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Curie Point Depths of Macedonia and Thrace, N. Greece

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Abstract—The aeromagnetic data of Macedonia and Thrace were used to produce Curie point estimates. The data were high pass filtered to remove components arising from topography and magnetic core fields which were not adequately modeled by a DGRF. The depth to the centroid, z_0, of the deepest distribution of the magnetic dipoles was obtained by computing a least-squares fit to the lowest-frequency segment of the azimuthally averaged log power spectrum. The average depth to the top of the deepest crustal block was computed as the depth to the top, z_t, of the second lowest-frequency segment of the spectrum. The depth to the bottom of the deepest magnetic dipoles, the inferred Curie point depth, was then calculated from $z_b = 2z_0 - z_t$. The Curie depth estimates for Macedonia and Thrace range between 11.2 and 17.3 km. These results are consistent with the depths inferred by extrapolating known geothermal gradient and heat-flow values.

Key words: Curie point depth (CPD), power spectrum, Macedonia and Thrace.

Introduction

The Curie point (approximately 580°C for magnetite at atmospheric pressure) is the temperature at which spontaneous magnetization vanishes and magnetic minerals exhibit paramagnetic susceptibility. This type of magnetization is much smaller than magnetizations of the ferromagnetic family, rocks are essentially nonmagnetic at temperatures greater than the Curie point of magnetite. Here we use “Curie point depth” to describe the depth to the inferred Curie point TRANSITION of magnetite.

Aeromagnetic data have been used at various parts of the world in order to estimate Curie point depths (e.g., VACQUIER and AFFLECK, 1941; SERSON and HANNAFORD, 1957; BHATTACHARYYA and MORLEY, 1965; SCHELLINGER, 1972; DEMENITSKAYA *et al.*, 1973; SMITH *et al.*, 1974, 1977; BHATTACHARYYA and LEU, 1975, 1977; BYERLY and STOLT, 1977; SHUEY *et al.*, 1977; WASILEWSKI *et al.*, 1979; BLAKELY and HASSANZADEH, 1981; CONNARD *et al.*, 1983; HUPPUNEN, 1983; MAYHEW, 1982, 1985; OKUBO *et al.*, 1985, 1989; TSELENTIS and DRAKOPOULOS, 1988; BLAKELY, 1988; SMITH *et al.*, 1994; TSÖKAS *et al.*, 1998).

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The computation of the depth to the bottom comprises one of the most difficult problems in potential field inversion (BLAKELY, 1995). The signal from the top of a magnetized body dominates the signal from the bottom at all wavelengths. This was recognized from the fundamental work of SPECTOR and GRANT (1970), who established the well-known method for estimating the average depths to the top of magnetized bodies, based on the slope of the log power spectrum.

OKUBO *et al.* (1985, 1989) provided a method to obtain the depth to the bottom, z_b, of the deepest magnetic sources in two steps: First, obtain the depth to the centroid, z_0, and second, determine the depth to the top, z_t, of the deepest magnetic sources. The depth z_b is then calculated from those two depths: $z_b = 2z_0 - z_t$.

The aeromagnetic data of Macedonia and Thrace were analyzed in the present study. The method used to calculate Curie point depths is similar to that of OKUBO *et al.* (1985, 1989) and TSÖKAS *et al.* (1998), who expanded the method of BHATTACHARYYA and LEU (1975) for ensembles of sources.

