CURIE POINT DEPTHS OF THE BULGARIAN TERRITORY INFERRED FROM GEOMAGNETIC OBSERVATIONS

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Abstract

During last years spectral analysis of geomagnetic data has often been applied to estimate Curie point depths. It is used to delineate thermal and crustal structures on the basis of geomagnetic observations. The most popular mathematical model on which the spectral analysis is applied was introduced by Spector and Grant (1970) and comprises a collection of rectangular prisms with constant magnetization. The expectation value of the spectrum for the model is the same as that of a single body with the average parameters for the collection. .A satisfactory algorithm based on this model is used in the present research to calculate the thickness of magnetically active part of the lithosphere on the Bulgarian territory. The algorithm estimates x_0, y_0 and z_0, the coordinates of the centroid, and depth to the top z_t of the source distribution, trough least-squares fit of a straight line to the log averaged power spectrum in the lowest part of the radial frequency's range. The depth to the bottom (Curie point depth) is z_b,= $2z_0$,- z_t. An useful compilation of data was made merging Bulgarian and South Romanian geomagnetic maps which allows to expand the result's area. Calculated values of the Curie point depths of Bulgarian territory range between 17 and 35km. Several anomalous zones are delineated, mostly in the southern part of the area. As a criterion of reliability a correlation with the heat flow data of Bulgarian territory was used.

Keywords: curie point depth, geomagnetic, spectral analysis, geothermal.

Introduction

Determination of the depth at which lithosphere does not exhibit its magnetic properties is an actual problem, successfully solved using geophysical data. As is known, crustal rocks lose their magnetization at the Curie point temperature, become paramagnetic and their ability to generate detectable geomagnetic anomalies disappears. The Curie temperature for titanomagnetite, the most common magnetic mineral in igneous rocks, is approximately 570^{o}C. Therefore, it may be possible to locate a point on the isothermal surface by determining the depth to the bottom of a magnetized rock mass. In certain approximation, adequate for the inverse problem solution, this surface could be marked as Curie temperature isotherm. One of the important parameters which determine the relative depth of the isotherm with respect to sea level is the heat content in a particular region. It is therefore to be expected that a region having significant geothermal energy near the surface of the Earth will be associated with a conspicuously shallow Curie point isotherm, relating to the adjoining regions.

Method

The idea of using geomagnetic data to estimate the thickness of the magnetized part of the lithosphere was widely used by geophysicist working in the last decade. One of the most profound methods of Curie point depth's (CPD) determination are based on spectral analysis of geomagnetic data. The earliest papers on the subject are those of Spector and Grant (1970), Bhattacharyya and Leu (1975, 1977), Smith et al. (1974, 1977) and Byerly and Stolt (1977) where analysis for different areas of USA have been published. More recently, investigations have been made for parts of the territory of Japan (by Okubo 1985, 1989, 1994), USA (by Mayhew 1982, 1985, Blakely 1988), Greece (Tsokas et al. 1998, Stampolidis and Tsokas 2002), Portugal (Okubo et al. 2003) etc. Computation of the CPD is one of the difficult problems in potential field inversion (Blakely, 1995). Two fundamental methods serve as a basis of all subsequent analysis, first provided by Spector and Grant (1970), estimating the average depths to the top of magnetized bodies from the slope of the log power spectrum and second by Bhattacharyya and Leu (1975) for obtaining the depth to the centroid of the causative body.

Authors consider the power spectrum of the total geomagnetic field intensity anomaly over a single rectangular block (Fig. 1) using the expression, which was first given by Bhattacharyya. The equation was transformed into polar wave number coordinates (s,ψ) and average depths to the top of magnetized bodies from the slope of the log power spectrum were calculated. The model has proven very successful in estimating average depths to the tops of magnetized bodies.

