Curie Depth Estimation from Aeromagnetic for Fractal Distribution of Sources

A.R. Bansal, V.P. Dimri, Raj Kumar and S.P. Anand

Abstract The earth's magnetic field is used to find the depth of anomalous sources as shallow as few metres to tens of kilometres. The deepest depths found from the magnetic field sometimes correspond to Curie depth, a depth in the crust where magnetic minerals lose their magnetic field due to increase in temperature. Estimation of depth from magnetic/aeromagnetic data generally assumes random and uncorrelated distribution of magnetic sources equivalent to white noise distribution. The white noise distribution is assumed because of mathematical simplicity and non-availability of information about source distribution, whereas from many borehole studies it is found that magnetic sources follow random and fractal distribution. The fractal distribution of sources found many applications in depth estimation from magnetic/aeromagnetic data. In this chapter Curie depth estimation from aeromagnetic data for fractal distribution of sources will be presented.

1 Introduction

Curie depth is a depth in the earth's crust where ferromagnetic mineral changes to paramagnetic due to increase in temperature and generally no detectable magnetic field is observed below this depth in the crust. This depth may be very deep or

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shallow depending on heat flow in the region and composition of rocks. The Curie depth in a region serves as a proxy for heat flow. Direct measurement of heat flow is carried out from bore holes in land and drilling cores from the ocean. The direct measurement of heat flow is very sparse because of higher costs for drilling, whereas proxy estimation from aeromagnetic/magnetic data provides homogeneous coverage. The magnetic surveys are easy to carry out and cheap in terms of cost involved in field surveys.

The estimation of depth from magnetic data is an ambiguous process and there are many methods for its estimation. None of the methods provide reliable depth estimations. These methods are applied in space and frequency domain. The frequency domain methods are generally preferred as compared to the space domain (Gundmundsson 1966, 1967; Heirtzler and Le Pichon 1965; Neidell 1966; Naidu 1968, 1970; Bhattacharyya 1967; Spector and Grant 1970; Treitel et al. 1971; Negi et al. 1986; Dimri 1992) because convolution operator changes to multiplication. The Fourier domain methods became very popular in depth estimation because of simplicity. The classical methods of depth estimation assume random and uncorrelated distribution of sources which is equivalent to white noise distribution.

From many boreholes it is found that source distribution follows random and fractal distribution of sources which is known as scaling distribution (Pilkington and Todoeschuck 1990, 1993, 2004; Pilkington et al. 1994; Maus and Dimri 1995a, b; Leonardi and Kumpel 1998; Bansal et al. 2010; Bansal and Dimri 2010). The power spectrum of scaling distribution is frequency dependent in contrast of white noise which is frequency independent and mathematically it is defined as:

$$P(k) = Ak^{-\beta} \tag{1}$$

where P is the—power spectrum, k is the wavenumber, β is the scaling factor and A is constant. The values of scaling exponents represent degree of correlation and larger the value stronger is long range correlation.

The values of scaling exponents due to source and field are related and estimated easily if one is known and vice versa (Maus and Dimri 1994). A known value of scaling exponents can be easily represented in different dimensions using simple formula (Maus and Dimri 1994). The β values are found to vary with space (Pilkington and Todoeschuck 1993; Bansal et al. 2010; Bansal and Dimri 2014) but still the exact relation with tectonic and rock formations is not yet established mainly due to limited studies. The use of scaling distribution of sources provides better depth estimation (Pilkington and Todoeschuck 1993; Maus and Dimri 1994, 1996; Fedi et al. 1997; Bansal and Dimri 1999, 2001; Bansal et al. 2006a, b; Dimri 2000; Dimri et al. 2003). The values of scaling exponents can be converted to fractal dimension using a simple formula (Mandelbrot 1982; Turcottee 1997; Bansal and Dimri 2005a). Fedi et al. (1997) have shown inherent power law due to Spector and Grant ensemble.

Curie depth estimations are carried out worldwide from aeromagnetic data using Fourier domain methods mostly assuming random and uncorrelated distribution of sources (Okobu et al. 1985; Tanaka et al. 1999; Chiozzi et al. 2005; Trifonova et al. 2009). Few recent studies have claimed better depth estimation for fractal distribution of sources (Maus et al. 1997; Bouligand et al. 2009; Bansal et al. 2011; Salem et al. 2014).

