SATELLITE DERIVED CURIE ISOTHERM MAP OF THE INDIAN SUB-CONTINENT

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INTRODUCTION

From an analysis of the long wavelength part of the crustal magnetic field, it is possible to make an estimate of the depth to the bottom of the magnetic sources where the ferromagnetic minerals loose their ferromagnetic properties. This depth extent of magnetic sources has become more or less synonymous with the depth to the Curie temperature, though sometimes it may represent a petrological boundary (*Langel and Hinze, The Magnetic Field of the Lithosphere: The Satellite perspective. Cambridge Univ. Press., U.K., p.429, 1998*). Estimates of the thickness of the magnetized portion of the earth's crust suggest that two genetic types of lower boundaries of the layer of the magnetized rocks may be distinguished. The first type of boundary corresponds to vertical changes in crustal composition and the second type, where high temperatures at depth cause the rocks to lose their ferromagnetic properties (*Connard et al., Geophysics, v. 48, p.376–390, 1983*). Where the Curie depth correlates with an inferred velocity or density boundary, it possibly reflects the change in composition; however, where it does not coincide with a velocity or density boundary, it may be interpreted as the Curie temperature isotherm (*Beardsmore and Cull, Crustal heat flow: A guide to measurements and modelling. Cambridge Univ. Press, New York, USA, 2001*). Magnetite with a Curie temperature of 580 °C is believed to be the dominant magnetic mineral in the deep crust, within the continental region (*Frost and Shive, J. Geophys. Res., v.91, p.6513–6521, 1986*). Therefore, one can reasonably assume that this Curie temperature represents the temperature of 580 °C. Since the Curie isotherm depth is temperature dependent, estimation of Curie depth (*Rajaram, Encyclopedia of Geomagnetism and Paleomagnetism, Springer Publishers, p.157–159, 2007*) can indirectly constrain the thermal structure of a region.

Magnetic data, from which the effect of the main field and external current systems are removed, contain information of the crust up to the Curie depth. Hence analyzing the long wavelength part of the magnetic data can provide information about the depth to Curie isotherm (*Rajaram et al, EPSL, v.281, p.147-158, 2009*). Estimating depth to Curie temperature on a regional scale from long wavelength magnetic anomalies requires that large areas of survey data be used for the calculations (*Maus et al., GJI, 129, 163-168, 1997*). Both aeromagnetic data and the CHAMP satellite data contain information about the sources of long wavelength magnetic field. **Summarized here are the highlights of the study of the long wavelength magnetic anomaly generated from CHAMP satellite data from which the depth to bottom of the magnetic sources is derived through an iterative forward modeling approach. A detailed account of this study along with a comparison of the depths calculated from aeromagnetic data over Peninsular India is available in *Rajaram et al, EPSL, v.281, p.147-158, 2009*.**

SATELLITE DATA FROM CHAMP

The International Association of Geomagnetism and Aeronomy (IAGA) declared the current decade as the Decade of Geopotential Research at the IAGA meeting in 1997 following which several satellites making magnetic measurements at low altitude have been put into orbit (Orested, SAC-C, CHAMP). This has stimulated a lot of research work related to study of magnetization of the Earth's crust and associated mineral magnetic studies. On 15th July 2000, the CHAMP (Challenging Minisatellite Payload) satellite was put into a low-earth, near-circular orbit. The satellite continues to provide highly accurate scalar and vector magnetic field data. The initial measuring altitude of 454 km was expected to decay to less than 300 km over its earlier proposed life span of 5 years. However, the mission has now been prolonged until mid 2011 following three orbit manoeuvres during the last decade raising the orbital altitude of the satellite. The advanced instrumentation on board CHAMP, (*Maus et al*., *Geochem. Geophys. Geosyst. v.8, p.1-8, 2007*) its low-earth orbit and minimal contamination from solar activity, has led to the improvement of accuracy of derived field models by an order of magnitude compared to MAGSAT (*Maus et al*., *Geochem. Geophys. Geosyst. v.9, Q07021, doi:10.1029/2008GC001949, 2008*). In this paper we utilize MF5 model derived from CHAMP satellite data for further studies.

The fifth generation lithospheric magnetic field model, MF5, derived from almost six years of CHAMP satellite measurements (*Maus et al, Geochem. Geophys. Geosyst. v.8, p.1-8 2007*) extends up to spherical harmonic degree 100 and can be downloaded from the website http://www.gfz-potsdam.de/pb2/pb23/SatMag/litmod5.html. **Utilizing an iterative forward modeling approach (*Purucker et al., J. Geophys. Res., v.103, p.2563–2584, 1998*) we estimate the crustal thickness from the MF5 model of the lithospheric field. We utilize the total field from the MF5 evaluated at 400 km, using spherical harmonics above degree 16 (to remove the core field); an oceanic remnant field model (*Dyment and Arkani-Hamed, J. Geophys. Res., v.103, p.15423–15441, 1998*) is also removed.** As no regional model of remnant magnetization exists over the continents, it is assumed that induced magnetization dominates and this field is used in the modeling. An *a priori* model of the ocean continent magnetization contrast with constant susceptibility for the continents and oceans is assumed; starting with an initial model of the crustal thickness 3SMAC (*Nataf and Ricard, Phys. Earth Planet. Inter., v.95, p.101–12, 1996*), the induced magnetic field that this crust would produce is calculated using equivalent source magnetic dipole method. The induced field thus calculated is high pass filtered in order to compare it with the observed induced field from which effect of core field and remnant magnetization is removed. The difference between the calculated and the observed induced field is checked to verify if this difference is less than the uncertainty of the data. If not, a correction is made to the crustal thickness model by conjugate gradient inversion (*Purucker et al, Geophys. Res. Lett., v.23, p.507–510, 1996*) of the residual which is then added to the previous crustal thickness model and the iteration repeated until the difference between the model and the observations are sufficiently small (*Fox Maule et al, Science, v.309, p.464–467, 2005*). **The final crustal thickness thus derived is shown in Fig.1.**

GEOLOGICAL INFERENCES

A simplified tectonic map of the Indian sub-continent, redrawn from CGMW (*Commission for the Geological Map of the World, Geological map of the World. UNESCO, Paris, 2000*), is superposed on Fig.1 with each tectonic block being represented by numbers. On visual inspection of the crustal thickness map it can be seen that the Curie isotherm depths are deeper over the cratons and shallower over the mobile belts. The derived Curie isotherm pattern and trends (Fig.1) is in broad conformity with the regional structural trends of the major tectonic units within the Indian subcontinent and a few of these are discussed below:

(i). The curie isotherm along the E-W trending Central Indian Tectonic Zone (CITZ) [8] (including Narmada Son Lineament) appears to divide the Indian subcontinent into northern and southern blocks with the structural trends in the northern block being essentially ENE-WSW (Bundelkhand-Vindhyan [16]), the blocks to the south being NW-SE (related to Bastar [2], Deccan [9], Singhbhum [3]); further, the blocks to the west along the Marwar block [17] and to the east along the Eastern Ghat Mobile Belt (EGMB) [7] show a NE-SW trend all in keeping with the basic structural trend.

(ii). The Curie depth over the Eastern Dharwar is shallower than the Western Dharwar. This is also reflected in the Moho depths estimated from Deep Seismic Sounding (DSS) profiles where the average depth over the Western Dharwar is 40 km while that within the Eastern Dharwar is 37 km (*Reddy, Curr. Sci., v.88, p.1652–1657, 2005*). The Curie depth gets shallower towards the Cambay basin [11] (rift related) in the northwest and EGMB [7], Bengal basin [12] and Myanmar [18] (collision zone) towards the east.

(iii). The magnetic crust in the Deccan Volcanic Province [9], Bhundelkhand-Vindhyan Province [16] and the Marwar block [17] is estimated to be over 40 km. Further south, within the Southern Granulite Terrain (SGT) [6] the Curie isotherm becomes shallow suggesting compositional change in the crust (*Rajaram et al, Mem. Geol. Soc. India, v.50, p.163–175, 2003*). A velocity change noted in the study of DSS profiles supports our results.

Within continents, according to Wasilewski and Mayhew *(Geophys. Res. Lett., v.19, p.2259–2262, 1992),* seismic Moho is a magnetic boundary. Since, the mantle material is considered non-magnetic; the Curie isotherm should lie either within the crust (shallower than the Moho) or should coincide with the Moho. If the Curie depth coincides the Moho, then this depth may represent

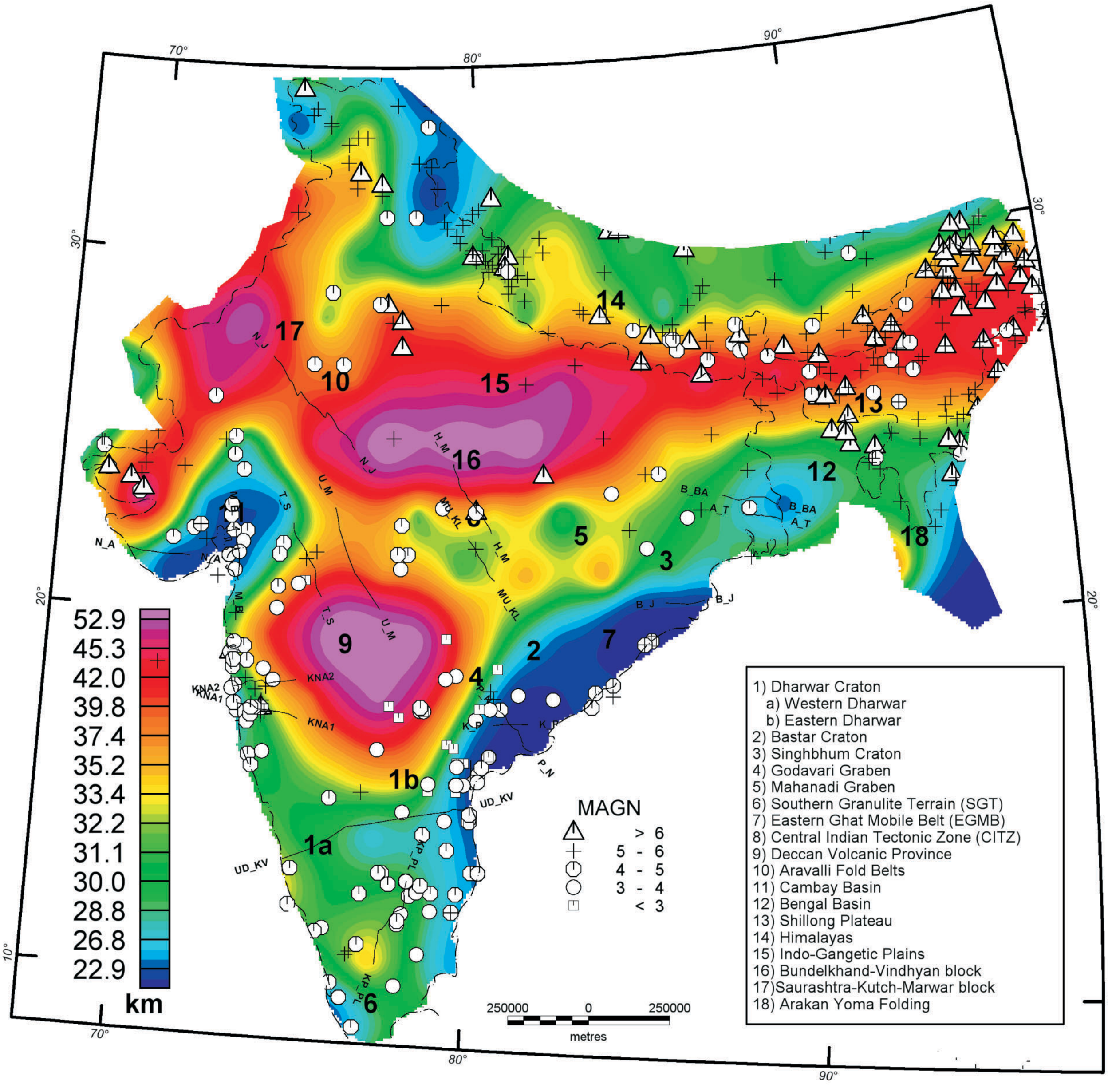

Fig. 1. Image plot of the depth to the bottom of the magnetic crust derived from the MF5 lithospheric model of the CHAMP satellite data. Superposed on this map is the simplified tectonic map of India redrawn from CGMW, 2000, the location of the DSS profiles used for the comparison of Moho depths and the earthquake epicenters with magnitude greater than 3 for the period 1063 to 1984. . A key is provided to indicate the names of the numbered tectonic blocks. N_J — Nagaur–Jhalawar (Aravalli), N_A — Navibandar–Amreli (Saurashtra), M_B — Mehamadabad– Billimora (Cambay), T_S ––Thuadara-Sindad (CITZ), U_M — Ujjain–Mahan (CITZ), H_M — Hirapur–Mandla (CITZ), B_J — Baliamba–Jagannathpur (Mahanadi graben), MU_KL — Mungwara–Kalmati (Bastar), A_T — Arambagh–Taki (Bengal Basin1), B_Ba — Burdwan–Bangaon (Bengal Basin2), KNA1 — Guhaghar–Chorochi (Koyna1), KNA2 — Kelsi–Loni (Koyna2), K_P — Kallur–Polavaram (Godavari graben), P_N — Paloncha–Narsapur (Godavari graben), KP_PL — Kuppam–Palani (SGT), UD_KV — Udipi–Kavali (Dharwar) (modified after *Rajaram et al., EPSL, v.281, p.147-158, 2009)*

