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Curie-point depth map of Turkey

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SUMMARY

A Curie-point isotherm map of the whole of Turkey has been prepared from aeromagnetic data by means of a spectral analysis technique. The most characteristic signature of this map is that the shallow depths generally correlated with the young volcanic rocks and the thinned crustal thicknesses in the west reveal geothermal fields and several hot springs. The orogenic Pontide belt of the Black Sea region in the north, the western Taurus belt in the south, and some high plateaus in eastern Turkey show that the deepest Curie isotherm depths range between 20 and 29 km. Depth contour lines elongating in an almost E–W direction are due to the overlapping percentage of adjacent data blocks of 50 per cent in the E–W direction and to magnetic anomalies trending in the E–W direction.

Curie isotherm depths are in the range 6 to 10 km in the Aegean region and are characterized by E–W- and NE–SW-trending graben structures, as expected, since the region has crustal thinning and many hot springs and geothermal fields. These imply the existence of shallow heat sources that could be utilized for electricity, heating of towns and cities, greenhouse and health purposes.

Key words: aeromagnetics, Curie isotherm, Curie-point depth, geothermics, heat flow, Turkey.

1 INTRODUCTION

The magnetism of rocks diminishes at the Curie-point temperature (approximately 580°C for magnetite) and magnetic bearing rocks do not create any magnetic signatures in the measured geomagnetic field. Thus the depth at which the temperature reaches the Curie point is assumed to be the bottom of the magnetized bodies in the crust. The Curie-point temperature varies from region to region, depending on the geology of the region and mineralogical content of the rocks. Therefore, one normally expects shallow Curie-point depths in regions that have geothermal potential, young volcanism and thinned crust.

In order to determine the Curie-point depths, i.e. the bottom of the magnetized rocks, and to map these depths, a frequently used method is the analysis of magnetic data. Many authors, for example Vacquier & Affleck (1941), Bhattacharyya & Leu (1975), Shuey *et al.* (1977), Connard *et al.* (1983) and Tanaka *et al.* (1999), have carried out studies on magnetic anomalies to estimate bottom-depths of the related bodies for various purposes and applying various techniques, and have mapped the Curie-point isotherm depths.

In Turkey, some studies have been carried out to understand the geothermal structure of the country. The first comprehensive study was the preparation of a heat-flow map for the whole country using temperature gradients in wells (Tezcan 1979). That map was later revised by the addition of new well data. In the preparation of the final heat-flow distribution map of Turkey, temperature data from a total of 204 oil, coal and a few deep geothermal wells, after making necessary corrections, were utilized by taking the thermal conductivity constant to be 2.1 W m^{-1} K^{-1} (Tezcan 1995). Koçak (1989) studied the convective heat discharge of hot springs using silica geothermometers and prepared a map indicating the major heat-discharge areas related to the thinned crust in western Turkey and the young volcanic areas in other regions of Turkey. İlkışık *et al.* (1990), İlkışık (1995) and İlkışık *et al.* (1995) worked on heat-flow determinations using silica temperatures in thermal springs in western Anatolia, and made a correlation of the heat-flow data with crustal structure. An individual attempt was made to estimate the Curie-point depth for a limited part of Turkey (Hisarlı 1995). Hisarlı (1995) applied the least square inversion technique to compute the bottom depth of the anomaly causing bodies and calculated the heat flow values by taking the thermal conductivity value of 2.1 Wm^{-1} K^{-1}.

A further comprehensive geothermic study was performed in Central Turkey by Koçak (1997), who considered heat transfer mechanisms, alteration and reservoir temperature, and estimated the depth of heat sources for geothermal system to be 12–13 km by assuming a temperature gradient and acidic intrusion melting point. There have been a few more studies related to the Curie-point depth determination carried out by Tsokas *et al.* (1998) and Stampolidis & Tsokas (2002) in the mid-south of the Aegean Sea and northern Greece neighbouring Turkey.

