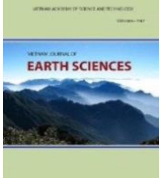
Vietnam Journal of Earth Sciences, 41(3), 216–228, Doi: 10.15625/0866-7187/41/3/13830

(VAST)

Vietnam Academy of Science and Technology

Vietnam Journal of Earth Sciences

http://www.vjs.ac.vn/index.php/jse



Estimation of Curie point depths in the Southern Vietnam continental shelf using magnetic data

Pham Thanh Luan[1*], Do Duc Thanh[1], Erdinc Oksum[2], Le Thi Sang[1]

[1] *VNU University of Science, Faculty of Physics, Department of Geophysics, Hanoi, Vietnam*

[2] *Süleyman Demirel University, Engineering Faculty, Department of Geophysical Engineering, Isparta, Turkey*

Received 12 February 2019; Received in revised form 18 April 2019; Accepted 18 May 2019

ABSTRACT

This study attempts to estimate the thermal structure in the Southern Vietnam continental shelf by calculating the Curie point depth isotherm using magnetic data. The Curie point depth values, from 49 overlapping blocks 128 × 128 km in size, have been estimated by the exponential approach. This approach is based on the analytical solution of the exponential equations obtained from transforming the magnetic anomaly data into the frequency domain. According to the obtained results, the range of Curie point depths is from 15.3 to 35.6 km. In the study area, the greatest Curie point depth is located in the South-Eastern part, and the smallest depth is located at North-Western part. The heat flows derived from the Curie point depths are also presented. The obtained results are at relatively high resolutions and in agreement with the published information available for the study area. The Curie point depths generally lie below the Moho surface in this region but lie above in some locations, notably the Cuu Long basin.

Keywords: Curie point depth; heat flow; exponential approach; magnetic data; Southern Vietnam continental shelf.

©2019 Vietnam Academy of Science and Technology

1. Introduction

Temperature is one of the main factor controlling the rheology of solids, thus, to understand the mechanical behavior of the Earth's crust and lithosphere, it is necessary to know its thermal structures (Turcotte and Schubert, 2002). Geological processes and events such as volcanism, intrusion, earthquakes, mountains uplift and metamorphism are controlled by heat generation and its transfer inside Earth (Fowler, 2005). Thereby, thermal structures of the Earth's crust can be manifested the deformation models, depths of brittle and ductile deformation zones, regional heat flow variations, seismicity, subsidence/uplift patterns and maturity of organic matter in sedimentary basins (Dolmaz et al., 2005a, 2005b). In general, evaluations on the thermal characters of the Earth's crust have been carried out from investigations by direct measurements of heat flow. However, such data are scarce and can be contaminated with shallow anomalies of the local geological environment (Blackwell, 1983; Siler and

---

[*] Corresponding author, Email: luanpt@hus.edu.vn

Kennedy, 2016; Correa et al., 2016). As an alternative method to examine the thermal structures of the Earth's crust is the estimation of the Curie point depth (CPD) which provides a proxy of the thermal regime at depth, and can be used to infer the heat flow pattern in wide regions. Hereby, the Curie point depth is known as the depth at which the dominant magnetic mineral in the Earth's crust changes its magnetic property from ferromagnetic to the paramagnetic state under the effect of increasing temperature (Nagata, 1961). According to this, the Curie point temperature related to the Curie point depth can be variable depending on the mineralogical content of rocks and the geological structure of the region. However, the Curie point depth isotherm of 580°C of the Earth's crust, which is the demagnetizing point of magnetite (Frost and Shive, 1986) is generally considered as an indicator of the extent of magnetic sources. Within this frame, shallow Curie point depths are excepted usually at regions comprising thinned crust, young volcanism and geothermal potential (Tanaka et al., 1999).

In this context, the idea of using aeromagnetic data to estimate Curie point depth is not new and has been extensively taken advantage worldwide in estimation of the thermal structure of the Earth's crust in various tectonic settings (i.e.; Serson and Hannaford, 1957; Smith et al., 1977; Okubo et al., 1985; Tanaka et al.,1999; Stampolidis and Tsokas, 2002; Trifonova et al., 2009; Saleh et al., 2013; Bansal et al. 2013; Starostenko et al. 2014; Rocha et al., 2015; Correa et al., 2016; Teknik and Ghods, 2017; Wang and Li, 2018). A number of methods have been proposed for estimating the basal depth of the magnetic sources, particularly to provide a statistical estimate of CPD for regional-scale studies. For example the spectral peak method (Spector and Grant, 1970), the centroid method (Bhattacharyya and Leu, 1975) used by Okubo et al. (1985) and Tanaka et al. (1999), the power law correction method (Maus and Dimri, 1996), forward modelling of spectral peaks (Finn and Ravat, 2004), exponential approach (Aydın and Oksum, 2010, 2012), fractal method (Bansal et al., 2011) and recently the de-fractal method (Salem et al., 2014).

Geodynamic studies based primarily on the interpretation of magnetic anomalies in the Southern Vietnam continental shelf have been so far very rare. In the past, Tanaka et al. (1999) used the centroid method to calculate the CPD in the East and Southeast Asia. Since their study covers a very large area, their map of estimated CPD in Southern Vietnam continental shelf is very low resolution. The aim of this work is to utilize magnetic anomaly to estimate the CPD in the Southern Vietnam continental shelf at relatively high resolutions through the exponential approach (Aydın and Oksum, 2010, 2012). The method is based on depth calculations of single prism or ensemble of prisms by using an exponential solution of the Fourier transform of magnetic data which might slightly differ from Bhattacharyya and Leu's (1977) approach. In this study, a modified MATLAB code using the exponential approach has been developed to compute the Curie point depth configuration in the study area.

2. Regional Geological setting

The Southern Vietnam continental shelf is an area of active hydrocarbon production (Fig. 1). The area is formed by the prograding Pliocene - Quaternary sediments of the Mekong Delta. The oil exploration has revealed the presence of two main basins beneath this recent sedimentary cover, the Cuu Long and Nam Con Son basins (Fig. 2). The Northern Cuu Long basin is the continuation of the onshore Mekong basin and is a major basin for oil production (Huchon et al., 1998; Gwang et al., 2001; Binh et al., 2011). The age of Cuu Long basin fill sediments ranges from Eocene to Quaternary (Binh et al., 2011). The Southern Nam Con Son basin is open to the deeper oceanic basin to the east and is a major gas-producing basin (Huchon et al., 1998; Gwang et al., 2001; Binh et al., 2011). The age of Nam Con Son basin fill sediments ranges from Oligocene to Quaternary (Binh et al., 2011). Two basins are separated by a basement high named Con Son ridge. The depth to the basement of the basins obtained from various sources and from the PONAGA'93 cruise, and is shown in Fig. 2 (Huchon et al., 1998).

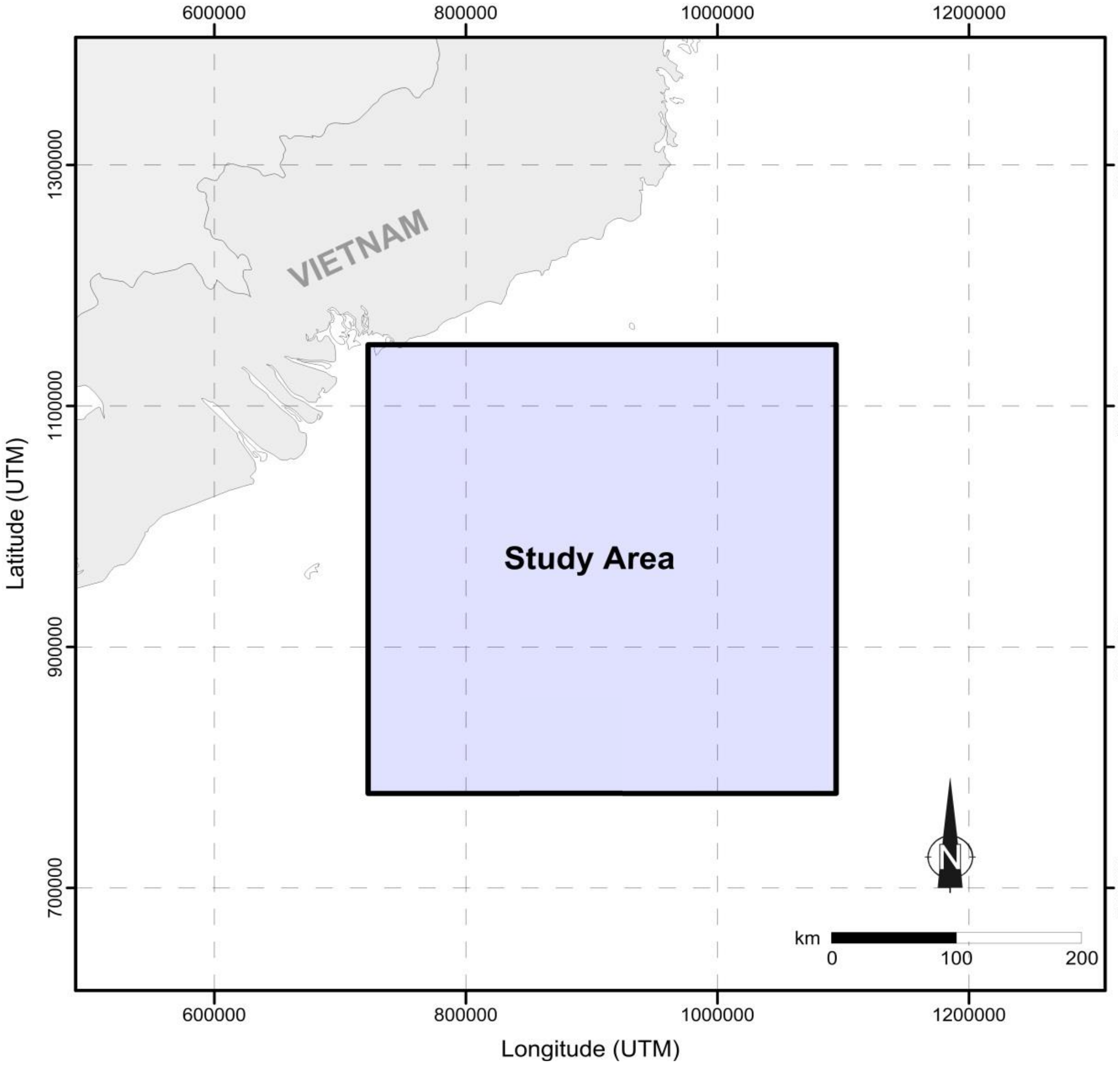


Figure 1. Location of the study area

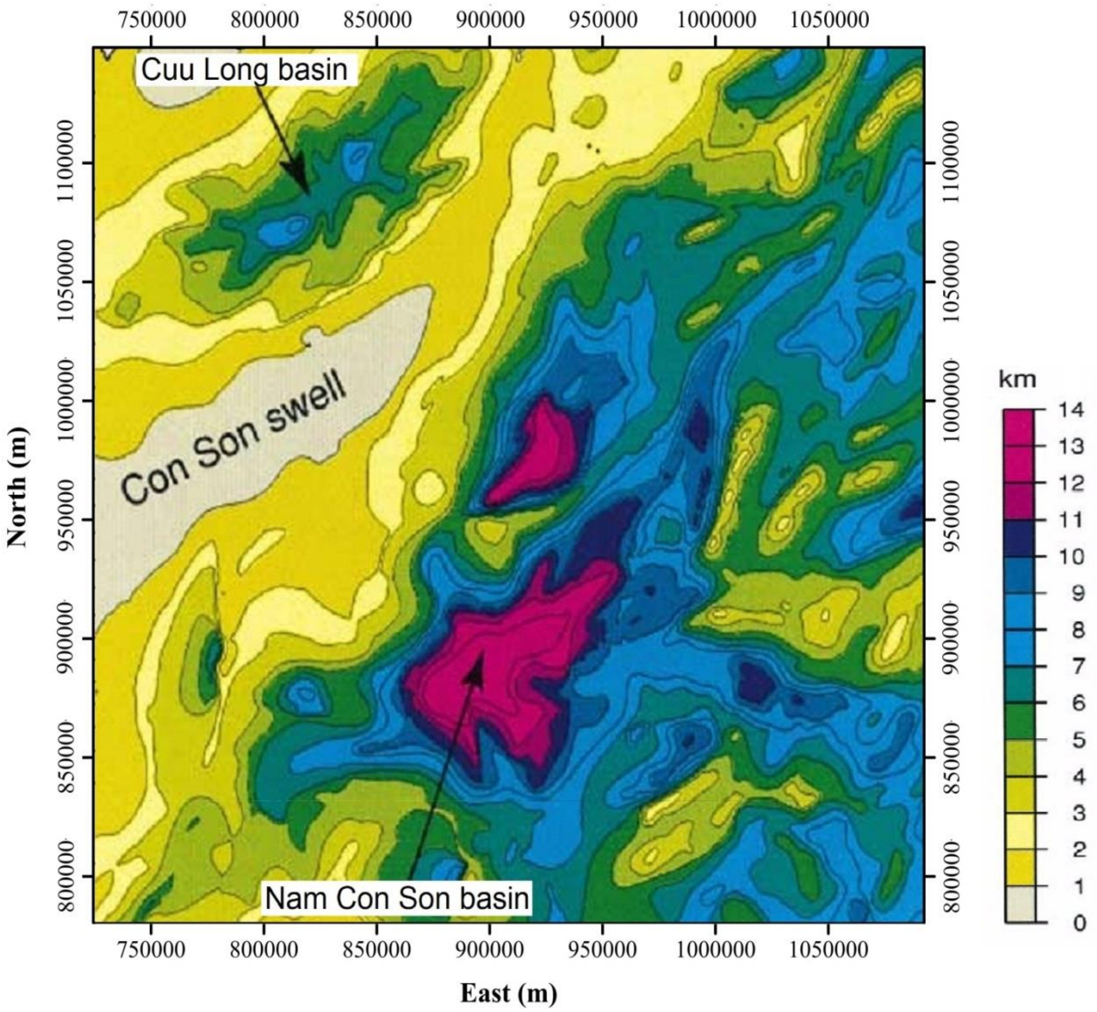


Figure 2. The depth to basement depth map (modified from Huchon et al., 1988)

3. Methodology

Following Aydın and Oksum (2010, 2012), the expression of the Fourier transform of the magnetic anomaly of a finite vertical prism model with the top depth h_1 and bottom depth h_2 can be written as:

$$F(u,v) = B\left\{\left(e^{-|s|h_1} - e^{-|s|h_2}\right)\left(\sum_{p=1}^{4} e^{-i(ux_p+uy_p)}\right)\right\} \qquad s = (u^2+v^2)^{(1/2)} \tag{1}$$

where x_p and y_p denote the corner coordinates of the top and bottom surfaces of the prism at the horizontal plane, B is the complex term related to the directions of the magnetization and the magnetic permeability (Blakely, 1996).

Setting the horizontal size of the prismatic body in Eq. (1) as infinitely expanded, it can be described as a kind of a magnetic layer comprising several prisms with depth limits close to each other. Aydın and Oksum (2010, 2012) introduced a statistical approach using the diagonal discrete values of $F(u,v)$ for estimating the top and bottom depths of a magnetic layer which might be defined as the average depths of an ensemble of prisms. Hereunder, by taking the frequency increment interval as $\Delta r = 2\pi/N$ for equally spaced $N \times N$ gridded data and $u = v = \Delta r$, the discrete radial values of $F(u, v)$ along the diagonal axis on $u - v$ plane is expressed with the form of $A(m\Delta r)$ as:

$$A(m\Delta r) = \sum_{p=1}^{q} B_p \mu_p^m \qquad (2)$$

where $\mu_p = e^{-\Delta r(h_p + i(x_p + y_p))}$ and $m = 0, 1, 2, 3, \ldots n$. Δr is the increment with eqiuspaced intervals and $n + 1$ is the number of data taken on the radial line in the $u - v$ plane. Based on the exponential approximation procedure explained comprehensively by Hildenbrand (1965, 1974) and Aydın and Oksum (2010, 2012), the unknown μ values in equation set (2) can be solved by letting the μ values be the roots of an algebraic Eq. (3):

$$\begin{aligned} \mu^q + \gamma_1 \mu^{q-1} + \gamma_2 \mu^{q-2} \\ + \ldots \ + \gamma_{q-1}\mu + \gamma_q = 0 \end{aligned} \qquad (3)$$

In order to obtain the γ values to be used for determining μ values, it follows setting of a linear Equation set (4) constructed from matrix components of the discrete radial values of equation set (2):

$$Da = Df \times \gamma \qquad (4)$$

where these matrices are indicated in open form as below,

$$Df = \begin{bmatrix} A((m-1)\Delta r) & A((m-2)\Delta r) & \ldots & A(0\Delta r) \\ A(m\Delta r) & A((m-1)\Delta r) & \ldots & A(1\Delta r) \\ \vdots & \vdots & \vdots & \vdots \\ A((n-2)\Delta r) & A((n-3)\Delta r) & \ldots & A((n-m-1)\Delta r) \end{bmatrix},$$

$$Da = \begin{bmatrix} -A(m\Delta r) \\ -A((m+1)\Delta r) \\ \vdots \\ -A((n-1)\Delta r) \end{bmatrix}, \quad \gamma = \begin{bmatrix} \gamma_1 \\ \gamma_2 \\ \vdots \\ \gamma_q \end{bmatrix}.$$

Once the unknown parameters γ's are obtained and the solutions of μ's is performed from Eq. (3), the depths of the corners of the prism can be computed by taking the natural logarithm of the absolute values of $\mu_p$values divided to the frequency interval as in Eq. 5 (Aydın and Oksum, 2010, 2012):

$$h_p = Ln(|\mu_p|)/2\pi/N \qquad (5)$$

It is noted that the number of corners depends on whether the problem is a finite extended prism model (8 corners), or an infinite extended prism model (4 corners). In the case of a finite model, the average value of the largest four depths estimated provides the depth to the bottom (Curie point depth) whereas the mean of the remaining four provide the depth to the top of the ensemble. However, in the case of an infinite depth extended model, 4 corners are used and the mean value of the estimated depths of these corners give the top depth of the magnetic layer (depth to the magnetic basement).

