Curie depth and apparent magnetic susceptibility contrast mapping from aeromagnetic data in parts of Dharwar Greenstone Belt and Singhbhum Craton and Mobile Belt, India

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ABSTRACT Curie depth and apparent magnetic susceptibility contrast (AMSC) have been mapped from aeromagnetic data for parts of Dharwar Greenstone Belt (DGB), and Singhbhum Craton and Mobile Belt (SCM), India. The Curie depth has been estimated using harmonic inversion of the total field aeromagnetic anomaly. Curie depth maps, thus obtained, show broad Curie depth variations, in the range of 51-63 km for DGB, and from 19 to 28 km for SCM. The mapped Curie crust shows a gradual increase from north to south in both areas under study. Based on a linear relation between the surface heat flow density and the Curie depths, Curie depths have also been estimated by using surface heat flow density information from the area. Curie depths, thus estimated, are found to be of the order of 22.5 km, 35 km and 67 km for Singhbhum mobile belt, Singhbhum craton, and DGB respectively, corresponding to their surface heat flow densities of 60 mWm^{-2}, 39 mWm^{-2} and 20 mWm^{-2}. AMSC mapping has been carried out using a stochastic inversion algorithm. In order to estimate AMSC, average crustal thicknesses (based on Curie depth variations) were taken as 57 km for DGB and 23 km for SCM. AMSC contour values (maps), thus derived, depict broad apparent magnetic susceptibility contrast variations for DGB (0 to $10x10^{-3}$ SI) and for SCM ($-32x10^{-3}$ to $16x10^{-3}$ SI), that are progressively on the increase from southeast to northeast, reflecting the overall subsurface magnetic characteristics of the areas under study.

1. Introduction

The Dharwar Greenstone Belt (DGB, Dharwar Craton) belongs to the Archaean–early Proterozoic age. Dharwar craton is possibly the oldest continental fragment of the world (Rogers, 1984). Swami Nath and Ramakrishnan (1981) have discussed in detail the geology of DGB. Singhbhum Craton and Mobile Belt (SCM) is of Proterozoic age, it formed either by reworking of the Archaean crust or through additions of juvenile materials during the Proterozoic. The geology of SCM has been provided by Dunn and Dey (1942) and Sarkar *et. al.* (1969). The present study is intended to provide comprehensive Curie depth and apparent magnetic susceptibility contrast variations for the DGB and the SCM. An area greater than 10,000 km^2, each in DGB (Lat: 13°-14°N; Long: 76°-77°E) and in SCM (Lat: 22°-23°N; Long: 86°-87°E) have been selected (Fig. 1) for Curie depth and apparent magnetic susceptibility contrast (AMSC) mapping from total field aeromagnetic data collected by the Geological Survey of India (GSI, 1995).

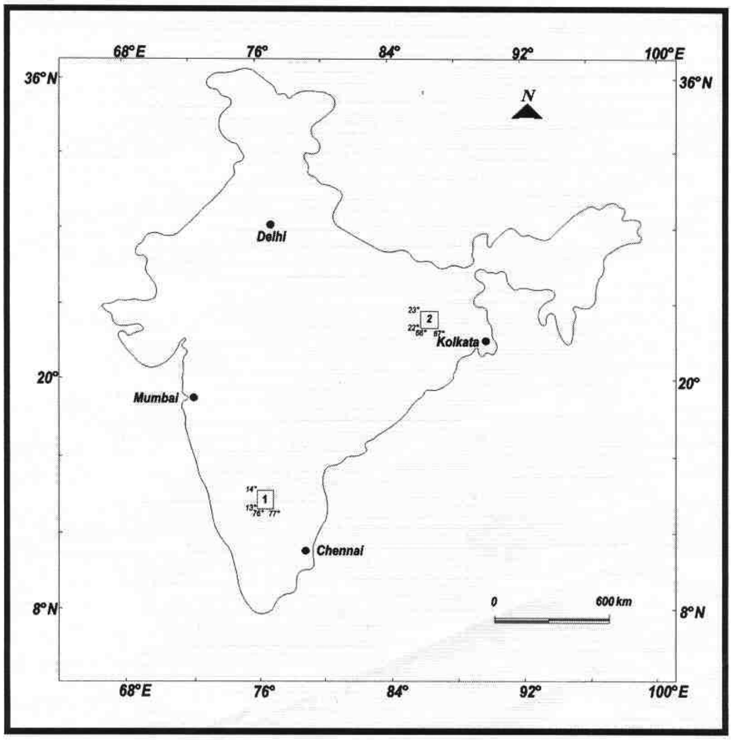

Fig. 1 - Location map of the study areas: 1 = Dharwar Greenstone Belt and 2 = Singhbhum Craton and Mobile Belt.

