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Curie point depth from spectral analysis of aeromagnetic data for geothermal reconnaissance in Afghanistan

H. Saibi [a, *], E. Aboud [b, c], J. Gottsmann [d]

[a] *Department of Earth Resources Engineering, Faculty of Engineering, Kyushu University, Fukuoka, Japan*
[b] *Geohazards Research Center, King Abdulaziz University, Jeddah, Saudi Arabia*
[c] *National Research Institute of Astronomy and Geophysics, Helwan, Egypt*
[d] *University of Bristol, Department of Earth Sciences, Bristol, UK*

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A B S T R A C T

The geologic setting of Afghanistan has the potential to contain significant mineral, petroleum and geothermal resources. However, much of the country's potential remains unknown due to limited exploration surveys. Here, we present countrywide aeromagnetic data to estimate the Curie point depth (CPD) and to evaluate the geothermal exploration potential.

CPD is an isothermal surface at which magnetic minerals lose their magnetization and as such outlines an isotherm of about 580 °C. We use spectral analysis on the aeromagnetic data to estimate the CPD spatial distribution and compare our findings with known geothermal fields in the western part of Afghanistan.

The results outline four regions with geothermal potential: 1) regions of shallow Curie point depths (~16–21 km) are located in the Helmand basin. 2) regions of intermediate depths (~21–27 km) are located in the southern Helmand basin and the Baluchistan area. 3) Regions of great depths (~25–35 km) are located in the Farad block. 4) Regions of greatest depths (~35–40 km) are located in the western part of the northern Afghanistan platform. The deduced thermal structure in western Afghanistan relates to the collision of the Eurasian and Indian plates, while the shallow CPDs are related to crustal thinning. This study also shows that the geothermal systems are associated with complex magmatic and tectonic association of major intrusions and fault systems. Our results imply geothermal gradients ranging from 14 °C/km to 36 °C/km and heat-flow values ranging from 36 to 90 mW/m^2 for the study area.

1. Introduction

To study Earth's shallow thermal structure, direct and indirect methods can be applied. Direct methods consist of temperature measurements taken in boreholes (from few meters to several kilometers depth). A major limitation of this approach is the limited availability of suitable and thermally well-equilibrated boreholes. Indirect methods using for example geophysical data to derive the Curie point depth (CPD) (Okubo and Matsunaga, 1994) provide a much wider coverage of temperature estimates. However, such methods have several constraints and limitations such as the depth resolution, which depends on the survey dimension, and uncertainties related to complex subsurface geology.

In this study, we apply spectral analysis on aeromagnetic data over the western portion of Afghanistan in order to estimate the CPD. Ferromagnetic materials lose their magnetism above the Curie temperature (580 °C for magnetite, Dunlop and Özdemir, 2001) because the thermal energy is sufficient to maintain a random alignment of the magnetic moments of the iron minerals (Dunlop and Özdemir, 2001). The bottom of magnetic sources may not generally correspond to a Curie temperature isotherm, but may instead correspond to a lithologic contact. For instance, if the mantle is devoid magnetic minerals and if the Moho is shallower than the Curie temperature isotherm, the base of magnetic sources estimated with aeromagnetic data should correspond to the Moho and not the Curie temperature isotherm as suggested by Wasilewski et al. (1979). Therefore, using the bottom of the magnetized crust as a proxy we can map the Curie isotherm. Changes in the thickness of the magnetized crust can be explained as changes in Curie temperature, but only if the Moho is above the

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* Corresponding author.
E-mail address: saibi-hakim@mine.kyushu-u.ac.jp (H. Saibi).

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Curie temperature isotherm.

A number of studies of CPDs have been performed in various parts of the globe. Here we highlight some of them. Bhattacharyya and Leu (1975) analyzed the CPD for geothermal reconnaissance at Yellowstone National Park with shallow CPD values ranging from 4 to 6 km depth associated with the central part of Yellowstone caldera. Okubo et al. (1985) estimated the CPD (6.5–15 km depth) of Kyushu Island (Japan) from aeromagnetic data and compared them with the setting of volcanic centres. They found that shallow CPDs are located in areas of current geothermal exploitation and future prospects. Espinosa-Cardeña and Campos-Enriquez (2008) determined the CPDs (between 14 and 17 km depth) with an elevated geothermal gradient and heat flow of the Cerro Prieto geothermal field in Baja California (Mexico) using spectral analysis of aeromagnetic data. Rajaram et al. (2009) mapped the CPDs (23–39 km depth) of the Indian subcontinent. A shallower CPD where shallow CPD is associated with the mobile belts while deeper a CPD delineates the cratons, Bouligand et al. (2009) mapped the CPDs of Western United States (from 4 to 30 km depth) using a fractal model for crustal magnetization, where shallow a CPD is related to the Yellowstone hot spot and Cascade Arc. Using ground magnetic data, Aboud et al. (2011) mapped the CPD of Sinai Peninsula (Egypt) (CPDs from 15 to 25 km) to highlight geothermal prospects and to show that CPDs become more shallow towards the tip of the peninsula. De Ritis et al. (2013) detected a shallow-seated heat source in the central Aeolian Ridge in Italy from CPD analysis using aeromagnetic data with CPDs ranging from 2 to 3 km below Salina and Vulcano Islands.

