Geoscience Frontiers 5 (2014) 3–15

Contents lists available at SciVerse ScienceDirect

China University of Geosciences (Beijing)

Geoscience Frontiers

journal homepage: www.elsevier.com/locate/gsf

Research paper

Aeromagnetic signatures of Precambrian shield and suture zones of Peninsular India

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ARTICLE INFO

Article history:
Received 1 November 2012
Received in revised form
18 June 2013
Accepted 18 June 2013
Available online 12 July 2013

Keywords:
Aeromagnetic interpretation
Southern Granulite Terrain
Metamorphism
Precambrian
Subduction
Collision

ABSTRACT

In many Precambrian provinces the understanding of the tectonic history is constrained by limited exposure and aeromagnetic data provide information below the surface cover of sediments, water, etc. and help build a tectonic model of the region. The advantage of using the aeromagnetic data is that the data set has uniform coverage and is independent of the accessibility of the region. In the present study, available reconnaissance scale aeromagnetic data over Peninsular India are analyzed to understand the magnetic signatures of the Precambrian shield and suture zones thereby throwing light on the tectonics of the region. Utilizing a combination of differential reduction to pole map, analytic signal, vertical and tilt derivative and upward continuation maps we are able to identify magnetic source distribution, tectonic elements, terrane boundaries, suture zones and metamorphic history of the region. The magnetic sources in the region are mainly related to charnockites, iron ore and alkaline intrusives. Our analysis suggests that the Chitradurga boundary shear and Sileru shear are terrane boundaries while we interpret the signatures of Palghat Cauvery and Achankovil shears to represent suture zones. Processes like metamorphism leave their signatures on the magnetic data: prograde granulites (charnockites) and retrograde eclogites are known to have high susceptibility. We find that charnockites intruded by alkali plutons have higher magnetization compared to the retrogressed charnockites. We interpret that the Dharwar craton to the north of isograd representing greenschist to amphibolite facies transition, has been subjected to metamorphism under low geothermal conditions. Some recent studies suggest a plate tectonic model of subduction–collision–accretion tectonics around the Palghat Cauvery shear zone (PCSZ). Our analysis is able to identify several west to east trending high amplitude magnetic anomalies with deep sources in the region from Palghat Cauvery shear to Achankovil shear. The magnetic high associated with PCSZ may represent the extruded high pressure–ultra high temperature metamorphic belt (granulites at shallow levels and retrogressed eclogites at deeper levels) formed as a result of subduction process. The EW highs within the Madurai block can be related to the metamorphosed clastic sediments, BIF and mafic/ultramafic bodies resulting from the process of accretion.

1. Introduction

Understanding the tectonic evolution of Precambrian cratons and shear/suture zones is very complex. The Precambrian geologic history of Peninsular India covers around 3.0 billion years. The area comprises of several cratons and surrounding mobile belts that have challenged the Earth scientists. The Department of Science and Technology, Government of India, under its Deep Continental Studies Program, identified the South Indian shield as a challenging and critical area of research and selected a transect corridor from Kuppam to Palani (and later extended to Kanyakumari) for integrated multidisciplinary research to be carried out on a national scale. The outcome of this multidisciplinary venture including studies like Deep Seismic Studies (Reddy et al., 2003), magnetotelluric (Harinarayana et al., 2003), geochronological (Bhaskar Rao et al., 2003), geo-chemical (Ravindra Kumar and Sukumaran, 2003), gravity (Singh et al., 2003), etc. has been published as a book (Ramakrishnan, 2003) and later a volume on crustal structure

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Peer-review under responsibility of China University of Geosciences (Beijing)

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http://dx.doi.org/10.1016/j.gsf.2013.06.005

and tectonic evolution of Southern Granulite Terrain (SGT) was published (Chetty et al., 2006). Further, as summarized by Sharma (2009) three geodynamic models have been proposed for the evolution of the SGT: the subduction–collision model, the accretion model and the reworked granulite terrane sans mobile belt model. Santosh et al. (2009) believed the tectonic history of southern India represents a progressive sequence from Pacific-type to collision-type orogeny operating in subduction–collision setting. Also, Naganjaneyulu and Santosh (2010) from reanalysis of magnetotelluric and gravity data along a profile across Palghat Cauvery shear zone (PCSZ) suggested a plate tectonic model of subduction–collision–accretion tectonics along this zone. To have a three-dimensional understanding of the region, uniform data coverage over the entire area is required. It is in this regard that the aeromagnetic and gravity data can prove useful.

In many Precambrian provinces the understanding of the tectonic history is constrained by limited exposure which leads to difficulty in developing links between local and regional architecture. High resolution aeromagnetic data can provide information, below the surface cover (Li and Morozov, 2008) allows interpretation and modeling at a scale comparable to structural mapping (Aitken et al., 2008; Aitken and Betts, 2009; Metelka et al., 2011). In the absence of high resolution aeromagnetic data in the present paper we look at the aeromagnetic data collected at the reconnaissance scale to understand the tectonic evolution of the South Indian shield. We analyze data from the southern tip of India up to latitude 19°N to lay emphasis on the Dharwar craton, Southern Granulite Terrain and the surrounding Eastern Ghat mobile belt (EGMB) to help build a tectonic model of the region.

2. Generalized geology and tectonics

Peninsular India is a mosaic of Precambrian crustal blocks that exhibit low- to high-grade crystalline rocks, surrounded by mobile belts, with varied lithologies, tectonic style and evolutionary history that have been brought into juxtaposition and sutured together during different epochs. The study area up to 19°N latitude is composed mainly of the Dharwar craton and a part of the Bastar craton separated by the Godavari Gondwana graben. Toward the east of the Dharwar and Bastar cratons is the Eastern Ghat mobile belt, the junction between them being the Sileru shear zone. South of the Dharwar craton is the Southern Granulite Terrain (SGT). Fig. 1 gives the generalized geology and tectonic map of the study region redrawn from Ramakrishnan and Vaidyanadhan (2008) and GSI (2001, 2010).

