UTILITY OF MAGNETIC ANOMALY DATA COLLECTED FROM DIFFERENT PLATFORMS

S.P. ANAND* AND MITA RAJARAM*

Technological advancement in the past two decades coupled with better acquisition, processing and interpretation techniques have made the magnetic method an important tool for exploration. The information content provided by magnetic surveys ranges from global to very detailed scales depending on the survey platform and resolution. At the Indian Institute of Geomagnetism in addition to conducting ground surveys, we have extensively utilized aero, satellite and marine magnetic data for unraveling the tectonics, geothermal and geodynamic history of the Indian sub-continent.

Introduction

Magnetic method is one of the oldest and cheapest geophysical methods that are routinely used to solve a wide variety of geophysical problems. The variation in magnetic anomaly field of the earth is caused by the change of structure or magnetic susceptibility of the rock formations. The anomalous magnetization can be associated with: local mineralization that may be of potential commercial interest, subsurface structures capable of bearing oil deposits, inhomogeneities in the composition of basement rocks, structural or topographic relief of the basement surface, etc. Apart from these, magnetic surveys help to map the Curie isotherm depth or depth to the bottom of the magnetic crust that can indirectly account for the heat flow in a given region, delineate the different metamorphic zones and also help in reconstructing the tectonic evolution of a region as the geodynamical process at work in the geological past leaves its imprints on the structural patterns in the subsurface. The bipolar nature of the magnetic field often creates complexity in the interpretation of magnetic anomalies with respect to their causative sources. Hence very little effort is generally put in for a serious interpretation of the magnetic anomalies. When properly interpreted magnetic anomalies can provide information quite disproportionate to the money and time spend on their collection. It may be mentioned here that the first aeromagnetic anomaly map of Australia has become one of the foundations of the continent's geological information infrastructure and aeromagnetic surveys may be considered to be the modern precursor for geological mapping.

The magnetic method was used as a prospecting tool right from the 19th century but gained importance during World War II when the first flux gate magnetometers were developed to locate the submarines. The discovery of alternate positive and negative magnetic polarities over the ocean floor was achieved during late 1950's with the help of magnetometers that gave substantial support to the theory of plate tectonics. The availability of GPS by early 1990's tremendously improved the location accuracy and thus the error budget of airborne surveys[1]. Higher resolution was achieved by decreasing the lines between adjacent flights and also by reducing the aircraft height. This helped to solve subtle magnetic field variations such as those caused by the intra-sedimentary sources[1]. Thus over the last two decades, major strides have been made in the acquisition, processing and interpretation of aeromagnetic data. Improvement in the instrumentation technology have led to the development of accurate magnetometers, with gradiometers measuring horizontal and vertical gradients in the total magnetic field; this coupled

Indian Institute of Geomagnetism, Navi Mumbai 410210.
Email: anand@iigs.iigm.res.in ; mita@iigs.iigm.res.in

with precise aircraft positioning using GPS and software/hardware for suppressing airplane noise has resulted in marked improvement in the data acquisition, quality and resolution. With the availability of sophisticated computers and data processing and imaging techniques, the interpretations have become further refined and have contributed to a quantum jump in the application of magnetic data to exploration. By flying closer to the ground with decreasing flight line spacing, there is a dramatic increase in resolution. Several countries have repeated their aeromagnetic surveys keeping in pace with the technology especially in regions of viable resources.

At the Indian Institute of Geomagnetism, ground, marine, air-borne and satellite borne magnetic data have been used to study the subsurface and interpret the data in terms of tectonic, geothermal and geodynamic evolution of the Indian subcontinent and also for possible identification of mineral and water resources. In this paper a few representative examples of the utility of magnetic data collected from different platforms is presented. The first section deals with the composite magnetic anomaly map generated from aeromagnetic, ground and marine data. The second section looks at a case study for identification of mineral resources from aeromagnetic data. The third section covers the generation of the Curie isotherm depth map from satellite magnetic data and the fourth section covers a representative case of use of marine magnetic data to derive the crustal structure of the 85 E Ridge.

Composite Magnetic Anomaly Map

Peninsular India, Australia, Antarctica, Africa, South America and Madagascar constituted the Gondwanaland. Due to the breakup of the Gondwanaland in Early Mesozoic, around 137 Ma[2], Peninsular India was transformed into a mobile Indian plate which moved northwards with an anti-clockwise rotation to collide with the Eurasian plate, resulting in a change of configuration of the East Coast from initial EW to ENE and finally to NE-SW. The easterly tilt gave rise to southeasterly drainage pattern along the East Coast with five major sedimentary basins viz. Cauvery, Palar-Pennar, Krishna-Godavari (KG), Mahanadi and the Bengal basin, starting from the south to the north. The structure, evolution and sedimentation history of these basins should be inferred from all possible geophysical and geological evidences to understand the tectonic evolution of the East Coast of India and to reconstruct the association of Gondwanaland. Indian Institute of Geomagnetsim has conducted long wavelength ground magnetic surveys in the Krishna-Godavari[3] and Mahanadi[4] basins to understand their structure and tectonics. From the analysis it was inferred that both the basins were made up of deeper NW-SE and shallow NE-SW trending structural units. The shallow NE-SW unit represents the horst and graben structure formed as a result of the formation of the pull apart sedimentary basins while the deeper NW-SE trends are associated with the Gondwana grabens developed due to the rifting of Dharwar-Bastar and Singhbhum cratons. The extension of these deeper NW-SE features is seen in the offshore magnetic data and also in Antarctica.

A Bouguer anomaly map of the country was published by NGRI in 1975 and even thirty years later we do not have a complete magnetic anomaly map of the country. To tackle this discrepancy to some extent a composite magnetic anomaly of India and its adjoining regions was generated[5] by compiling all available aeromagnetic data supplemented by marine and ground magnetic data. The most striking feature in the map is the smooth continuation of magnetic anomalies independent of the data source and resolution i.e., the signatures of the ground and airborne data (even though collected at different altitudes) merge seamlessly and also the continental and marine anomalies blend smoothly. From the composite anomaly map, India and its contiguous regions can be divided into five major blocks 1) EW trending Southern Granulite Terrain 2)NW-SE trending Dharwar-Bastar craton 3) NE-SW trending Eastern Ghat Mobile Belt 4) EW trending region of high tectonic activity above the Main Peninsular Shear[6] in the Narmada Son region 5) Ganga valley. The NW-SE trending cratons bounded by EW and NE-SW trending high grade granulite mobile belts is clearly evident in the anomaly map. Several faults / lineaments, 2D and 3D circular features depicting iron ore bodies, high frequency anomalies related to trap flows etc are evident in the composite anomaly map. Some of the continental scale lineaments are seen to run into the offshore areas and are probably related to the break-up of India from Gondwanaland. Several of the faults / lineaments can be associated with mineralized zones, earthquake epicenters, potential ground water horizons, etc. The regions of EW trending anomalies above the Main Peninsular Shear[6], appears to be a highly active tectonic zone as this region is also found associated with major earthquakes, thermal springs etc. Although the inherent resolution of the varying data sets is different, the composite map is useful for providing a regional frame work for studying the distribution and character of regional geological and tectonic features. This map also helps in selecting areas where detailed magnetic surveys can be carried out. It maybe noted that although most of the available data sets have been incorporated in this map, crucial data gaps still remain.

Identification of Mineral Resources

The demand for energy is growing globally, and it is necessary to apply innovative techniques to explore for all viable resources to meet this growing need. Uranium is a key element in the generation of Nuclear Power, and one needs to explore different methods to recognize uranium provinces. The Singhbhum region, located in the northeastern part of the Indian sub-continent, has rich resources of metallic as well as non-metallic minerals. This region contains rich deposits of copper, iron, manganese and chromium and workable deposits of uranium and vanadium. The literature recognizes this area as a region of polymetallic mineralization, denoting it as the Singhbhum Uranium Province (SUP). Two distinctive types of uranium mineralization occur in the SUP: (1) early quartz-pebble conglomerate type and (2) shear-controlled hydrothermal type[7]. The country's main uranium producing mines, which exploit the second type of mineralization, are located on the mapped Singhbhum Shear Zone (SSZ). Hence, the delineation of faults / shear zones either exposed or under cover, forms the primary step for the identification of uranium deposits. Uranium ore occurs in several structural settings within igneous, metamorphic and sedimentary rocks of various geological ages. Chlorite-quartz schist with magnetite and apatite, belonging to the early Proterozoic-late Archaean Age, is the most common host for mineralization. The magnetite-apatite bodies are believed to be products of interaction between chlorite schist derived by metamorphism of basic rocks and migmatizing solutions. As uranium mineralization is closely associated with magnetite, the analysis of high resolution aeromagnetic data can play a crucial role in the identification of concealed, near surface, uranium deposits. High resolution aeromagnetic data was collected over the Singhbhum Uranium Province (SUP) by Atomic Minerals Division during 1968-69 with a flight altitude of 61-122m and line spacing of 500m under a program called Operation

