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Geothermal structure revealed by curie isothermal surface under Guangdong Province, China

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Abstract: Guangdong Province in Southeast China is noted for its numerous geothermal resources due to tectonic episodes, mainly occurred during the Cretaceous. The surface heat flow and geothermal gradient are the most direct ways to understand the temperature of the Earth. However, geothermal resources are poorly utilized in Guangdong Province due to limited numbers of boreholes and surficial hydrothermal fluids. To improve the understanding of underground temperature distribution in Guangdong Province, we have applied power-density spectral analysis to aeromagnetic anomaly data to calculate the depth of the Curie isothermal surface. Upward continuation is applied and tested to the magnetic data. The calculated Curie isotherm is between 18.5 km and 25 km below surface. The fluctuation in the depth range reflects lateral thermal perturbations in the Guangdong crust. In particular, the eastern, northern, western and coastline areas of the province have a relatively shallow Curie isotherm. By comparing the surface heat flow, geothermal gradient, distribution of Mesozoic granite-volcanic rocks, and natural hot springs, we conclude that during Mesozoic, magmatism exerted great influence on the deep thermal state of Guangdong Province. A shallow Curie isotherm surface, as well as numerous natural hot springs and high heat flow, show clear signatures of shallow heat sources.

Keywords: Curie isotherm surface; Geothermal structure; Spectrum analysis; Guangdong Province

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Introduction

Guangdong Province has an area of nearly 180 000 square kilometers and a population of over 100 million people. The province is located on the southeast coast of China mainland, a region well known for its natural hot springs. About 320 hot springs with temperatures over 30℃, or 10% of all hot springs in China, occur in Guangdong Province, seven of which exceed 90°C. The number of hot springs in Guangdong Province ranks the third in China, after Tibet and Yunnan provinces. The Pearl River Delta in Guangdong Province is a highly industrialized region, and to understand the thermal structure of the crust may facilitate the exploitation of hot springs for geothermal energy to supplement the energy demand of the region (Zhang et al. 2020). Tomographic studies (Li and Van, 2010) indicate the widespread low-velocity anomalies in the upper mantle, about 100-400 km beneath Guangdong Province. Low-velocity anomalies in the upper mantle may be related to Cretaceous tectonism in East Asia that thinned lithosphere and elevated heat flow. The sub-surface thermal state of Guangdong Province has been studied with seismology (An and Shi, 2006), heat flow (Artemieva and Mooney, 2001; Sun et al. 2013), hydrogeochemical study (Wang et al. 2019), geothermal modeling (Quenette et al. 2015), aeromagnetic methods (Tanaka et al. 1999) and gravity methods (Xi et al. 2018), but the resolution of the results from all these studies was not good enough and could not reveal detailed crustal structure beneath Guangdong. The purpose of this

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paper is to provide a better understanding of the crustal temperatures beneath Guangdong by determining the Curie isothermal surface and relating it to other available geophysical data. The Curie point depth is estimated using aeromagnetic anomaly data from Guangdong.

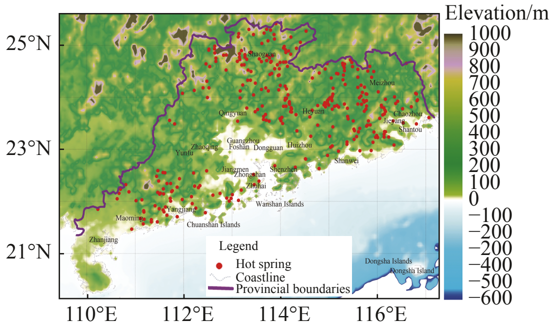

Fig. 1 Topography and natural springs of study area

The background of Fig. 1 is the elevation model from SRTM data (Farr et al. 2007), where elevation lower than -600 m is not shown.