Mathematical basis which is used in the present work is the improvement of that method, developed by Okubo et al. Authors use the expression given by Spector and Grant

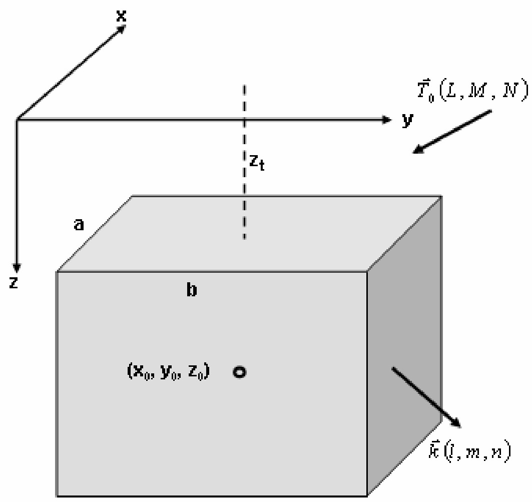

Fig.1. Rectangular, vertical-slided parallelepiped: an interpretational model [1] in the form:

$$\begin{aligned} F(s,\psi) = {} & 2\pi JA[N + i(L\cos\psi + M\sin\psi)] \\ & \times[n + i(l\cos\psi + m\sin\psi)] \\ & \times \sin c(\pi sa\cos\psi)\sin c(\pi rb\sin\psi) \\ & \times \exp(-2\pi is(x_0\cos\psi + y_0\sin\psi)) \\ & \times[\exp(-2\pi sz_t) - \exp(-2\pi sz_b)] \end{aligned} \tag{1}$$

where

J – magnetization per unit volume;
A – average cross-sectional area of the bodies;
L,M,N – direction cosines of geomagnetic field;
l, m, n – direction cosines of the average magnetization vector;
a, b – average body x- and y- dimensions;
$\mathbf{x_0}$, $\mathbf{y_0}$ – average body x- and y- centre location;
$\mathbf{z_t}$, $\mathbf{z_b}$ – average depths to the top and bottom of the bodies;

$$\sin c(x) = \frac{\sin x}{x}.$$

Following Bhattacharyya and Leu (1975, 1977) estimation of the bottom depths could be approached in two steps: first, find the centroid depth $\mathbf{z_0}$, and second, determine the depth to the top $\mathbf{z_t}$. Then CPD is calculated from these values: $\mathbf{z_b=2z_0-z_t}$.

At very long wavelengths compare to the ensemble dimensions, the terms of equation (1) which involve the body parameters (**a**, **b** and $\mathbf{z_b-z_t}$) may be approximated by their leading terms to yield:

$$F(s,\psi) = 2\pi JA[N + i(L\cos\psi + M\sin\psi)] \times [n + i(l\cos\psi + m\sin\psi)] \times \exp(-2\pi is(x_0\cos\psi + y_0\sin\psi)) \times \exp(-2\pi sz_0) \tag{2}$$

It is obvious that equation (2) is the spectrum of a dipole. As a result, the ensemble average at these very low frequencies is that of a random distribution of point dipoles. Therefore details of the body parameters (prism, cylinders, or whatever) do not contribute to the expression of the spectrum.

Okubo (1985) defined a function G(s,ψ) by

$$G(s,\psi) = F(s,\psi)/s;$$

Following the method of Spector and Grant (1970)

$$H^2(s) = \frac{1}{2\pi}\int_{-\pi}^{\pi} G^2(s,\psi)d\psi \tag{3}$$

Then *H(s)* has the form:

$$H(s) = A\exp(-2\pi sz_0)$$

Therefore

$$\ln H(s) = \ln A - 2\pi sz_0 \tag{4}$$

The centroid depth $\mathbf{z_0}$ can be obtained from the slope of a straight line by the least squares fitting to the ***lnH(s)*** (Fig. 2).