The Method

SPECTOR and GRANT (1970) describe the statistical consideration of the magnetic sources in the crust. The mathematical model they used is based on the assumption that sources consist of a number of independent ensembles of rectangular vertical prisms, each ensemble being characterized by joining a frequency distribution for the depth, the width, the length, the depth extent and the direction cosines of the magnetization. They assumed that the expectation value of the spectrum of an ensemble of sources is the same as that of a single prism with the average parameters for the collection, which in polar wavenumber coordinates $(s = (u^2 + v^2)^{1/2}$ and $\psi = \tan^{-1}(\frac{u}{v}))$ has the form:

$$\langle E(s,\psi)\rangle = 4\pi^2 M^2 R_G^2 \langle \mathrm{e}^{-2hs}\rangle \left\langle (1 - e^{-ts})^2 \right\rangle \langle S^2(s,\psi)\rangle \langle R_P^2(\psi)\rangle \tag{1}$$

where $\langle\rangle$ indicates the expected value, M = magnetic moment/unit depth, h = depth to the top of the prism, t = thickness of the prism, S = factor for the horizontal size of the prism, R_G = factor for geomagnetic field direction and R_P = factor for magnetization direction of the prism.

OKUBO *et al.* (1985) based their analysis on a collection of random samples from a uniform distribution of rectangular prisms, each prism having a constant magnetization. They emphasize that the rectangular prism is only a convenient geometry from which to develop the necessary theory, not a required geologic model. They propose an algorithm which is independent of such details as the assumed body shape, as long as the ratio of horizontal dimensions to each other or to vertical dimensions is not of order of unity. They wrote equation (1) in the form

$$F(s,\psi) = 2\pi JA[N + i(L\cos\psi + M\sin\psi)] \times [n + i(l\cos\psi + m\sin\psi)] \times \sin c(\pi s\alpha\cos\psi)\sin c(\pi sb\sin\psi) \times \exp[-2\pi si(x_0\cos\psi + y_0\sin\psi)] \times [\exp(-2\pi sz_t) - \exp(-2\pi sz_b)] \quad (2)$$

where $J =$ magnetization per unit volume, $A =$ average cross-sectional area of the bodies, L, M, $N =$ direction cosines of the geomagnetic field, l, m, $n =$ direction cosines of the average magnetization vector, a and $b =$ half the width and half the length of the ensemble, i.e., half the average dimensions along the x and y directions, respectively, x_0 and $y_0 =$ average body x and y center locations, z_t and $z_b =$ average depths to the top and bottom of the bodies and where $\sin c(x) = \sin(x)/x$.

The estimation of z_b is then approached in two steps as suggested by BHATTACHARYYA and LEU (1975, 1977) and OKUBO *et al.* (1985). First, the centroid depth z_0 is estimated and second, the depth to top z_t. The depth to the bottom of the ensemble, i.e., the inferred Curie point depth, is then obtained as

$$z_b = 2z_0 - z_t \ . \quad (3)$$

According to OKUBO *et al.* (1985), the terms of equation (2) involving z_t and z_b can be recast into a hyperbolic sine function of z_t and z_b plus a centroid term. At very long wavelengths the hyperbolic sine tends to unity and thus a single term remains, which is a function of z_0. At somewhat shorter wavelengths the depth to the top can be obtained because its signal dominates the spectrum.

At very long wavelengths compared to the ensemble dimensions, the terms of equation (2) which involve the body parameters (*a*,*b*) may be approximated by their leading terms. Also, a single term involving z_0 is present as explained. Therefore, equation (2) reduces to

$$F(s,\psi) = 4\pi^2 VJs[N + i(L\cos\psi + M\sin\psi)] \times [n + i(l\cos\psi + m\sin\psi)] \times \exp[-2\pi is(x_0\cos\psi + y_0\sin\psi)] \times \exp(-2\pi sz_0) \quad (4)$$

where V is the average body volume.

Equation (4) describes the spectrum of a dipole or equivalently that of an ensemble of point dipoles. A direct consequence is that the details of the shape of the body do not contribute to the expression of the spectrum for the long wavelengths.

In order to estimate z_0, OKUBO *et al.* (1985) defined $G(s,ø)$ by

$$G(s,\psi) = \frac{1}{s}F(s,\psi) \quad (5)$$

and following SPECTOR and GRANT (1970), and SHUEY *et al.* (1977), the squared amplitude of G is integrated in frequency space to yield

$$H^2(s) = \frac{1}{2\pi} \int_{-\pi}^{\pi} |G(s,\psi)|^2 \, d\psi \ . \tag{6}$$

Then $H(s)$ takes the form

$$H(s) = A \exp(-2\pi s z_0) \ . \tag{7}$$

Hence,

$$\ln H(s) = \ln A - 2\pi s z_0 \tag{8}$$

and z_0 can be obtained by least squares fitting to ln $H(s)$.