2 Conventional Centroid Depth Method

In centroid method (Bhattacharyya and Leu 1975; Okobu et al. 1985; Tanaka et al. 1999) Curie depth is estimated in two steps: (1) top depth of anomalous body and (2) centroid depths are computed from the power spectrum of magnetic field data and then these depth values are converted to Curie depths. Spector and Grant (1970) proposed a method to estimate top depth of assemblage of magnetic sources. In this method, power spectrum of total magnetic field is represented in terms of top depth and thickness of magnetic body (Blakely 1995):

$$P\left(k_x, k_y\right) = 4\pi^2 C_m^2 \varphi_{\mathrm{m}}\left(k_x, k_y\right)|\Theta_{\mathrm{m}}|^2|\Theta_{\mathrm{f}}|^2 \mathrm{e}^{-2|k|z_{\mathrm{t}}} \times \left(1 - \mathrm{e}^{-|k|(z_{\mathrm{b}} - z_{\mathrm{t}})}\right)^2 \quad (2)$$

where k_x and k_y are the wavenumbers in the x- and y-directions; C_m is a constant of proportionality; φ_{m} is the power spectrum of the magnetization; Θ_{m} and Θ_{f} are the directional factors related to the magnetization and geomagnetic field, respectively; Z_{t} and Z_{b} are the top and bottom depths of the magnetic sources.

It is common practice in geophysics for converting 2-D power spectrum to 1-D by taking radial average. In this case terms Θ_{m} and Θ_{f} become constant and φ_{m} is constant for random and uncorrelated distribution of sources. In case of radial averaging of power spectrum, and random and uncorrelated distribution of sources, Eq. 2 can be written as:

$$P(k) = A_1 \mathrm{e}^{-2|k|z_{\mathrm{t}}}\left(1 - \mathrm{e}^{-|k|(z_{\mathrm{b}} - z_{\mathrm{t}})}\right)^2 \quad (3)$$

where A_1 is a constant and for very thick magnetic body the right-hand side of Eq. 3 contains only top depth and Eq. 3 reduces as:

$$P(k) = A_1 \mathrm{e}^{-2|k|z_{\mathrm{t}}} \quad (4)$$

Equation (4) is frequently used for finding the top depth of anomalous magnetic bodies.

The centroid depth of magnetic body is given as (Bhattacharyya and Leu 1975, 1977; Okobo et al. 1985; Tanaka et al. 1999):

$$\ln\left(\frac{P(k)^{\frac{1}{2}}}{k}\right) = A_2 - |k|Z_0 \tag{5}$$

The Curie depth is finally computed from centroid and top depth as:

$$Z_b = 2Z_0 - Z_t \tag{6}$$

The centroid method has become very popular for estimating Curie depth from aeromagnetic data and is applied to aeromagnetic data of many parts of world (Bhattacharyya and Leu 1975; Okubo et al. 1985; Tanaka et al. 1999; Okubo and Matsunaga 1994; Chiozzi et al. 2005; Dolmaz et al. 2005; Trifonova et al. 2009 etc.).

3 Fractal Based Methods of Curie Depth Estimation

Fourier domain methods became very popular in Curie depth estimation from aeromagnetic data because of their simplicity. However, these methods provide overestimation of depth values due to the assumption of random and uncorrelated distribution of sources (Pilkington and Todoechuck 1993; Maus and Dimri 1994, 1996; Fedi et al. 1997; Bansal and Dimri 1999, 2001, 2005b, 2014). These methods are modified for scaling distribution of sources. The scaling distribution of sources is equivalent to fractal distribution of sources and these modified methods are called fractal based methods of depth estimation.

Maus et al. (1997) proposed a method for estimating Curie depth for fractal distribution of sources where scaling exponents, top depth and thickness of magnetic body are estimated simultaneously from power spectrum of magnetic field. Radial average of power spectrum is expressed in terms of scaling exponent and depth component as (Maus et al. 1997):

$$P(k) = C - 2kz_t - tk - \beta\ln(k) + \ln\left[\int_0^{\infty}[\cos h(tk) - \cos(tw)]\left(1 + \frac{w^2}{k^2}\right)^{-1-\beta/2} \mathrm{d}w\right]. \tag{7}$$

where k is the wavenumber, z_t is the top depth, t is the thickness of slab and β is the scaling exponent due to source distribution, w is the wavenumber in vertical plane. Maus et al. (1997) found a value of β equal to 4 from aeromagnetic data of South Africa and Central Asia and Curie depths vary from 15 to 20 km. Bouligand et al. (2009) derived an analytical solution for solving Eq. 7 and found difficulty in simultaneous estimation of top depth and scaling exponents. Therefore, Bouligand et al. (2009) fixed the value of scaling exponents for estimating top depth based on the shape of power spectrum of aeromagnetic data. Manual checking of estimated parameter is essential for a reliable estimation. Bansal et al. (2011) proposed a modified centroid method for the estimation of Curie depth from aeromagnetic data for scaling distribution of sources. This method computes Curie depth in two steps similar to classical centroid method for scaling distribution of sources. The top and centroid depths are computed by correcting power spectrum for scaling distribution of sources as:

Top depth:

$$\ln\left(k^{\beta}P(k)\right) = A_2 - 2kz_t \tag{8}$$

and Centroid depth:

$$\ln\left(k^{\beta}\frac{P(k)}{k^2}\right) = A_3 - 2kz_0 \tag{9}$$

Bansal et al. (2011) also pointed out the difficulty in estimating scaling exponent and depth values simultaneous from inversion method and they fixed the value of scaling exponent equal to 1 corresponds to 1/f noises found from seismic velocity fluctuations and fault structures (Holliger 1996). Salem et al. (2014) also corrected their power spectrum before computing the top depth from the power spectrum of aeromagnetic data and applied to the magnetic data of central Red Sea. Their values of scaling exponent vary between 0 and 1.7 with an average value of 0.85 very close to 1 used by Bansal et al. (2011) in the estimation of Curie depth. The Curie depths estimated by classical and modified centroid method for fractal dimension sometimes have a large difference (Table 1). This method is successfully applied to the German, Indian and Nigerian aeromagnetic data (Bansal et al. 2011, 2013; Nwankwo 2015).

Table 1 Comparison of depth values computed using fractal (scaling) and non-fractal (conventional) distribution of sources

Block no.	Estimated Curie depths		% Higher
	Scaling	Conventional	
2	33	47	30
3	28	42	33
21	35	51	31
31	37	63	41

The difference in the computed values may be more than 40 % in some of cases (Table 1). The difference in computed values also depends on values of scaling exponents used. Higher the value of scaling exponent used larger is difference in computed values

4 Case Study: Application of Modified Centroid Method for Fractal Distribution of Sources to Central India

Bansal et al. (2013) carried out a detailed study of the Curie depth estimation in central India. The central India is tectonically complex and covers many geological entities, e.g. Deccan volcanic province, central Indian Tectonic zone, Godavari and Mahanadi intracratonic failed rifts, Chhattisgarh basin and the Proterozoic Eastern Ghat Mobile Belt.

Aeromagnetic data over central India is compiled by the Indian Institute of Geomagnetism over a common elevation of 1.5 km (Rajaram and Anand 2003; Rajaram et al. 2009). We selected four blocks of dimension 200 km × 200 km covering Eastern Dharwar, Godavari-Graben and Baster Craton. Centres of selected blocks are lying in Godavari-Graben (Blocks 2, 21) and Baster Craton (Blocks 3 and 31), whereas a large size of block covers surrounding geological entities. The Curie depths are computed using conventional (Figs. 1 and 2) and centroid method

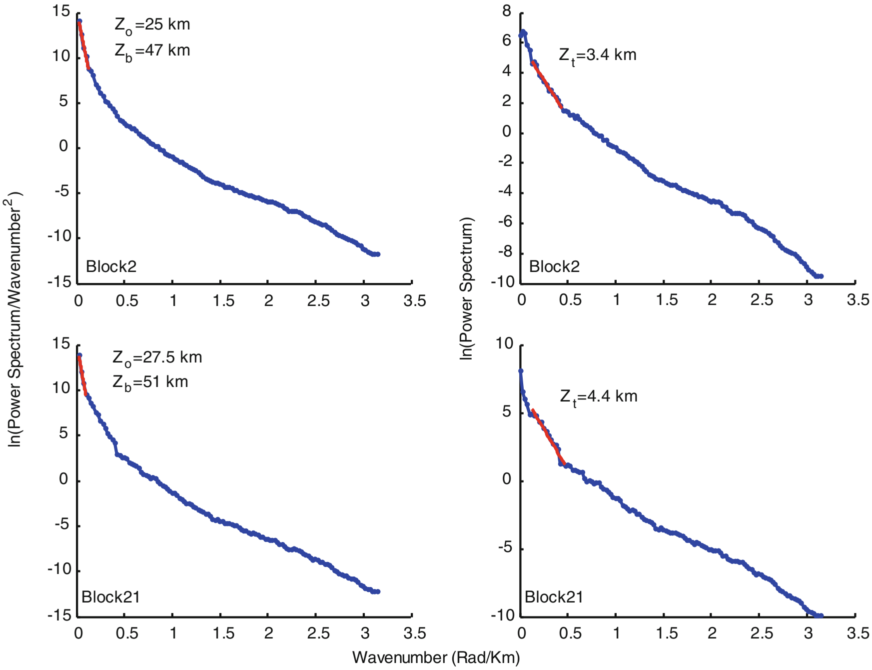

Fig. 1 Estimation of Curie depth for central India using conventional centroid method for block 2 and 21. The *left* and *right* panels indicate the estimation of centroid and top depth, respectively

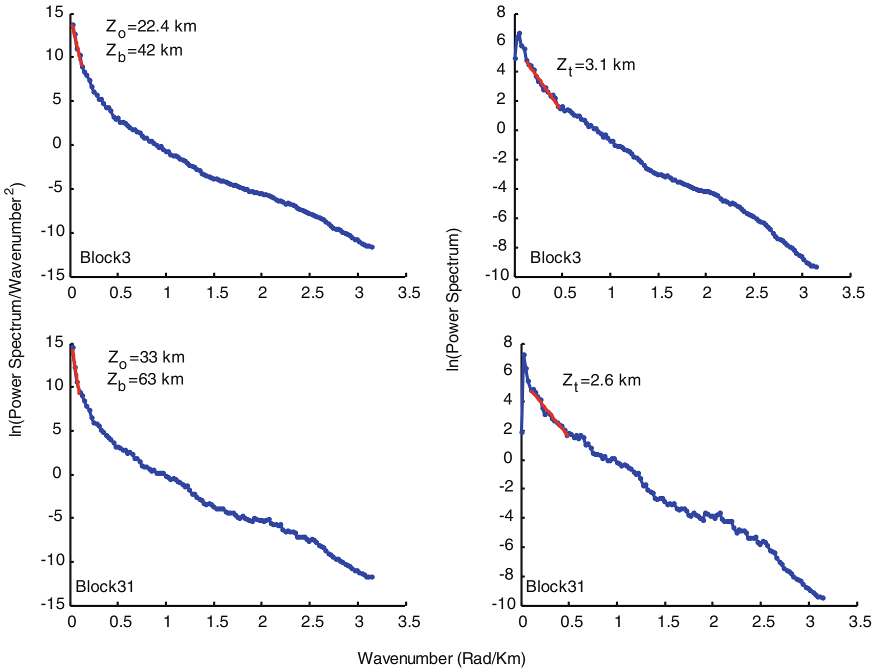

Fig. 2 Estimation of Curie depth for central India using conventional centroid method for block 3 and 31. The *left* and *right* panels indicate estimation of centroid and top depth, respectively

for fractal distribution of sources (Figs. 3 and 4). Godavari-Graben is a passive rift orthogonal to the east cost of India and the Curie depth is found to vary between 33 and 35 km (Fig. 3). Deep seismic study has shown Moho depth of 37 and 42 km in the Eastern Dharwar Craton (Reddy et al. 2005) and Godavari-Grabens (Kaila et al. 1990). Godavari-Graben region is found to have underplating of high density rocks (Behera et al. 2004; Rao 2002) and evolved during permo-carboniferous rifting. The region has undergone a number of volcanism in the past and these thermal episodes have a large effect on the Curie depth in Godavari-Graben. The centres of Blocks 3 and 31 are on the south part of Baster Craton and magnetic data also covers Godavari-Graben and Eastern Ghat mobile belts. The Baster Craton is bounded by Godavari-Graben in the west and Eastern Ghat mobile belt in the east. The Baster Craton contains vast traces of granites and gneisses with basement of