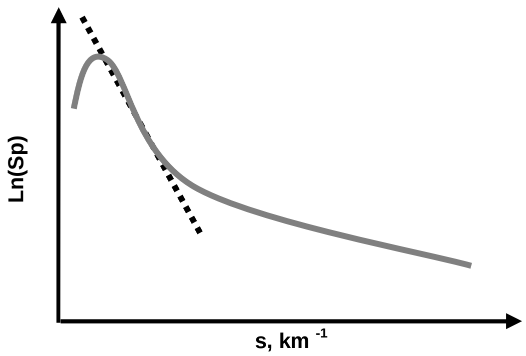

Fig. 2. Scheme of radially averaged log power spectrum diagram for $\mathbf{z_0}$ estimating and calculation of depth to the bottom of the magnetic earth crust $\mathbf{z_b}$

The second step of the process is the estimation of the dept to the top. If we return to the equation (1) and assume that a range of wavelengths can be found for which the following approximations hold:

$$\sin c(\pi s a \cos\psi) = 1;$$
$$\sin c(\pi s b \cos\psi) = 1;$$

and $\exp(-2\pi s z_b) \approx 0.$

The bodies must in general be large in depth compared to their horizontal dimensions.

The spectrum reduces to the form:

$$\begin{aligned} F(s,\psi) = 2\pi JA[N + i(L\cos\psi + M\sin\psi)] \\ \times[n + i(l\cos\psi + m\sin\psi)] \\ \times\exp(-2\pi i s(x_0\cos\psi + y_0\sin\psi)) \\ \times\exp(-2\pi s z_t) \end{aligned} \qquad (5)$$

Equation (5) is in fact the spectrum of a monopole. Because of the similarities the same two basic approaches to estimate $\mathbf{z_t}$ can be used:

$$K^2(s) = \frac{1}{2\pi}\int_{-\pi}^{\pi} F^2(s,\psi)d\psi \quad ; \qquad (6)$$

From which

$$K(s) = B\exp(-2\pi s z_t)$$

Therefore

$$\ln K(s) = \ln B - 2\pi s z_t \qquad (7)$$

The reliability of this method has been proven in many cases (e.g. Okubo, 1994, 1998; Tsokas et al.,1998 etc.).

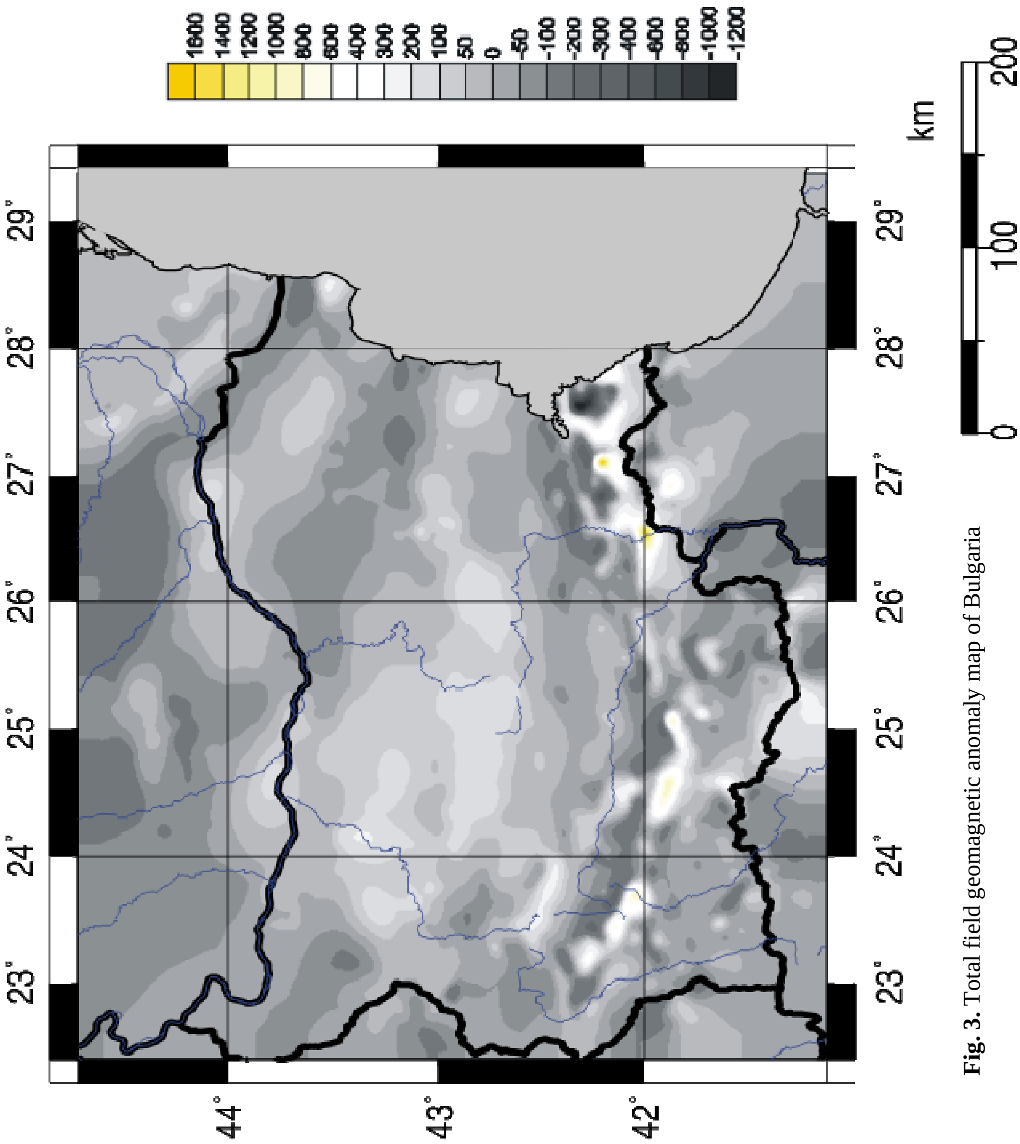

Fig. 3. Total field geomagnetic anomaly map of Bulgaria

Spectral analysis of geomagnetic data

Geological nature of the Bulgarian geomagnetic field can be discussed separating the territory in two parts- northern and southern. To the geomagnetic field in the northern part reflects basement structures of the Moesian platform. It is considered that the whole consolidated crust and to some extent the upper mantle, are magnetically active but having unsteady general magnetization varying from 0.01 to 0.5-0.8 A/m (Dachev, 1988).This factor reflects the nature of regional geomagnetic anomalies of the North-western strike in the Moesian platform. To the south, in the Alpine area, geomagnetic anomalies are related to magnetic products of different age (mainly-Upper Cretaceous and Priabonian-Oligocene) and less commonly to different varieties of metamorphic rocks (Dobrev et al.,1984). These disturbers are situated on the present erosion level or in the upper part of the geological section.

In the northern geomagnetic part several magnetic regions are differentiated: positive anomalous zones - Moesian and Tjulenovo-Spasovska, and negative – Dulovska and Central Bulgarian (Fig. 3).

Southern geomagnetic part of Bulgaria is remarkable with its complicated field which has a variable sign. It consists of seven geomagnetic regions: South- and Central Srednogorian (positive), Burgas (with intensive mosaic field), two Central Rodopian and one East Rodopian zone (connected to the Paleogene magmatic spreading), and finally West Rodopian zone (positive).