As for the depth to the top of the ensemble, we revert to equation (1). SPECTOR and GRANT (1970) showed that $\langle e^{-2hs} \rangle$ reduces to $e^{-2\bar{h}s}$, assuming that the distribution of the prism depths is in the range of $0.75\,\bar{h} < h < 1.25\,\bar{h}$, where $\bar{h}$ is the mean depth to the top of the prisms, and is the dominant term controlling the spectrums shape. For somewhat smaller wavelengths than those considered for the z_0 estimate, we can calculate the depth z_t to the top of the deepest crustal block from the slope of the spectrum.

Of course there are other publications (e.g. PILKINGHTON and TODOESCHUCK, 1993, 1995; PILKINGHTON, *et al.*, 1994; MAUS and DIMRI, 1996; FEDI, *et al.* 1997), which use fractal terms to describe rock magnetization, pointing out that the Spector and Grant's interpretation of the power spectrum is misleading. Fractal methods of CPD estimation require very large grids (MAUS, *et al.*, 1997) and are therefore not suitable for the small-scale investigation undertaken here. However, the method used in the present approach has produced meaningful results in similar small scale investigations (e.g. TSÖKAS *et al.*, 1998; OKUBO *et al.*, 1985).

The Aeromagnetic Data

The aeromagnetic survey of Macedonia and Thrace was flown between June and October 1966 by ABEM-Elektrisk Malmetning, on behalf of IGME (Greek Institute of Geology and Mineral Prospection). Flight lines were flown at constant terrain clearance of 275 ± 75 m above ground level, with a line spacing of 800 m for traverses and 30 km for tie lines. The direction of the flights was perpendicular to the regional strike of Hellenides (WSW-ENE).

The original analogue flight-line magnetic data were digitized in the framework of the present study. The digitized profiles were corrected for digitizing errors, then the 1966.5 DGRF was removed after which the data were leveled and microleveled. The data were interpolated to a square grid with grid spacing 500 m. Figure 1 shows

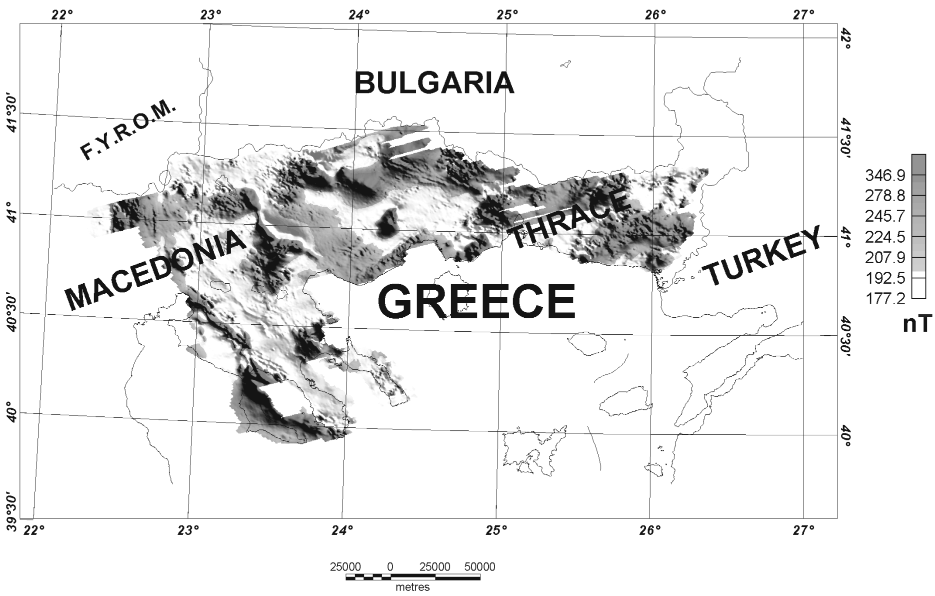

Figure 1
The aeromagnetic map of Macedonia and Thrace. Total field magnetic anomaly (STAMPOLIDIS, 1999). (F.Y.R.O.M. - Former Yugoslavic Republic of Macedonia).