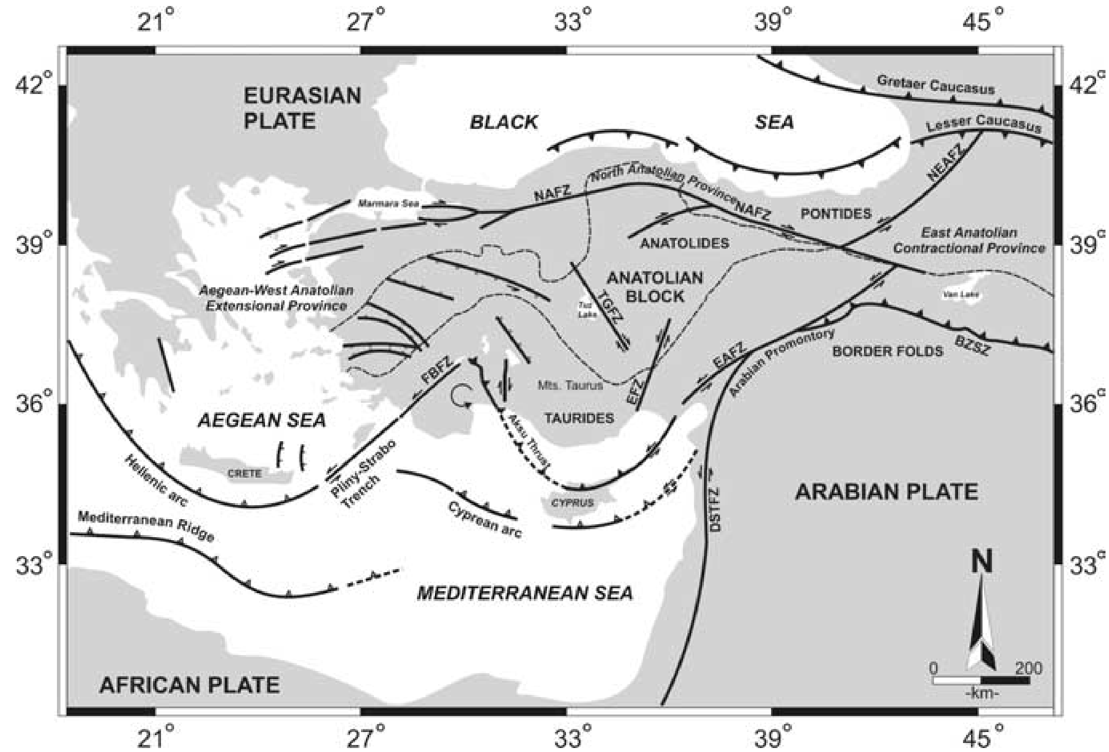

Figure 1. General neotectonic context of Turkey and the eastern Mediterranean region showing major structures and provinces. (Modified after Ketin 1966; Şengör 1980; Ketin 1983; Jackson & McKenzie 1984; Şengör *et al.* 1985; Barka 1992; Dilek *et al.* 1999; McClusky *et al.* 2000; Bozkurt 2001; Huguen *et al.* 2001; Zitter *et al.* 2003,.) Abbreviations: BZSZ, Bitlis–Zagros suture zone; DSTFZ, Dead Sea transform fault zone; EAFZ, East Anatolian fault zone; NAFZ, North Anatolian fault zone; NEAFZ, Northeast Anatolian fault zone; FBFZ, Fethiye Burdur fault zone; EFZ, Ecemiş fault zone; TGFZ, Tuz Gölü fault zone. Heavy lines with half arrows are strike-slip faults with arrows showing the relative movement sense. The heavy line with filled triangles shows a major fold and thrust belt (Bitlis–Zagros suture): small triangles indicate direction of vergence. The heavy line with open triangles indicates an active subduction zone, its polarity indicated by the tip of the small triangles. Rounded arrows indicate areas of possible rotation in the Isparta Angle, SW Turkey.

The latest study concerning the Curie-point depth estimation carried out by Karat & Aydın (2004) covers the whole country in a preliminary report of a project on the 'Preparation of the Curie Isotherm Depth Map of Turkey', carried out under the patronage of General Directorate of Mineral Research and Exploration of Turkey (MTA).

Here in this study, we tried to estimate the Curie-point depths on a country-wide scale and to map the computed depths. The aim was to bring additional information to the active tectonics and geodynamics of Turkey, and to contribute to the considerable geothermal potential and other resources related to geothermics.

2 TECTONIC FRAMEWORK AND VOLCANOLOGY OF TURKEY

The tectonic framework of the eastern Mediterranean is dominated by the collision of the Arabian and African plates with Eurasia (McKenzie 1972; Jackson & McKenzie 1984, 1988a,b). This region encompasses a wide variety of tectonic processes, including various stages of continental collision (Zagros/Caucasus/Black Sea), subduction of lithosphere and associated backarc spreading (Cyprus/Hellenic/Calabrian arcs, Aegean and Tyrrhenian Sea), continental extension (western Turkey/Marmara Sea/Gulf of Corinth), continental 'escape' (Anatolia block or plate which is here defined as the region of Turkey west of the Karlıova triple junction lying between the East Anatolian and the North Anatolian faults), major continental strike-slip faults (e.g. North and East Anatolian and Dead Sea faults), and a variety of smaller-scale processes associated with African–Arabian–Eurasian plate interactions (Fig. 1).

A kinematic analysis of the region (McClusky *et al.* 2000) indicates that the Arabian plate is moving in a north-northwest direction relative to Eurasia at a rate of about 18–25 mm yr^{-1}, and that the African plate is moving in a northerly direction relative to Eurasia at a rate of about 10 mm yr^{-1} (at 30°N, 31°E). Differential motion between Africa and Arabia ($\approx$10–15 mm yr^{-1}) is thought to be taken up predominantly by left-lateral motion along the Dead Sea Transform Fault Zone (DSTFZ). This northward motion results in continental collision and a thrust belt, intense earthquake activity and high topography in eastern Turkey and the Caucasus Mountains, and the westward movement of the Anatolian plate. The leading edge of the African plate is being subducted along the Hellenic arc at a higher rate than the relative northward motion of the African plate itself, requiring that the arc moves southwards relative to Eurasia proper. Subduction of the African plate is also thought to occur along the Cyprian arc and/or the Florence rise south of Turkey, although it is less defined in these regions than along the Hellenic arc.