a compositional boundary rather than a thermal boundary. Magnetite with a Curie temperature of 580 °C is the dominant magnetic mineral in the lower crust that accounts for the long wavelength induced magnetization. Although hematite has much higher Curie temperature, its magnetization is weak and hence cannot give rise to long wavelength anomalies at aeromagnetic and satellite altitudes.

COMPARISON WITH DSS PROFILE DATA

Several DSS profiles (*Murthy and Reddy, Phys. Earth Planet. Inter., v.95, p.101–122, 2007*) have been recorded across different geological units within India during the past few decades which accounts for detailed variation of the Moho within the subcontinent. **A comparison of the Moho depths from 16 DSS profiles and depth to the bottom of the magnetic crust from the present study is presented in Fig.2.** Location of the various DSS profiles used in this comparison is shown in Fig.1. The DSS profiles considered are the Navibandar–Amreli profile of Saurashtra [17] (*Rao and Tewari, Geophys. J. Int., v.160, p.318–330, 2005*), Nagaur–Jhalawar profile in Aravalli [10] (*Tewari and Kumar, J. Virtual Expl., v.12, p. 30–54,.2003*), Mungwara–Kalmati in Central Indian Sheild [2] (*Reddy and Rao, Mem. Geol. Soc. India, v.53, p.79-98, 2003*), Baliamba–Jagannathpur in Mahanadi coastal basin (*Kaila et al., J. Geol. Soc. India, v.29, p.293–308, 1987*), three profiles: Thuadara–Sindad, Ujjain–Mahan and Hirapur–Mandla across the Narmada Son lineament in CITZ [8] and two profiles across the Bengal Basin [12]: Arambagh–Taki and Burdwan–Bangaon (*Tewari and Kumar, J. Virtual Expl., v.12, p. 30–54,.2003*), Mehmadabad–Billimoria profile across Cambay [11] (*Kaila et al., Tectonophysics, v.76*