The objectives of this study are to estimate the CPD using spectral analysis applied to aeromagnetic anomalies, and to provide geothermal gradient and heat flow maps for western Afghanistan. The results may be useful for future geothermal exploitation.

2. Geological and geothermal settings

The color shaded relief map of Afghanistan and the surrounding area in Fig. 1 shows large areas of mountainous terrain especially in the central and northeastern parts of the country. A broad lowland area is situated in the Helmand province in southwestern Afghanistan.

Afghanistan has a complicated geology. The oldest rocks are Precambrian and succeeded by rocks from the Paleozoic up to the Quaternary (Fig. 2). Tapponnier et al. (1981) studied the tectonic evolution of Afghanistan since the Permian in relation to accretion of fragments of Gondwana to the margin of Laurasia. The Cimmerian Orogeny affected the study area by two different collisions, which brought first the Farad block against the Tajic block, succeeded by the Helmand block against the Farad block. The Herat fault (Hari Rod) represents the suture line of this collision, and the Panjao Suture records the line of the second collision that was ended by early Cretaceous. In the late Mesozoic the two blocks Pamir and West Nuristan were accreted to Eurasia. These two blocks with the Farad, Helmand, and Tajic blocks are all known as the Afghan block. The Kandahar volcanic arc developed as a result of subduction of the Indian plate beneath the Eurasian plate, with the formation of a complex magmatic and volcanic rock suites. Igneous activity was, however, not restricted to this region only, but can also be found in younger alkaline intrusions of Oligocene age and basaltic extrusions in the Farad block and the sedimentary basins along the Herat fault.

In the early Cenozoic, the Himalayan Orogeny affected the Afghan block by reactivating the blocks boundaries along with the Herat fault (HR) and the Chaman fault (CH).

The Kabul block is a fragment of continental crust, separated from the Indian and Afghan blocks by oceanic crust, which got caught up in the collision and was accreted to the edge of the Afghan Block before final collision with India (Schindler, 2002; Wheeler et al., 2005).

3. Methodology

The dataset used in this study is derived from 2006 to 2008 aeromagnetic surveys provided by U.S. Geological Survey and the Naval Research Laboratory (NRL) (Ashan et al., 2007; Shenwary et al., 2011). Details on aeromagnetic datasets used in this study and data processing are presented by USGS (2011). The grid elevation is 5000 m above the terrain. Five base station magnetometers were used during the survey. In order to correct the airborne magnetic data for time-varying anomalies, a weighted average of data from the five base stations was used to predict the time-varying field at the aircraft. In order to facilitate the interpretation and analysis of aeromagnetic anomalies which are influenced by the orientation of the magnetic field and of the magnetization, the map of total magnetic intensity is gridded by minimum curvature method (with a grid size of 1000 m) and then reduced to the pole (RTP) using magnetic inclination of 48.74° and a declination of 2.01°. The total intensity magnetic anomalies range from -168 nT to 650 nT (Fig. 3).

To estimate the CPD we applied the method of spectral analysis to the observed aeromagnetic data in Afghanistan. Tanaka et al. (1999) assumed that the magnetic layer extends infinitely in all horizontal directions. The depth to the top of the magnetic source is hence much smaller than the magnetic source's horizontal scale As a result the layer's magnetization $\boldsymbol{M}(x, y)$ is a random function of x and y.

Okubo et al. (1985) developed an algorithm to estimate the basal depth from magnetic data by using a 2-D modeling method for the calculation of the depth to the base for a single window. Then, the algorithm calculates the depth to the centroid (Z_0) and to the top (Z_t) of the magnetic source from the slope of radially averaged power spectrum of the magnetic anomaly.

Blakely (1995) presented the power-density spectra of the total-field anomaly $\Phi_{\Delta T}$

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

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

Φ_M is power-density spectra of the magnetization, C_{m} is a proportionality constant, Θ_m and Θ_f are factors for magnetization direction and geomagnetic field direction, and Z_t and Z_b are top and basal depth of magnetic source, respectively.

The above equation can be simplified by noting that all terms, except $|\Theta_m|^2$ and $\left|\Theta_f\right|^2$ are radially symmetric. Moreover, the radial average of Θ_m and Θ_f are constant. If $\boldsymbol{M}(x, y)$ is completely random and uncorrelated, $\Phi_M(k_x, k_y)$ is a constant. Hence, the radial average of $\Phi_{\Delta T}$ is:

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

where A is a constant and k is a wavenumber. For wavelengths less than about twice the thickness of the layer, Eq. (2) can be simplified as:

$$\ln\left[\Phi_{\Delta T}(|k|)^{1/2}\right] \approx \ln B - |k|Z_t, \tag{3}$$

where B is a constant.

Eq. (2) can be-rewritten as: