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Proxy Heat Flux and Magnetisation Model from Satellite Magnetic Data

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Abstract

From the Curie isotherm depths derived from the aeromagnetic data, the geothermal heat flux was calculated utilizing the 1D heat conduction, steady state thermal model for the continental crust. Available values of the surface heat-production and thermal conductivity for the various tectonic blocks of India are incorporated for computing the heat flux. The calculated heat flux for several areas matches reasonably well with the surface heat flow measurements. As the aeromagnetic data coverage over India is limited, the heat flux for the Indian region is calculated using magnetic crustal thickness derived from MF5 lithospheric model of CHAMP satellite data utilizing an iterative forward modelling approach assuming a constant susceptibility contrast for the ocean and continents. Higher heat flux are observed over the mobile belts and rift zones while lower heat flux are observed over the cratons. Further, a Vertical Integrated Susceptibility (VIS) model incorporating both Curie depths from the aeromagnetic data together with realistic susceptibility values is used to better reproduce the observed satellite data. With the upcoming multi satellite high-resolution SWARM data the lithospheric models would be superior; and these maps could be effectively used to reconstruct the thermal regime of the continents.

Introduction

Depth to the Curie temperature is the depth at which crustal rocks reach their Curie temperature. As magnetite with a Curie temperature of 580°C is believed to be the dominant magnetic mineral in the deep crust within the continental region, it is reasonable to assume that below the Curie isotherm the lithosphere is virtually non magnetic. Thus, from an analysis of the crustal magnetic field it is possible to make an estimate of the depth below which no magnetic sources exist. The remotely sensed magnetic (airborne, satellite borne) measurements thus indirectly provide a temperature data at a depth within the lower crust that in turn can then be translated to give the geothermal gradients of the region.

In this paper we utilize the available aeromagnetic data over the Indian subcontinent to calculate the Curie isotherm depths. The equation of heat conduction helps to convert these depths into heat flow values so that these may be compared with heat flow measurements.

One of the primary goals of the upcoming SWARM Mission is to estimate the lithospheric fields in the intermediate wavelength, so as to bridge the gap between the existing satellite and aeromagnetic data. We believe that the Swarm data could be fruitfully utilized to generate the thermal models of the continents. We therefore utilize the currently available satellite magnetic data to estimate the heat flow over the Indian subcontinent and discuss the possibilities of improving the modeling of the satellite data so as to derive reliable heat flow estimates from such data.

Analysis of Aeromagnetic Data

A composite magnetic anomaly map of India and its contiguous regions prepared by Rajaram et al (2006) from available aeromagnetic data supplemented by marine and ground magnetic data at an altitude of 1.5 km is depicted in Fig. 1. Although different data sources with their resolutions varying enormously are used as inputs to this map, they merge seamlessly. India is a multi cratonic assembly of Precambrain crustal blocks, surrounded by mobile belts; a quick look at the image map shows that the cratonic part (Dharwar and Bastar cratons) reflects NW-SE trending linear anomalies that are bounded by EW trending Central Indian Tectonic Zone and Southern Granulite Terrain (SGT) respectively to the north and south and NE-SW Eastern Ghat Mobile Belt (EGMB) to the east. A very striking feature of this map is a region of high frequency anomalies, starting near the West coast at around 22° N extending up to the eastern boundary of the map near 26° N, trending essentially ENE-WSW, suggesting that this region of the peninsula has been subjected to major tectonic activity. We refer to this high tectonic activity zone as HTAZ that divides the country into two blocks.

Curie Isotherm Depth

We utilize the aeromagnetic data over India, available up to 25° N latitude, to calculate the Curie isotherm depths using spectral analysis (Spector and Grant, 1970). It is very difficult to estimate the depth to the bottom of the magnetic sources, Z_{cc} as the spectra in the Fourier domain is dominated at all wavelengths by the contribution from the shallower parts. The limited depth extent of the body leads to a maximum in the power spectrum and when a significant spectral maximum does occur, indicating that the source bottoms are detectable, the wavenumber of this maximum k_{max} is related to the depth to the Curie isotherm Z_c and the depth to the top of the body, Z_t, by the following relation:

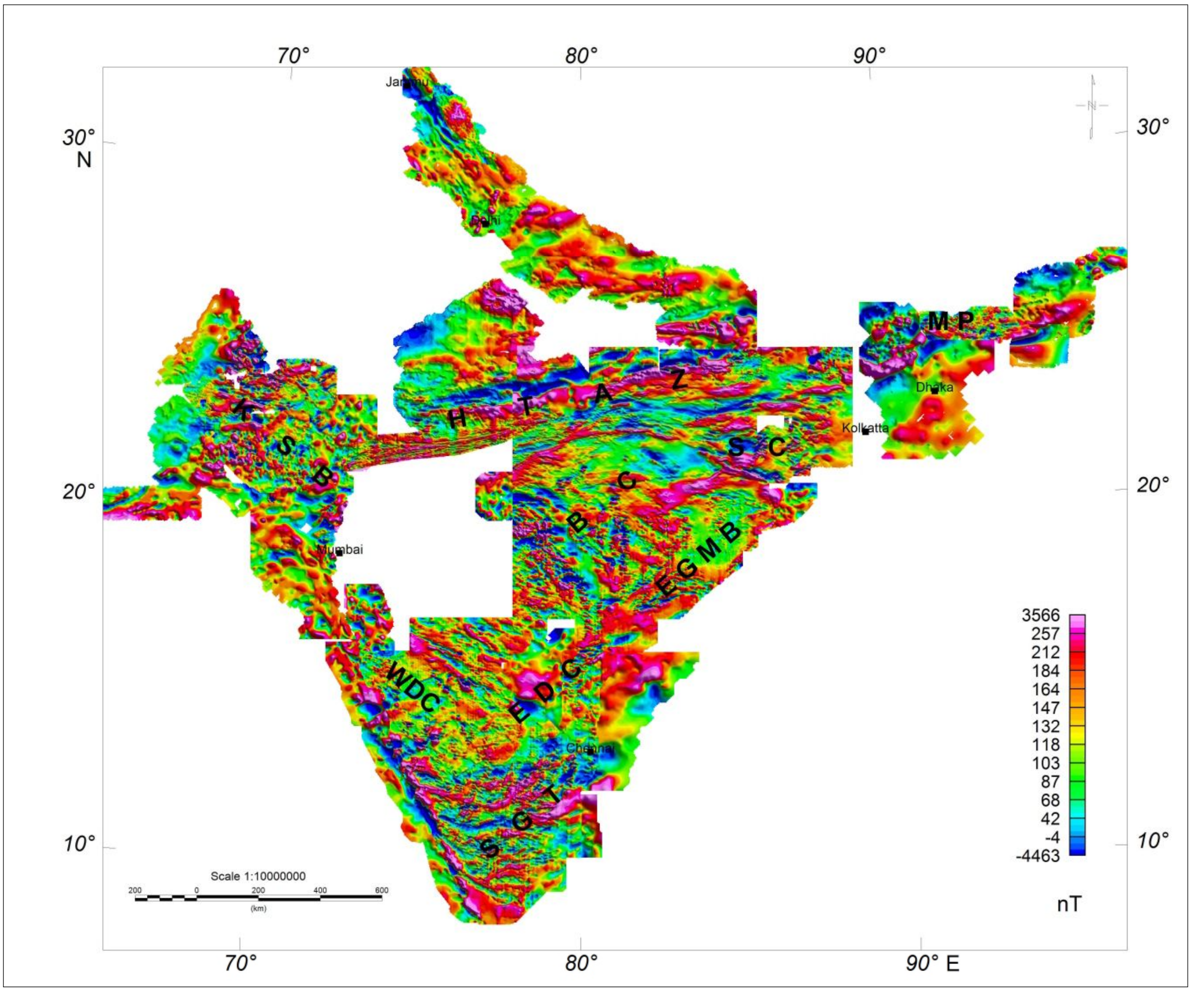

Fig. 1. Composite magnetic anomaly map over the Indian subcontinent at a height of 1.5 km. Key: SGT- Southern Granulite Terrain, WDC – Western Dharwar Craton, EDC- Eastern Dharwar Craton, EGMB- Eastern Ghat Mobile Belt, BC- Bastar Craton, SC- Singhbhum Craton, MP- Meghalaya Plateau, HTAZ- High Tectonic Activity Zone, KSB- Kutch Saurashtra Basin.

$$k_{\max} = \frac{\log Z_c - \log Z_t}{Z_c - Z_t}$$

For determining the depth to the Curie isotherm the power spectral estimates were made for every 2° X 2° blocks to see if the spectral peak exists and the size of the block was increased; we found that a significant spectral maxima existed only for 4°X 4° for SGT and 5°X5° for part of the Dharwar and Bastar craton. These were repeatedly estimated by moving the blocks by a degree at a time. We find that the Curie isotherm depth (Fig. 2) is shallow in the mobile belts and deep in the cratons (Anand and Rajaram, 2007). In particular, we find shallow depths in HTAZ and SGT. It may be noted that due to the stringent requirement of 5°×5° grid size (4°×4° for southern region), no information on the depth to the Curie isotherm could be ascertained for a region of 2.5^0 X 2.5^0 (2°×2° for southern region) on the edges of the studied area and the map in Fig. 2 extends from 10^0 N to 22^0 N.

Calculation of Heat Flux

We utilize the 1-D heat conduction, steady state model for the continents (Fox Maule et el, 2005) assuming that the depth to the Curie isotherm, represents the 580°C Curie isotherm of magnetite. The heat flux Q at the surface (z=0), is calculated using the equation (Fox Maule et el, 2005) given below, where d is the scale depth assumed as 8 km, k is the thermal conductivity and H_o is the crustal heat production:

$$Q(z=0) = -\frac{k(T_c - T_{sur})}{Z_c} - H_0 d + \frac{H_0 d^2}{Z_c}(1 - \exp(-\frac{Z_c}{d}))$$

In this equation we utilize the parameters k and H_0 from published literature (Rao et el, 2003, Gupta et el, 1993) as shown in Table 1. The Central Indian Region (CIR) is considered as the region bounded by the Eastern Ghat mobile belt (EGMB) to the south east and by the Godavari graben to the south west; thus comprising of the Singhbhum, Bastar cratons and HTAZ. It may be noted that no aeromagnetic

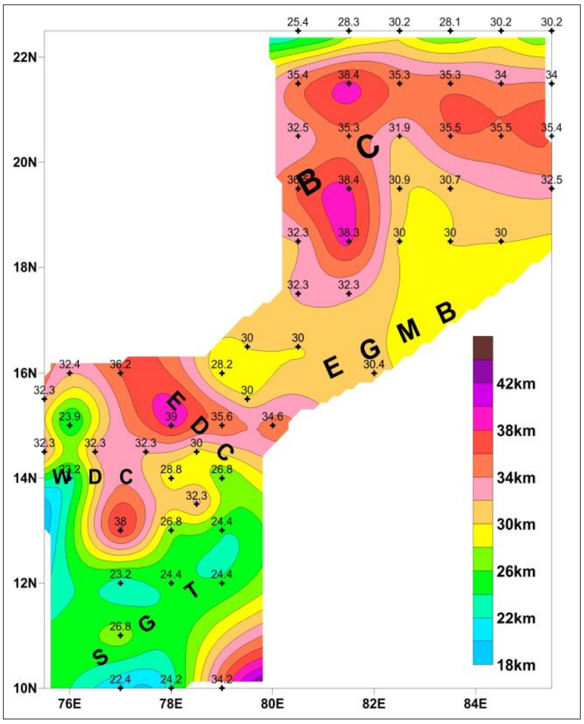

Fig. 2. Curie isotherm depths estimated from the aeromagnetic anomaly data over India. Key: SGT- Southern Granulite Terrain, WDC – Western Dharwar Craton, EDC- Eastern Dharwar Craton, EGMB- Eastern Ghat Mobile Belt, BC- Bastar Craton

data was collected over the Deccan trap covered region. The calculated surface heat flux is plotted in Fig. 3. We find high heat flow values are associated with HTAZ, EGMB and SGT and relatively low values are associated with the cratons. A comparison with the measurements is given in Table 2.

Table 1. H_0 and k values used for the various blocks

Parameters used:	$H_0 \mu W/m^3$	k W/mK
Western Dharwar	1.2	2.8
Eastern Dharwar	2.3	2.8
Central Indian Region	1.1	3.0
Southern Granulite Terrain	0.3	2.8

Table 2. Comparison of calculated and measured (Rao et al.,2003) surface heat flux for different tectonic blocks over India

Region	QmW/m^2 Cal. range	QmW/m^2 Obs. range
Sonata Belt	64 – 75	69 – 79
Singhbhum craton	56 - 60	59 - 63
Bastar craton	52 – 64	51 - 63
Western Dharwar	50 – 74	25 – 50
Eastern Dharwar	56 - 74	40 – 75
Southern Granulite Terrain	49 – 79	28 - 42

The comparison reveals a very good match in the Central Indian region (CIR). The CIR comprises of the HTAZ: Sonata belt and two cratons (Singhbhum and Bastar). As expected we obtain high heat flow values in the HTAZ and relatively low values over the two cratons. Within the Dharwar craton we find from Fig. 3 that the heat flow values over Eastern Dharwar (ED) are higher than those in the Western Dharwar (WD), and this is borne out by measurements. However, the values within the SGT do not match the measurements. This is related to the fact that the bottom of the magnetic crust does not reflect the Curie isotherm but a compositional change (Rajaram et al, 2003) corresponding to the change in seismic velocity. The reasonably good match of the calculated heat flow with the measurements lends credence to the methodology adopted. In the next section we extend this procedure to the crustal thickness derived from satellite data.

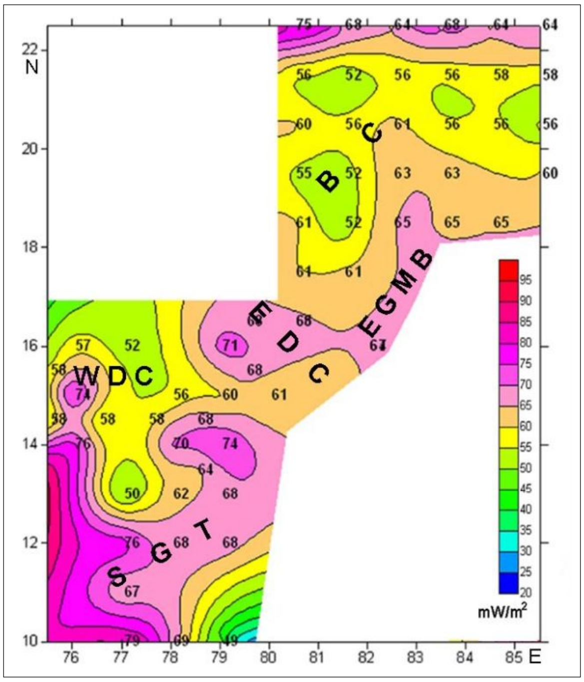

Fig. 3. Calculated heat flow values over India estimated from the Curie isotherm depths derived from the aeromagnetic data. Key: SGT- Southern Granulite Terrain, WDC – Western Dharwar Craton, EDC- Eastern Dharwar Craton, EGMB- Eastern Ghat Mobile Belt, BC- Bastar Craton

Heat Flux from Satellited Data

The fifth generation MF5 lithospheric model up to degree 100 derived from almost 6 years of CHAMP measurements (Maus et al, 2007) can be downloaded from the website http://www.gfz-potsdam.de/pb2/pb23/SatMag/litmod5.html

Also available on this website are the 15' grid data of the Z component of the MF5 model downward continued to 50 km from the surface. For a better appreciation of the intermediate wavelength anomalies we reproduce here in

Fig. 4 the vertical component of the magnetic anomaly derived from the MF5 model and downward continued to 50 km. We find from Fig. 4 that a prominent almost E-W high around 25^0 N extends from 75° to 98° E that divides the country into a northern and southern block; also another high stretches from 22° to 33°N in the longitude range of 70^0 to 75^0 E. These highs are also reflected in the composite magnetic anomaly map seen in Fig. 1.