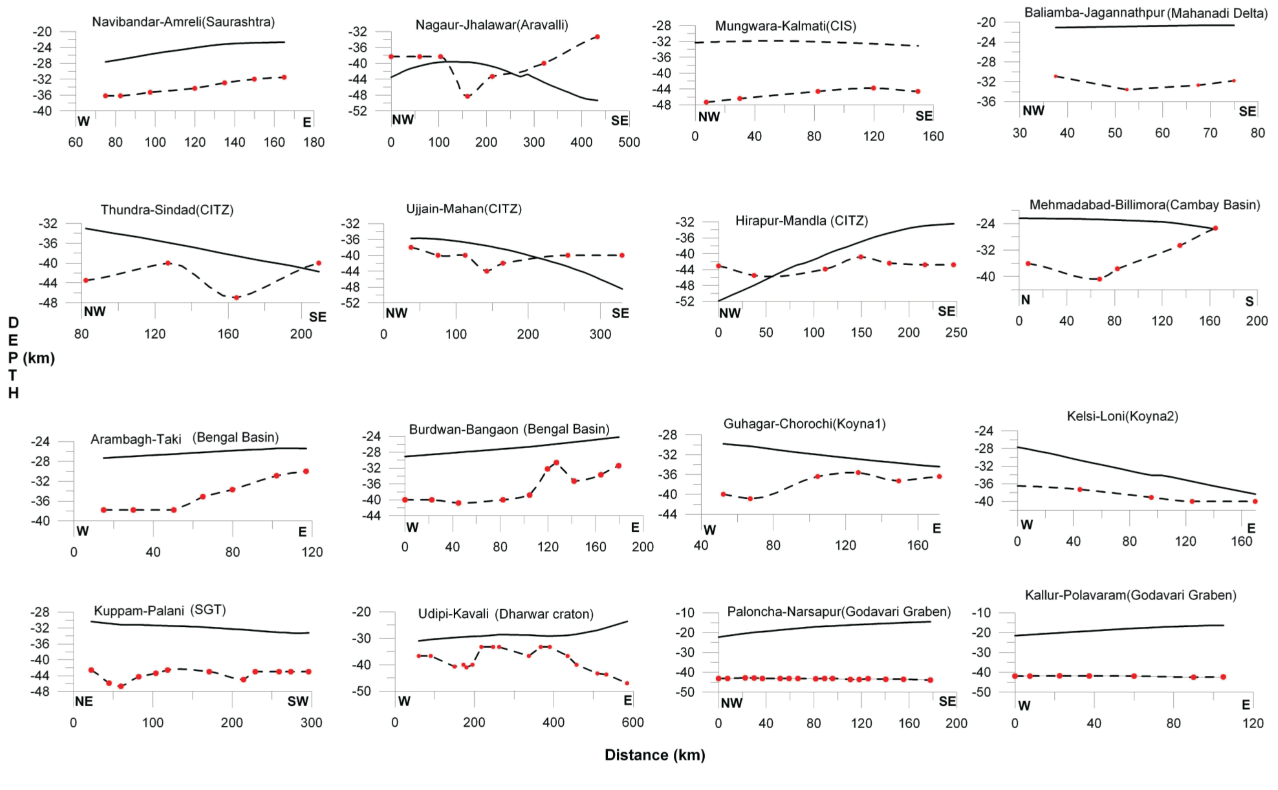

Fig. 2. Comparison of the estimated depth to the bottom of the magnetic crust with the Moho depths (dashed lines) at the shot points (shown as dots) calculated from various DSS profiles over India. It may be noted that at some of the shot points the Moho was not defined and therefore we have only shown dots where the Moho was clearly defined. The location of these profiles has been demarcated in Fig. 1 (modified after *Rajaram et al., EPSL, v.281, p.147-158, 2009)*

(Issues 1-2), p.99–113, p.119–130, 1981), two profiles across Koyna [9]: Guhaghar– Chorochi and Kelsi–Loni (*Singh and Mall, Tectonophysics, v.290, p.285–297, 1998*), Kuppam–Palani across SGT [6] (*Reddy et al., Mem. Geol. Soc. India, v.50, p.79–106, 2003*), two profiles across Godavari graben [4]: Kallur–Polavaram and Paloncha–Narsapur (*Kaila et al., Tectonophysics, v.173, p.307-317, 1990*) and the long Udipi-Kavali profile across the Dharwars [1] (Kaila et al., *J. Geol. Soc. India, v.20, p.307–333, 1979*).