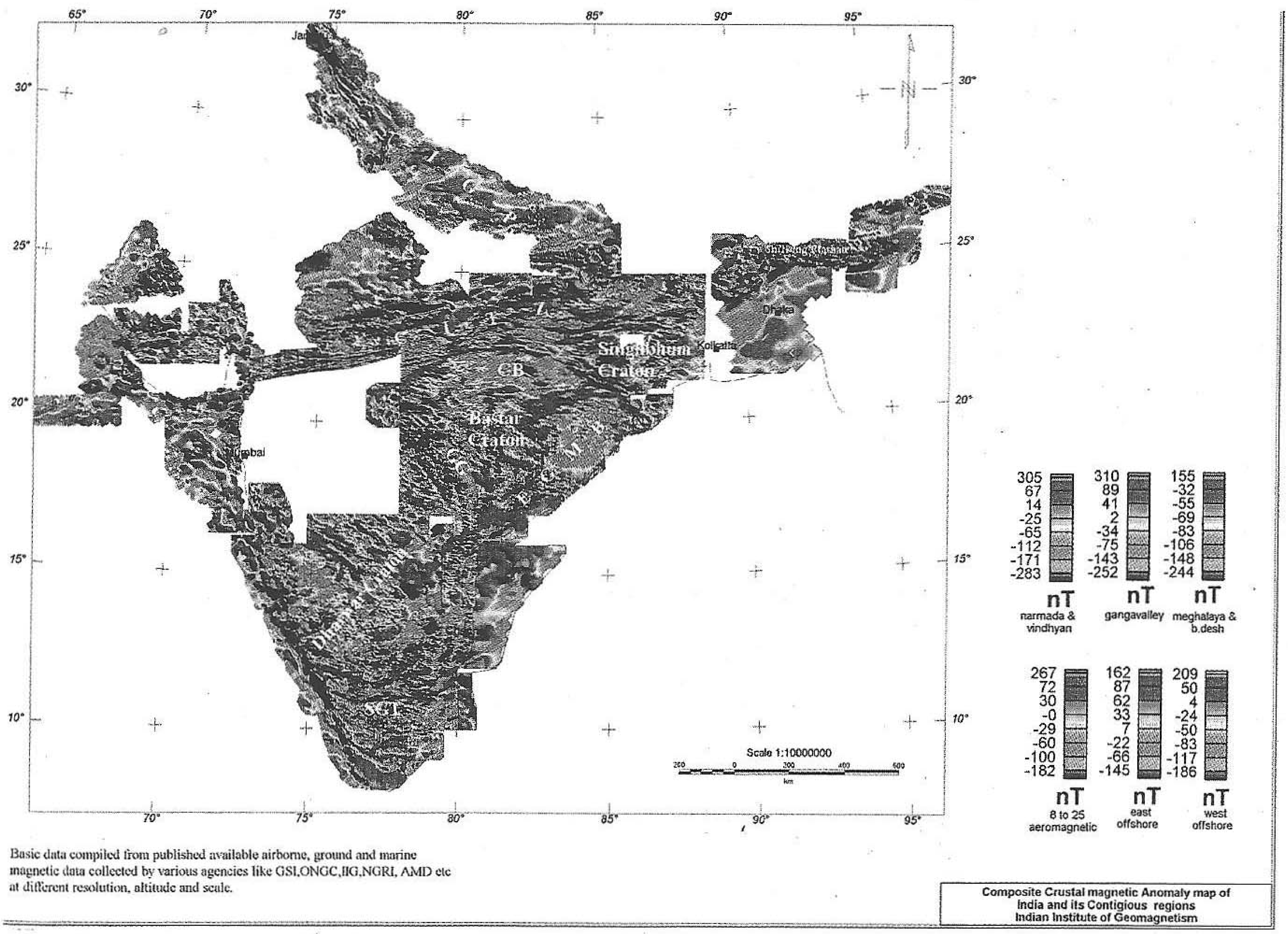

Figure 1. The composite total intensity magnetic anomaly map of India and adjoining regions represented as histogram equalized image map. Different scale bars have been used for various data sets. Key: SGT- Southern Granulite Terrain, GG- Godavari Graben, EGMB – Eastern Ghat Mobile Belt, CITZ – Central Indian Tectonic Zone, IGP – Indo-Gangetic Plain, CB – Chattisgarh Basin.