1 Geological setting and data

The present East Asian tectonic framework is controlled by the complex interactions between the Eurasian plate, paleo-Pacific Ocean plate, the Philippine Sea plate and the Indian plate. The upper mantle and transition zone structure was formed by the Yanshanian movement, which was a counterclockwise rotation of Chinese continent, with westwards subduction and compression of Okhotsk and Izanagi plate occurred from 205 Ma to 135 Ma during the Mesozoic Era (Wan, 2011). Mesozoic granites and volcanic rocks are widely distributed in Guangdong Province, indicating an intercontinental tectonic evolution of the South China Block. Natural springs in Guangdong are mostly located near granites and volcanic rocks.

The aeromagnetic data was collected and compiled by Airborne Geophysical Remote Sensing Center, China Geological Survey. The original aeromagnetic data were collected at different times, with different resolutions and intervals. The aeromagnetic data used in this paper has a resolution of 0.02° by 0.02°, which consists of longitude, latitude and magnetic anomaly (Fig. 2). The latitude of study area is relatively low and the geomagnetic inclination is small. In order to reduce the influence of oblique magnetization, the original magnetic anomaly was reduced to the pole before further procedure.

2 Spectral analysis

The Curie point is defined to be the temperature

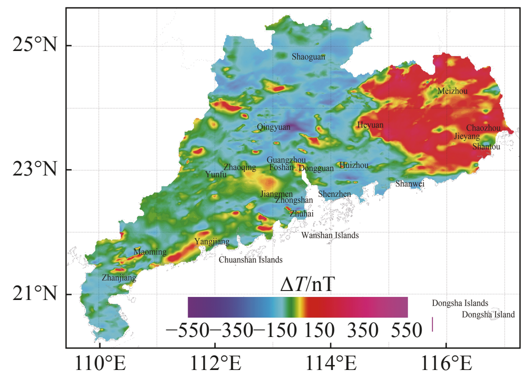

Fig. 2 Aeromagnetic anomalies in the study area

above which the ferromagnetic materials lose the ability to maintain permanent magnetism (Kittel, 1996), and the Curie isotherm is the depth at which lithospheric materials reach their Curie point. The Curie point depends on the mineralogy of rocks and generally ranges between 550℃ and 580℃ for the crustal rocks (Turcotte and Schubert, 2014). The Curie isotherm is, in general, the bottom of the magnetic part of the Earth's crust. The depth of the Curie isotherm was estimated by employing the method of power density spectral analysis. This concept has been discussed and used in many places around the world (Spector and Grant, 1970; Blakely, 1995; Tanaka et al. 1999; Okubo et al. 2003).

The top and centroid depth of a magnetic source, Z_t and Z_0 were determined, respectively, from the power spectrum of magnetic anomalies and they are used to estimate the basal depth of a magnetic source Z_b. To develop the mathematical formulae for the method, assuming that the layer extends infinitely in horizontal directions, depth to the top of a magnetic source is very small compared with the horizontal scale of a magnetic source, and the magnetization M(x,y) is a random function of x and y, Blakely (1995) introduced the power-density spectra of the total-field anomaly $\Phi_{\Delta T}$:

$$\Phi_{\Delta T}(k_x,k_y) = \Phi_M(k_x,k_y) \times F(k_x,k_y) \tag{1a}$$

$$F(k_x,k_y) = 4\pi^2 C_m^2 |\Theta_m|^2 |\Theta_f|^2 e^{-2|k|Z_t} \left(1 - e^{-|k|(Z_b - Z_t)}\right)^2 \tag{1b}$$

where: k_x and k_y are wavenumbers in the x and y directions, respectively, and $|k|=(k_x^2+k_y^2)^{1/2}$, Φ_M is the power-density spectrum of the magnetization, C_m is a proportionality constant, and Θ_m and Θ_f are factors that depend on magnetization and geomagnetic field directions, respectively. We can simplify this equation by noting that all terms, except $|\Theta_m|^2$ and $|\Theta_f|^2$, are radially symmetric. Moreover, the radial averages of Θ_m and Θ_f are constant. If M(x,y) is completely random and uncorrelated, then $\Phi_M(k_x,k_y)$ is a constant. Hence, the radial average of $\Phi_{\Delta T}$ is:

$$\Phi_{\Delta T}(k) = Ae^{\ 2kZ_t} \approx \rbrack 1 \quad e^{\ k(Z_b \ \ Z_t)} \lbrace^2 \qquad (2)$$

where: A is a constant. For wavelengths are twice less than twice the layer thickness, Equation (2) can be simplified to:

$$\ln \rbrack \Phi_{\Delta T}{}^{1/2}(k) \lbrace = \ln B \quad k \approx Z_t \qquad (3)$$

where: B is a constant. Equation (3) provides an estimate of the depth to the top of a magnetic sources from the slope of the power spectrum of the total-field anomaly.

We can also rewrite Equation (2) as

$$\Phi_{\Delta T}{}^{1/2}(k) = C \approx e^{\ kZ_0} \approx \rbrack e^{\ k(Z_t \ \ Z_0)} \quad e^{\ k(Z_b \ \ Z_0)} \lbrack \qquad (4)$$

where: C is a constant. At long wavelengths, Equation (4) is:

$$\Phi_{\Delta T}{}^{1/2}(k) = C \approx e^{\ kZ_0} \approx \rbrack e^{kd} \quad e^{\ kd} \lbrack \,| \ \ C \approx e^{\ kZ_0} \approx (2\ k\ d) \qquad (5)$$

where: $2d$ is the thickness of the magnetic source. From Equation (5), it can be concluded that:

$$\ln \rbrace \rbrack \Phi_{\Delta T}{}^{1/2}(k) \lbrace / \ k \ \ = \ln D \quad k\ Z_0 \qquad (6)$$

where: D is a constant. Thus, we can estimate depths to the top and centroids of the magnetic sources by fitting straight lines through both the high and low wave number portions of the radially averaged spectrum of $\ln \rbrack \Phi_{\Delta T}(k)^{1/2} \lbrace$ and $\ln \rbrace \rbrack \Phi_{\Delta T}(k)^{1/2} \lbrace / \ k$ from Equation (3) and Equation (6), respectively. Fig. 2 shows an example of a power spectrum, where both the top and the centroid of a magnetic layer are estimated. Finally, the basal depth of the magnetic source is written as:

$$Z_b = 2Z_0 \quad Z_t \qquad (7)$$

Where: Z_b is the extension of magnetic sources, is assumed to be the Curie point depth. It must be pointed out there is no guarantee that Z_b represents the real Curie isotherm. The method used here requires a high degree of randomness for the distribution of crustal magnetization M(x,y), so that its power density spectrum $\Phi_M(k_x,k_y)$ is constant. The degree of randomness, however, may depend on the geology of the region. The magnetization of an extrusive volcanic terrane may be more variable than that of a plutonic terrane. A sequence of relatively nonmagnetic sediments below young volcanic formation may limit the depth of magnetic sources regardless of the temperature of Curie point. Some other assumptions and limitations are also made for this method. A full discussion is given by Blakely (1995) and Ross et al. (2006). It provides an effective way to study the thermal structure of the Earth.

3 Data processing and results

Aeromagnetic anomalies reflect a combination of effects from both shallow and deep crustal magnetic sources. Magnetic anomalies caused by rocks at different depths will mix and reduce the accuracy of Curie surface inversion. Different methods of suppressing the effect of shallow magnetic bodies include low-pass filter (Bektaş, 2013), upward continuation (Hu et al. 2006; Zhao et al. 2010) and multiscale 2D discrete wavelet transform analysis (Wu et al. 2010) and so on. We have analytically continued the aeromagnetic data upward by 15 km in North Eastern China (Hu et al. 2006), where the magnetic anomaly is strong in volcanic zone. In our study, aeromagnetic data were continued upward by 10 km in order to reduce the impact of shallow magnetic bodies (Fig. 3).