Central Turkey (Anatolia) moves in a coherent fashion with internal deformation $<$2 mm yr^{-1}. The motion of Anatolia is bounded on the north by the right-lateral North Anatolian Fault Zone (NAFZ) and on the southeast by the left-lateral East Anatolian Fault Zone (EAFZ). The upper bounds on fault slip rates for these faults are 24 $\pm$ 1 mm yr^{-1} and 9 $\pm$ 1 mm yr^{-1}, respectively. Right-lateral strike-slip deformation associated with the NAFZ extends into the north Aegean (north Aegean trough), terminating near the Gulf of Corinth. The southern Aegean region is separated from Anatolia by a zone of N–S extension in western Turkey (Western Turkey Extensional Province). On the basis of this kinematic picture it could be speculated that the oceanic lithosphere of the Black and Caspian seas forms a resistant 'backstop', diverting the impinging Anatolian plate to the west and 'funnelling' the continental lithosphere of eastern Turkey and the Caucasus around the eastern side of the Black Sea.

According to the geodynamical models proposed by McKenzie (1972), Dewey *et al.* (1973), Alptekin (1973) and Şengör (1980), the neotectonics of Turkey developed as a result of the collision of the Eurasian and African plates in the late Miocene (Fig. 1). This collision caused a compressional regime in eastern Turkey and formed high-land territory by folding and faulted structures and some intracraton volcanic activity. The compressional strength in the east made some part of Anatolian plate cause a break at Karlıova where strike-slip NAFZ and EAFZ meet forming a wedge-shape and escape of Anatolian plate towards west. As a consequence of the movement of the Anatolian plate to the west, an extension regime has developed in the western Anatolia and Aegean domain, and widespread volcanism took place from the Oligocene to the Quaternary causing local and regional tectonic developments, especially in the northern part of western Turkey (Fig. 2).

The aforementioned plate tectonic activity has formed four distinct configuration terrains in Turkey. (1) As mentioned above, high-land territory exists due to the compressional regime in the east. (2) A basin regime occurs due to extensional strength (characterized by NW–SE extension; NE–SW compression noted by Şengör (1980)) and continuous sedimentation that causes crustal thickening owing to the subsidence of the bottom of the basin due to heavy loading overriding sediments, and a stagnant geological structure in central Turkey. (3) Subduction of the African plate beneath the Aegean and Anatolian plates may cause an upper mantle flow and astenospheric upwelling towards the slab–lithosphere interface (Gülen 1990). Downbending and final detachment of the leading edge of the slab could accelerate this process, causing uplift and the exposure of metamorphic core complexes such as the Menderes metamorphic belt and the establishment of an extensional stress field causing graben structure and a result of lithospheric thinning. (4) Orogenic chains are formed between the Mediterranean and Black Sea due to the subduction of the African plate.

The effects of the above-mentioned activities and related plate tectonics have caused considerable overthrusts and nappe structures in SE Turkey. This region can be divided into two main structural components from a geological point of view (Fig. 1). (1) The Southeast Orogenic belt, the so-called Bitlis Zagros Suture Zone (BZSZ), is a roughly east–west arcuate trending overthrusted orogenic structure including metamorphic and ophiolitic rocks. (2) The Arabian platform represents an autochthonous sedimentary succession that has accumulated with minor interruptions since the early Palaeozoic (Yılmaz *et al.* 1993). The volcanic sequence often occurs in two units: the lower and upper lavas that have developed around the sporadic centres since the Neogene to the Quaternary. In addition, the whole volcanic rock association is cut from felsic intrusives (Yılmaz *et al.* 1993).

A widespread magmatism that has produced calc-alkaline and alkaline lavas, pyroclastics and granitoids has been active since the Oligocene in western Turkey. The volcanic products cover extensive areas from the active volcanic arc located in the Aegean Sea in the south towards the Marmara and Black Sea in the north. Isotopic ages of these volcanic activities exhibit a progressive younging trend from the north towards the subduction zone, where active plate consumption is taking place in the Aegean Trench (Pliny–Strabo Trench) in SW Turkey (Gülen 1990).

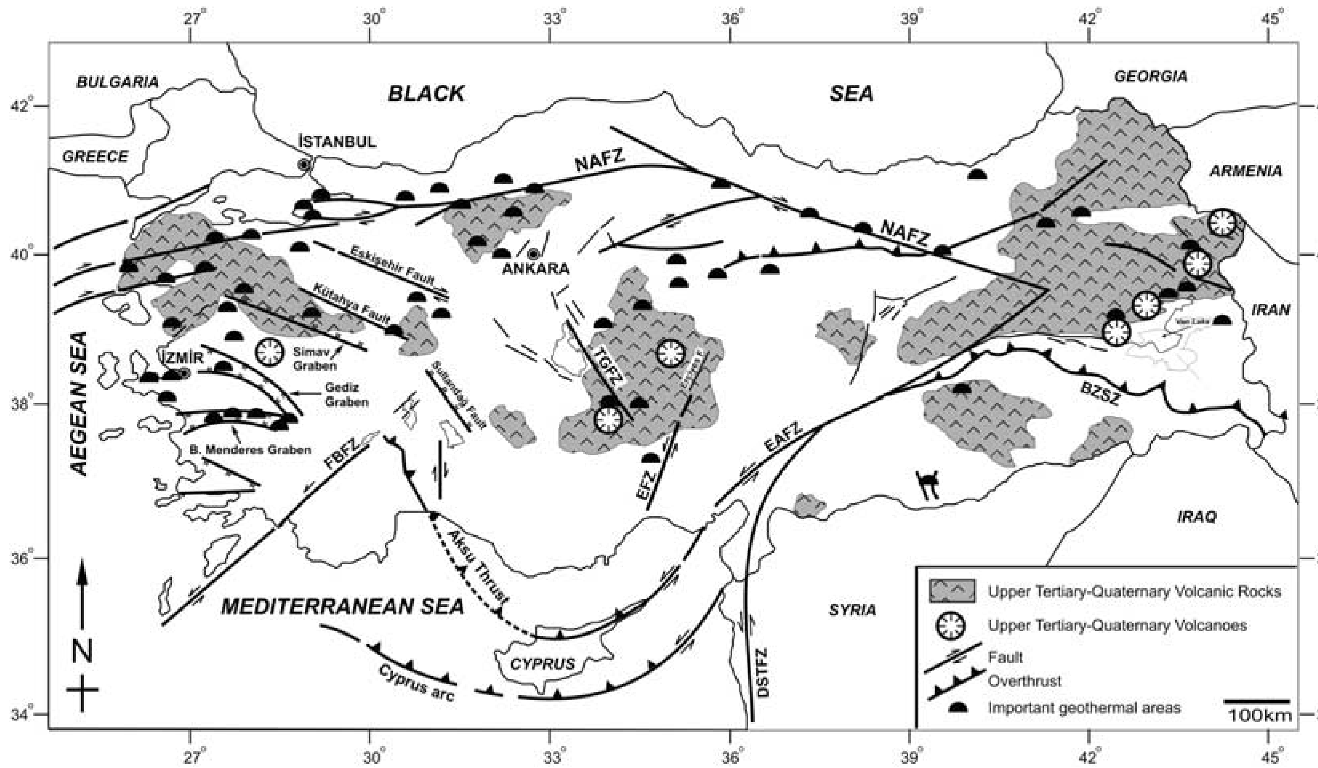

Figure 2. Neotectonics, volcanic features and geothermal fields of Turkey (Koçak 1990). See Fig. 1 for abbreviations.

3 DATA AND TECHNIQUE

MTA has prepared aeromagnetic maps of Turkey at various scales to be used for a variety of purposes. The aeromagnetic data were gathered between the years 1978 and 1989 for a length of 460 000 km over the whole country, sector area by sector area. Flight directions in the sectors were chosen by regarding the topographical as much as geological trends in order to keep the average flight altitude 2000 feet above ground level, something that was accomplished with the use of a radar altimeter. Flight-line spacing in flown sectors was chosen in intervals between 1 and 5 km, depending on the region in which expected mineral, geothermal or any other resources potential.

The removal of diurnal changes was monitored by measurements at a base station located close to the flown sector area, and the heading errors were determined before each flight season and corrected for. Shared flight-line data between adjacent sectors were used to check the annual changes in the geomagnetic field and to reduce the last flight data to the previously flown sector data. Data in both sectors used in reduction were selected from lines flown at the same altitude, that were reasonably coincident with each other, and were non-anomalous or had very low magnetic field gradients. Averaged differences found between shared lines of data of each sector were added to or subtracted from the latest flown sector to reduce the previous or adjacent one. Finally, IGRF (1982.5) was removed from the data for the preparation of the aeromagnetic anomaly map of Turkey (Fig. 3). The year 1982 was chosen for the removal of IGRF since it was the mid-date of the survey span and the larger sectors were flown during this year.

The aeromagnetic $1 \times 1\ \mathrm{km}^2$ grid data were divided into blocks of size $128 \times 128\ \mathrm{km}^2$, i.e. almost 2° by 2° for the preparation of the Curie-point depth map. Each block was overlapped by 50 per cent in the E–W direction and by around 33 per cent in the N–S direction by the adjacent block. In order to remove the geomagnetic gradient, a linear surface was fitted to the data of each block. Then, 380 block data were individually treated with the spectral analysis to make the Curie-point depth estimation. Fig. 4 shows the Curie-point depth contour map.