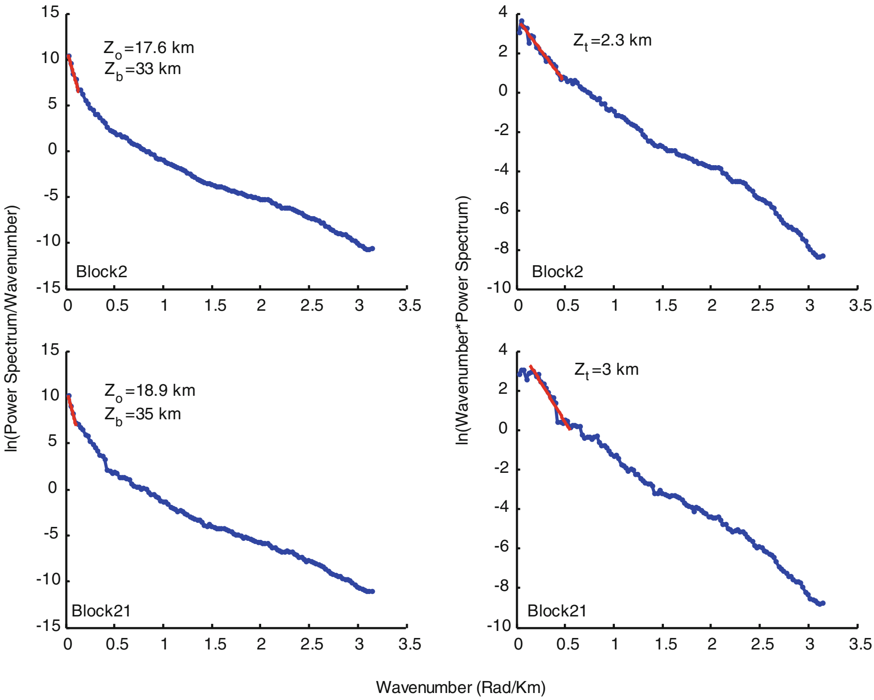

Fig. 3 Estimation of Curie depth for central India using modified centroid method for fractal distribution of sources for block 2 and 21. The *left* and *right* panels indicate estimation of centroid and top depth, respectively

mainly Archean to mid-proterozoic. The Moho depth in the North of Baster Craton is found as 48 km from deep seismic studies (Mandal et al. 2013). In the south of Baster Craton, values of Curie depth are found to vary from 28 to 37 km (Fig. 4). The region of the lowest Curie depth includes Godavari-Graben and Eastern Ghat mobile belt. The south-west part of Eastern Ghat mobile belt is found to have lower values of Curie depth 26–27 km from an earlier study (Bansal et al. 2013). The Curie depths estimated in central India using fractal distribution of sources are found to be lower than the values computed using conventional method (Fig. 5, Table 1) and reasonably well while considering other tectonic and geophysical constraints.