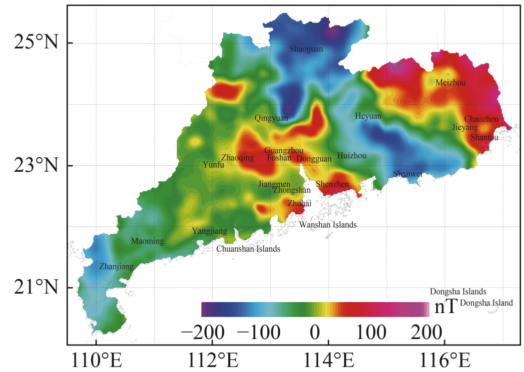

Fig. 3 Residual aeromagnetic anomaly map of the study area

This residual aeromagnetic anomaly map was then subdivided into sub areas, for the purpose of 2D spectral analysis while ensuring that the essential parts of the anomaly were not cut out by the blocks. Average Curie geotherm was approximately 23 km based on the thermal gradient data. The size of the sub areas must be at least four or six times the depth of the magnetic source (Dimitriadis et al. 1987; Nwogbo, 1998). The dimension of 160 km by 160 km was used for the sub areas and a Curie-point depth was calculated for each of them. Each sub area overlaps its neighboring by 40 km.

In Fig. 4, k is the wavenumber. Black dots represent original reduction to pole data. Blue dots represent continued upward 10 km data. Fig. 4(a) shows estimation on depth of top Z_t. Fig. 4(b) shows estimation on the depth of centroid Z_0. Then

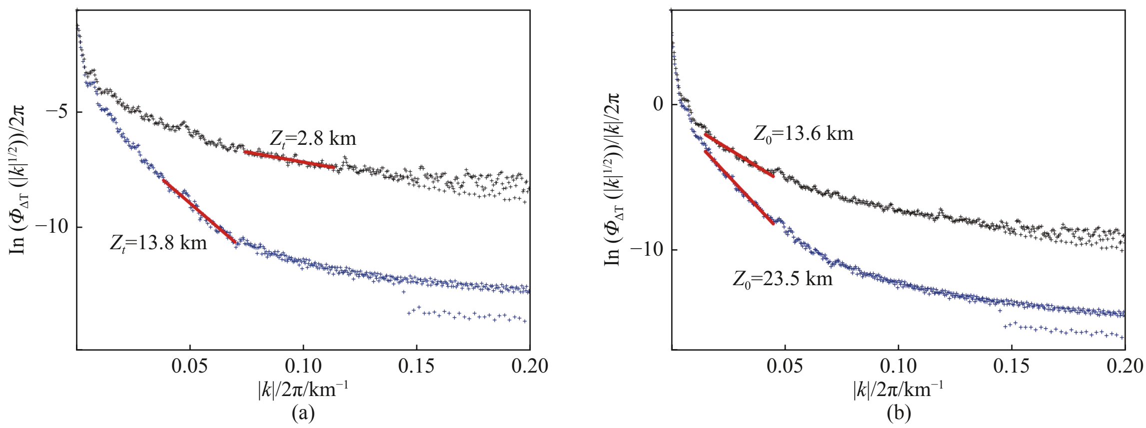

Fig. 4 Example of spectra for the estimation of the depth to Curie isotherm using the radially averaged spectrum of the magnetic anomaly

the basal depth is determined by Z_b=2Z_0−Z_t, which is 24.4 km with original magnetic anomaly and 23.2 km with filtered data. $\Phi_{\Delta T}(k)$ is the spectrum of the magnetic anomaly.

Fig. 4 is an example of the spectral analysis method. Basal depths were calculated with original magnetic anomaly and upward continuation of 10 km. Upward continuation is also a low-pass filter, so the high frequency part has been changed. It is not advised to use the same wavenumber as the original magnetic anomaly to get the top depth, which is the main cause of high frequency. But the same wavenumber can be used to get the depth of centroid. In the bottom figure, the difference between the depths to centroid is 9.9 km. It is negligible after subtracting the previous upward continuation of 10 km.