Curie depth provides the depth persistence of the Earth's magnetic field. Curie temperature is generally defined as the temperature of 550±30°C at which Fe-Ti oxide minerals of the Earth lose their ferromagnetic properties. Until recently, Curie depth was, in general, assigned to be about 20 km, presuming the average geothermal gradient over the continents is of the order of 25-30°C/km. However, analysis of MAGSAT (Satellite based magnetic data) data showed that Curie depth is nonuniform and may range from 18 to about 70 km over India (Negi *et al*., 1987).

We used harmonic inversion in order to estimate the thickness of the Curie crust. Harmonic inversion, based on the spectral technique, envisages potential field anomalies caused by one dimensional/two dimensional sources at various subsurface levels that are statistical population. Conceptually, it implies that a layer/bed contains all random susceptibility variations and ensemble average depth to such a layer/bed may be estimated from the radial/azimuthal spectrum (Naidu, 1983). This method provides an easy, reliable and robust way of obtaining mean or average depths to the sources of such anomalies.

For this purpose, the areas under study (Fig. 1) have been modelled into a number of square blocks (three dimensional bodies with square bases). For the DGB area, based on the Curie depth contour map, the mean depth of the Curie crust is taken as 57 km. Thus the dimension of a block (square prism) for DGB is taken to be 10x10x57 km. Similarly, based on the Curie depth contour map of SCM area, the mean depth of Curie crust for SCM turns out to be 23 km. Therefore, the dimension of a block (square prism) in regard to SCM is taken as 10x10x23 km.

Stochastic processes, defined on the real Hilbert space (Franklin, 1970) have been used in

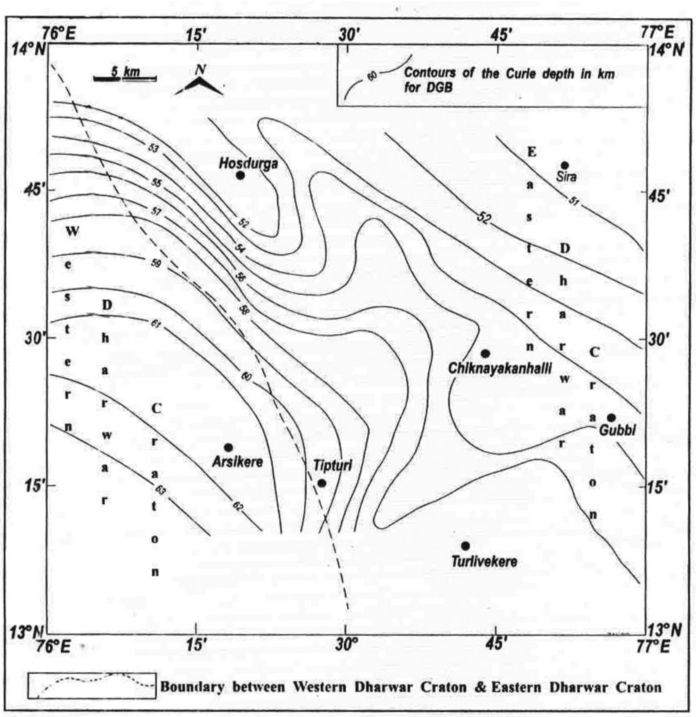

Fig.2 - Curie depth contour map of the Dharwar Greenstone Belt.

deriving a formula for obtaining the susceptibility contrast of a given volume of rock mass. The formula deduced is given by

$$\Delta K = \left(\phi^T r_{nn}^{-1} \phi + \theta_{mm}^{-1}\right)^{-1} \phi^T r_{nn}^{-1} \delta\mu \tag{1}$$

where ΔK is the susceptibility contrast of a given rock mass to be obtained, ϕ is the Frechet kernel of the data, r_{nn} is the noise autocorrelation operator of data, r^{-1}_{nn} being its inverse. In using the above formula, noise components of the data are assumed to be statistically uncorrelated i.e., noise associated with data is not influenced by noise content of any other data. Thus, r_{nn} becomes a diagonal matrix with the diagonal elements representing the data variances. θ_{mm} is the a priori variance (square of the standard deviation) of the sought parameter (susceptibility contrast of the individual block to be estimated), θ^{-1}_{mm} being its inverse. T refers to transposes of the concerned operators, $\delta\mu$ being the magnetic anomaly values in nT, obtained after applying various corrections to the magnetic observations as specified. The estimated susceptibility contrast was plotted at the mid point of each block.