A plot of the logarithm power spectrum versus wavenumber usually shows linear segments that decrease in slope with increasing wavenumber. Generally, low radial wavenumbers mainly relate to deep sources, and intermediate radial wavenumbers mostly correspond to shallow ones, while high radial wavenumbers are dominated by noise (Spector and Grant, 1970). Aydın and Oksum (2012) stated that obtaining reasonable results from their statistical approach mostly depends on regularly changing depths, entirely covered anomaly in the subarea and a properly selected critical frequency on the radial line at which the authors suggest to construct the matrices in Equation (4) by the values after that critical frequency. The authors also noted that this critical frequency generally occurs on the point, which stands at the end of the rapidly decaying low radial wavenumber part of the power spectrum plot curve.

Using the CDPs, the heat flow (q) can similarly be estimated as (Tanaka et al., 1999)

$$q = \frac{k\theta_c}{D_c} \qquad (6)$$

where k is the coefficient of thermal conductivity, θ_c is the Curie temperature and D_c is the Curie point depth.

4. Data and Results

The most comprehensive magnetic anomaly database for Southeast Asia as compiled by the Geological Survey of Japan and the Coordinating Committee for Coastal and Offshore Geoscience Programs in East and Southeast Asia (CCOP, 1996). The compilation includes aeromagnetic surveys, shipboard measurements, and some land data processed into a single 1 × 1 arcminute grid. Fig. 3 shows a map of total magnetic intensity used for estimation of the CPDs in the Southern Vietnam continental shelf from the CCOP compilation. For our analysis, the magnetic anomaly was gridded into a 249 × 249 grid at a 2 km interval in the x- and y-directions, respectively. The magnitudes of the magnetic field of the Southern Vietnam continental shelf vary from – 400 nT to + 600 nT. The map shows the patterns of the magnetic anomalies that are mostly elongate to oval or relatively round. The map is also characterized by magnetic anomalies that are irregular and do not show any significant patterns. Thus, they can be ascribed to lateral inhomogeneities in the magnetic properties.

The magnetic anomaly in the study area was subdivided into 49 blocks (B1, B2,…, B49) with 50% overlapping windows each in size of 128 km × 128 km. The configuration and the center positions of these sub-areas are shown in Fig. 4. For each block, the basal depths of the sources were estimated (Table 1) by averaging the deepest four depths calculated in the analytical solutions of the exponential approach from the Fourier transform of the magnetic data. Fig. 5 presents two examples of the plot of the spectrum along with the diagonal elements in the Fourier plane for the magnetic anomaly data of sub-regions B10 and B47, and the frequency range where the first equation set was built for the calculations. The CPDs were gridded by applying a minimum curvature algorithm, and they were subsequently mapped to image the Curie isotherm surface as shown in Fig. 6. The obtained results show that the CPDs range from 15.3 to 35.6 km with an average value of 26.9 km. Although there are many active and potentially active volcanoes in Southeast Asia (Whelley et al., 2015), our results showed that there are not any volcanoes in the study area because typical CPD values for areas of subduction zone volcanism and active volcanoes are commonly shallower than about 10 km (Tanaka et al., 1999; De Ritis et al., 2013). The CDPs in the Northern Cuu Long basin is from 21 to 26 km, and the CDPs is from 24 to 31 km in the Southern Nam Con Son basin. Fig. 7 shows the contour map of the depth to Curie point presented by Tanaka et al. (1999), for the same area derived from the centroid method. According to Tanaka et al. (1999), the CPDs in the study area is between 26 and 32 km. As can be seen, the exponential approach and centroid method yielded similar results qualitatively (i.e., deep and shallow CPD locations). Here, there are very good correlations between our results and those of Tanaka et al. (1999), with the shallow portion in the North-Western, North-Eastern parts of the area; and the deep portion in the South-Western, South-Eastern parts of the area. However, it can be seen that our results in a higher resolution, compared to those of Tanaka et al. (1999).

Using $k\theta_c$= 2000 $\mathrm{W/m^1}$ for Southwest region in East and Southeast Asia (Tanaka et al., 1999) and CPDs, the heat flows of the area was calculated. The obtained heat flows are shown in Fig. 8 with the values ranges from 56.2 to 130.7 $\mathrm{mW/m^2}$ (Table 1). CPDs have an inverse relationship with the heat flow in so much that regions indicating high heat flow are associated with shallower CPDs, whereas regions of lower heat flow are associated with deeper CPDs. The high heat flows related to the shallow CPDs in the area are thought to be responsible for the early maturation of the organic matter and generation of petroleum in the sedimentary basins, Southern Vietnam continental shelf.