In many cases the result could be variable because it is not clear which part to choose. To test the error in the results, the high and low wavenumber slopes at different locations were measured and determined the basal depth. In order to constrain the result, the average Curie isotherm to be around 23 km from geothermal gradient data was chosen. The range of variation for the top of the magnetic body is 1.5 km while the range of variation for the depth of the centroid is 3.5 km. These variations would produce a potential error of 5 km in the Curie isothermal surface, as shown in Fig.5.

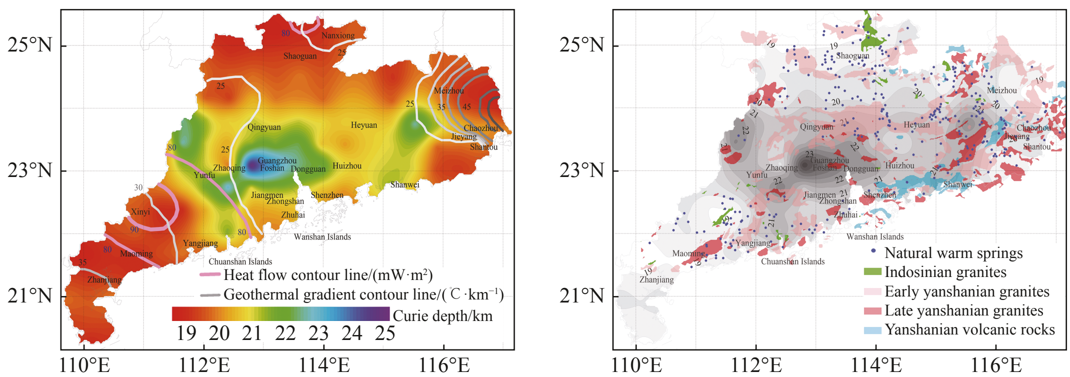

Fig. 5 (a) Curie isotherm surface depth and heat flow, geothermal gradient Heat flow and gradient data are taken from Yuan et al. (2006) (b) Curie isothermal surface depth (km), natural hot springs, and Mesozoic granite-volcanic rocks (Zhou et al. 2006)

4 Discussions

The estimated depth of the Curie isotherm (Fig. 5) lies between 18.5 km and 25 km over the area of interest. The Moho depth in this area is about 30-35 km (Zhang et al. 2013), so the calculated Curie isotherm does not extend into the mantle. We interpret the undulations as lateral thermal perturbations in the shallow crust of Guangdong Province caused by magmatic events (Zhou et al. 2006), each magmatic episode having transformed the local thermal structure.

The vertical thermal gradient (℃/km) in crustal environments mainly relates to deep tectonic activities, tectonothermal settings, and thermal conductivities of the rocks. The present geothermal gradient in South China mainly reflects the characteristics of tectonic activity since Cenozoic Era (Yuan et al. 2006) and Mesozoic geological activities have no significant influence on the current geothermal gradient.

Thermal gradients measured at 16 thermal stations in the Guangdong Province range from 19℃/km to 35.8℃/km and the average is 24.37℃/km (Hu et al. 2001; Wang and Huang, 1990). Assuming that the Curie-temperature and topographic surface temperatures are 576℃ and 20℃, respectively, the average depth to the Curie isotherm in Guangdong should be 22.8 km, which is consistent with the depth revealed by the inversion of aeromagnetic data. Measured thermal gradients exceed 25℃/km near Meizhou and Chaozhou in the eastern part of Guangdong, Nanxiong in the northern part and in the western part of Zhaoqing according to the geothermal gradient map of the South China continent (Yuan et al. 2006). The Curie isotherm surface is shallower than 20 km at these places. The highest gradient, about 55 ℃/km, occurs at Chaozhou in the eastern part of Guangdong Province.