the total anomaly field of Macedonia and Thrace. Areas without data have been masked (STAMPOLIDIS, 1999).

Curie Point Depth Estimates for Macedonia and Thrace

The data were reduced to the north magnetic pole, utilizing the program FFTFIL (HILDENBRAND, 1983). Figure 2 shows reduced to the North Pole aeromagnetic map of the area. The azimuthally averaged log power spectrum was then computed (Fig. 3A) using the software of PHILLIPS (1997). Various segments of the spectrum represent the various components of the magnetic field. The total field data contain long wavelength anomalies which will create erratic estimates of the Curie point depths. These components arise from topography, regional features and magnetic core fields that were not adequately removed by the DGRF model. These long wavelength components could affect the centroid depth estimates because they would tend to violate the mathematical model implicit in the algorithm.

The theoretical development is based on the assumption of a collection of random prisms. Also, to enhance the broad features, due to deep structures, the small wavelength anomalies (< 10 km) must be removed from the data set.

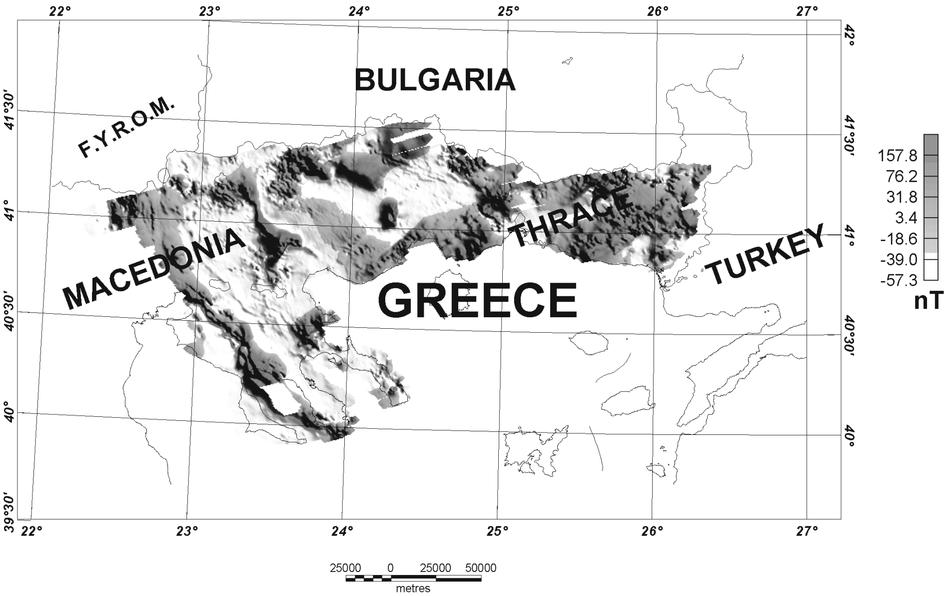

Figure 2
Reduced to the north magnetic pole aeromagnetic map of the regions of Macedonia and Thrace in NE Greece. High magnetic areas are shown by dark tones. (F.Y.R.O.M. stands for Former Yugoslavic Republic of Macedonia).