Hard Rock. Analysis of the high-resolution aeromagnetic data over the SUP helps identify the magnetic sources and their depth extent[8]. The magnetic sources are mainly associated with apatite-magnetite viens, formed as by-product of uranium mineralization, in the SSZ. The identified magnetic sources lie along the mapped uranium deposits, consistent with the known geological associations. The calculated depth to the magnetic sources in the SSZ matched well with the mining depth, thus lending credence to the methodology adopted. A linear feature (L in Fig.2) similar in character to the SSZ was identified in the region towards the north, within the Singhbhum mobile belt at an average depth of 200m. This region is also associated with abundance of radiometric anomalies[7]. Hence we believe that the newly identified linear feature is also a zone where there is possibility of finding concealed uranium deposits[8].

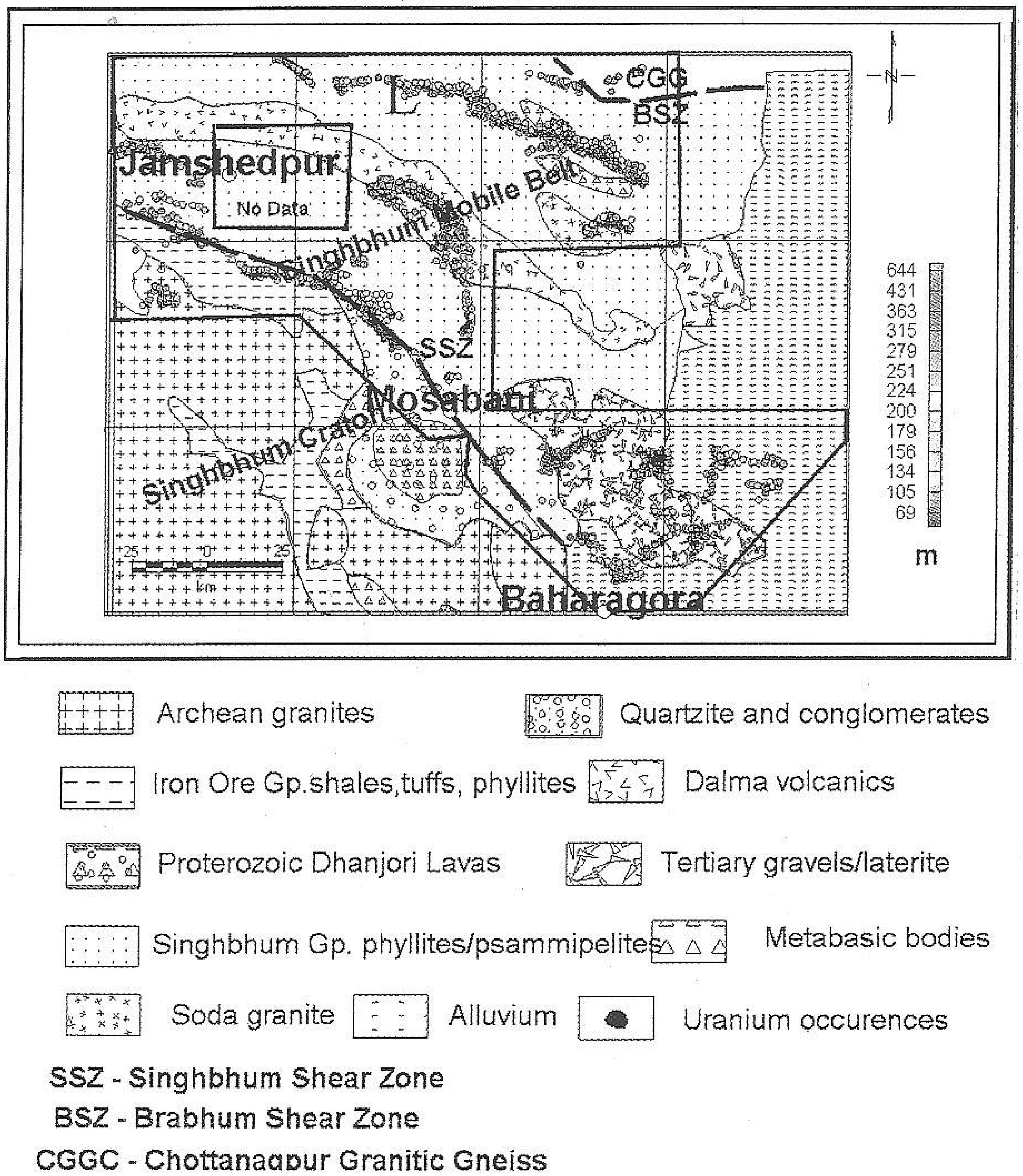

Figure 2. Plot of the located Euler solutions of the magnetic anomaly depicting the linear trends of SSZ (representing magnetite-apatite veins) and the newly identified shear zone (L) (possible location of concealed uranium deposits) superposed on the geology map. The depth estimates of the Euler solutions are depicted in the color scale bar in meters.

Curie Isotherm Depth estimates

Magnetite with a Curie temperature of 580°C is believed to be the dominant magnetic mineral in the deep crust within the continental region[9]; as temperature rises further, the magnetization is lost. Therefore, from an analysis of the crustal magnetic field it is possible to make an estimate of the depth below which no magnetic sources exist. This depth extent of magnetic sources has become synonymous with the depth to the Curie temperature[10] though sometimes it may represent a petrological boundary[11]; where the Curie depth correlates with an inferred velocity or density boundary, it is likely to reflect the change in composition. One can assume that within the continental region, the Curie temperature represents the temperature of 580°C, the Curie point of magnetite. 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. Hence we utilized the MF5 lithospheric model of the magnetic data collected by the CHAMP satellite for estimating the thickness of the magnetic crust as satellite surveys cover large areas and are not dominated by near surface short wavelength anomalies. The magnetic data is inverted using an iterative forward modelling approach and complex gradient inversion technique[12]. Depth to bottom of the magnetic sources was also calculated using the aeromagnetic data available up to 25°N latitude. For the calculation using aeromagnetic data the spectral peak method was adopted[13]. The depths calculated from both these independent methods matched reasonably well lending credence to the methodology adopted and assumptions made. In continental region the Moho marks a magnetic boundary[14], as the mantle material is non-magnetic; and therefore the Curie isotherm should lie either within the crust (shallower than the Moho) or should coincide with the Moho. If the Curie depth matches the Moho depth, then the Curie depth represents a compositional boundary rather than thermal boundary. The calculated depth to bottom of the