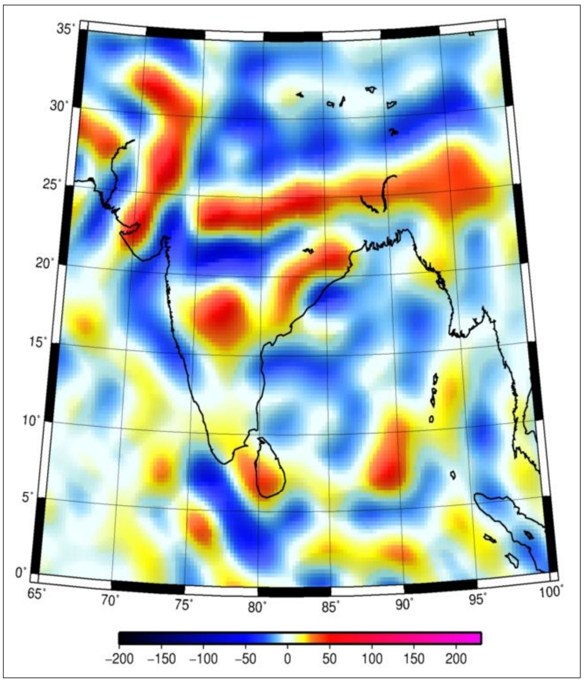

Fig. 4. Vertical field magnetic anomaly of the MF5 lithospheric model derived from CHAMP satellite data over India, downward continued to 50 km.

Purucker (2005) utilizing an iterative forward modeling approach estimated the crustal thickness (see Fig. 5) from the MF5 model of the lithospheric field. In this derivation, a constant susceptibility was assumed for the continents and also for the oceans and starting with an initial model of the crustal thickness 3SMAC (Nataf et al, 1996), the induced magnetic field that this crust would produce is calculated. This is compared with the MF5 field and a change in the crustal thickness is calculated iteratively as described in (Fox Maule et el, 2005) .The Curie isotherm depths of Fig. 5 (Rajaram et al, 2009) are utilized to calculate the heat flux over the Indian subcontinent, using the same heat conduction equation with $k = 2.8$ W/mK and $H_0 = 2.5$ ìW/m^3 (Fox Maule et el, 2005) . The errors that could arise in the heat flux thus calculated from satellite data are discussed in Fox Maule et al (2005). Fig. 6 is a plot of the calculated heat flux over the subcontinent.

From Fig. 6 we find that the computed heat flow values from the satellite derived Curie isotherm depths show acceptable ranges in areas like the Bastar and Singhbhum cratons but in the HTAZ they depict low heat flow values

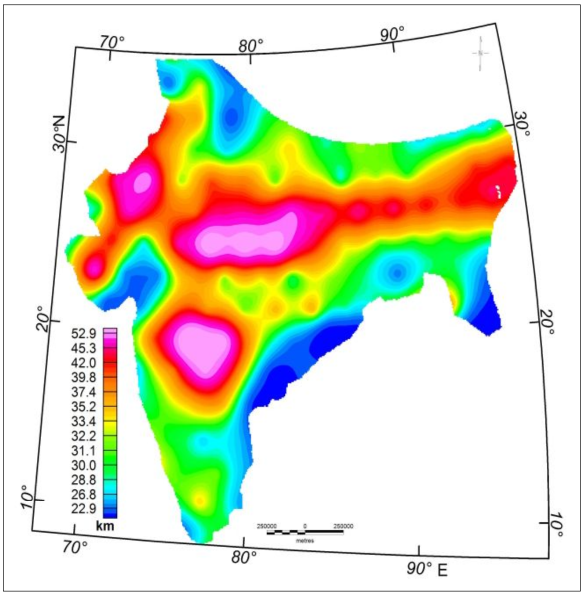

Fig. 5. Curie isotherm depth in km., derived from the MF5 lithopheric model (Purucker, 2005)

rather than the expected high values. This possibly suggests that in the modelling of the satellite data we need to incorporate both susceptibility changes and crustal thickness change in the continental region to improve the heat flow estimates. In the next section we try to forward model the satellite data incorporating both crustal thickness and susceptibility variations in the continental crust.