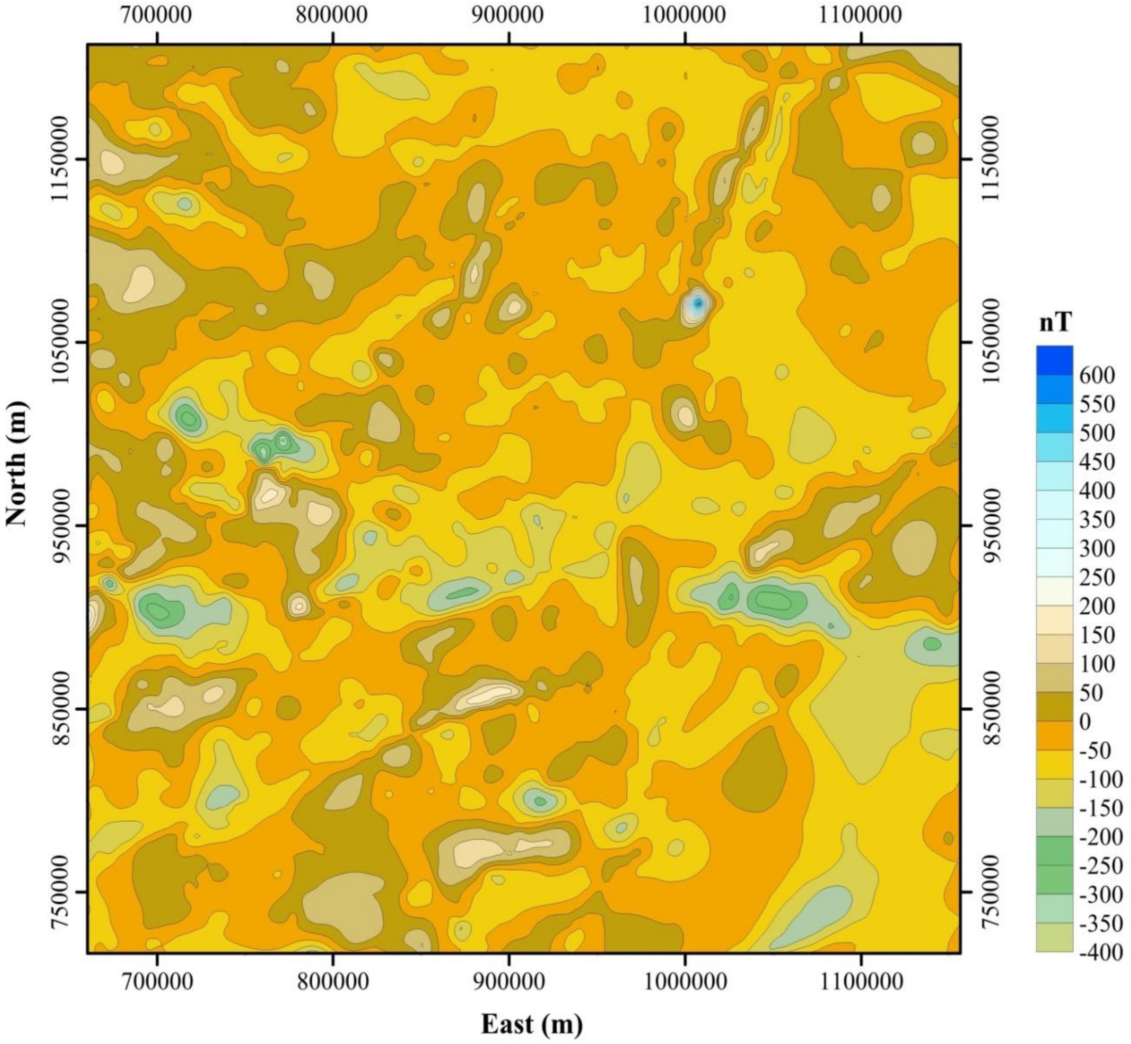


Figure 3. The magnetic anomaly map used for estimation of the CPDs in the Southern Vietnam continental shelf

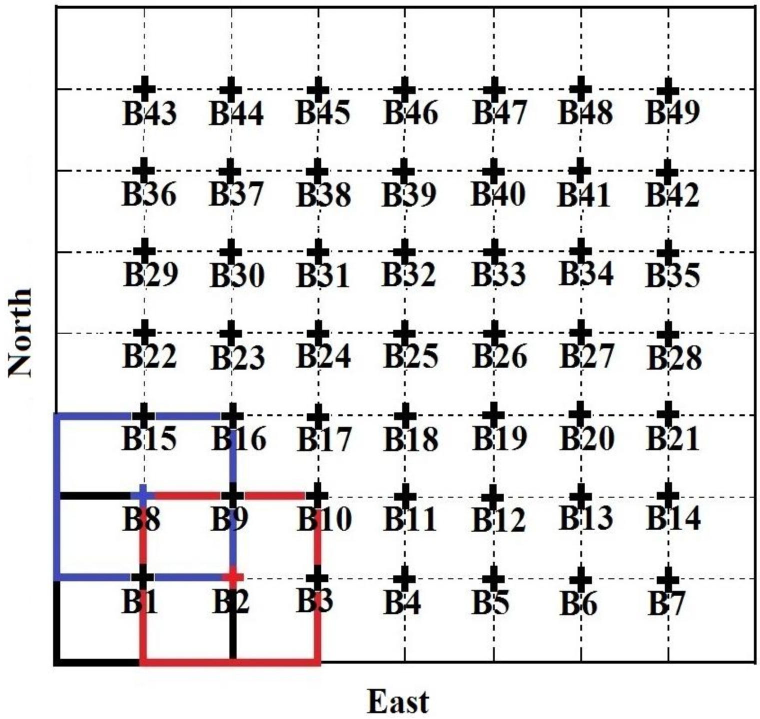


Figure 4. Sketch of the positions of the overlapping blocks (plus signs are centers of the sub-regions)

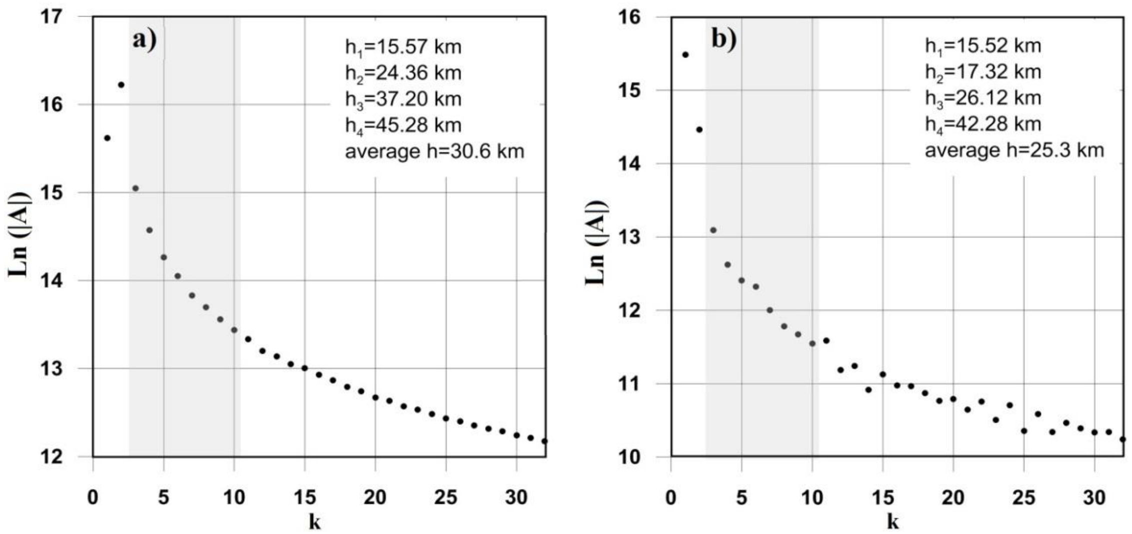


Figure 5. The logarithmic absolute diagonal elements of blocks B10 (a) and B47 (b) as representative examples for the depth calculations. Data remaining within the bounded area with gray color show the selection range where the first equation set (the first row of the matrix D_f in Eq.4) was built for the calculations in the procedure of the exponential approach. The average of the largest four depths (h_1, h_2, h_2, h_4) estimated provide the depth to the bottom (CPD)