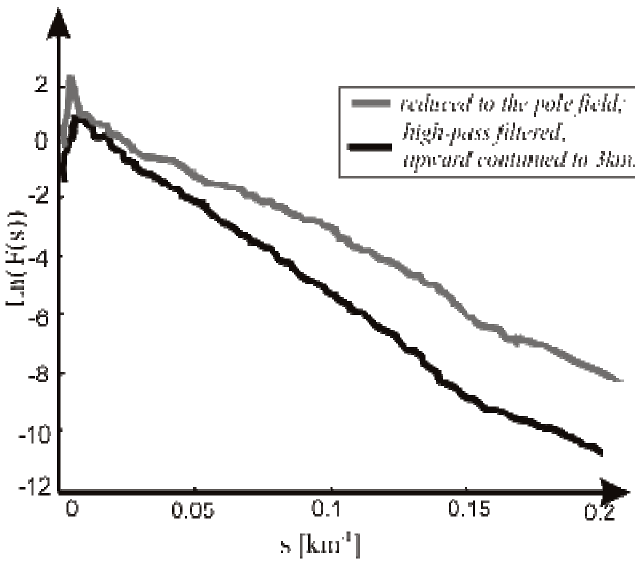

Fig. 4. Log averaged power spectra

The total field geomagnetic anomaly map is used for the calculation of the present research. Geomagnetic data of Bulgaria and South Romania are compiled to a common dataset with grid space of 1 km. Subsequently they were reduced to the pole, upward continued to a barometric altitude of 3km and their frequency components were analyzed. It was recognized that geomagnetic anomaly map contains long-wavelength components arising from regional structures and gross terrain features. These components could affect the centroid depth estimates and an attempt to remove them before evaluating the demanding parameters was made.

After the complex estimating, appropriate high-pass filtration was used and the significant pick in the longest wavelength part of the spectrum was removed.

The operational dataset was divided into overlapping squared blocks 150x150km in size. Averaged power spectrum for each block was then calculated, processed and analyzed.

Results

As we expected Curie point depths of Bulgarian territory range between 17 and 35km. In the Moesian platform they vary from 28 to 32 km, except two anomalous zones having shallower depths. They are situated in western part-around Vratza and in central part-around Veliko Tarnovo. These anomalous zones are in good agreement with the heat flow density map of Bulgaria (Bojadgieva et al., 2001) and clarifying their correlation with seismicity is the forthcoming process.

The smallest values of CPD were obtained in the southern part of Bulgaria where some areas with significantly high heat flow are presented. The sources' nature of these anomalies should be classified as zones of late magmatism, sharply expressed neotectonic or recent movements, or increased seismic activity.