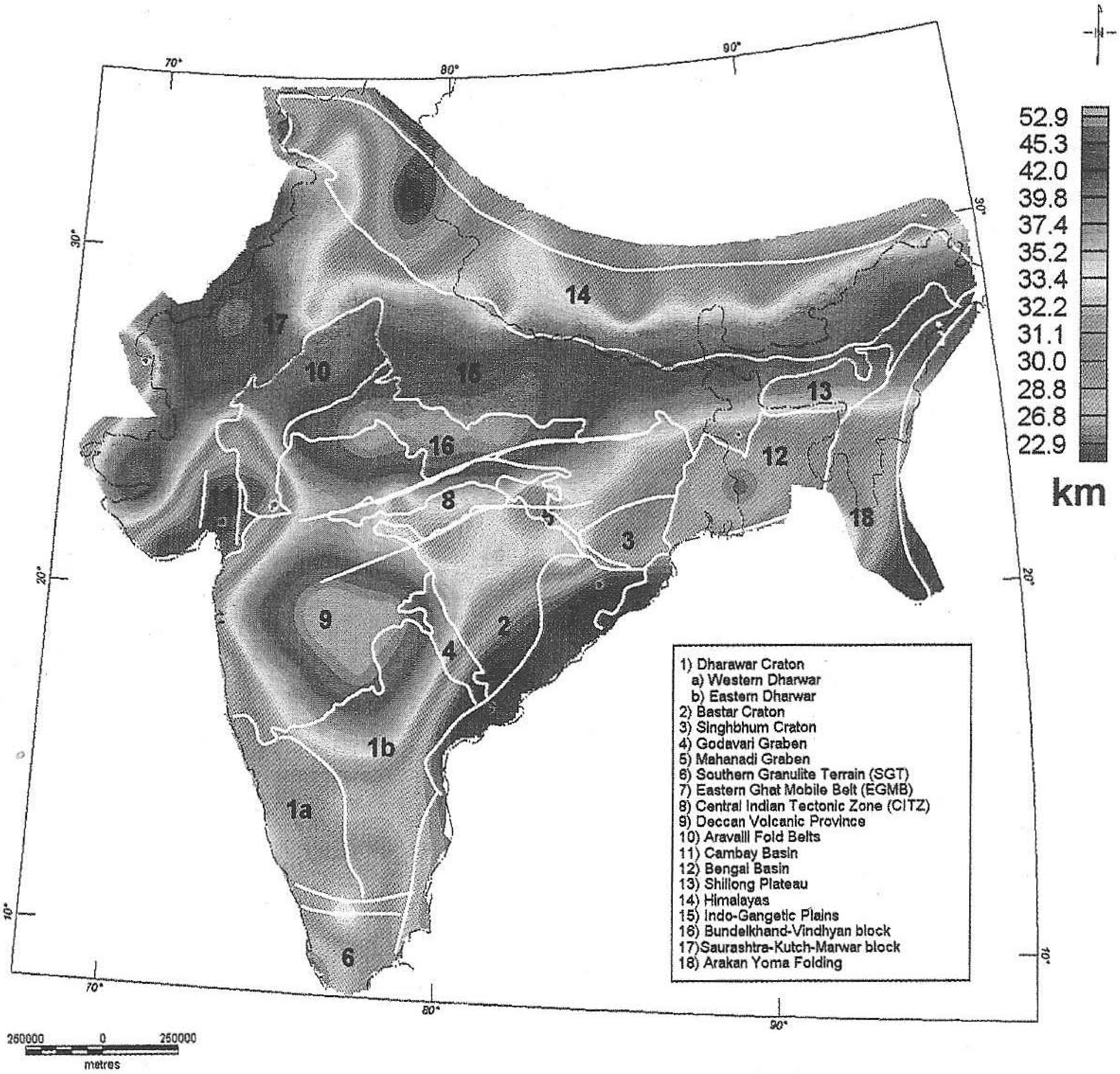

Figure 3. Image plot of the depth to the bottom of the magnetic crust derived from the MF5 lithospheric model of the CHAMP satellite data. Superposed on this map is the simplified tectonic map of India with various tectonic units demarcated. A key is provided to indicate the names of the numbered tectonic blocks.

magnetic sources was compared with moho depths along published DSS profiles and we find that in more than 90% of the regions the depth to bottom of magnetic sources were well above the moho depth implying that they represent a thermal boundary rather than a compositional one. The calculated Curie depth[13] reproduced in Fig. 3, was found to be thick over the shield areas of Dharwar, Bastar, Singhbhum, Decann Volcanic Province etc while they were thin along the mobile belts like EGMB, SGT and hydrocarbon bearing sedimentary basins like Cambay, Bengal basin etc. Also high gradients in the Curie depth are found to be associated with earthquake epicenters[13]. Further, assuming a one dimensional heat conduction equation with steady state, it is possible to generate a proxy heat flow map of the whole region from the depth estimates of the Curie isotherm made from the magnetic data[15].

85 E Ridge

The 85°E ridge is one of the much debated tectonic element in the Bay of Bengal. Several theories including hotspot trace, lithospheric flexure, sagging of the crust, etc. have been postulated for the nature and origin of this ridge. The thick sediment deposits carried by several rivers in India into the Bay of Bengal mask the underlying crust and pose severe restrictions in mapping the structural configuration and constructing the geodynamical history of the region. It is the Geopotential data (magnetic and gravity) that offers a unique opportunity of seeing below the thick sediments. The availability of high resolution