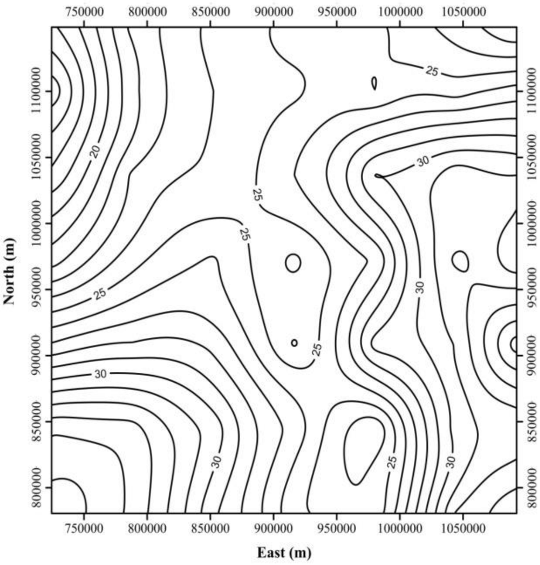


Figure 6. Map of Curie point depth in the Southern Vietnam continental shelf derived from the exponential approach

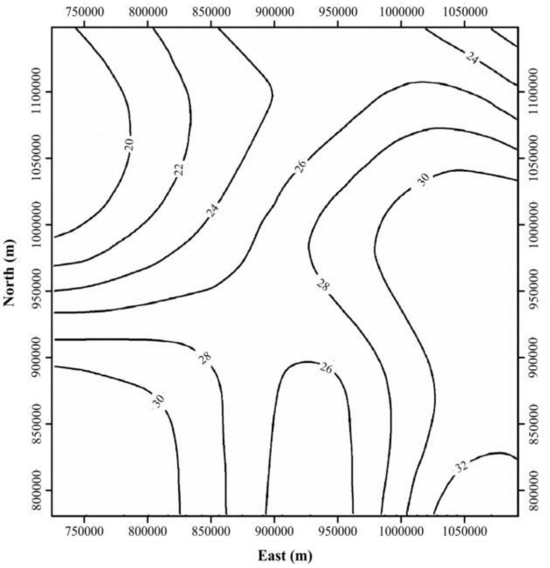


Figure 7. Map of Curie point depth in the Southern Vietnam continental shelf derived from centroid method (redrawn from Tanaka et al., 1999)

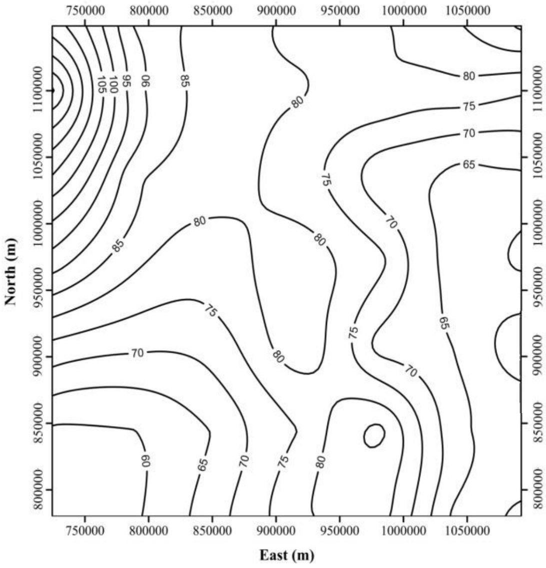


Figure 8. Map of heat flow distribution (mW/m^2) in the study area derived from the CPD map (Fig. 6)

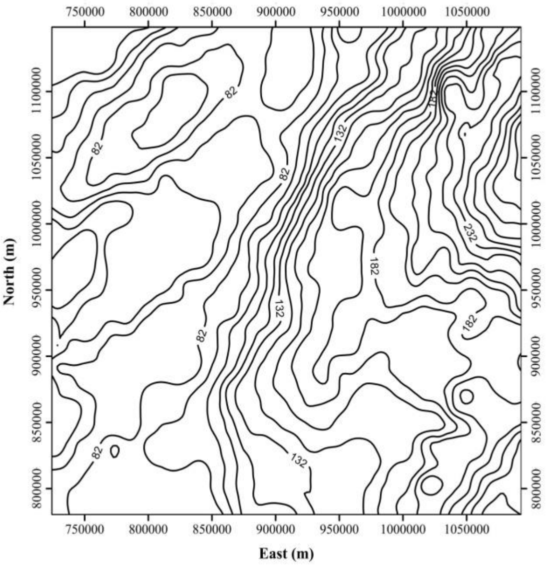


Figure 9. The mantle Bouguer anomaly used for estimation of the Moho depths in the Southern Vietnam continental shelf

Table 1. Estimated CPD and heat flow values derived from magnetic data

Blocks no.	CPD (km)	Heat flow (mW/m^2)	Blocks no.	CPD (km)	Heat flow (mW/m^2)
1	35.6	56.2	26	26.1	76.9
2	33.7	59.2	27	32.2	80.6
3	29.2	73.8	28	30.1	78.7
4	25.3	93.0	29	18.2	82.3
5	24.3	109.9	30	23.2	86.6
6	32.1	130.7	31	24.2	68.0
7	33.8	112.4	32	26	76.6
8	33.8	59.3	33	30.03	66.6
9	33.4	59.9	34	31.6	80.0
10	30.6	71.2	35	31	79.1
11	26.7	81.3	36	15.3	62.3
12	23.1	86.2	37	21.7	65.8
13	30.4	92.2	38	24	64.3
14	31	89.7	39	24.8	62.1
15	27.1	68.5	40	25	63.3
16	28.1	65.4	41	25.5	78.4
17	27.7	72.2	42	26.4	84.7
18	23.9	76.6	43	17.8	59.2
19	29.4	82.6	44	22.3	64.5
20	31.1	83.3	45	24.3	56.3
21	35.5	82.3	46	25.4	66.4
22	21.5	79.1	47	25.3	64.5
23	24.6	74.9	48	23.6	75.8
24	26.1	83.7	49	22	90.9