The method used in this study to estimate the Curie isotherm depths has been taken from Tanaka *et al.* (1999), and was originally developed by Okubo *et al.* (1985) based on the technique of Spector & Grant (1970). The radial average of the power density spectra of a magnetic anomaly $\Phi_{\Delta T}$ is written as

$$\Phi_{\Delta T}(|k|) = Ae^{-2|k|Z_t}(1 - e^{-|k|(Z_b - Z_t)})^2, \tag{1}$$

where A is a constant related to the dimensions of the magnetic source, magnetization direction and geomagnetic field direction; Z_t is the depth to the top of the magnetic source; Z_b is the depth to the bottom of the magnetic source; and Z_0 is the depth to the centre of the magnetic source.

For wavelengths less than about twice the thickness of the magnetic source, eq. (1) can be approximated as

$$\ln\left[\Phi_{\Delta T}(|k|)^{1/2}\right] = \ln B - |k|Z_t, \tag{2}$$

where B is a constant. From eq. (2), it is possible to estimate the depth to the top of the magnetic source by the slope of the power spectrum of the total field anomaly. On the other hand, eq. (1) can be rearranged as

$$\Phi_{\Delta T}(|k|)^{1/2} = Ce^{-|k|Z_0}\left(e^{-|k|(Z_t - Z_0)} - e^{|k|(Z_b - Z_0)}\right), \tag{3}$$

where C is a constant. At long wavelengths, eq. (3) could also be written as

$$\Phi_{\Delta T} = Ce^{-|k|Z_0}\left(e^{-|k|(-d)} - e^{-|k|(d)}\right) \approx Ce^{-|k|Z_0}2|k|d, \tag{4}$$

where $2d$ is the thickness of the magnetic source. From eq. (4), it is possible to write an equation as follows:

$$\ln\left\{\left[\Phi_{\Delta T}(|k|)^{1/2}\right]/|k|\right\} = \ln D - |k|Z_0, \tag{5}$$

where D is a constant. The depths to the top and the centroid of the source could be estimated by fitting a straight line through the high- and low-wavenumber parts of the radially averaged spectrum of $\ln[\Phi_{\Delta T}(|k|)^{1/2}]$ and $\ln\{[\Phi_{\Delta T}(|k|)^{1/2}]/|k|\}$ from eqs (2) and (5), respectively. Finally, the depths to the bottom of the bodies were calculated using the equation $Z_b = 2Z_0 - Z_t$.

4 DISCUSSION OF THE RESULTS

Shallow Curie-point depths estimated from the aeromagnetic data are seen to be associated with crustal thinning, young volcanic rocks,

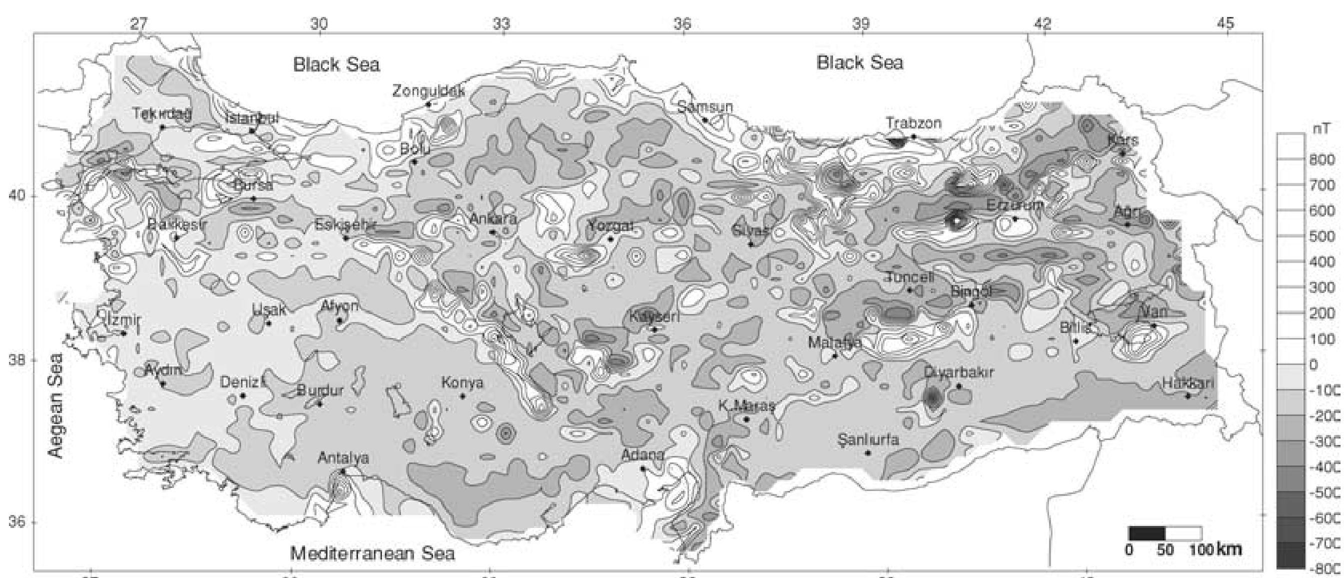

Figure 3. Aeromagnetic anomaly map of Turkey (Karat & Aydın 2004).