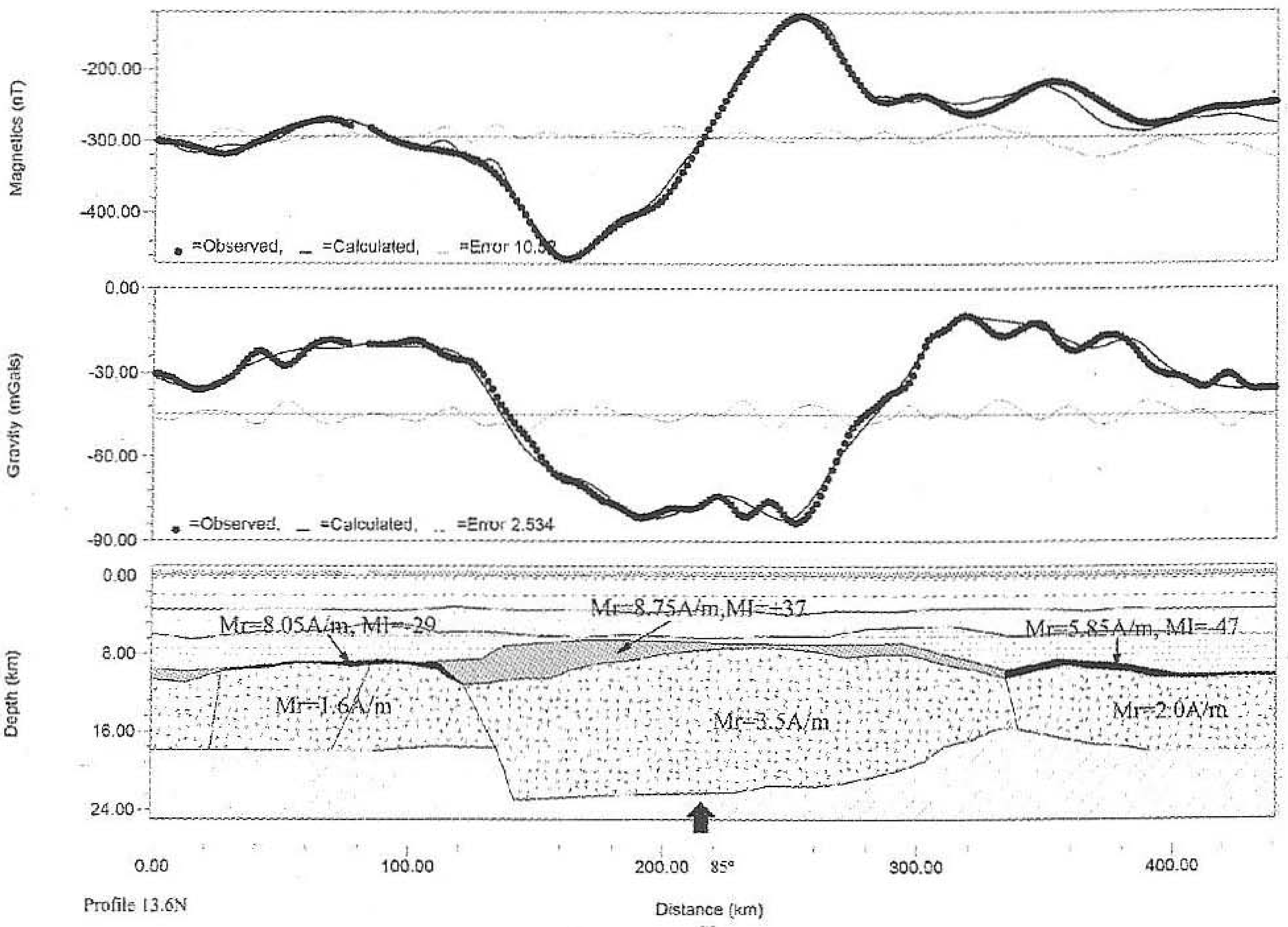

Figure 4. Crustal model derived from the gravity and marine magnetic data analysis along profile at 13.6°N. The water depths and sediment thickness have been obtained from the bathymetry and isopach maps. Dotted lines represent the observed gravity and magnetic data while the full lines depict the calculated values and the thin lines depict the errors. The assumed density used for sea-water, oceanic crust and mantle is 1020 kg/m^3, 3000 kg/m^3 and 3300 kg/m^3 respectively with density of 2450 kg/m^3 for post collision sediments; for pre-collision meta-sedimentary rocks, density of 2850 kg/m^3