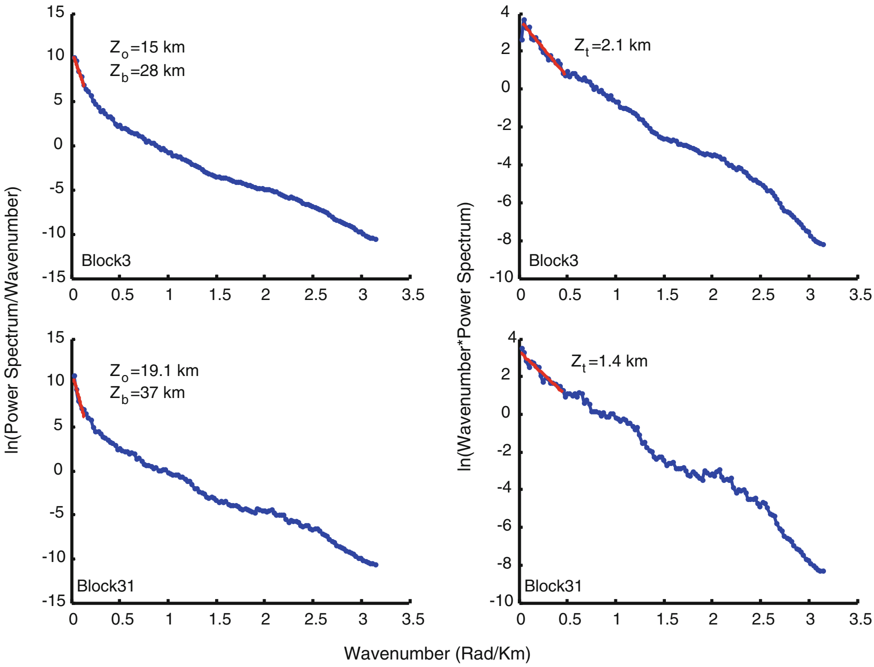

Fig. 4 Estimation of Curie depth for central India using modified centroid method for fractal distribution of sources for block 3 and 31. The *left* and *right* panels indicate estimation of centroid and top depth, respectively

5 Discussion and Conclusion

Depth estimation from magnetic data is ambiguous due to Green's equivalent layer problem. The information about source distribution is limited mainly due to limited information below the surface of earth from deep boreholes. Assumption of random and uncorrelated distribution of sources resulted in a simple relation between power spectrum and depth of magnetic sources. This method is commonly used for finding Curie depth from aeromagnetic data. The magnetic susceptibility distribution is found to follow random and fractal distribution. The fractal distribution of sources is incorporated in estimating depth from magnetic data. Many authors have claimed that methods based on fractal distribution of sources provide better depth estimation as compared to depth estimation based on white noise distribution (Maus et al. 1997; Bouligand et al. 2009; Bansal et al. 2011). Fractal based approach suffers the limitation of simultaneous estimation of depth and scaling exponents. At present, prior fixation of one of the parameters provides a better estimation of the other

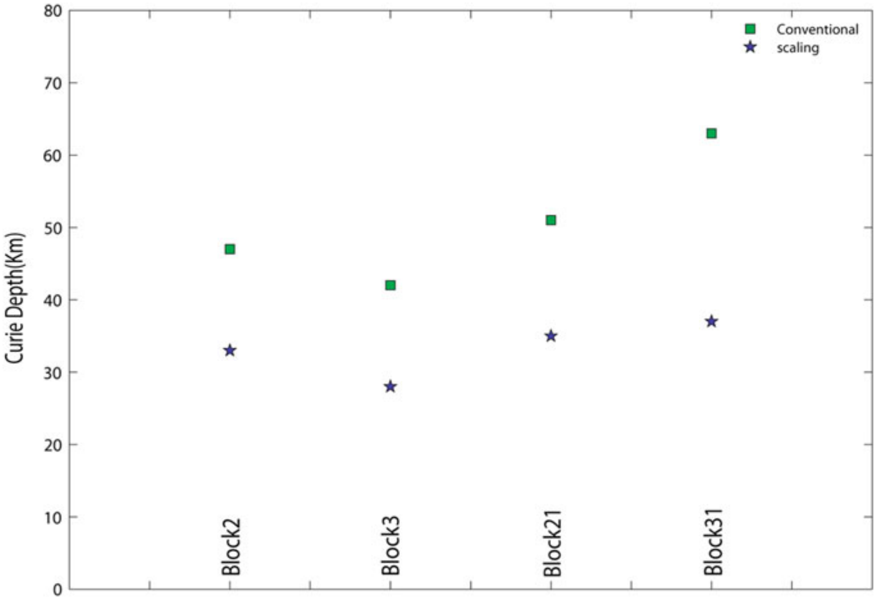

Fig. 5 The comparison of depth values estimated using conventional and modified centroid method

parameter. There is no doubt about better depth estimations using fractal distribution of sources and many researchers are working on simultaneous estimation of scaling exponent and depth values.

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