Modelling of the Satellite Data

Hemant and Maus (2005) developed a forward modelling technique to model the satellite anomalies, including laboratory susceptibility values for different geological blocks of the world and seismic thickness of the crust to generate a Vertical Integrated Susceptibility (VIS) grid. A similar exercise has been undertaken for the Indian region. All the known rock types from the geologic map of India (Naqvi and Rogers, 1987) are compiled and using their maximum volume Susceptibility (÷) value an average maximum ÷ is computed and assigned to the different terrains. A factor of 1.2 is assigned for the Archean and 1.6 for the post-Archean provinces lower crustal susceptibility. Thus the VIS value for the Indian sub-continent is:

$$\text{VIS} = 0.55 * \div * (\text{sm3u} + 1.2 * \text{sm3l})$$

where sm3u is thickness of the upper crust & sm3l is thickness of the lower crust taken from 3SMAC (Nataf et al, 1996). In this VIS model only induced fields has been assumed for the continental region.

However, we inbuilt into the model, the Curie isotherm depths calculated from the aeromagnetic data (Fig. 2) up to 22^0 N latitude and calculate the VIS over the Indian region (Fig .7). It may be noticed that this VIS does not reflect the HTAZ.

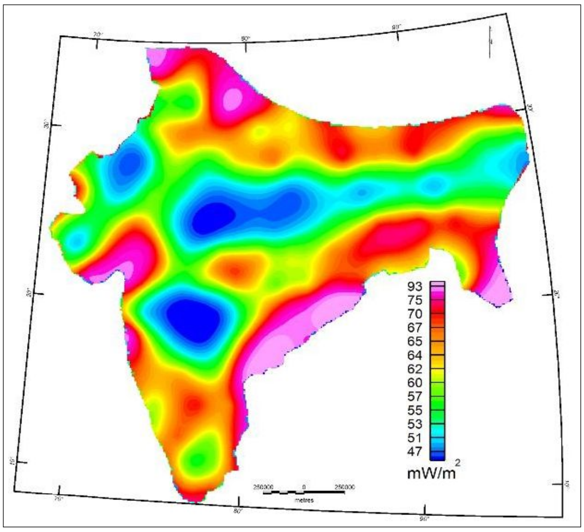

Fig. 6. Plot of the surface heat flux over the Indian subcontinent estimated from the Curie isotherms derived from the MF5 lithospheric model.

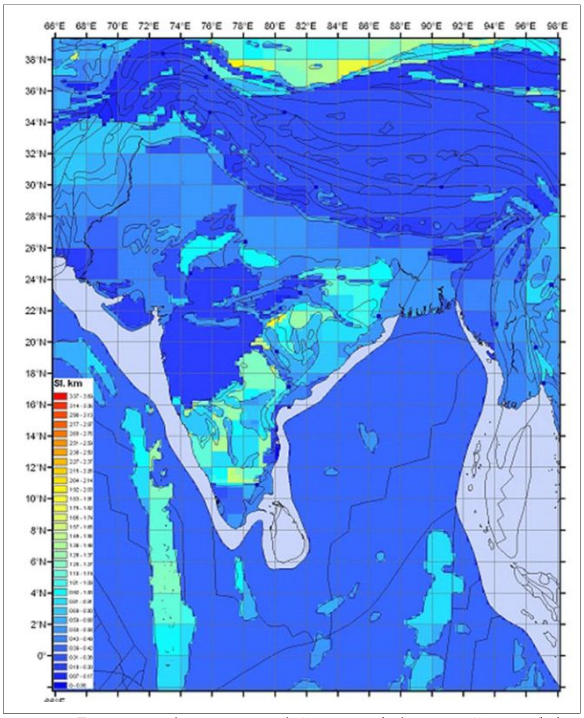

Fig. 7. Vertical Integrated Susceptibility (VIS) Model over the Indian Subcontinent.