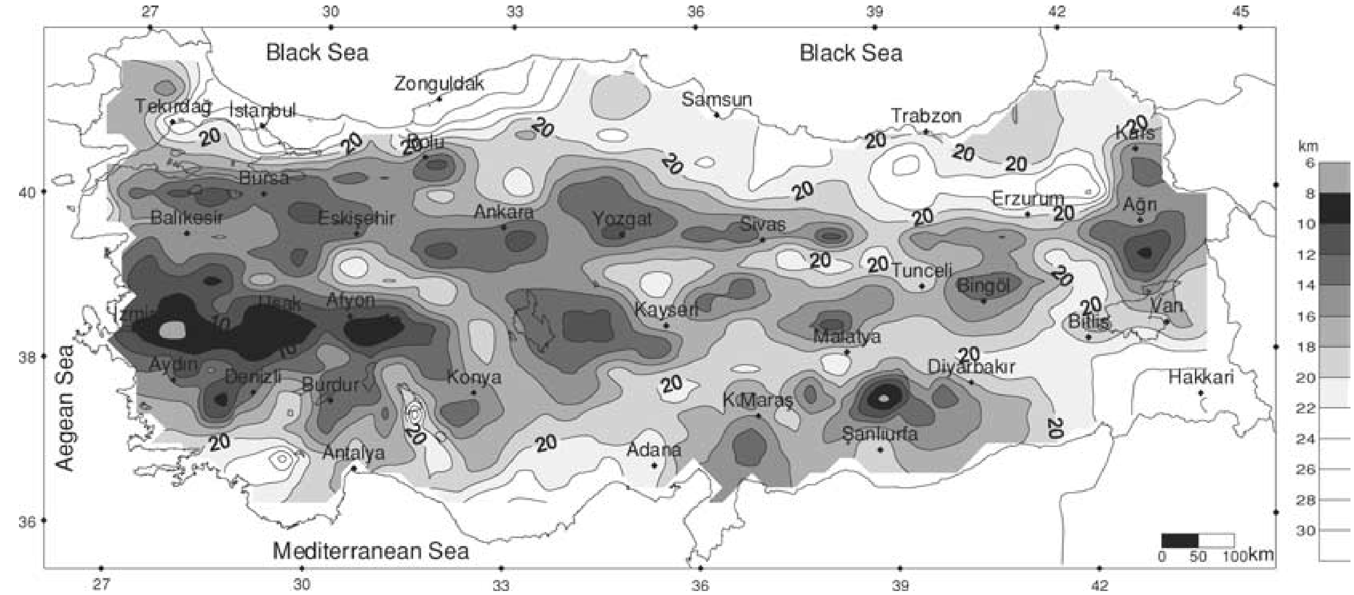

Figure 4. Curie-point depth map of Turkey.

and have a positive correlation with the hot springs and the geothermal potential fields, except for a few areas. The other result, that depth contour lines are elongating in an almost E–W direction, is due to the overlapping percentage of adjacent blocks of 50 per cent in the E–W direction and the E–W trend of magnetic anomalies (Figs 3 and 4).

One can say that some of the estimated Curie point depths do not reflect depth at which the temperature reaches 580°C. These depths can be interpreted just as the bottom depths of the magnetized bodies causing the magnetic anomalies.

The nature of western Turkey, which is known to have E–W grabens as well as N–NE-trending older lineaments and several high-enthalpy geothermal fields revealed by hot springs in the grabens or on their flanks and thin continental crust, is reflected in the Curie isotherm map. The heat-flow map (Fig. 5) also reflects the geothermic nature of the region. It is suggested that the shallow Curie-point temperature depth pattern depends on the tectonic regime and morphology, which continues westwards through the Aegean Sea. In the western part of the Fethiye Burdur Fault Zone (FBFZ) in the south of the Aegean Region, however, the