The entire Dharwar craton can be viewed as a matrix of Peninsular gneisses interspersed with high- and low-grade schist belts (greenschist to amphibolites facies) and the intrusive granites. Within the Dharwar craton, the grade of metamorphism changes from greenschist facies in the north through amphibolite facies in the middle to high-grade granulite facies in the south (Radhakrishna and Vaidyanadhan, 1997). The Dharwar craton is divided into western Dharwar craton and eastern Dharwar craton based on the differences in the metamorphic facies of the schist belts, their relationship with the surrounding gneisses and limited geochronological data. It is debated whether the Chitradurga boundary shear (Swami Nath and Ramakrishnan, 1981; Anand and Rajaram, 2002; Gokarn et al., 2004) or the Closepet granite is the divide between the western and eastern Dharwar cratons (Ramakrishnan and Vaidyanadhan, 2008). Western Dharwar craton, associated with intermediate pressure kyanite–sillimanite type metamorphic facies, is prominently occupied by tonalite–trondhjemite–granodiorite (3.0–3.4 Ga) with minor schist belts of Sargur age (3.0–3.3 Ga), major large schist belts of Dharwar age (2.9–2.6 Ga) and few late Archean granitoid plutons (2.6–2.65 Ga) (GSI, 2010). Eastern Dharwar craton, registered with low pressure–high temperature andalusite–sillimanite type metamorphism, is characterized by voluminous late Archean Granitoids (2.51–2.75 Ga) with minor tonalite–trondhjemite–granodiorite gneiss and thin volcanic dominated schist belts of Dharwar age (GSI, 2010). The Dharwar craton is affected by NNW–SSE to NW–SE trending transcrustal faults/shears which are intersected by major ENE–WSW to EW and NE–SW trending faults/lineaments. Deep Seismic Sounding studies (Kaila et al., 1979) have shown that the western Dharwar craton is thicker than the eastern Dharwar craton, the depth to Moho being 40–45 km and 35–37 km respectively under the two cratons. The crescent shaped Proterozoic Cuddapah basin consists of highly metamorphosed sediments while the Godavari graben forming the northern limit of the Dharwar craton comprises Gondwana sediments. High-grade granulite rocks of Karimnagar (Rajesham et al., 1993) and Bhopalpatnam are reported along the shoulders of the Godavari graben (Anand and Rajaram, 2003). The Eastern Ghat mobile belt toward the east of the Dharwar craton, is a granulite terrane composed mainly of charnockites, khondalite, quartzite, calc-granulite, pyroxene granulite and leptynites (Ramakrishnan et al., 1998) having a predominant NE–SW trend. EGMB is separated from the Dharwar–Bastar craton by the Sileru shear zone (Chetty and Murthy, 1994). Age determination from recent isotopic data has provided information on the chronostratigraphy of this Precambrian terrane which range from Archean to pan-African (GSI, 2010).

In this paper we refer to the region south of the Fermor line/orthopyroxene isograd as the Southern Granulite Terrain (SGT). The NW–SE trending Moyar shear joins the NE–SW trending Bhavani shear and continues east as Moyar Bhavani shear zone (MBSZ). The region between the orthopyroxene isograd and the Moyar Bhavani–Salem Attur shear system is called northern block and comprises the Coorg (c), Biligirirangan (b) and Shevaroy granulite hills massifs. The low lying area, Palghat gap, bounded by MBSZ and the Palghat Cauvery shear zone (PCSZ) is the central block (Meert et al., 2010). Within the central block, the Moyar shear zone to the north and the NE–SW trending Bhavani shear to the south delineate the Nilgiri block or the Nilgiri (n) granulite massif. The Madras block lies to the east of Salem Attur shear and is bounded by the PCSZ to the south. Lithologies present in the northern block include charnockites, migmatitic gneiss, mafic granulites, and ultra mafic intrusives. Dating of charnockitic rocks (Clark et al., 2009) within the northern block indicated ages of 2530 Ma and subsequent high-grade metamorphism and partial melting at 2480 Ma (Santosh et al., 2009). The lithologies within the central block consist of deformed and variably retrograded charnockitic gneiss associated with biotite and hornblend bearing migmatites and metavolcanics intercalated with metaphilites, calc-silicate rocks, series of quartzite bands and banded iron formation (Santosh et al., 2009). The E–W trending crustal-scale shear zones, namely Moyar, Bhavani, and Palghat Cauvery have been taken to represent major lineaments that are associated with significant regional strike-slip movements and delineated by major river valleys. The region bounded to the north by PCSZ and south by the NW–SE trending Achankovil shear zone (AKSZ) is the Madurai block and further south of AKSZ is the Kerala khondalite block, a seat of meta-sedimentary granulites. Within the Madurai block, the rocks are predominantly charnockites with the Anamalai–Kodaikanal ranges comprising of massive to gneissic charnockites with minor bands of metasediments (mainly khondalites). Kerala khondalite block consists of assemblage of migmatized meta-sedimentary and meta-igneous rocks (khondalite–charnockite assemblages). Several intrusive igneous bodies occur amidst the granulites, greenstone belts, gneiss and the Proterozoic sediments. The alkaline related plutonism, recorded in the form of several NNE–SSW trending