Utilising this VIS the vertical field at 50 km altitude is calculated (Fig. 8). A comparison of Fig. 8 with the downward continued anomalies at 50 km (Fig. 4) reveals that the observed high anomalies in the HTAZ are not reproduced. This suggests that we need to modify the VIS incorporating local geological and geophysical information. It may be mentioned that HTAZ is not reflected in the geology map (Naqvi and Rogers, 1987) and is a new information derived only from the aeromagnetic map (Fig.1). It is in this context

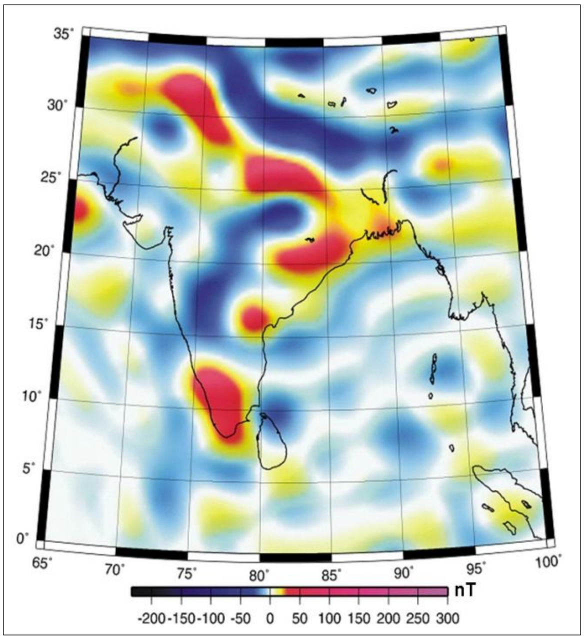

Fig. 8. Vertical Field magnetic anomaly calculated at 50 km altitude using the VIS in Fig. 7.

that we modify the VIS by incorporating known susceptibility values (GSI, 1995) in the HTAZ (Mahakhosal granulites are exposed in this region) with crustal thickness value incorporated form the aeromagnetic data for the entire HTAZ (Anand and Rajaram, 2004). We believe this represents a more realistic VIS especially for the HTAZ. Fig. 9 reproduces the modified VIS.

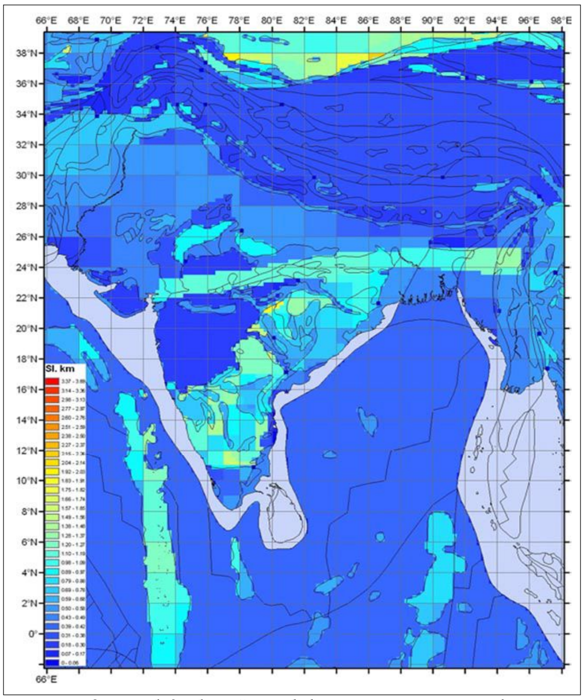

Fig. 9. Modified VIS model incorporating realistic susceptibility values and thickness in the HTAZ.

The calculated vertical field anomaly at 50 km altitude is reproduced in Fig. 10. A comparison of Fig. 10 with the downward continued anomalies at 50 km (Fig. 4) reveals that there is an improvement in the magnetic anomalies. The predicted model is closer to the observations. The observed high anomalies in the HTAZ are much better reproduced with the modified VIS indicating that the incorporation of better ground truths improves the fit. The VIS model can be iteratively modified so that the fit between the modelled and observed improves and this will help interpret the sub-surface geology. We believe that if this kind of a forward model is combined with an inverse modelling of the observed field, it should be possible to finally make reasonable estimates of the thermal regime of the area.