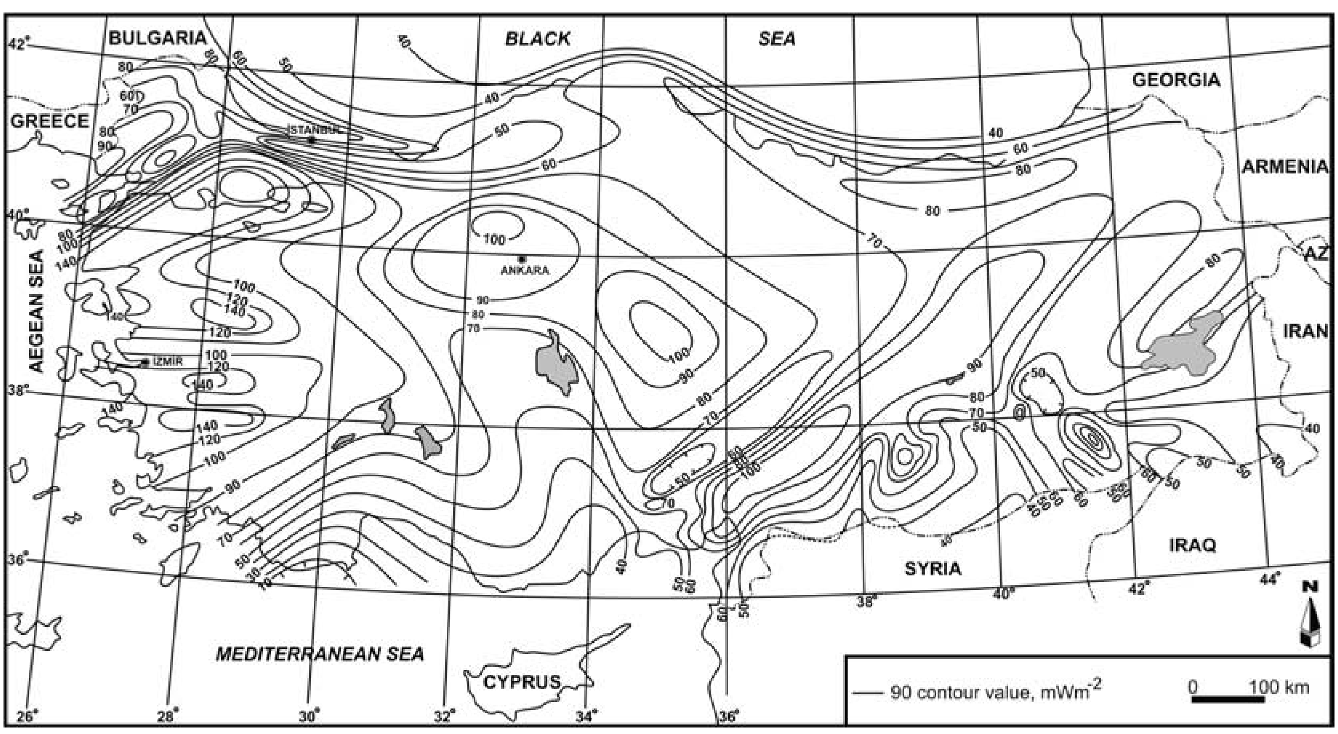

Figure 5. Heat-flow distribution map of Turkey (from Tezcan 1995).

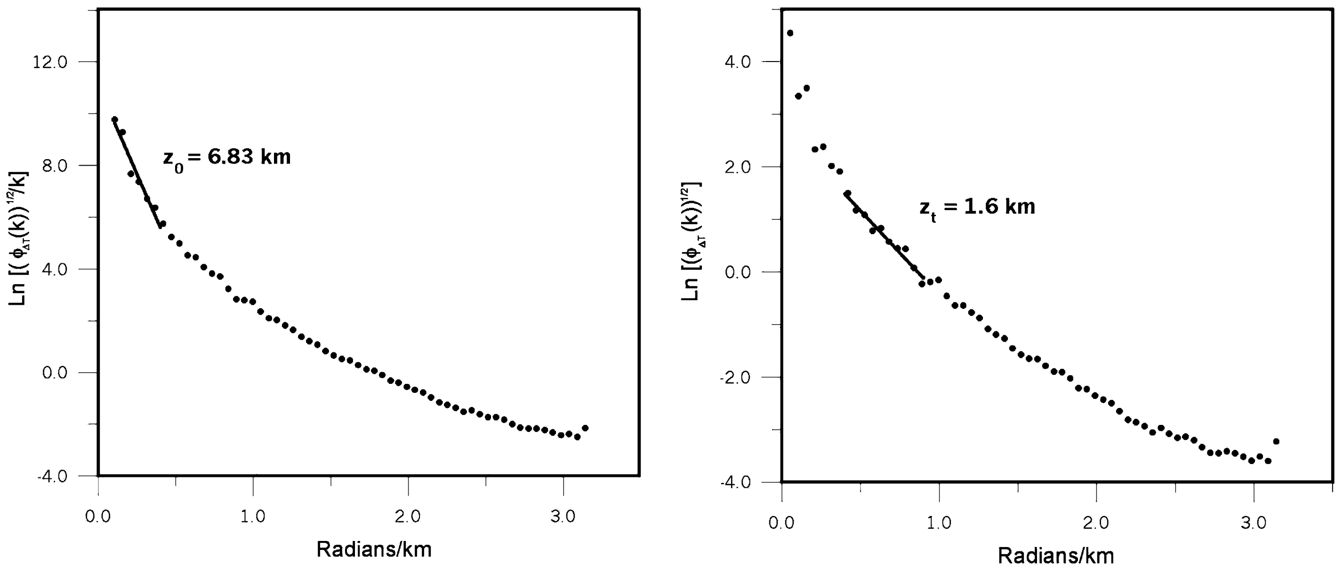

Figure 6. Examples of spectra for the Curie depth of the block (north of Van Lake) with the southwest and northeast corner coordinates 42° 16′E–38° 50′N and 43° 46′E–39° 48′N.