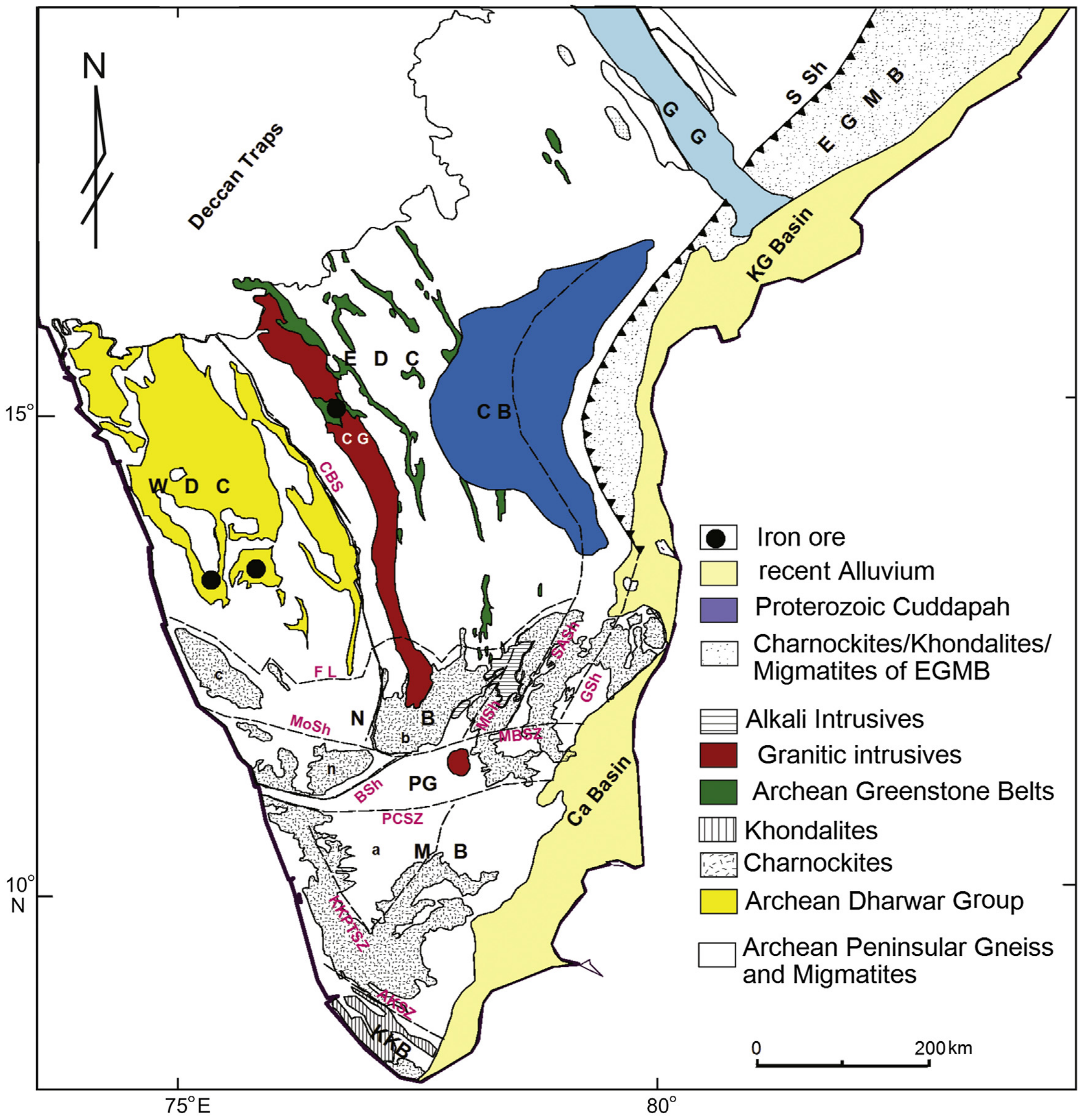

Figure 1. Geological and tectonic map of Peninsular India, up to 19° N latitude (redrawn from Ramakrishnan and Vaidyanadhan, 2008; GSI, 2001, 2010). Basins: Ca – Cauvery, KG – Krishna Godavari, CB – Cuddapah, GG –Godavari graben. Lineaments/faults/shears: SSh – Sileru shear, CBS – Chitradurga boundary shear, FL – Fermor line, GSh – Gangavalli shear, MSZ – Moyar shear zone, SASh – Salem Attur shear, MSh – Mettur shear, BSh – Bhavani shear, PCSZ – Palghat Cauvery shear zone, KKPT – Karur–Kambam–Painvu–Trichur, KOSZ – Karur–Oddanchatram shear zone, AKSZ – Achankovil shear zone. Hills: c – Coorg, b – Biligirirangan, n – Nilgiri, a – Anamalai. Major blocks: EGMB – Eastern Ghat mobile belt, WDC – western Dharwar craton, EDC – eastern Dharwar craton, NB – northern block, PG – Palghat gap, MB – Madurai block, KKB – Kerala khondalite block. CG – Closepet granite.

syenite–carbonatite bodies, occurs mainly to the east of the Mettur shear. The Mettur shear has been interpreted as a collision boundary using magnetotelluric studies (Harinarayana et al., 2006). Recent geochronological and isotopic studies (GSI, 2010) indicate the region to the south of PCSZ (Madurai block and Kerala khondalite block) has a geological history distinctly different from the Dharwar craton. The Madurai block preserves the imprint of the Neoproterozoic–Cambrian thermal event (Collins et al., 2007; Santosh et al., 2009 and references therein).

3. Aeromagnetic data and its analysis

Aeromagnetic surveys over Dharwar craton and Southern Granulite Terrain were carried out by the National Remote Sensing Agency during the period from 1980 to 1989 at altitudes of 5000 ft, 7000 ft with a narrow strip in the central part covered with a flying height of 9500 ft. The line spacing for all the blocks was maintained at 4 km. Aeromagnetic data were collected over the western part of Cuddapah basin and the adjoining crystallines at a flight altitude of 500 ft during 1980–1981 with line spacing of 500–1000 m. Aeromagnetic data over the eastern segment of Cuddapah basin have been covered under Operation Hard Rock but these data are not available with us and results in a data gap. Due to the varying altitudes of data collection, it becomes inevitable to reduce the magnetic data to a common barometric altitude to obtain an overall idea of the magnetic response of the geological terrane in general. The results of these surveys, after initial processing, were available with the Geological Survey of India as degree sheet aerogeophysical contour maps produced at 1:250,000 scale. The degree sheet maps were digitized, corrected for main field, gridded at 1 km interval and continued to a common altitude of 7000 ft to obtain the final aeromagnetic image map of the region up to latitude of 19°N. A composite magnetic anomaly map of India and its contiguous area have been produced by putting together all the available aeromagnetic, ground and marine magnetic data (Rajaram et al., 2006).

3.1. Differential reduction to pole (DRTP)

The goal of the reduction to the pole process is to remove the skewness of magnetic anomalies caused by the non-vertical direction of magnetization, so that the maxima of the reduced to pole anomalies are located directly above the causative bodies, which facilitate interpretations (Blakely, 1995). The standard reduction to pole operation is strictly valid at only a single observation point. When study areas are small (order of 100 km^2) associated reduced to pole errors caused by using only a single inclination and declination will be small, because the earth's magnetic field direction does not vary rapidly. However, for larger areas these errors can be significant. The inclination of the study area ranges from 0° to 19°. In order to alleviate these errors, it is necessary to apply a different filter, designed with the appropriate magnetic inclination and declination, at each observation point, thereby accomplishing differential reduction (Arkani-Hamed, 2007). Such a filter is termed differential reduction to pole (DRTP). Fig. 2 is a plot of the DRTP map of the aeromagnetic data reduced to 7000 ft for the Peninsular India.

3.2. Analytic signal

The analytic signal of the total field reduces the magnetic data to anomalies whose maxima mark the edges of the magnetized bodies if the sources are resolvable (Nabighian, 1984; Roest et al., 1992; MacLeod et al., 1993) but appear as cluster of highs for a combination of nearby sources, regardless of the regional magnetic field direction and source magnetization. The analytic signal map is very useful for delineating magnetic source location at shallow subsurface levels. The analytic signal map of the aeromagnetic anomaly of Peninsular India is represented in Fig. 3. The highs in this map are associated with magnetic sources.

3.3. Tilt derivative

The complex analytic signal of a structure is $A = |A| \exp(j\theta)$ where $|A|$ is known as the analytic signal and θ is the local phase or tilt angle or tilt derivative (Verduzco et al., 2004). Generally, if there is more than one source present the resolution of the analytic signal varies and shallower sources are resolved better than the deeper ones; the tilt derivative overcomes this problem by dealing with the ratio of the vertical derivative to the horizontal derivative; the tilt derivative will be relatively insensitive to the depth of the source and has the ability to resolve shallow and deep features equally well. Fig. 4 is a plot of the tilt derivative of the DRTP map of