satellite-derived free-air gravity (FAG) data and the magnetic vector data from CHAMP satellite, provides an opportunity to look into the structure and tectonics of the Indian offshore region on a regional scale. We developed a crustal model across the 85°E ridge by combined forward modeling and inversion of gravity and marine magnetic data along six profiles of 325 to 440km length, assigning normal (N) and reverse (R) polarity to different units for magnetic representation of the anomalie[16]. First, the gravity response of the crust was calculated, constrained using inputs from seismic, bathymetry and isopach maps. The gravity model thus generated was used as starting model for calculating the magnetic response. For modeling of the magnetic data the three layer model of the oceanic crust[17] was adopted to incorporate the sea-floor spreading anomalies. The models have been generated without prior information of the magnetic polarity reversals. The polarities are found iteratively through modeling. From the crustal model thus generated, it was found that within the crust there was no need to introduce any density variations implying that the crustal structure below the 85°E ridge is similar to the adjacent oceanic crust except for the down warping of the moho. Reproduced in Fig.4 is a representative model, profile along 13.6° N latitude. The FAG anomaly along this profile depicts a low of the order of 75mGal. Modeling of gravity and magnetic anomaly along this profile depicts that the 85 E ridge is characterized by crustal roots but overlain by thick sediments and with a reverse magnetization over the ridge. Along the profile the magnetic model shows a RNR polarity. Of the several theories put forth for the evolution of the 85° E Ridge, the study[16] supports the sagging of the crust and rules out the hotspot trace and magmatic under-plating theories.

Conclusions

Magnetic data collected from ground, marine, air-borne and satellite borne probes can be fruitfully utilized in studying the tectonic, geodynamic, geothermal evolution of a region and for viable resource location. ❐

References

1. M.N. Nabighian, V.J.S Grauch, R.O. Hansen, T.R. LaFehr, Y. Li, J.W. Peirce, J. D. Phillips and M.E. Ruder. *Geophysics,* **70**, pp 33-61. doi:10.1190/1.2133784 (2005)
2. J. R. Curray, E. J. Emmel, D. G. Moore and R. W. Reitt, The ocean Basins and Margins (1982), (Plenum Press, New York).
3. M. Rajaram, S. P. Anand and V. C. Erram. *Gondwana Research,* **3**, pp 385-393 (2000).
4. S. P. Anand, V.C. Erram and Mita Rajaram. *J. Geol. Soc. India,* **60**, 283 – 291, (2002)
5. M. Rajaram, S.P.Anand and T.S. Balakrishna. *J. Geol. Soc. India* **68**, 569–576 (2006).
6. M. Rajaram and S.P. Anand. *Earth Planet Space* **55**, e1-e4 (2003)
7. T.M. Mahadevan. *Proc. Tech. Committee Meeting, International Atomic Energy Agency Vienna,* 337–369, (1988).
8. S.P. Anand and Mita Rajaram. *Earth Planet Space* **58**, 1099–1103 (2006).
9. B.R. Frost and P.N. Shive. *J. Geophys. Res.* **91**, 6513–6521 (1986).

10. Mita Rajaram, D. Gubbins and E. Herrero-Bervera pp. 157–159. (2007) (Eds.), Springer Publishers,

11. R.A. Langel and W.J. Hinze. The Magnetic Field of the Lithosphere: The Satellite perspective. p. 429 (1999) (Cambridge Univ. Press., U.K.)

12. C. Fox Maule, M.E .Purucker, O. Olsen and K. Mosegard. *Science* **309**, 464–467 (2005).

13. M. Rajaram, S.P.Anand, Hemant K. and M.E. Purucker. *Earth Planet. Sci. Let.*, **281**, 147–158. doi: 10.1016/j.epsl.2009.02.013 (2009)

14. P.J. Wasilewski and M.A. Mayhew. *Geophys. Res. Lett.* **19**, 2259–2262 (1992).

15. S.P. Anand and Mita Rajaram. *Int. Assoc. Gondwana Res. Mem.* 10, 233–242 (2007).

16. S. P. Anand, Mita Rajaram, T. J. Majumdar and R. Bhattacharyya. *Tectonophysics*, doi:10.1016/j.tecto.2008.09.036. pages 11 (2009)

17. G. Kent, A. Harding and J. Orcutt. *J. Geophys. Res.*, **98**, 13945-13969 (1993)