Curie isotherm depths were estimated to be 18–22 km. FBFZ is on the arc that extends to Crete Island situated near the Aegean Arc. Tsokas *et al.* (1998) estimated Curie isotherm depths in the range 24 to 28 km. On the other hand, in the northern Aegean Sea, in northern Greece and in northwest Turkey, the Curie-point depths are rather shallow, varying between 11.2 and 17.3 km (Stampolidis & Tsokas 2002). Almost the same values for the Curie point depths, namely 17–18 km, were found for Thrace in NW Turkey.

The Curie-point depth map of Turkey roughly coincides with the geological (plate) structure and volcanism of the territory. The deep Curie point anomalies in the southeastern part of the country coincide roughly with the BZSZ because of the subduction of the Arabian plate together with volcanic activity. These phenomena might reveal that imbrications and piling over the thrust plate have caused the area to be quickly heated, presumably by friction at the starting zone of subduction together with the volcanism. The volcanism activated from the Neogene to the Quaternary in the area is Karacadağ volcanism, to the southwest of Diyarbakır city, and has given a shallow Curie-point depth of around 7 km due to the emplaced feeding magma chamber. To the north of Karacadağ, however, Curie-point depths were estimated to be more than 20 km on the ophiolitic belt known as the BZSZ, which is the plate boundary between the Anatolian and Arabian plates. This deep Curie-point anomaly begins in the western Taurus Mountains, runs through the ophiolitic belt mentioned, and reaches the Iraq and Iran border in the east. This zone has two northwesterly intruding branches in the west. One of the branches reaches up to north of Eskişehir city, the other lies almost along the Aksu thrust with depths of about 20 km.

In the northern Turkey Pontide orogenic belt of the Black Sea region along the Black Sea coast, the estimated Curie-point depths of the oldest granitoids comprising subvolcanics might not be the depths at which the temperature reaches the Curie point (Akıncı 1985). These depths of 20–25 km might be considered to be the bottom of the extent of the magnetized bodies up to the mid or lower layers of the crust. Similar situation also appears in the western Taurus Mountains where long wavelength and nearly E–W-elongating magnetic lows present. Curie-point isotherm depths of over 20 km in the western Taurus Mountains elongate almost along the Mediterranean Sea coast (Figs 3 and 4).

The easternmost shallow Curie-point depths in the east and north of Van Lake can be directly correlated with young volcanic activity such as the Nemrut, Süphan, Tendürek and Mount Ararat volcanoes that took place in the eastern territory, implying that a shallow magma chamber has yielded the volcanic activity or magma plumb (Fig. 6). This shallow depth zone extends close to Kars city in the north, and runs westwards, deepening in some places and correlating with the magnetic-anomaly chain up to the northern Aegean Sea coast.

Anomalies lying along the NAFZ give mid to deep Curie-point isotherms, in some places covered with volcanic rocks. An interesting situation is that, along the southern Marmara branch of the NAFZ, the Curie-point depths are about 15 km.

Gönen, Yalova and Bursa are the famous hot-spring fields situated at the northern edge of the Aegean region and or to the south of Marmara Sea. They have shallow Curie depths of 10–12 km as expected, and have temperatures at the surface of 52°C, 59°C and 53°C, respectively. Just south of these hot-spring fields, in the Balıkesir area, Hisarlı (1995) has estimated Curie-point depths of between 8 and 12 km. The Bolu district in the eastern Marmara Sea is also a significant geothermic area, with the shallow Curie-point depths varying between 8 and 14 km, and hot springs with surface temperatures in the range 40 to 60°C.

Moderate Curie-point depths with the E–W elongation in the central part of eastern Turkey can be correlated with the heavily faulted Karlıova depression formed due to a break in the Anatolian Plate owing to the relative movements at the conjunction point of the NAFZ and EAFZ. One can postulate that these depths have been caused by an upper mantle flow and asthenospheric updoming (upwelling) due to loss of the cap weight (the heavy load of overriding and overthrust structure continuing to the west).

Another remarkable shallow Curie-depth region is located in central Turkey and can be correlated with the Erciyes and

Hasandağı volcanics and the Yozgat Massif (with the contribution of the ophiolitic melange) in the north. Ateş (1999) analysed an aeromagnetic anomaly in central Turkey and calculated the bottom depth of the related gabbroic body to be 10 km. This depth coincides fairly well with the Curie-point depth estimated in this study.

5 CONCLUSIONS

(1) The shallow depths in the Curie-point depth map generated by spectral treatment of the aeromagnetic data of Turkey are well correlated with the young volcanic areas and geothermal potential fields and also with the heat-flow highs.

(2) The depths less than about 10 km generally occur in the geothermal fields and in the areas that have the highest heat-flow contribution.

(3) Orogenic belts with some nappe structure such as the Taurus and Pontides and suture zones are the regions that have the deepest Curie-point depths of more than 20 km.

(4) Depth contour lines elongating in an almost E–W direction are due to the overlapping percentage of adjacent blocks of 50 per cent in the E–W direction and to magnetic anomalies trending in an E–W direction.

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