Based on the Parker-Oldenburg iterative method (Oldenburg 1974), we also estimate the Moho depths in the area from mantle Bouguer anomaly (Fig. 9) (Huchon et al., 1998). Fig. 10 shows the Moho depth map of the study area. The obtained result shows that the Moho depths range from 9 to 31 km with an average value of 23.5 km. It is found that the minimum Moho depth corresponds to the oceanic propagating tip of the East Sea (less than 10 km), the Moho depth in the Cuu Long basin is from 24 to 29 km while the Moho depth in the Nam Con Son basin is from 18 to 26 km. Comparison of Fig. 7 and Fig. 10 shows that the Moho generally lies above the Curie isotherm in the area but lies below this boundary in some locations, notably in the Cuu Long basin. This result indicates that the uppermost mantle in the most area is also magnetized and contributes to surface magnetic anomalies. Magnetization in the uppermost part of the mantle is also shown in many other studies (Counil et al., 1989; Chiozzi et al., 2005; Ferré et al., 2013; Friedman et al., 2014; Li and Wang 2016).

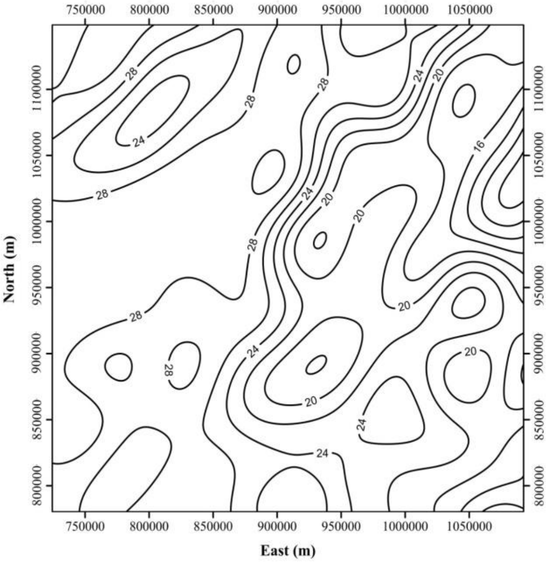


Figure 10. Moho depth map of the study area calculated from the mantle Bouguer anomaly data (Fig. 9)

5. Conclusions

The exponential approach was applied to the magnetic anomaly in the Southern Vietnam continental shelf to map the depth in the Earth's crust to the Curie point temperature (~580°C) where magnetization disappears. Within the study area, the shallowest CPD value of 15.3 km is located in North-Western area. The average CPD is about 19 km in this region. The highest value of 35.6 km is located in the South-Western part of the Southern Vietnam continental shelf where the average CPD is about 33 km. A comparison between the Curie depths and the Moho surface revealed that the Curie isotherm surface, in general, is deeper than the Moho surface, except at some locations in the Cuu Long basin and Con Son ridge. The crustal heat flow obtained from the CPDs varies between 56.2 mW/m^{2}and 130.7 mW/m^2 with an average of 76.8 mW/m^2. The obtained CPDs from this study are quite high in resolution, therefore these results are anticipated to contribute significantly to the quantitative appraisal of the rheology, geological processes and events, and understanding of the heat flux variations in the Southern Vietnam continental shelf.

Acknowledgments

The authors record with pleasure their sincere thanks to the editor and the two reviewers for their very constructive suggestions to improve the manuscript. This research is funded by the VNU University of Science under project number TN.18.05.

References

Aydın I., Oksum E., 2010. Exponential approach to estimate the Curie-temperature depth. Journal of Geophysics and Engineering, 7, 113–125.

Aydın I., Oksum E., 2012. Matlab code for estimating magnetic basement depth using prisms. Computers and Geoscience, 46, 183–188.

Bansal A., Gabriel G., Dimri V., Krawczyk C., 2011. Estimation of depth to the bottom of magnetic sources by a modified centroid method for fractal distribution of sources: An application to aeromagnetic data in Germany. Geophysics, 76(3), L11–L22.

Bansal A., Anand S., Rajaram M., Rao V., Dimri V., 2013. Depth to the bottom of magnetic sources (DBMS) from aeromagnetic data of Central India using modified centroid method for fractal distribution of sources. Tectonophysics, 603, 155–161.

Bhattacharyya B.K., Leu L.K., 1975. Analysis of magnetic anomalies over Yellowstone National Park: mapping of Curie point isothermal surface for geothermal reconnaissance. J. Geophys. Res., 80, 4461–4465.

Bhattacharyya B.K., Leu L.K., 1977 Spectral analysis of gravity and magnetic anomalies due to rectangular prismatic bodies Geophysics, 42, 41–50.

Binh N.T.T., Tokunaga T., Goulty N.R., Son H.P., Van Binh M., 2011. Stress state in the Cuu Long and Nam Con Son basins, offshore Vietnam. Marine and Petroleum Geology, 28(5), 973–979.

Blackwell D.D., 1983. Heat flow in the northern basin and range province. Geotherm. Resour. Counc. Spec. Rep., 13, 81–93.

Blakely R.J., 1996. Potential Theory in Gravity and Magnetic Applications. Cambridge University Press, pp. 300–305.

Chiozzi P., Matsushima J., Okubo Y., Pasquale V., Verdoya M., 2005. Curie-point depth from spectral analysis of magnetic data in central–southern Europe, Phys. Earth planet. Inter., 152, 267–276.

Counil J.L., Achache J., Galdeano A., 1989. Long-wavelength magnetic anomalies in the Caribbean: Plate boundaries and allochthonous continental blocks. Journal of Geophysical Research, 94, 7419–7431.

Correa R.T., Vidotti R.M., Oksum E., 2016. Curie surface of Borborema Province, Brazil. Tectonophysics, 679, 73–87.