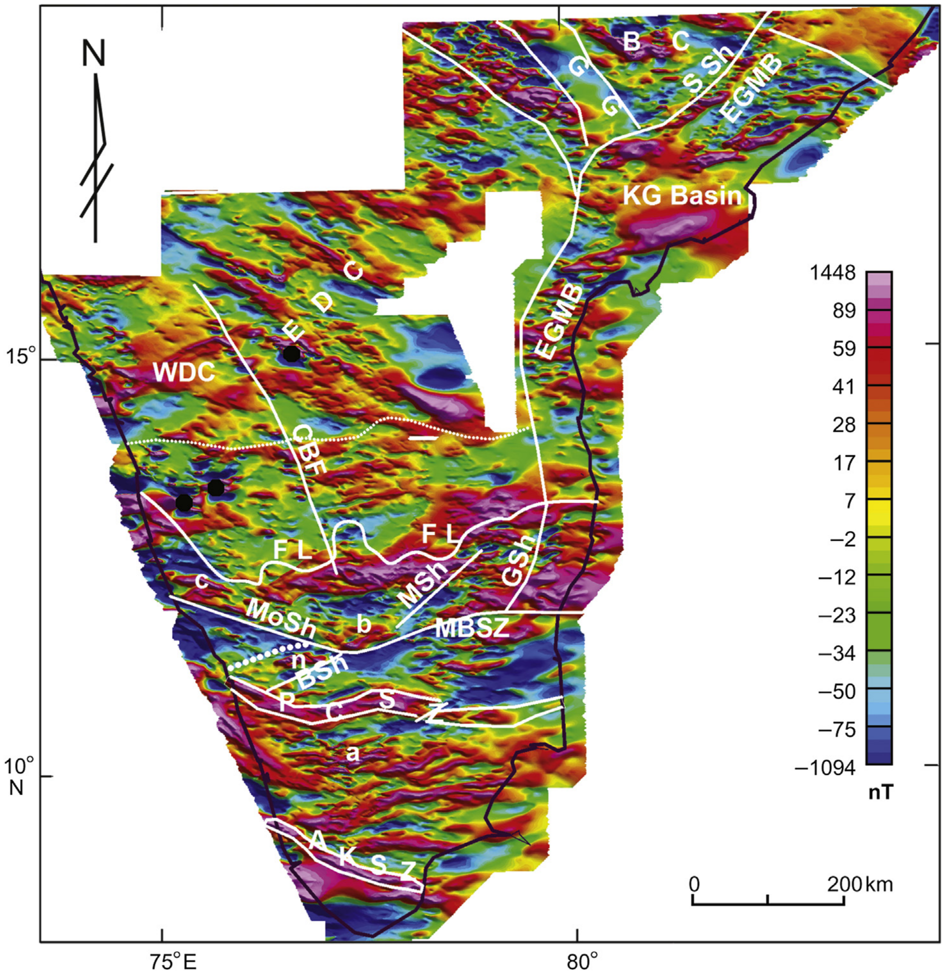

Figure 2. Differential reduction to pole (DRTP) map of the aeromagnetic anomalies over Peninsular India. The warm red colors depict highs and the cool blue colors depict lows. The simplified tectonics from interpreted map Fig. 5 is marked on the map and the abbreviations are as in Fig. 1.

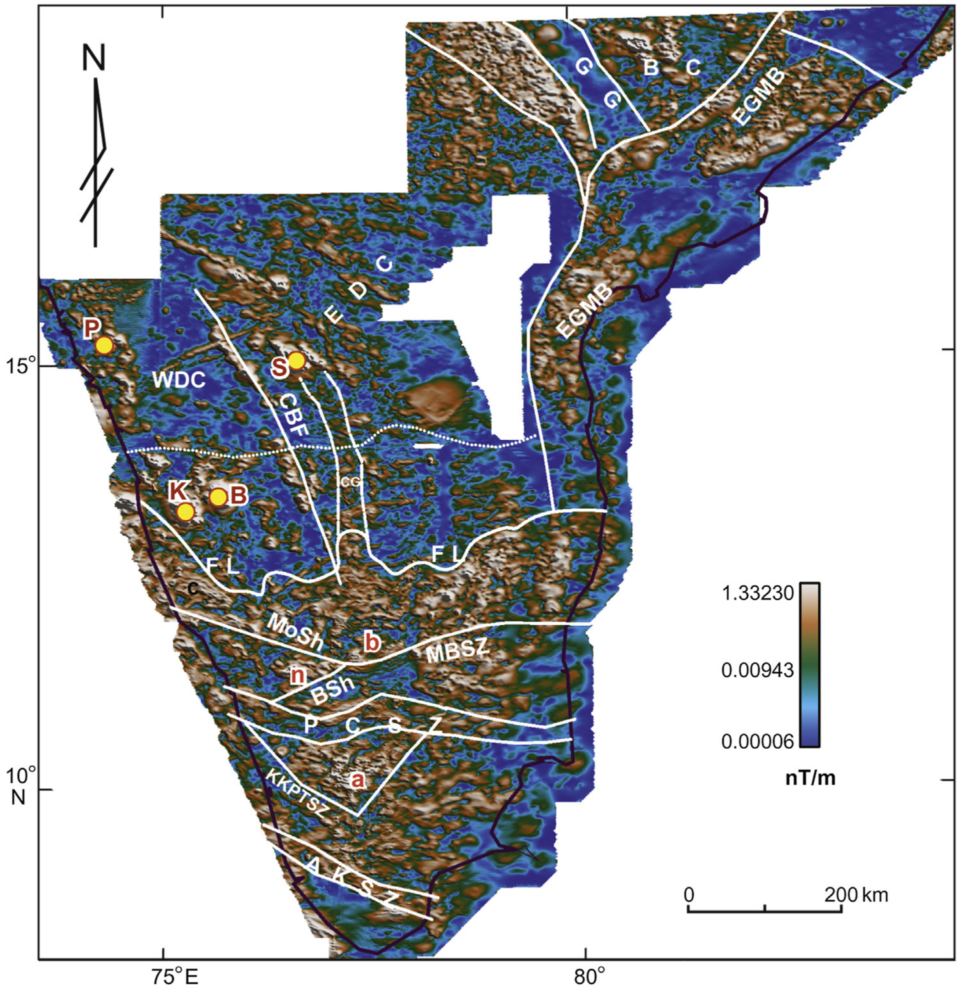

Figure 3. Map of the analytic signal of the aeromagnetic anomaly of Peninsular India depicting the location of the magnetic sources. Brown color represents magnetic sources. The simplified tectonics from Fig. 5 is marked on the map and the abbreviations are as in Fig. 1. B – Bababudan, K – Kudremukh, S – Sandur and P – Panaji.

Peninsular India upward continued to 5 km which essentially provides an idea of the division of the magnetic anomalies into different domains based on the nature, trends and texture of the anomalies.

4. Interpretation of aeromagnetic data over Peninsular India

A map showing the distribution of magnetic sources and structural/tectonic elements interpreted using the aeromagnetic anomalies and its various transformations is represented in Fig. 5. Magnetic sources were picked from the analytic signal map, while the tectonic elements were interpreted from a combination of the DRTP map and tilt derivative maps. In the interpretation of the tectonic structures using the aeromagnetic data and its transformations, we are guided by Paterson and Reeves (1985) and Wellman (1985). According to them, the primary structure of the continent is considered to be a mosaic of crustal blocks of 500–1000 km extent with distinctive history and structure. These primary crustal blocks can be delineated by the predominant trend direction within a block, terminated at a province boundary, as seen in the long wavelength geopotential anomalies. The block containing trends oblique to the boundary is inferred to be older than the boundary and the blocks with trends parallel to be younger. The secondary structure of the continent is the dominant structure within the block and the tertiary structure is considered to be the cross fractures segmenting the secondary structure. These cross features separate the magnetic trend segments and displace the geologic structures forming the trends. The cross features are moderate to weak features on the main trend with some other trend extending across the province boundary. From the interpreted map (Fig. 5), it can be seen that most of the magnetic sources (Fig. 3) are concentrated toward the south of orthopyroxene isograd, along the Eastern Ghat mobile belt and the shoulders of the Godavari graben (GG). Few of the schist belts in the Dharwar craton are also associated with high amount of magnetic minerals. The main magnetic sources can be attributed to the charnockites, iron ore and alkaline intrusive (Rajaram and Anand, 2003). The distribution of these sources is in turn controlled by faults/shears.