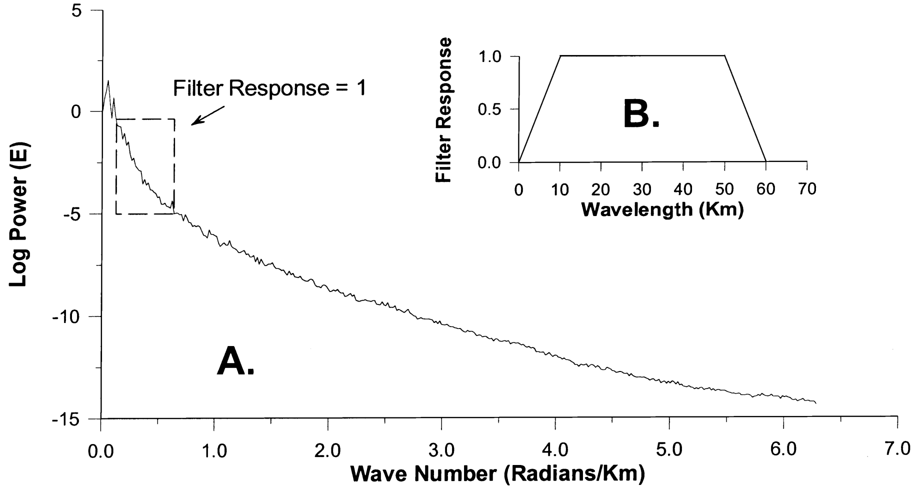

Figure 3
A. Azimuthally averaged logarithmic power spectrum of the reduced pole data. The dashed box represents the portion of the spectrum for which the response of applied data, was unity. B. The response function of the bandpass filter.

Following OKUBO *et al.* (1985) and TSÖKAS *et al.* (1998) the area under investigation was divided into 13 overlapping blocks, 90 × 90 km in size (Fig. 4). A simple bandpass filter was designed and applied to the data in order to remove these components, employing once again FFTFIL of HILDENBRAND (1983). The full pass threshold was set between 10 and 50 km (Fig. 3B). This filtered field was used for the deepest magnetic source depth calculation, using the above methodology.

Several filtered versions of the data were also used which produced Curie depth estimations incompatible with the geological setting and temperature data inferred from deep drilling. In fact the unfiltered data produced an estimate of about 17.5 km for block numbered 9 in Figure 4. However, the mean temperature gradient in this block is about 4°/100 m (Fytikas, M. personal communication, data extracted from the unpublished new Heat Flow Map of Europe) which suggests a shallower Curie point. Further, the block is dominated by granitic intrusions, a fact that strengthens the idea that the Curie Point depth should be considerably shallower than the estimate inferred from unfiltered data.

On the other hand, long mountain ranges are present in northern Greece. In particular the mountain complexes of the regions of Macedonia and Thrace are mainly composed of metamorphic rocks intruded by large plutonic bodies. Thus long