2. Analysis of the aeromagnetic data

Estimations of magnetic susceptibility contrast and Curie depth from aeromagnetic data (GSI,

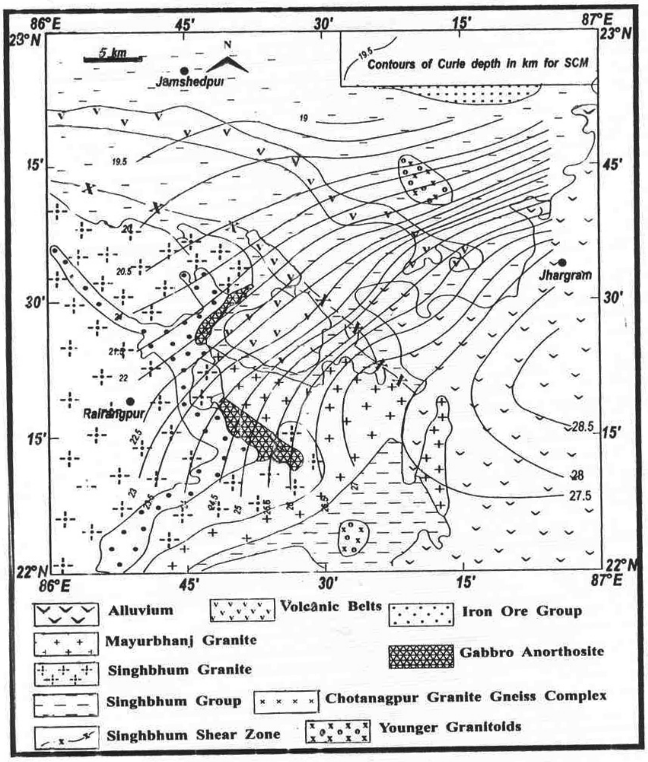

Fig.3 - Curie depth contour map of the Singhbhum Craton and Mobile Belt.

1995) consist basically of six stages of processing depicted as follows:

- digitization of aeromagnetic maps;
- IGRF correction;
- flight height equalisation by analytical continuation;
- application of low pass filter to extract longer wavelength magnetic anomalies;
- harmonic inversion (radial spectrum) of data to obtain depth extent of the magnetic basement which by definition being the Curie depth;
- stochastic inversion of data to determine the magnetic susceptibility contrast of the rock mass.

The total magnetic field which is calculated every five years is called the International Geomagnetic Reference Field (IGRF) and the year of calculation is known as the Epoch. In order to produce a magnetic anomaly map, the data have to be corrected to take into account the effect of latitude and, to lesser extent, longitude. Thus, IGRF correction is applied for correcting the regional magnetic variations. Analytic continuation was resorted to for variable flight heights caused by topographic undulations. The entire data set of the two areas were reduced to a common 7000 feet (2121 m) datum by upward continuation of the data. The low pass filter was intended to extract longer wavelength magnetic anomalies, reflecting deeper structures.

Determination of the Frechet kernel appearing in Eq. (1) involves inclination, azimuth of the declination and quantum of the Earth's magnetising field. According to Mishra (1984), crustal magnetising field of the Indian subcontinent was principally acquired during the period when