From a combination of DRTP map (Fig. 2) and its transformations (Fig. 4), the region above 14°N, is characterized by essentially NE–SW trends in the western part of Dharwar changing completely to NW–SE in the eastern part. The eastern part has a higher concentration of magnetic sources while the major magnetic source in the western part is related to the iron ore formations of Bababudan, Kudremukh and Panaji (Figs. 3 and 5). Thus based on the distribution of magnetic sources and their structure, the west and east are different and represent different terranes. The location where the trend changes from NE–SW to NW–SE can be considered as the terrane boundary and this boundary matches with the Chitradurga boundary shear dividing the Dharwar craton into

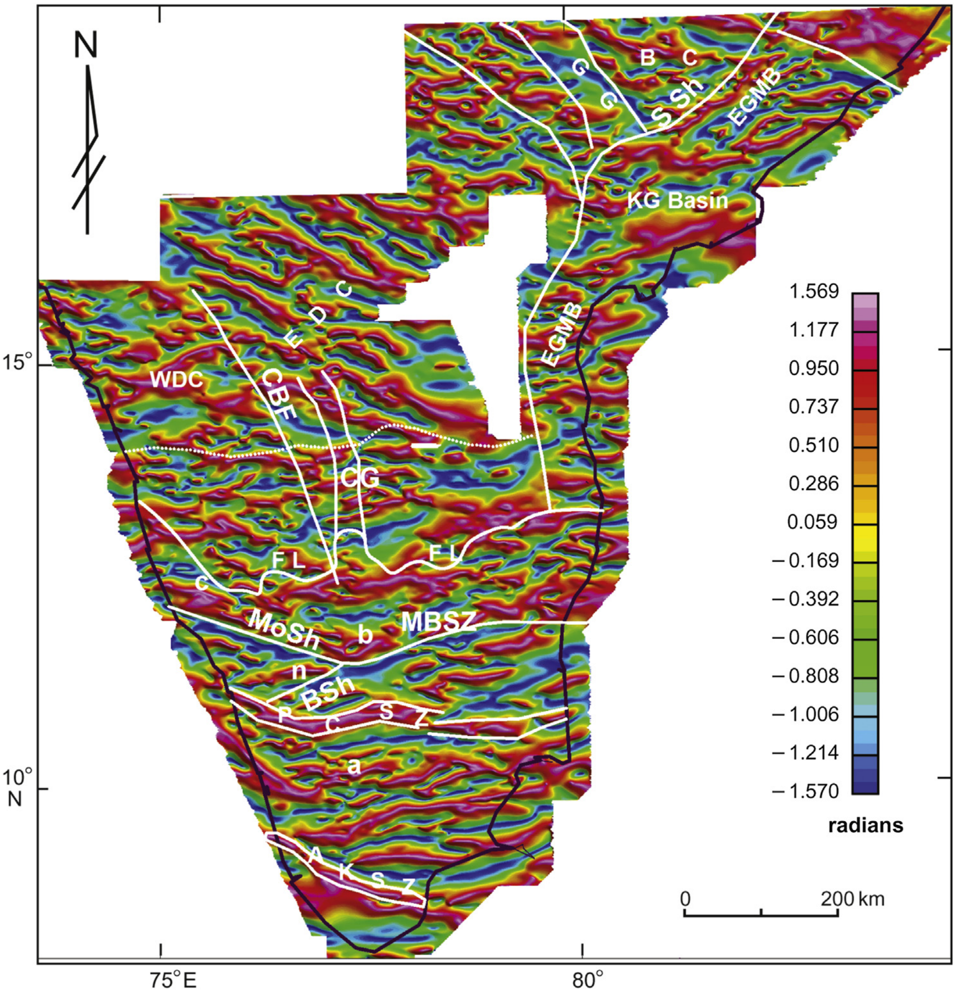

Figure 4. Map of the tilt derivative of DRTP of Peninsular India (upward continued to 5 km). The simplified tectonics from Fig. 5 is marked on the map and the abbreviations are as in Fig. 1.

western and eastern parts. Another important observation from Figs. 2 and 4 is the absence of NW–SE trends in the region south of 14°N up to orthopyroxene isograd while the essential trend here is ENE–WSW. This coincides with the change of facies of metamorphism (Sharma, 2009) from greenschist facies to the north of 14°N and amphibolite facies to the south (represented by dotted white line in Figs. 2–4, 6). The NW–SE trends are seen north up to 19°, i.e. even within the Bastar craton. These trends are in accordance with the Godavari graben trends and may have been influenced by the opening of the Godavari graben. The Godavari graben is devoid of any magnetic sources (Fig. 3). High-grade charnockitic rocks of the Karimnagar and Bhopalpatnam granulite belt (Anand and Rajaram, 2003) flank the shoulders of the Godavari graben on either side. A clear change in trend from NW–SE to NE–SW can be noticed as one moves from east of Bastar craton and Cuddapah basin toward Eastern Ghat mobile belt suggesting a terrane boundary, the line of divide being the Sileru shear. The EGMB is divided into two blocks: block to north is devoid of magnetic sources while the charnockitic rocks are the main magnetic carriers in block to the south. The difference in magnetic characteristics of the two blocks has been attributed to the difference in metamorphic history (Anand and Rajaram, 2003). To have an idea of the distribution of the sources at deeper levels within the Dharwar craton, from orthopyroxene isograd to 17°N, we generated the analytic signal map of the DRTP upward continued to 20 km (Fig. 6). This map depicts that the region to the north of the orthopyroxene isograd is essentially devoid of any significant magnetic sources at depth with the exception of iron ore and intrusive.

Near 13°N, coinciding almost with the line of orthopyroxene isograd (change of amphibolite to granulite facies), the trend of the anomalies changes from ENE–WSW in the north to essentially EW in the south (Figs. 2 and 4). A clear change in the amplitude of the anomalies (Fig. 2) is visible across the MBSZ but the trend of the anomaly remains same. The Nilgiri (n), Coorg (c), Biligirirangan (b) and the Madras granulite (m) massifs depict highs and are associated with strong magnetic sources (Fig. 3). The distribution of shallow magnetic sources (Fig. 3) shows that magnetic sources associated with the Dharmapuri Rift Zone (DRZ) (Fig. 5) extend southwards up to Palghat Cauvery shear zone. Hence it appears that in the shallow subsurface levels the MBSZ is terminated by the Mettur shear which forms the western limit of the Dharmapuri Rift Zone while at deeper levels (evidenced from Fig. 6) MBSZ extends up to the east coast. An NE–SW trend is evident toward the west of the Nilgiri block (shown as dotted line in Figs. 2 and 5) where all the NW–SE anomalies running from the west coast are terminated, probably forming the western limit of the Nilgiri block. This lineament, reported for the first time, joins with the Moyar shear toward the northeast. The striking contrast in gradients across the MBSZ (Figs. 2 and 4) is indicative of a change in characteristic of the magnetic sources. The Palghat