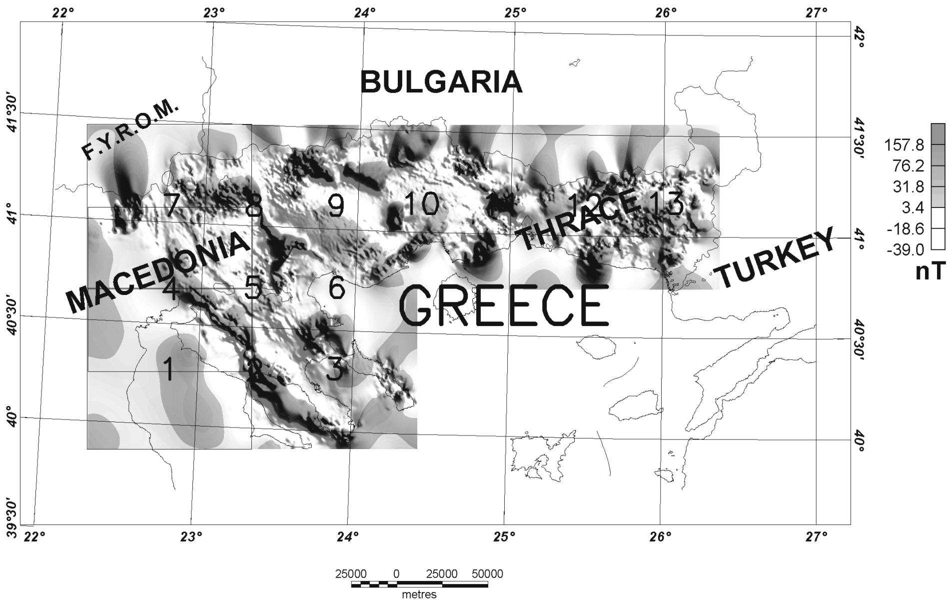

Figure 4
The bandpass (full pass 10–50 km) filtered map, used for the Curie point depth calculations. The map was subdivided into 13 overlapping blocks (90 × 90 km). Each block is denoted by a number at its center (e.g., blocks 1, 4, 7). The Curie point depth for each block was estimated and attributed to the center of each block of the filtered map.

wavelength anomalies arise from topography which are partly responsible for the Curie point depth overestimation.

The particular filtering used in this work is thus mainly the product of a trial and error approach. The leading principle was the compatibility of the inferred estimates to regional geology and tectonics, plus the borehole data.

Depth to the top, z_t, of the deepest magnetic sources and depth to the centroid, z_0, of the deepest magnetic sources where obtained by modeling the power spectrum of the data. Depth to the top, z_t, was calculated using a magnetic half-space model, while depth to the centroid, z_0, was estimated using a magnetic dipole layer model. Figure 5 presents an example of spectral analysis for a specific block (numbered 9 on Fig. 4). We can observe the good fit between the model and the data. Depth values that were calculated from this analysis were used to create the Curie point depth map (Fig. 6).

Comparison with Geological and Heat-Flow Data

The main geological setting of the area has four rock formations: a) The metamorphic basement (of pre-alpine age) with folded alpine sediments, b) magmatic

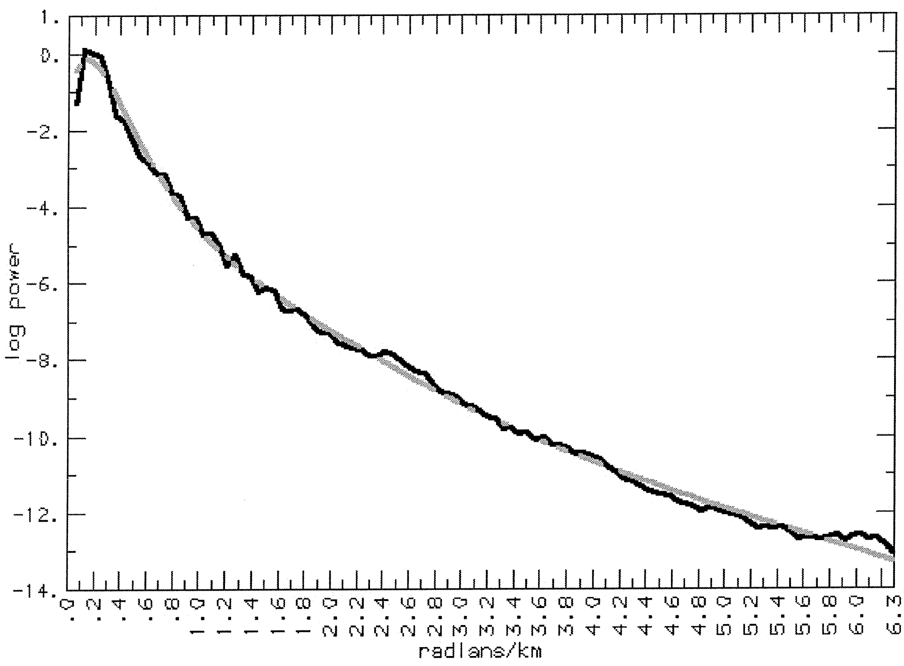

Figure 5
Spectral analysis for block numbered 9 on the filtered aeromagnetic map (Fig. 4). Dark line is the power spectrum of the filtered field of block numbered 9, while the gray line shows the mathematical fit of the model.