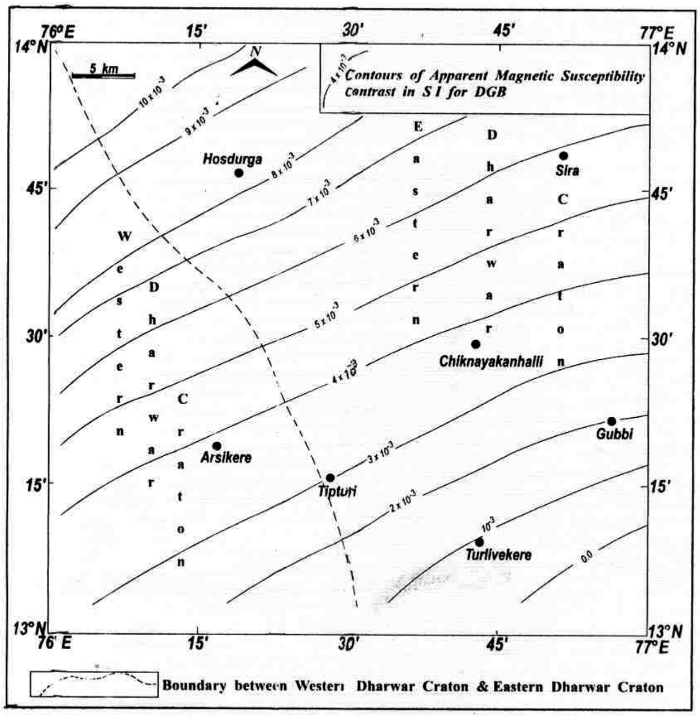

Fig.4 - Apparent magnetic susceptibility contrast map of the Dharwar Greenstone Belt.

India and Antarctica were in juxtaposition. Therefore, appropriate inclination, azimuth of the declination and intensity of the magnetisation were taken as –65°, 315° and 200 *nT* respectively (Mishra, 1984). ϕ appearing in Eq. (1) is calculated using the expression for total magnetic field of a prismatic body having a square base (Ku, 1977), constituting the forward problem. The a priori standard deviations of the susceptibility contrasts ΔK to be estimated are taken as ±0.001 SI for DGB and ±0.004 SI for SCM respectively, subject to the criteria that estimated ΔK's should be stable, consistent and physically acceptable. The standard deviations of the digitized aeromagnetic data are taken as 10%. This level of a uniform 10% contamination is justified because of error introduced into the data owing to various stages of processing of aeromagnetic data, right from data acquisition to preparation of anomaly maps leading to digitized magnetic profiles. Utilisation of only two-dimensional harmonic inversion does not generate sufficient number of Curie depths due to its restricted use (Naidu, 1983). Therefore, one dimensional harmonic inversion has also been used for augmenting the number of estimated Curie depths.

3. Results and discussions

Estimated Curie depth variations of the DGB were found to be in the range of 51-63 km (Fig. 2). The contours show smooth variations over the area. However, considering the average continental geothermal gradient as 25-30°C/km, the temperature at the base of the Curie crust exceeds the Curie temperature of 570°C. For the SCM, the estimated Curie crust (Fig. 3) varies in the depth range of 19-28 km. The Curie depth, in general, is indicative of broad, Curie crust

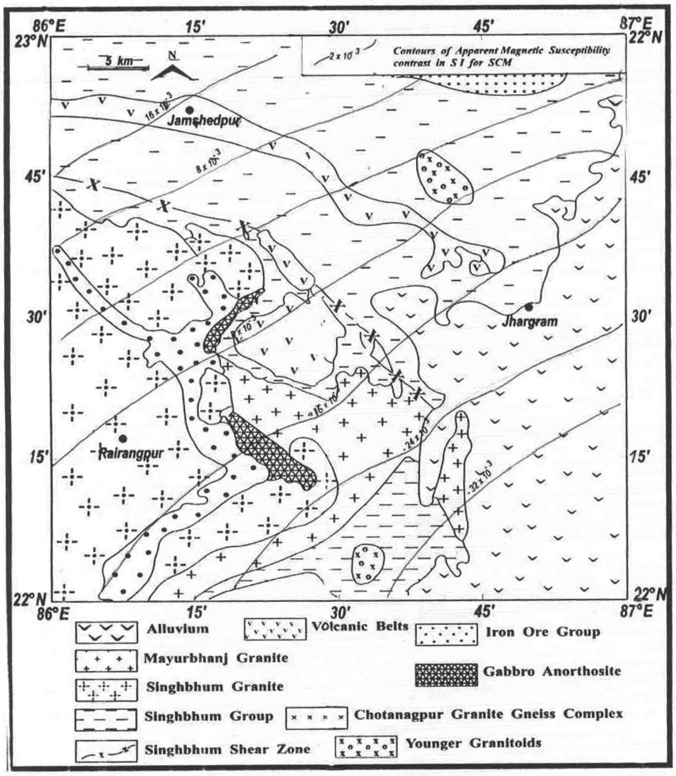

Fig. 5 - Apparent magnetic susceptibility contrast map of the Singhbhum Craton and Mobile Belt.