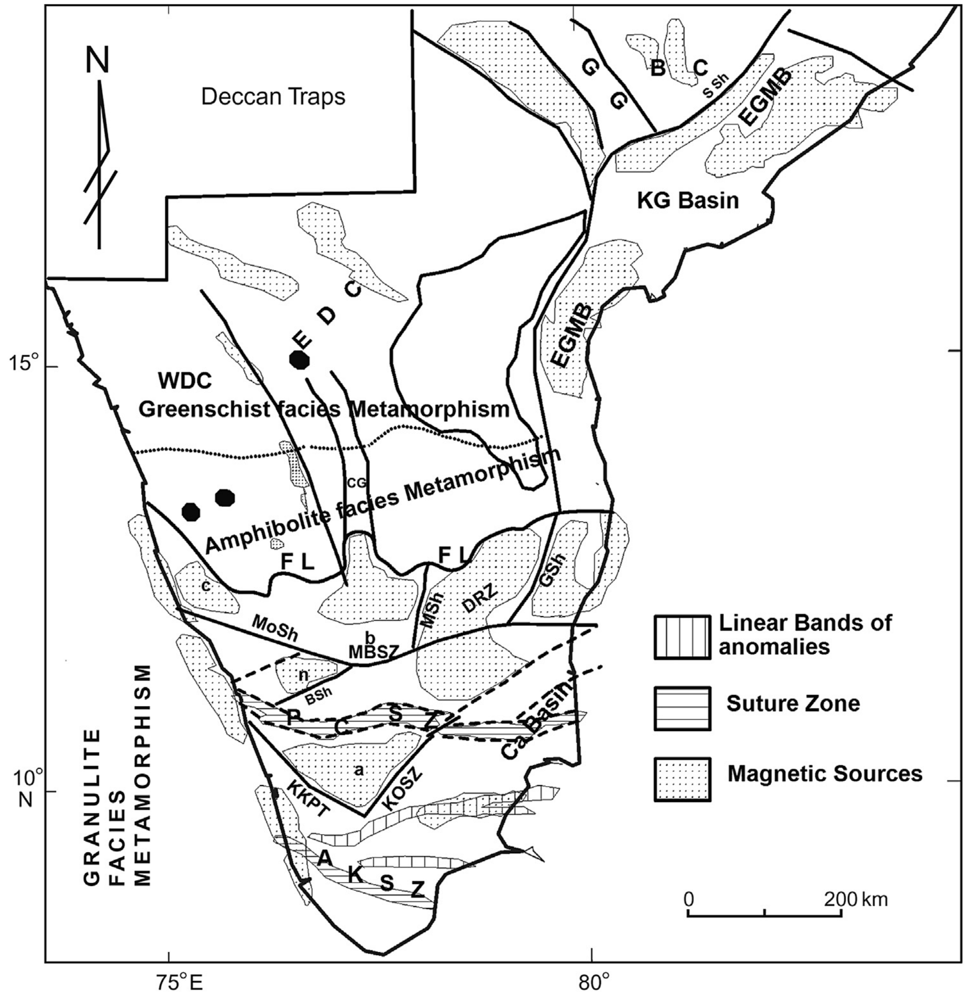

Figure 5. Interpreted tectonic map of Peninsular India from a combination of different analysis of the aeromagnetic data. The abbreviations are as in Fig. 1. B – Bababudan, K – Kudremukh, S – Sandur and P – Panaji.

Cauvery shear zone is evident as a high on the west and central part (Figs. 2 and 4) but toward the east is shifted southward probably due to strike-slip movement and is down faulted further east, below the sediment cover of the Cauvery basin. South of orthopyroxene isograd up to the NW–SE trending AKSZ, the trends are essentially EW in the central part with NW–SE trends toward the west coast changing to NE–SW toward the east coast (Figs. 2 and 4). The E–W trends in the central part do not have any surface manifestation. The rifting and drifting of India from the Gondwanaland in the Mesozoic that resulted in the formation of the east (Prabhakar and Zutshi, 1993) and west coast (Biswas, 1987) sedimentary basins might have shaped the crustal structure in this regions which is being reflected as NE–SW and NW–SE anomalies respectively in the aeromagnetic data in accordance with the trend of the ridges and depressions characterizing these sedimentary basins. High amplitude NW–SE trending anomalies along the west coast between 8° and 14°N latitudes (Rajaram et al., 2006) represent post-Gondwana rifts and Cretaceous–Eocene magmatic activity. Aeromagnetic anomalies on the east coast continue smoothly and merge gently with the marine magnetic anomaly till the ocean continent boundary (Rajaram et al., 2001). The Kerala khondalite block, south of AKSZ, where there is large exposure of khondalitic pelite is not showing any signature in the analytic signal map suggesting magnetization of khondalite are less than charnockites in the Madurai block. The AKSZ is evident as an NW–SE trending high zone separating Kerala khondalite block from the Madurai block suggesting that these are associated with major lithological changes.

To lay emphasis on the understanding of the shallow and deep features of the Southern Granulite Terrain (including the northern block, central block, Madurai block and Kerala khondalite belt) we restrict the area of study from southern tip of India going up to a latitude of 14°N. The power spectrum of the aeromagnetic data gives an idea of the distribution of magnetic sources at different depth levels, the shallow levels being represented by high frequency part of the spectrum while deeper or regional levels are reflected in the low frequency part of the spectrum (Spector and Grant, 1970). Vertical derivatives (Blakely, 1995) of the potential field amplify short wavelength information at the expense of long wavelength information and thus help to resolve shallow sources. Fig. 7 is a plot of the vertical derivative of the DRTP map of the SGT area. This map is dominated by essentially EW striking anomalies. Most of the high frequency anomalies, seen in the vertical derivative map, concentrated between the orthopyroxene isograd and Achankovil shear zone, are associated with the exposed and shallow subsurface charnockitic massifs of Coorg, Nilgiri, Shevaroy and Madras granulites and the ultrabasic rocks seen in the Salem–Dharmapuri Rift Zone (region to the east of Mettur shear). Within the Madurai block, high frequency anomalies are observed over the Anamalai hills (a) bounded by the Karur–Kambam–Painvu–Trichur shear zone (also seen in Fig. 3).

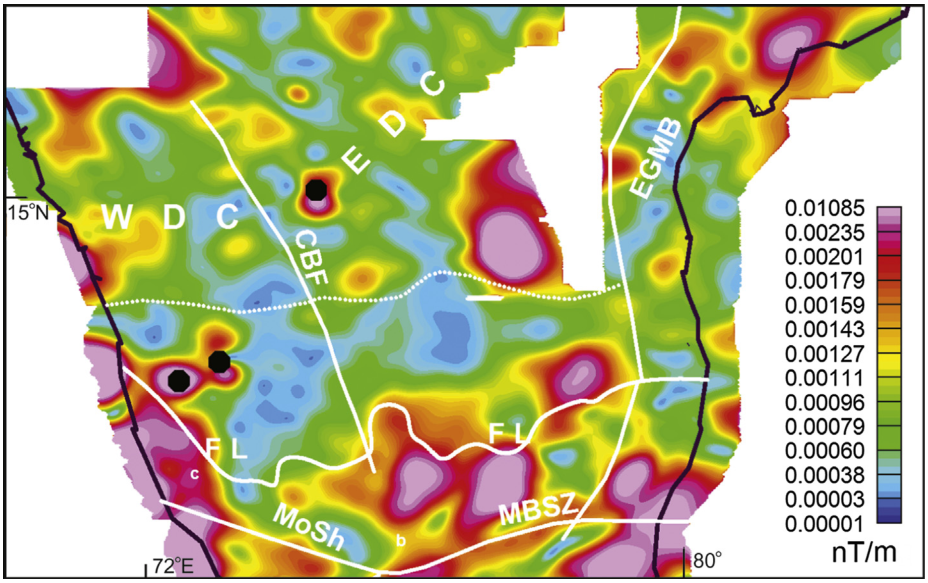

Figure 6. Map of the analytic signal of the aeromagnetic anomaly (upward continued to 20 km) of Dharwar craton depicting the location of the deep magnetic sources. The simplified tectonics from Fig. 5 is marked on the map and the abbreviations are as in Fig. 1.