De Ritis R., Ravat D., Ventura G., Chiappini M., 2013. Curie isotherm depth from aeromagnetic data constraining shallow heat source depths in the central Aeolian Ridge (Southern Tyrrhenian

Sea, Italy). Bulletin of Volcanology, 75(4). Doi: 10.1007/s00445-013-0710-9.

Dolmaz M.N., Hisarli Z.M., Ustaomer T., Orbay N., 2005a. Curie point depths based on spectrum analysis of the aeromagnetic data, west Anatolian extensional province, Turkey. Pure Appl. Geophys., 162, 571–590.

Dolmaz M.N., Ustaomer T., Hisarli Z.M., Orbay N., 2005b. Curie Point Depth variations to infer thermal structure of the crust at the African-Eurasian convergence zone, SW Turkey. Earth Planets Space, 57, 373–383.

Friedman S.A., Feinberg J.M., Ferré E.C., Demory F., Martín-Hernández F., Conder J. A., Rochette P., 2014. Craton vs. rift uppermost mantle contributions to magnetic anomalies in the United States interior. Tectonophysics, 624, 15–23.

Ferré E.C., Friedman S.A., Martín-Hernández F., Feinberg J.M., Conder J.A., Ionov D.A., 2013. The magnetism of mantle xenoliths and potential implications for sub-Moho magnetic sources. Geophysical Research Letters, 40(1), 105–110.

Finn C.A., Ravat D., 2004. Magnetic depth estimates and their potential for constraining crustal composition and heat flow in Antarctica. EOS Transactions American Geophysical Union, Fall Meeting Abstracts, 1 December 2004.

Fowler C.M.R., 2005. The Solid Earth: An Introduction to Global Geophysics. Cambridge Univ. Press, 685p.

Frost B.R., Shive P.N., 1986. Magnetic mineralogy of the lower continental crust. J. Geophys. Res., 91(6), 513–521.

Gwang H. Lee, Keumsuk Lee, Joel S., 2001. Geologic evolution of the Cuu Long and Nam Con Son basins, offshore southern Vietnam, South China Sea. AAPG Bulletin, 85(6),1055–1082.

Geological Survey of Japan (GSJ) and Coordinating Committee for Coastal and Offshore Geoscience Programmes in East and Southeast Asia (CCOP), 1996. Magnetic anomaly map of East Asia 1: 4,000,000 CD-ROM Version.

Huchon P., Nguyen T. N., Chamot-Rooke N., 1998. Finite extension across the South Vietnam basins from 3D gravimetric modelling: relation to South China Sea kinematics. Marine and Petroleum Geology, 15(7), 619–634.

Li C.F., Wang J., 2016. Variations in Moho and Curie depths and heat flow in Eastern and Southeastern Asia. Marine Geophysical Research, 37(1), 1–20.

Maus S., Dimri V., 1996. Depth estimation from the scaling power spectrum of potential fields. Geophysical Journal International, 124(1), 113–120.

Nagata T., 1961. Rock Magnetism. Maruzen Company Ltd., Tokyo, 350p.

Okubo Y., Graf R.J., Hansen R.O., Ogawa K., Tsu H., 1985. Curie point depths of the island of Kyushu and surrounding areas, Japan. Geophysics, 50, 481–494.

Oldenburg D.W., 1974. The inversion and interpretation of gravity anomalies. Geophysics, 39(4), 526–536.

Rocha M.L.G., Pires A.C.B., Carmelo A.C., Oksum E., 2015. Curie surface of the alkaline provinces of Goiás (GAP) and Alto Paranaíba (APAP), central Brazil. Journal of Volcanology and Geothermal Research, 297, 28–38.

Saleh S., Salk M., Pamukcu O., 2013. Estimating Curie depth and heat flow map for northern Red Sea rift of Egypt and its surroundings, from aeromagnetic data. Pure Appl. Geophys., 170, 863–885.

Salem A., et al., 2014. Depth to Curie temperature across the central Red Sea from magnetic data using the de-fractal method. Tectonophysics, 624, 75–86.

Serson P.H., Hannoford W.L.W., 1957. A statistical analysis magnetic profiles. J. Geophys. Res., 62, 1–18.

Siler D.L., Kennedy B.M., 2016. Regional crustal-scale structures as conduits for deep geothermal upflow. Geothermics, 59, 27–37.

Smith R., Shuey R., Pelton J., Bailey J., 1977. Yellowstone hot spot: Contemporary tectonics and crustal properties from earthquake and aeromagnetic data. Journal of Geophysical Research, 82(26), 3665–3676.

Spector A., Grant F., 1970. Statistical models for interpreting aeromagnetic data. Geophysics, 35(2), 293–302.

Stampolidis A., Tsokas G.N., 2002. Curie point depths of Macedonia and Thrace, N. Greece. Pure appl. Geophys., 159, 2659–2671.

Starostenko V.I., et al., 2014. Thermal structure of the crust in the Black Sea: Comparative analysis of magnetic and heat flow data. Marine Geophysical Research, 35(4), 345–359.

Tanaka A., Okuba Y., Matsubayashi O., 1999. Curie point depth based on spectrum analysis of the magnetic anomaly data in East and Southeast Asia. Tectonophysics, 306, 461–470.

Teknik V., Ghods A., 2017. Depth of magnetic basement in Iran based on fractal spectral analysis of aeromagnetic data. Geophysical Journal International, 209(3), 1878–1891.

Trifonova P., Zhelev Z., Petrova T., Bojadgieva K., 2009. Curie point depths of Bulgarian territory inferred from geomagnetic observations and its correlation with regional thermal structure and seismicity. Tectonophysics, 473(3), 362–374.

Turcotte, D.L., Schubert, G., 2002. Geodynamics. Second ed. Cambridge Univ. Press, 456p.

Wang J., Li. C.F., 2018. Curie point depths in Northeast China and their geothermal implications for the Songliao Basin. Journal of Asian Earth Science, 163, 177–193.

Whelley P.L., Newhall C.G., Bradley K.E., 2015. The frequency of explosive volcanic eruptions in Southeast Asia. Bulletin of Volcanology, 77(1). Doi: 10.1007/s00445-014-0893-8.