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Depth to Curie temperature across the central Red Sea from magnetic data using the de-fractal method

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ABSTRACT

The central Red Sea rift is considered to be an embryonic ocean. It is characterised by high heat flow, with more than 90% of the heat flow measurements exceeding the world mean and high values extending to the coasts — providing good prospects for geothermal energy resources. In this study, we aim to map the depth to the Curie isotherm (580 °C) in the central Red Sea based on magnetic data. A modified spectral analysis technique, the "de-fractal spectral depth method" is developed and used to estimate the top and bottom boundaries of the magnetised layer. We use a mathematical relationship between the observed power spectrum due to fractal magnetisation and an equivalent random magnetisation power spectrum. The de-fractal approach removes the effect of fractal magnetisation from the observed power spectrum and estimates the parameters of depth to top and depth to bottom of the magnetised layer using iterative forward modelling of the power spectrum. We applied the de-fractal approach to 12 windows of magnetic data along a profile across the central Red Sea from onshore Sudan to onshore Saudi Arabia. The results indicate variable magnetic bottom depths ranging from 8.4 km in the rift axis to about 18.9 km in the marginal areas. Comparison of these depths with published Moho depths, based on seismic refraction constrained 3D inversion of gravity data, showed that the magnetic bottom in the rift area corresponds closely to the Moho, whereas in the margins it is considerably shallower than the Moho. Forward modelling of heat flow data suggests that depth to the Curie isotherm in the centre of the rift is also close to the Moho depth. Thus Curie isotherm depths estimated from magnetic data may well be imaging the depth to the Curie temperature along the whole profile. Geotherms constrained by the interpreted Curie isotherm depths have subsequently been calculated at three points across the rift — indicating the variation in the likely temperature profile with depth.

1. Introduction

The Red Sea represents an early stage in the break-up of a continental plate and the development of two divergent sub-plates. The crustal heat flow within the Red Sea is high with more than 90% of the measured values exceeding the world mean. The high heat flow values are not restricted to the axis of the Red Sea, but extend to the coasts where they are nearly twice the world mean (Girdler and Evans, 1977). Understanding the thermal structure of the embryonic continental margins and its local variations is an important factor in understanding the early stage of plate separation and identifying natural earth resources for the countries bordering the Red Sea. This requires building constrained thermal models of the lithosphere. The constraints include heat production and thermal conductivity at different levels, knowledge of seismic velocities at different depths, thickness of the crust and the lithosphere and estimates of basal heat flow into the lithosphere (Hemant and Mitchell, 2009; Ravat et al., 2011).

Spectral analysis of magnetic data can also help in the constraining of the temperature within the crust based on identifying and mapping the depth of the Curie isotherm. Above the Curie temperature, magnetic minerals lose their ferromagnetism. As magnetite is the most common magnetic mineral in the Earth's crust, the Curie temperature of magnetite, $T_c = 580$ °C, is commonly used to represent the Curie temperature of crustal rocks (e.g. Ross et al., 2006). This means that deeper layers at greater temperatures are essentially non-magnetic. This Curie isotherm interface can be detected through a number of spectral magnetic

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methods (Bhattacharyya and Leu, 1977; Bouligand et al., 2009; Maus et al., 1997). The depth of the Curie isotherm is controlled by the variability of the geothermal heat flow from the mantle as well as from radioactive decay of minerals within the crust. Mapping the regional variation in the depth to the Curie isotherm provides an important constraint on temperatures within the Earth's crust and on maturation within sedimentary basins.

In this paper, we attempt to study the crustal thermal structure of the central Red Sea by determining the depth to the "magnetic bottom"; i.e. the base of the magnetised layer within the crust. We use the term "magnetic bottom" rather than the commonly used term "Curie isotherm depth", since the Moho or other crustal boundary can represent the bottom of the magnetic layer for petrological reasons (e.g. Rajaram et al., 2009; Ravat et al., 2011; Wasilewski et al., 1979). We estimate magnetic bottom using a new "de-fractal" spectral analysis approach applied to magnetic data. This approach assumes that the observed power spectrum is equivalent to the random magnetisation model multiplied by the effect of fractal magnetisation. This de-fractal approach removes the effect of fractal magnetisation from the power spectrum and estimates the parameters of depth to top and depth to bottom of the magnetic layer using iterative forward modelling of the power spectrum.

2. Spectral analysis

In the last four decades, variations on several methods have been proposed and applied for estimating the depth to the bottom (z_b) of magnetic sources using azimuthally averaged Fourier spectra of magnetic anomalies (e.g., Bhattacharyya and Leu, 1975; Bouligand et al., 2009; Fedi et al., 1997; Manea and Manea, 2011; Maus et al., 1997; Okubo et al., 1985; Rajaram et al., 2009; Ravat et al., 2007, 2011; Ross et al., 2006; Spector and Grant, 1970; Tanaka et al., 1999). The mathematical formulae of these methods are based on assumptions of flat layers with particular distributions of magnetisation, namely: 1) random (uncorrelated) magnetisation models or 2) self-similar (fractal) magnetisation models.