variations over the entire area. However, towards the northern part of the area, the Curie depth gradually decreases, reaching a minimum value of 19 km. Taking the aforestated continental geothermal gradient 25-30°C/km into account, the temperature at the base of the Curie crust, for the majority of the area, is also found to be exceeding the Curie temperature of 570°C. It is surprising to note the existence of magnetism beyond the Curie temperature of 570°C for both the areas, namely, DGB and SCM. According to Dunlop (1974), susceptibility gets increased at higher temperatures (>570°C) caused by the Hopkinson effect. Haggerty (1978) suggested formation of an alloy involving Ni, Fe, Cd and Co under the physico-chemical conditions prevailing under mantle condition having a Curie temperature higher than 570°C. Coles and Haines (1979) invoked the existence of viscous remanent magnetism to account for the existence of magnetism at a temperature higher than 570°C. The Curie depth of a given area is inversely proportional to the surface heat flow density (Negi *et al*., 1987). The surface heat flow density map of India (Ravi Shanker, 1988) generally corroborates the trend of the Curie depths as arrived at in regard of the two areas under study. Mean Curie depths of DGB and SCM as estimated in this study are in agreement with the spot Curie depths as obtained from surface heat flow density data for DGB and SCM areas (Negi *et al*., 1987).

The prepared AMSC distribution maps generally show the variation of magnetic characteristics in a constant layer thickness in respect of each area. The magnetization properties represent only the relative susceptibility contrast of different magnetized bodies since the true zero of the input anomalies is not known.

Figs. 4 and 5 provide the apparent magnetic susceptibility contrast maps of the DGB and SCM areas respectively. In general, susceptibility contrast variations are smooth enough for both the areas. Susceptibility contrast values are generally higher in SCM (Fig. 5) compared with the DGB (Fig. 4). In both the areas, the susceptibility contrast gradually increases from a SE to a NE direction.

Assuming a mean crustal thermal conductivity of 2.5W/m°C, a mean surface temperature of the Indian crust at 25°C (Negi *et al*., 1987) and a mean Curie temperature of 550°C, Sarkar and Saha (2006) deduced a relation as

$$Qd_c = 1350 \qquad (2)$$

where Q is the mean surface heat flow density in mWm^{-2} and dc being the compatible Curie depth in km. Corresponding to heat flow density of 60 mWm^{-2} for Singhbhum mobile belt (Ravi Shanker, 1988), 39 mWm^{-2} for Singhbhum craton and 20 mWm^{-2} for DGB (Ravi Shanker, 1988), Curie depths as estimated from Eq. (2) are 22.5 km, 35 km and 67 km respectively. The Curie depths, thus obtained are not far off from the estimated Curie depths (Figs. 2 and 3) for these areas based on harmonic inversion of the total field airborne magnetic data.

4. Conclusions

The present study provides Curie depth and apparent magnetic susceptibility contrast variations over parts of the DGB and SCM. The higher Curie depth variations in the range of 51-63 km over DGB are characteristic of a shield area. In fact, all over the world, the shield areas are characterised by higher Curie depths and lesser heat flows. The mean heat flow of DGB is also of the order of 20 mWm^{-2} (Ravi Shanker, 1988). The broad magnetic susceptibility contrast variations over the same area are devoid of any significant magnetic signatures.

Curie depth variations over a part of the SCM registers a Curie depth variation in the range of 19-28 km. Curie depth progressively increases from a north to a south direction whereas magnetic susceptibility contrast increases from a SE to a NE direction. Since the decreased Curie depth is associated with higher heat flow density (Negi *et al*., 1987), Singhbhum mobile belt is tectonically more active as compared to the cratonic segment. The cratonic part of SCM has a mean heat flow density of about 39 mWm^{-2} whereas the mobile belt, north of Jhargram, as shown in Fig. 3 has a higher mean heat flow density of the order of 60 mWm^{-2} (Ravi Shanker, 1988).

In general, estimated higher Curie depth of DGB is indicative of DGB having possessed (a) less surface heat flow density and therefore less geothermal gradient (Ravi Shanker, 1988) than SCM since Curie depth is inversely proportional to the surface heat flow density (b) less apparent magnetic susceptibility contrast variation than SCM (Figs. 4 and 5) and (c) higher lithospheric thickness than SCM (Negi *et al*., 1987). The aforestated characteristics are useful for understanding the tectono-thermal evolution of the areas.

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