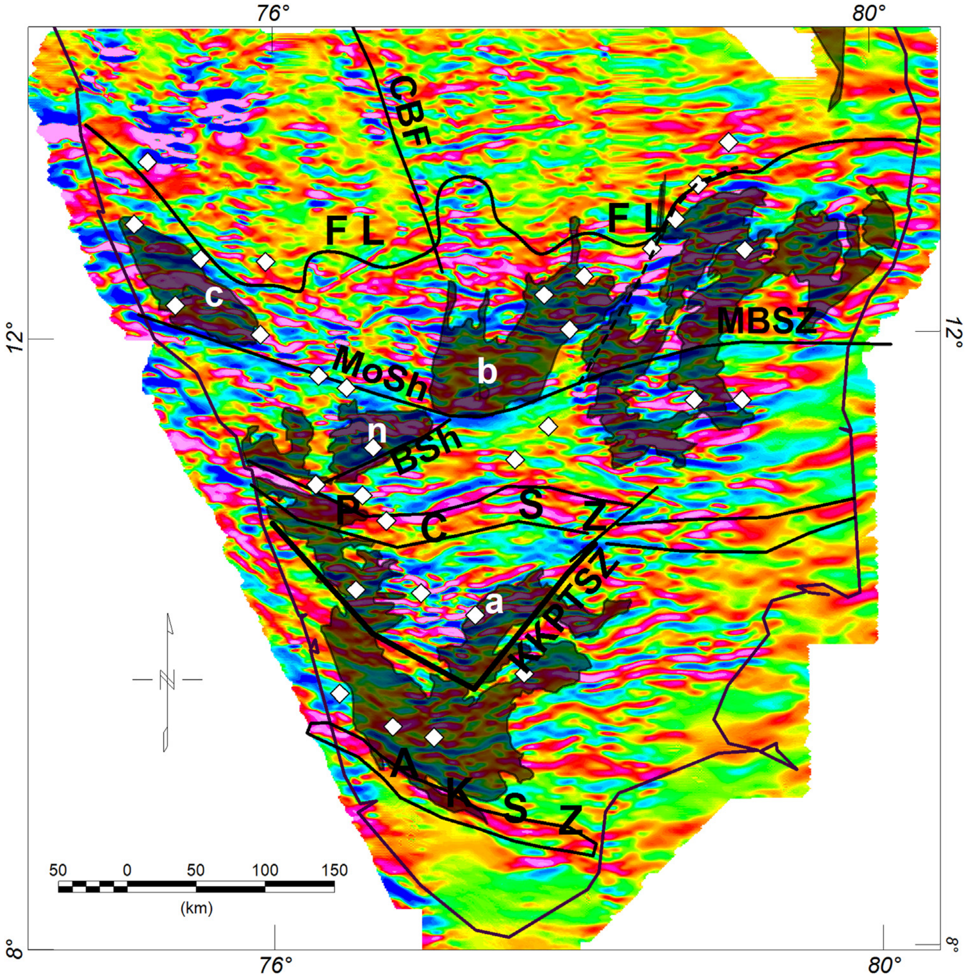

Figure 7. Map of the vertical derivative of DRTP of SGT. The simplified tectonics within SGT from Fig. 5 is marked on the map and the abbreviations are as in Fig. 1. Mapped charnockites are superposed on this map. Filled white box represents the location of the alkali plutons and ultrabasic intrusives (Mahadevan, 2003).

The high frequency anomalies are also seen over the alluvium covered Cauvery basin suggesting charnockite rocks may be the basement for the deposition of the Cauvery basin sediments.

Upward continuation is the process of transforming potential field data measured on one surface to some other higher surface that helps to accentuate anomalies due to deeper sources, at the expense of shallower ones. To have an understanding of the deeper regional sources, the DRTP map for SGT has been continued to levels of 5, 10, 20, 30 and 40 km and we have reproduced the DRTP maps upward continued to 10 and 30 km in Fig. 8a and b respectively. At each level of upward continuation we have calculated the radially averaged power spectrum (Spector and Grant, 1970) and found that the average depth of the sources at upward continuation levels of 10 and 30 km are 12 and 33 km, respectively. To resolve all the sources below different depths, we also calculated the tilt derivative of the DRTP maps continued upward to 10, 20, 30 and 40 km and a plot of the tilt derivative of the DRTP maps continued upward to 10 and 20 km is given in Fig. 8c and d respectively. The highs associated with the PCSZ and AKSZ are clearly evident in the tilt derivative images at all levels of continuation suggesting its deep seated nature. The amplitude peak associated with the PCSZ appears to shift southwards as the level of upward continuation increased suggesting that the magnetic sources along the PCSZ dip southwards while the AKSZ is nearly vertical. The Karur–Kambam–Painvu–Trichur shear zone is not observed in the deeper features (Fig. 8) though it is visible in the shallow features (Figs. 3 and 7); we believe this shear zone is not a terrain boundary as suggested by Ghosh et al. (2004). To have a better understanding

