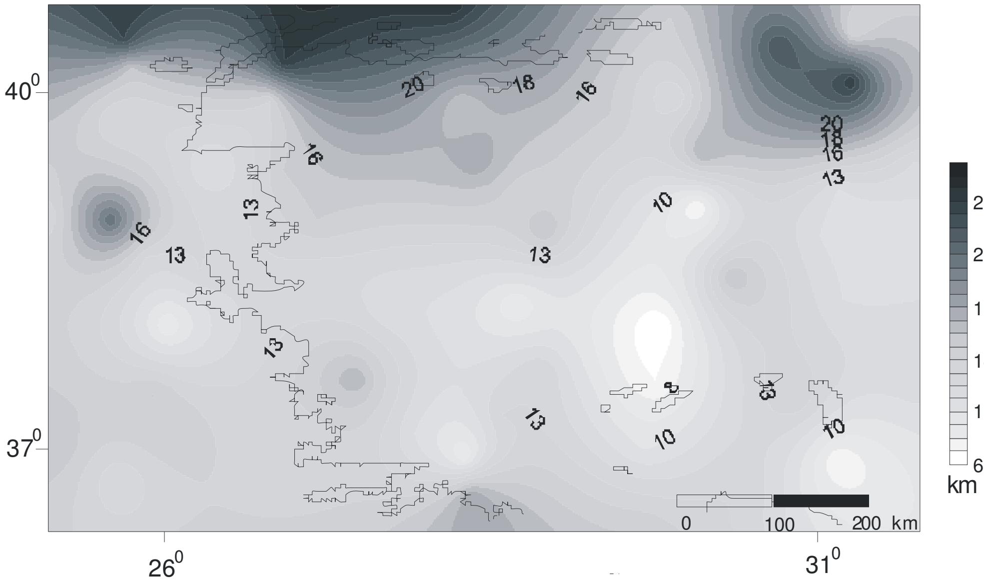

Figure 6. Curie depth map obtained from spectral analysis (contour interval is 1 km).

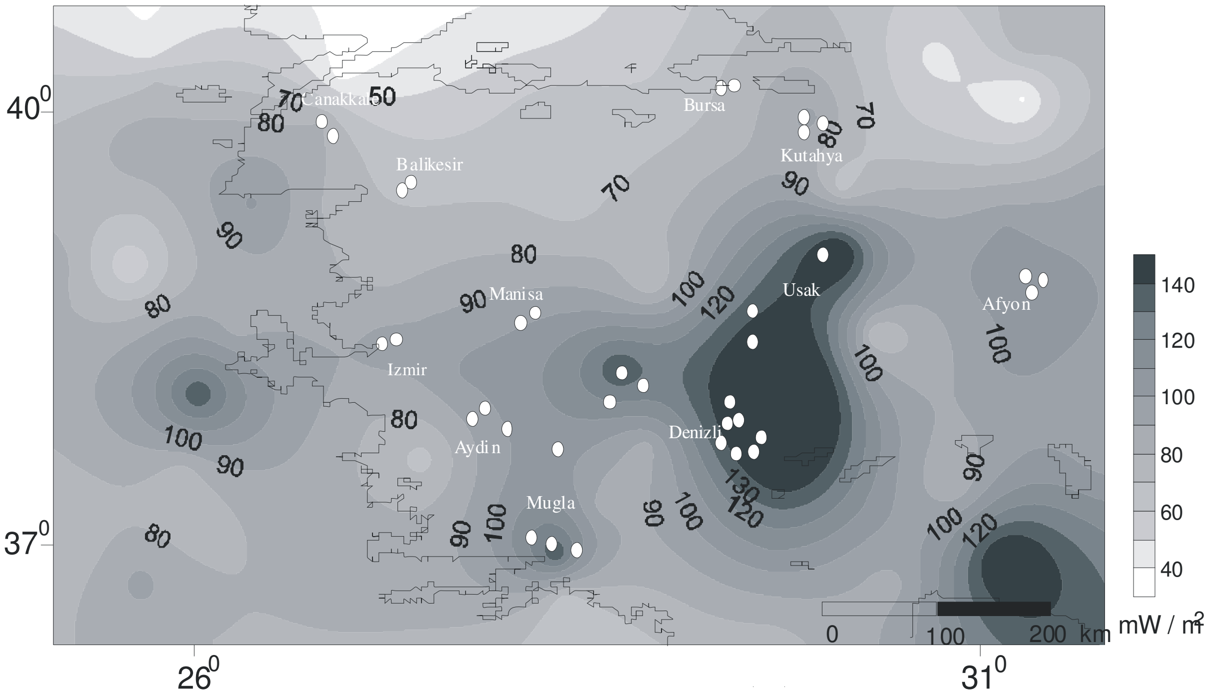

Figure 7. Heat flow map of West Anatolia computed from Curie depths in Fig. 6 and Main geothermal fields (contour interval is 10 mW/m^2).

Discussions and Conclusions

All the current literature state that the Curie point depth is greatly dependent upon geological conditions. Curie point depths are shallower than 10 km for volcanic and geothermal fields, between 15-25 km for island arcs and ridges, and deeper than 20 km in plateaus and trenches (Tanaka et al., 1999). Generally, the units that comprise high heat flow values correspond to volcanic and metamorphic regions since these two units have high heat conductivities. Additionally, tectonically active regions affect the Curie depth and heat flow.