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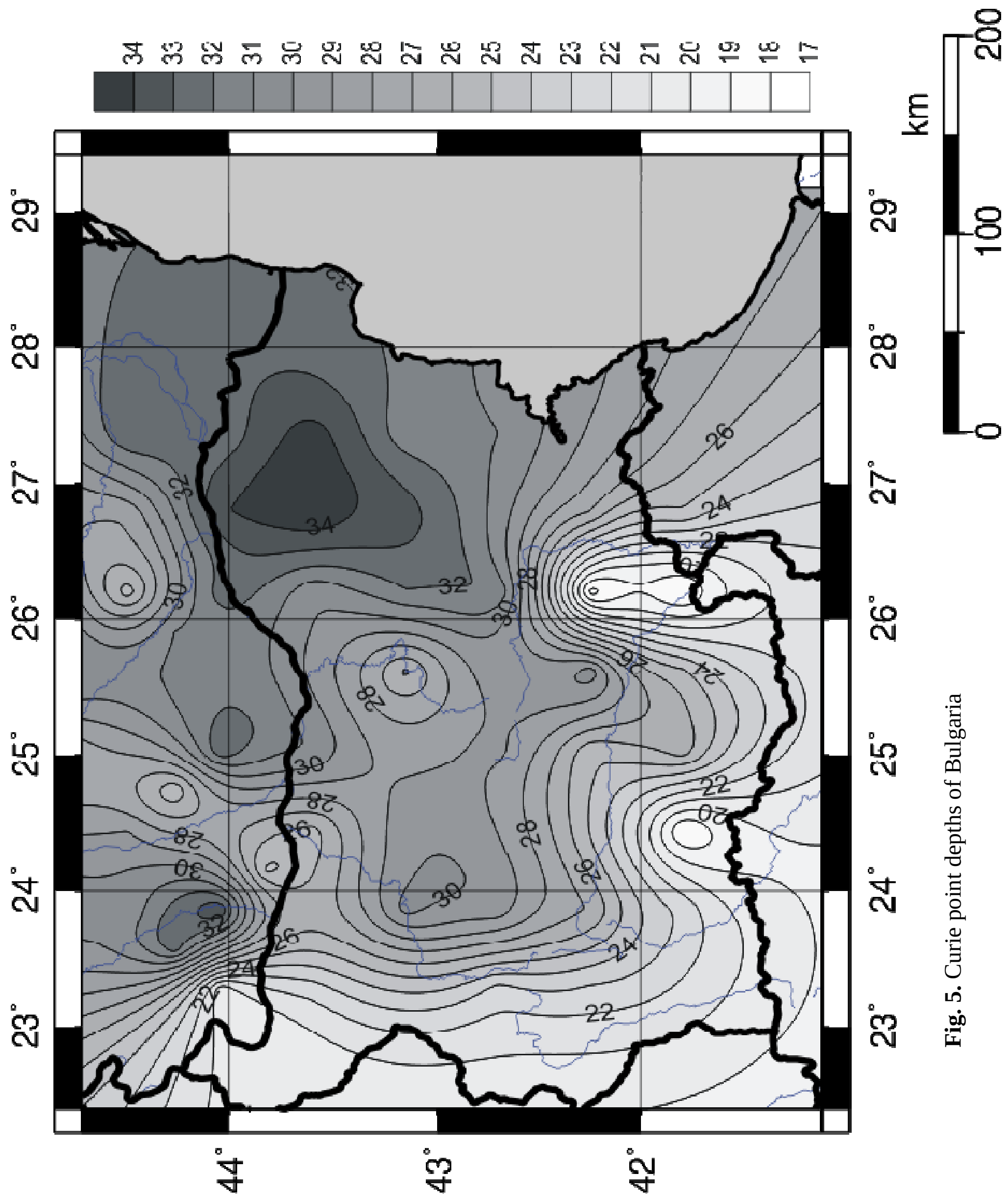