2.1. Random magnetisation models

Two types of method have been commonly used in the spectral estimation of z_b (depth to bottom of the magnetic layer) assuming random magnetisation models: (a) the spectral peak method originally described in a landmark paper by Spector and Grant (1970) and used by Shuey et al. (1977), Connard et al. (1983), Blakely (1988) and Salem et al. (2000) among others and (b) the centroid method originally presented by Bhattacharyya and Leu (1977), Okubo et al. (1985), and Tanaka et al. (1999). Both methods need a priori – generally independent – estimation of the depth to the top (z_t) of the magnetised layer, although a development by Ross et al. (2006) and Ravat et al. (2007) proposed methods to estimate depths to the top and the bottom of the magnetic layer simultaneously in cases where spectral peaks are observed. Theoretically, the power–density spectrum of the observed magnetic field is given by Blakely (1995) as

$$\Phi\left(k_x,k_y\right) = A\left(k_x,k_y\right)\Phi_M\left(k_x,k_y\right)\left(e^{-kz_t} - e^{-kz_b}\right)^2 \tag{1}$$

where $\Phi_M(k_x, k_y)$ is the power–density spectrum of magnetisation, $A(k_x, k_y)$ is a function that depends on the vector directions of magnetisation and ambient field (Blakely, 1995), z_t and z_b are, respectively, the depth to the top and the depth to the bottom of the magnetised layer, k_x and k_y are wavenumbers in the x and y directions respectively and

$$k = \sqrt{{k_x}^2 + {k_y}^2}. \tag{2}$$

is the radial wavenumber. For estimating the depth to the top of a magnetic layer, Spector and Grant (1970) showed that the slope of the logarithm of the azimuthally averaged Fourier power spectrum of magnetic anomalies from an ensemble of simple sources, at mid to high wavenumbers, is related to the depth to the top of the ensemble:

$$\log\left[\overline{\Phi}(k)\right] = B_1 - 2kz_t, \tag{3}$$

where B_1 is a constant. According to Blakely (1995), if the magnetic data set is large enough such that the low-frequency anomalies caused by the bottom of the source are included in the anomaly map (Connard et al., 1983), a peak should be evident in the spectrum, whose central wavenumber relates to the depth of the bottom of the sources (Spector and Grant, 1970). The observed spectral peak position (k_{peak}) is a function of z_t and z_b and is given by the following equation (Blakely, 1995; Connard et al., 1983)

$$k_{peak} = \frac{\log(z_b) - \log(z_t)}{z_b - z_t}. \tag{4}$$

Bhattacharyya and Leu (1977) presented a method for the determination of the depth to the centroid of a rectangular parallelepiped with uniform magnetisation, which they had used earlier in their study of Curie isotherm depths of the Yellowstone Caldera (Bhattacharyya and Leu, 1975). Okubo et al. (1985) expanded their method to ensembles of sources with random magnetisation. In this method, the estimate of the depth to the centroid (z_c) is obtained from the logarithm of an azimuthally averaged wavenumber-scaled Fourier amplitude spectrum in the low wavenumber region such that

$$\log\left[\overline{\Phi}(k)^{1/2}/k\right] = B_2 - kz_c, \tag{5}$$

where B_2 is a constant. Once the centroid depth is obtained from Eq. (5) and the estimate of the depth to the top of the source is obtained from Eq. (3), the depth to the bottom of the magnetic layer can simply be calculated as

$$z_b = 2z_c - z_t. \tag{6}$$

The above two methods assume a layer of random magnetisation. In some cases, these methods may lead to incorrect determinations of the Curie isotherm depth/magnetic bottom if the layer has fractal magnetisation (Bouligand et al., 2009; Maus et al., 1997) or it is made up of an ensemble of sources with different dimensions than those implicit in the method of Spector and Grant (Fedi et al., 1997).

2.2. Fractal magnetisation models

The idea of using models with fractal magnetisation distribution comes from the concept of self-similarity (Kolmogorov, 1941; Mandelbrot, 1983), which is consistent with susceptibility logs (Maus and Dimri, 1995; Pilkington and Todoeschuck, 1993), susceptibility surveys (Pilkington and Todoeschuck, 1995) and magnetic maps (Maus and Dimri, 1994, 1995; Pilkington and Todoeschuck, 1993). Based on this concept, Maus et al. (1997) derived a spectral density model for the anomaly of the total intensity of the magnetic field. The model accounts for the self-similarity as well as the limited depth extent of the crustal magnetisation. The theoretical power spectrum due to a slab of self-similar magnetisation distribution is given by Maus et al. (1997) as

$$\frac{1}{2\pi}\int_0^{2\pi} \ln\left[\Phi\left(k_x,k_y\right)\right]d\theta = B_3 - 2kz_t - tk - \beta\ln(k) + \ln\left[\int_0^{\infty}\left[\cosh(tk) - \cos(tw)\right]\left(1 + \frac{w^2}{k^2}\right)^{-1-\beta/2} dw\right] \tag{7}$$