Surface heat flow in Guangdong ranges from 61.6 mW/m^2 to 97 mW/m^2, with a mean of 73 mW/m^2, higher than the global mean of 55 mW/m^2 for Proterozoic continental crust (Rudnick et al. 1998). The highest heat flow is 97 mW/m^2 at Xinyi in western Guangdong. Heat in the study area is transported by both conductive and convective processes, and the latter is often associated with hot springs.

Thermal gradient and surface heat flow measurements are limited to very few thermal stations, while natural hot springs are the most direct indication of thermal anomalies. Hot springs are concentrated in the eastern, northern, and southeast coastal areas and in the west of Yangjiang-Xinyi of Guangdong. Our calculated Curie isotherm depths are relatively shallow at places with natural springs. The formation of natural hot springs is very complicated, being related to both the deep thermal state of the crust and shallow structures, such as local faults that promote hydrothermal circulation. Shallow Curie isotherm indicates high geothermal gradients, possibly caused by shallow heat sources that lead to the formation of local springs.

Local granites are rich in heat producing elements, such as Th, K, and U. The heat production rate of local granites is higher than 2.8 $\mu W/m^3$. Heat production of the early Yanshanian granites, which are widely distributed in Guangdong, exceeds 4.9 $\mu W/m^3$ (Zhao, 1995; Zhou et al. 2020). Heat generated by the isotopic decay of heat producing elements and magmatic processes have altered the thermal condition of this area and also provide heat source for the springs.

A significant characteristic of the Curie isotherm surface is its great depth in Guangzhou area, which is underlain by the Mesozoic-Cenozoic Sanshui Basin. Deep seismic soundings revealed a shallow Moho in this area (Zhang et al. 2013). Why is the Curie isotherm deep where the Moho is shallow? Heat flows from the surface of the earth can be divided into three components (Vitorello and Pollack, 1980): (1) heat generated from radiogenic decay of HPEs (heat producing element, mainly K, Th and U) mainly concentrated in the crust, (2) heat conducted through the lithosphere from underlying convective mantle and (3) "orogenic" heat convectively transported from magma and fluids that enters the lithosphere from below during orogenic events. Granites are rich in HPE, but no granites crop out in the Sanshui Basin close to Guangzhou, only around the basin. Since the Moho is shallow, less heat is available from the radiogenic decay of HPE in this area. The conductivity of the basin is about 1.73 W/m·K, lower than the surrounding areas. Thus heat from underlying convective mantle is preferentially conducted along the basin's margin as indicated by the presence of hot springs on the edge of Sanshui Basin (Lysak, 2009). This differential heat conduction explains in the relatively deep Curie isotherm surface in this area. It must be noted that the rift basin is formed in an extensional environment, where the lithosphere and crust are uplifted. Although the Curie isotherm surface is deep in the area, significant heat could be concentrated at the base of Sanshui Basin.

5 Conclusions

The depth of the Curie isothermal surface beneath Guangdong Province was determined by using the spectral analysis method. Aeromagnetic data were continued upward by 10 km in order to reduce the impact of shallow magnetic bodies. The effect of upward continuation is tested.

The estimated depth of the Curie isotherm lies between 18.5 km and 25 km below surface in this region. The fluctuation reflects lateral thermal perturbations in the crust. The surface heat flow, geothermal gradient, distribution of Mesozoic granite-volcanic rock and natural springs were compared, and it was concluded that the modern crustal thermal state of Guangdong Province has been significantly impacted by Mesozoic volcanic-magmatic activity. The volcanic-magmatic activity created faults that promote hydrothermal circulation, and the heat production rate of Mesozoic granite is much higher than that of the surrounding strata. The Curie isotherm surface is shallow in regions with natural hot springs, suggesting that deep heat sources are associated with the hydrothermal fluids.

Considering that heat flow and thermal gradients work have been refined to certain stations, our investigation shows the importance of aeromagnetic methods in understanding regional thermal conditions, which is critical for the selection of potential geothermal areas.

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