Fig. 5. Curie point depths of Bulgaria

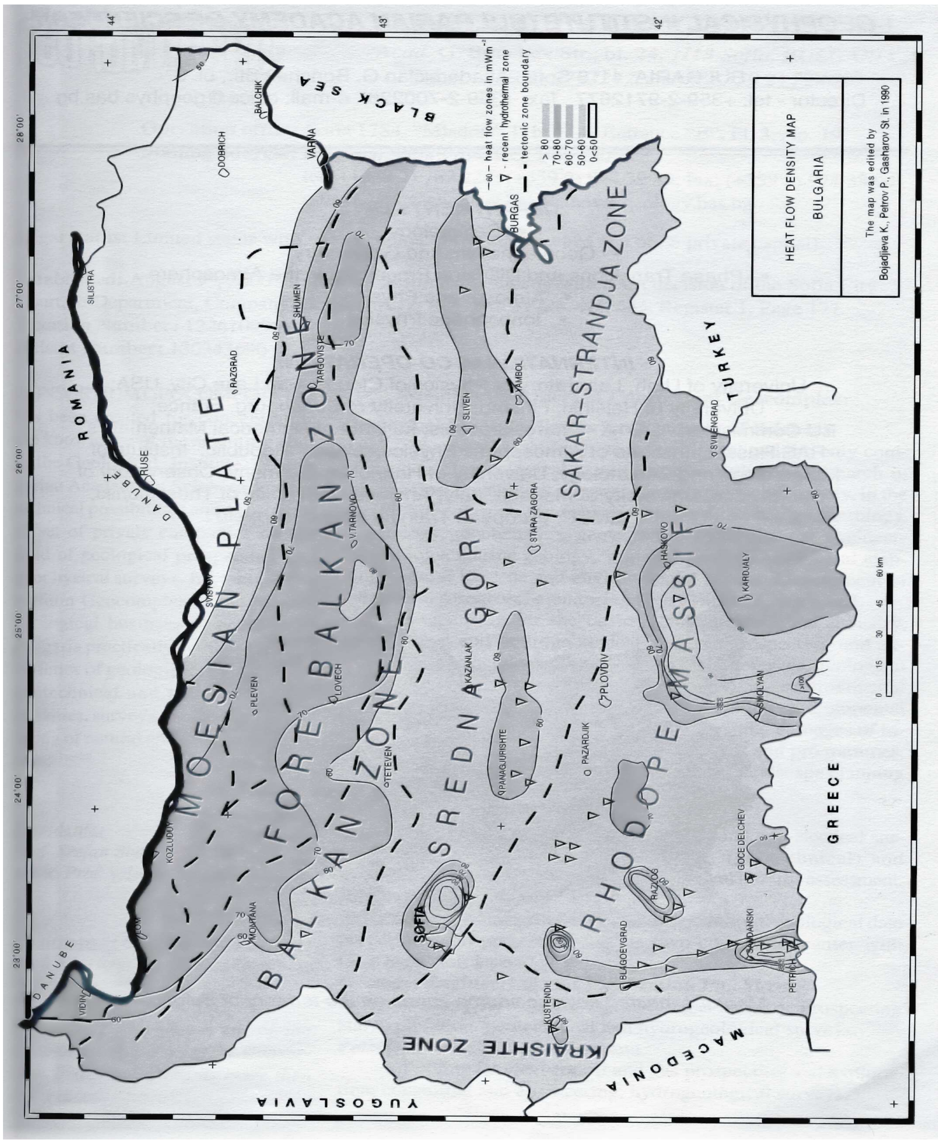

Fig. 6. Heat flow dencity map of Bulgaria (after Bojadgieva and Gasharov, 2001)

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Дълбочини до точката на Кюри на територията на България получени по геомагнитни данни

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Резюме. През последните години, спектрален анализ на геомагнитни данни често бива прилаган за изчисляване на дълбочините до точката на Кюри. Методът се

използва за очертаване на зони с повишена геотермална енергия и тектонски структури на базата на геомагнитни измервания. Известно е, че скалите губят своята намагнитеност при температури над точката на Кюри на съдържащите се в тях минерали, стават парамагнитни и способността им да създадат забележима магнитна аномалия изчезва. Температурата на Кюри за най-разпространения магнитен минерал в магмените скали- титаномагнетита е около 570^0. Следователно е възможно да се намери точка върху изотермалната повърхност за дадена територия чрез определяне на дълбочината до долната граница на магнитоактивния слой на литосферата. Най-използваният математически модел в световната практика е предложен от Spector and Grant (1970) и представлява набор (колекция) от правоъгълни призми с постоянна намагнитеност. Математическото очакване за спектъра на модела е същото като спектъра на единично тяло, имащо усреднените параметри на колекцията. В настоящото изследване е създаден успешен алгоритъм на базата на този модел за изчисляване на дебелината на магнитоактивният слой на литосферата на територията на България. Изчисляват се координатите $\mathbf{x_0}$, $\mathbf{y_0}$ и $\mathbf{z_0}$ на геометричният център на тялото и дълбочината до горната му повърхност $\mathbf{z_t}$ чрез наклона на права, апроксимирана по метода на най-малките квадрати към графиката на логаритъма на усреднения радиален енергетичен спектър. Тогава дълбочината до долната повърхност (респ. до точката на Кюри) се изчислява от израза $\mathbf{z_b}$,= $\mathbf{2z_0}$,- $\mathbf{z_t}$. Като данни в настоящата работа са използвани карти на тоталния вектор на интензитета на магнитното поле за територията на България и южната част на Румъния. Получените стойности за дълбочината до точката на Кюри варират между 17 и 35км. Очертават се няколко аномални зони, главно в южната част на територията. Като критерий за оценка, резултатите са съпоставени с данни за топлинния поток на територията на България.