From Fig. 2 it can be seen that in most of the geological terrains the depth to the bottom of the magnetic crust lies above the Moho depth and could represent a thermal boundary rather than a petrological or compositional boundary and may be referred to as the Curie isotherm. In parts of the profile across the Central Indian Tectonic Zone (CITZ) (3 profiles) and those across the Aravalli Fold Belts, the depth to the bottom of the magnetite sources is greater than that of the Moho. The large depth to the bottom of the magnetic crust at these places can possibly be associated with a low heat flow and low vertical thermal gradient (Epplelbaum and Pilchin, Earth. Planet. Sci. Lett. V. 243, p. 536 – 551, 2006). At a few regions, for instance in the western Africal Craton, the uppermost part of the mantle is, perhaps, magnetic due to serpentinisation.(Toft and Arkani-Hamed. J. Geophs. Res. V. 97, pp. 4387- 4406, 1992).Similar possibilities in these regions needs to be looked into.

CURIE DEPTHS AND TECTONIC STABILITY

A thick magnetic crust is consistent with stable continental regions while thin magnetic crust may conform to tectonically active regions, often associated with higher heat flow. From the Curie depth estimated using the satellite data we find that the magnetic crust is thickest in part of the Bundelkhand–Vindhyan block [16], the Deccan Volcanic Province [9] and a part of the Saurashtra–Kutch–Marwar Block [17] suggesting that these regions are relatively more stable. The Proterozoic mobile belts like the EGMB [7], the sedimentary basins like Cambay [11], Bengal basin [12], the trans-Himalayan conductor (*Arora and Mahashabde, Phys. Earth Planet. Inter., v. 45, p.119–127, 1987*), the Arakan Yoma folding [18] are associated with thin magnetic crust. The rest of the country including the Dharwar craton [1], Bastar craton [2], Singhbhum craton [3], the Aravalli Fold Belts [10], the CITZ [8], the lesser Himalayas etc have intermediate thickness. The Curie depth along CITZ [8] as inferred from the Curie isotherm map indicates thickening of the crust both in the north and the south. *Okubo et al.*, (*Geophysics, v.50, p.481–494, 1985; Blakely, J.Geophys. Res., v.93, p.817–832, 1988*) relates the Curie depth with the heat flow regimes. In a given region, the higher heat flow is indicative of shallow Curie depth and vice versa. Thus, it can be inferred that Dharwar [1], Bastar [2], Saurashtra–Kutch–Marwar[17], Singhbhum [3], Bundlekhand–Vindhyan [16] and Deccan Volcanic Province [9] are regions with low heat flow and forms stable continental shield regions of the subcontinent. While the EGMB [7], Cambay [11] and Bengal basins [12], the trans-Himalayan conductor, the Arakan Yoma folding [18] are associated with relatively high heat flow suggesting that these regions are tectonically active.

CURIE DEPTH AND SEISMICITY

It is worthwhile mentioning that strong earthquakes take place along the geothermal gradient zone in which the thermal stress is concentrated. So it is possible that the seismicity of a given region may be related to the Curie depth estimates. A plot of the earthquake epicenters (magnitude >3), for the period from 1063 to 1984 downloaded from NEIC (National Earthquake Information Center), have been superposed on the depth to the bottom of the magnetic crust (Fig. 1). From this map we find that most of the high magnitude earthquakes are associated with high gradients in Curie depth. This is particularly true in the tectonically active regions like Himalayas [14], Arakan–Yoma fold belt [18] etc. We thus find that the Curie isotherm map has imprinted on it the tectonic history of the region. It is entirely possible that if in the modeling of the satellite data we incorporate both vertical susceptibility changes (*Hemant and Maus, J. Geophys. Res. 110, p.B12105, 2005*) and crustal thickness change in the various blocks of the continental region it would further improve the estimates of the Curie isotherm depths. The upcoming multiple satellite mission *Swarm,* is expected to provide accurate magnetic field gradient measurements of the Earth's magnetic field. One of the many goals of the *Swarm* mission is to provide a high resolution lithospheric magnetic field model in the intermediate wavelength range to bridge the gap between the aeromagnetic and currently available satellite data. The study of such maps would further enhance our knowledge of the crustal composition, structure, thermal state and dynamics of the Earth's crust.