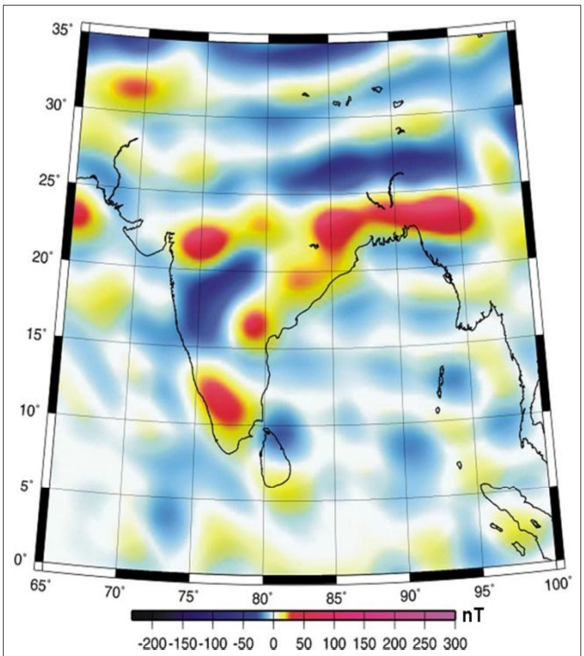

Fig. 10. Modified Vertical Field magnetic anomaly calculated at 50 km altitude using the VIS in Fig.9.

Conclusions

The Composite magnetic anomaly map prepared from the available aeromagnetic data supplemented by the ground and marine magnetic anomalies continued to a height of 1.5 km altitude over the Indian subcontinent, provides a regional framework for studying the distribution and character of the geological and tectonic features although the inherent resolution of the different datasets are very diverse (Rajaram et al, 2006). A very striking feature of the composite magnetic anomaly map is a high tectonic activity zone (HTAZ) running across the Indian Peninsula that divides the country into two blocks: the northern and southern block. The satellite derived MF5 lithospheric model downward continued to 50km also depicts a prominent high around 25^0 N running almost E-W across India as seen in the composite magnetic anomaly map. An attempt has been made to calculate the Curie isotherm depths from the regional aeromagnetic data using spectral methods. It is found that significant spectral maxima exist only for 4°X 4° over SGT and 5°X5° over the Central Indian Region datasets. The calculated Curie isotherm is shallow in the mobile belts and deep in the cratons (Rajaram et al, 2009). From the estimated Curie isotherm depths heat flux are calculated using the 1D heat conduction, steady state model (Fox Maule et el, 2005) . The calculated heat flux for Sonata Belt, Bastar craton and the Singhbhum craton match very well with the surface heat flow measurements depicting high heat flow values in the HTAZ. The calculated heat flux are higher for the Eastern Dharwar as compared to the Western Dharwar and this is borne out by the surface heat flow measurements and lend credence to the methodology adopted. The method is extended to the Curie isotherm depths calculated from the MF5 model (Purucker, 2005). Although the heat flow values match reasonably well with observations in some regions, the HTAZ reflects low heat flow values. We believe this is due to the fact that the model to derive the Curie isotherms utilizes constant susceptibility values for the continent; therefore we look into a model that incorporates both susceptibility and crustal thickness variations into the fit (Hemant and Maus, 2005). We find that the initial VIS model based on Geology and seismic model, did not reproduce the observed anomaly features especially in the HTAZ of the Indian subcontinent. Magnetic anomalies predicted using modified VIS model, incorporating information from the aeromagnetic data and realistic susceptibility values does result in a high over the HTAZ as seen in the observations. An iterative improvement in the VIS model should improve the overall fit and should be able to provide better depth estimates for the Curie isotherms from the satellite data.

The upcoming multiple satellite Mission: Swarm is to provide the most accurate measurements ever of the Earth's magnetic field. One of the primary goals of the Swarm Mission is to provide a lithospheric model in the intermediate wavelength range to bridge the gap between the aeromagnetic and currently available satellite data. Based on the results of this paper, it is expected that the lithospheric model derived from the SWARM Mission should prove to be very helpful in reconstructing the thermal regime of the continents.

Acknowledgement

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