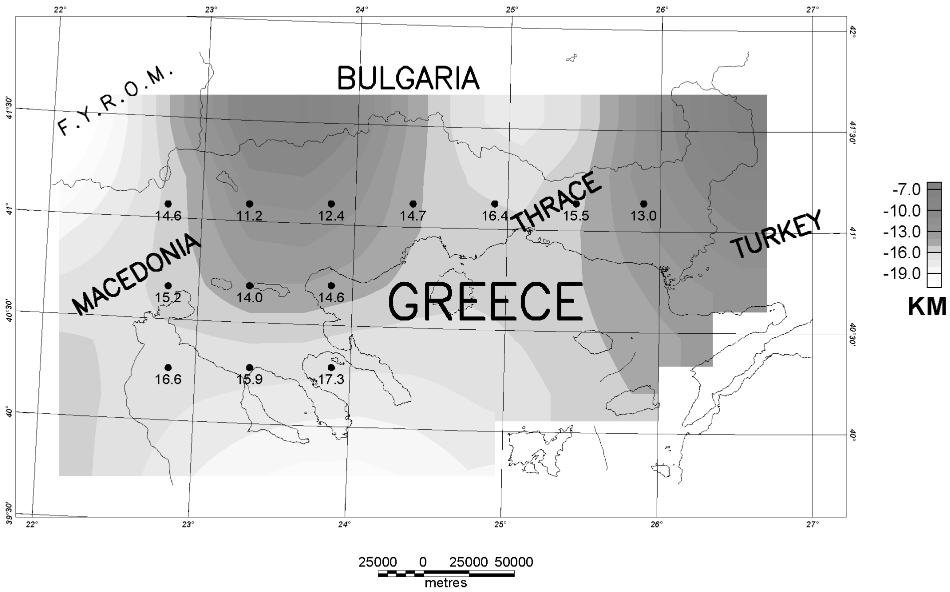

Figure 6
Curie Point Depth map for Macedonia and Thrace (N. Greece). Calculated values for each block (Fig. 4) are also posted on map.

intrusions, c) Quaternary sediments and d) ophiolitic rocks. The average thickness of the crust in the NE Greece has been estimated to be between 30–35 km (PAPAZACHOS, 1994; PAPAZACHOS *et al.*, 1995; TSÖKAS and HANSEN, 1997). Our Curie point estimates fall within the crust.

Shallow CPD on the Greece-Bulgaria border (blocks numbered 8 and 9 in Fig. 4) are correlated with the Miocene-Pliocene volcanism and the large granitic intrusion (e.g., granite of Vrontou) in this area. Blocks numbered 11 and 12 in Figure 4 cover the area of Komotini – Xanthi basin. TSÖKAS *et al.* (1996) suggested that the sedimentary cover of the basin is 1.8 km thick which justifies the deepening of CPD. The geological setting at Greece-Turkey borders is characterized by extended acid volcanism. The calculated CPD is in good agreement with that.

Thick sedimentary covers (TEN DAM and ROUVIERE, 1983) are present at the southwestern part of the area under investigation, which justifies the calculated deep CPD values of our model.

We have correlated the estimated CPD with geothermal gradient values (SACHARIDIS, 1991) and heat flow data (FYTIKAS and KOLIOS, 1979). We assumed that the Curie point temperature is that of pure magnetite (580°C at standard pressure) and we calculated the corresponding thermal gradient (gradT = 580°C/ Curie depth, see Table 1). Using this value we also calculated the corresponding heat flow values (HF = K·gradT, see Fig. 7), where K = 2.123 W/°K·m was the mean

Table 1

Curie Point Depths (CPD) and Thermal Gradient (gradT) values for each block of the aeromagnetic map analyzed (Fig. 4)

Block ID	CPD (km)	GradT °C/100 m
1	16.6	3.5
2	15.6	3.6
3	17.3	3.3
4	15.2	3.8
5	14.0	4.1
6	14.6	4.0
7	14.6	4.0
8	11.2	5.2
9	12.4	4.7
10	14.7	3.9
11	16.4	3.5
12	15.5	3.7
13	13.0	4.5

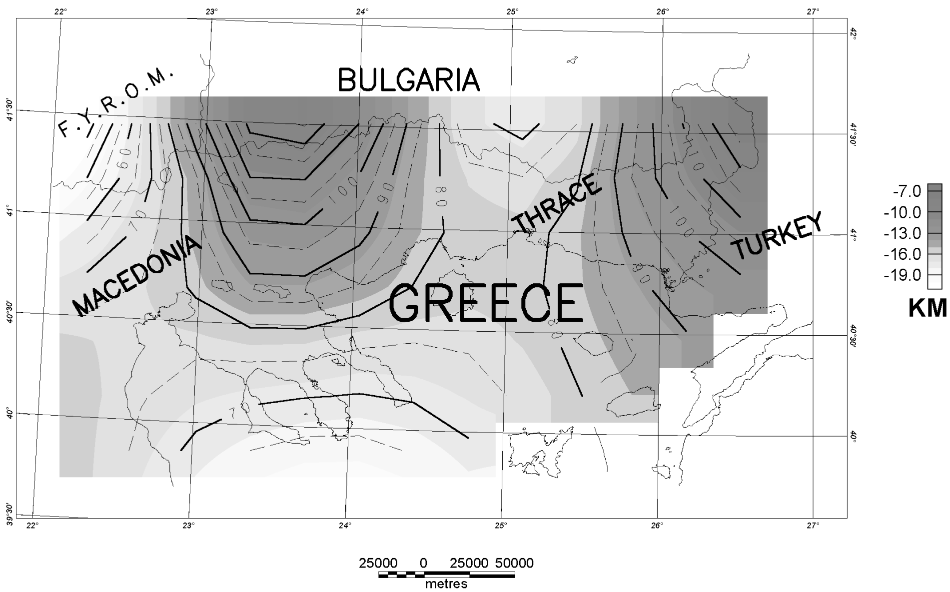

Figure 7
Inferred heat flow contours (mW/m^2) from Curie point depths. Curie point depths are also shown in gray scale.

thermal conductivity of the metamorphic basement (FYTIKAS and KOLIOS, 1979). Heat flow values are of the same order with those from the preliminary heat-flow map of Greece of FYTIKAS and KOLIOS (1979).

At the western part of the Greece-Bulgaria border, shallow Curie point depths coincide with high thermal gradient values, as suggested by SACHARIDIS (1991). However, the inferred thermal gradient estimates are smaller than those of SACHARIDIS (1991). In fact SACHARIDIS (1991) estimates the thermal gradient of the area to be about 5–6°/100 m. Following our estimates, the thermal gradient should be about 4–4.7°/100 m in the same area. This figure is in agreement with those given by FYTIKAS and KOLIOS (1979) and those of the new Geothermal Atlas of Europe (Fytikas, personal communication). The differences could be reasoned by the different approach followed. SACHARIDIS (1991) used the method of the continuation of analytic isothermal surfaces. Measured temperatures from boreholes in this zone are of the order 60–65°C at 500 m depth. This fact, along with the results of this study shows the great geothermal potential of the area.

Conclusions

The inferred Curie point depth for Macedonia and Thrace (N. Greece) ranges rom 11.2 to 17.3 km. These are rather shallow depths indicating that heat flow should be above the average value in the area. However, this figure is compatible with the known heat flow values and geothermal gradient measurements. Metamorphic rocks and plutonic intrusions compose the major proportion of the geological setting. Intense faulting is also present. The area is dominated by relatively high geothermal gradients, and hot springs manifest themselves in various sites. These facts support our estimates.

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