Two power spectrum methods have been compared in this manuscript. First of all, the mid-point depths have been found, followed by the determination of Curie depths and the heat flow map by using the power spectrum method that was developed by Spector and Grant (1970) (Figs. 4 and 5). In the next step, the spectrum analysis developed by Tanaka et al. (1999) has been conducted leading to the Curie depths and heat flow maps (Figs. 6 and 7).

The consequences of the practical work indicate that the Curie depth and heat flow values computed in the first approach are different than those found in the second. The heat flow values that were obtained in the second stage are compatible with the heat flow map that was drawn by Tezcan and Turgay (1989) based on the geological-geophysical studies and well base temperatures (Fig. 8).

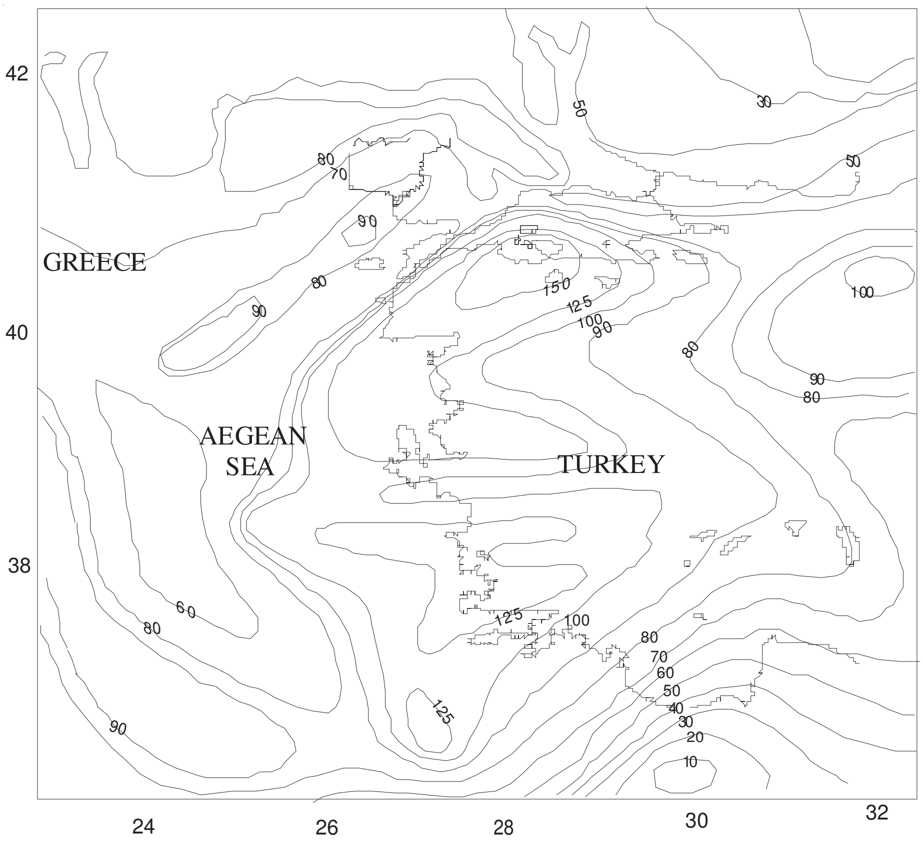

Figure 8. Map of heat flow including the study area of Tezcan and Turgay (1989).

In the light of these results, the spectrum analysis method yields better results in the calculations of Curie depth and heat flow when compared to mid-point depth determination.

It is a commonly known fact that shallower Curie depths create negative magnetization. Similarly, in our study, it was recorded low magnetic anomalies overlap with shallow Curie depths for both methods (Fig. 3), where high heat flow values were obtained (Figs. 4 and 7).

The main tectonic elements formed by Koçyiğit (1984) as in Fig 1 was compared to the computed Curie depth and heat flow values. Especially, in the areas with the increasing heat flow correspond to extension areas and continuation of trenches in the continent.

Additionally, the obtained Curie depths and heat flows are consistent with the young volcanics and metamorphics existing in the region. The heat source of a geothermal field is governed by a deep magmatic mass that has not completed its cooling yet in association with relevant young volcanism and a faulted structure. The progress of geothermal fields in western Anatolia is at the same time correlated with the active tectonic nature of the region. Generally the structural features that are considered to occur due to N-S extensions. This result could be explained by the horst and grabens which lead a significant geothermal effectivity by the convection of rain and ground water toward the surface. This situation supports the conclusion that Curie depth is shallow where the heat flow is high. Especially, the shallow Curie point depths observed in the study area correspond to recent geological features such as the grabens of the Menderes Massif. Additionally, shallow Curie point and high heat flow values is significant especially in the Aegean Sea around İzmir. This region is near Seferihisar-İzmir. Seferihisar is known to have a great geothermal potential with small spas.

By using two dimensional spectrum analysis, Curie depth map of Turkey was formed by Aydın et al. (2005). Investigating the Western Anatolia results of the study, the Curie depth range is 6 –22 km. In our study, Curie depth of Western Anatolia range is found 4-14 km by using moving windows power spectrum and 6-22 km by using spectrum analysis. The results of the spectrum analysis fit to the results of Aydın et al. (2005).

Finally, the identified geothermal fields (Erişen et al., 1996) have been indicated on the heat flow map of the West Anatolian region (Fig.7). As seen in this figure, there is a great abundance of geothermal resources where there is high heat flow, namely a shallow Curie depth.

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