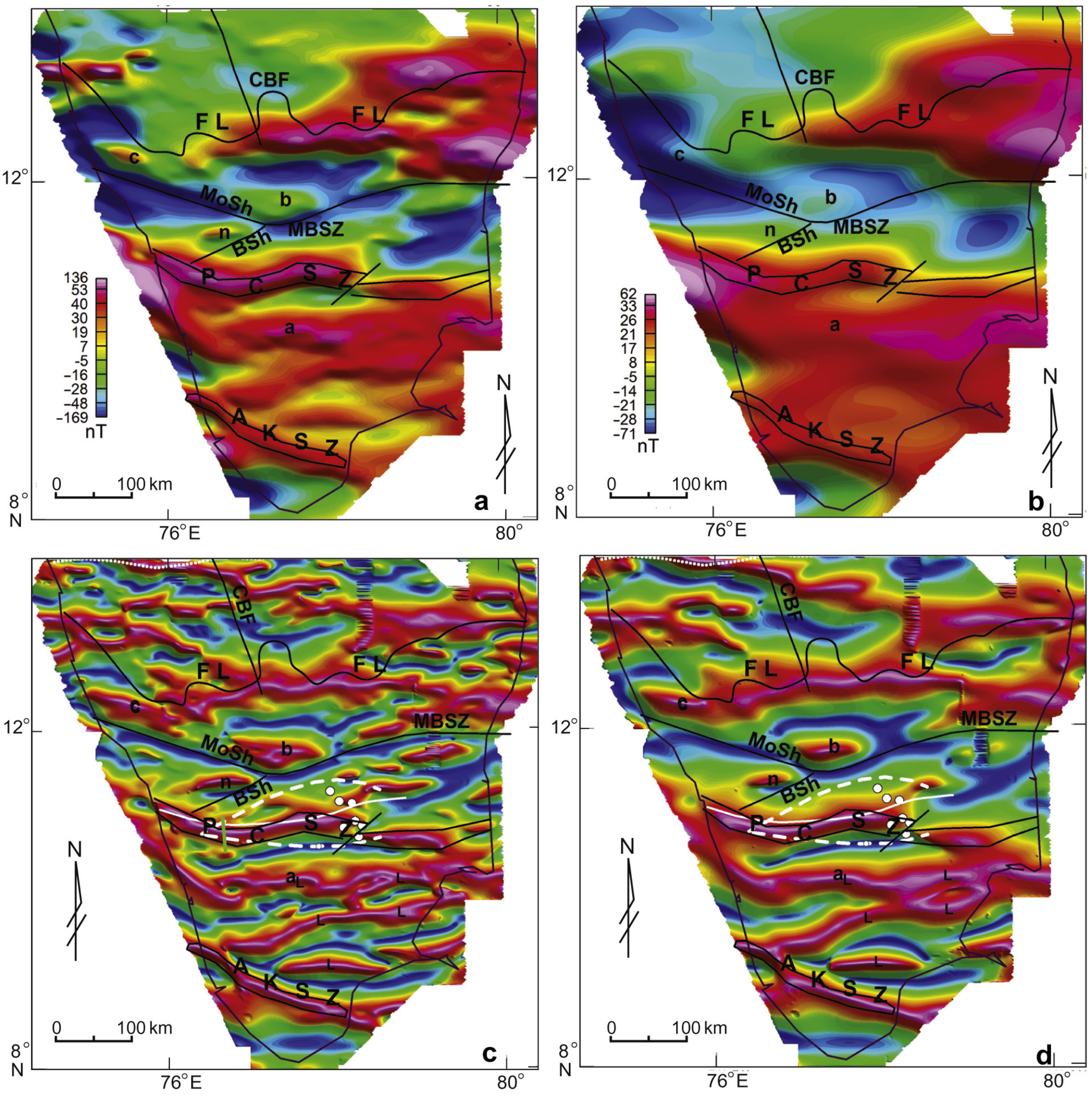

Figure 8. Upward continued maps of SGT region of DRTP to (a) 10 km, (b) 30 km and tilt derivative of upward continued maps of DRTP to (c) 10 km, (d) 20 km. Main shears/sutures from Fig. 5 is marked on the map and the abbreviations are as in Fig. 1. Location of the profile shown in Fig. 9 is superposed in green on (c). White dotted lines and white filled circles (in c and d) represent the location of the core of orogen and the high pressure–ultra high temperature (HP–UHT) granulites mapped by Santosh et al. (2009). White dashed line (c, d) shows the location of PCSZ from Fig. 1.

of the southward dip of the PCSZ, a 40 km long profile was chosen across PCSZ (location of profile shown in Fig. 8c in green). Fig. 9 shows the shift in the location of the peaks of the tilt derivative of the upward continued DRTP maps. It was found that the peak has shifted over a distance of approximate 9.6 km between the tilt derivative of DRTP at 5 km (shallowest level) and tilt derivative of DRTP at 40 km (deepest level) which confirms the southward dipping nature of the PCSZ. Another important feature of Fig. 8c and d is the distinct linear bands (L) trending EW visible in the Madurai block at all levels of continuation.

5. Results and discussion

5.1. Magnetic anomalies and metamorphism

Magnetic signatures of different rock types are dependent on the magnetic minerals present in them which in turn can be altered by metamorphism. Magnetic susceptibility has a tendency to increase with increasing metamorphic grade, as a result of the formation of coarser magnetite (Grant, 1984/85). Magnetic characteristics of metamorphic rocks depends on the composition of the protolith (especially the iron content of the source rock), the temperature regime, chemical effects brought out by the temperature/pressure conditions, especially the oxidation state that controls the amounts and types of iron oxides that can form and partitioning of iron between silicates and oxides (Grant, 1984/85). Partially retrograded eclogites (Xu et al., 2009) and prograde charnockites (Ramachandran, 1990) are known to exhibit higher magnetic susceptibility. It has been observed that during prograde metamorphism Fe–Ti oxides are produced at the expense of silicate assemblages. The variation in partial pressure of oxygen and water during metamorphism can also lead to large variation in magnetic mineralogy and consequently in magnetic susceptibilities. However on retrogression charnockite is depleted of magnetite and hence has lower susceptibility and widespread retrogression of charnockites has been observed in the SGT (Ramachandran, 1990). From rock magnetic studies Ramachandran (1990) grouped the charnockites in the SGT region into two groups with Group I charnockites showing low susceptibility and Group II showing higher susceptibility.

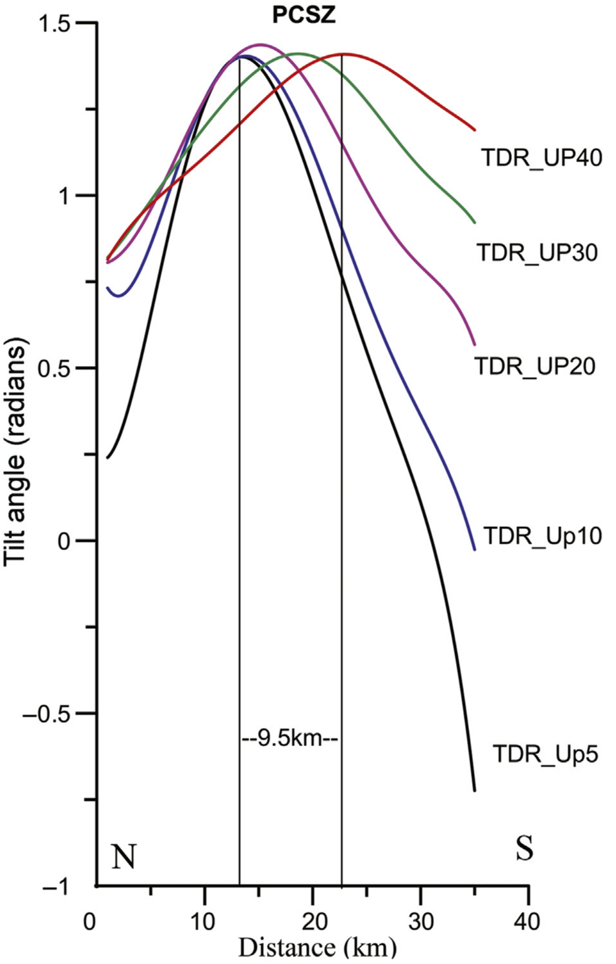

Figure 9. Magnitude of tilt derivative anomaly of DRTP for upward continued levels at 5, 10, 20, 30, 40 km across the PCSZ (location of profile shown on Fig. 8c). The peak of the high anomaly shifts southwards.

In the present study we have made an attempt to map the metamorphic grades of the different lithologies based on the magnetic signatures. The interpretations and inferences made are based on Fig. 3, the analytic signal (providing information on the distribution of magnetic sources) and Fig. 7, first vertical derivative map (enhancing high frequency anomalies representing shallow sources that may be related to younger activities). The charnockites mapped in the Madurai, central and northern block together with the location of intruded alkali plutons are superposed on Fig. 7. Previous studies have shown that most of the magnetic sources in Peninsular India are associated with exposed and subsurface charnockites, iron ores, intrusive and trap flows (Anand and Rajaram, 2007). The region to the east of the Mettur shear (Dharmapuri Rift Zone), the Nilgiri (n) and Coorg (c) charnockite massifs show several high frequency anomalies possibly related to later activities. Several alkali plutons and ultrabasic rocks have been reported from the Dharmapuri Rift Zone and Coorg region of pan-African age (Mahadevan, 2003) due to which the high-grade rocks in this region may have undergone prograde metamorphism thereby increasing the magnetite content and susceptibility (Ramachandran, 1990). The distribution of the high frequency anomalies (Fig. 7) and the magnetic sources (Fig. 3) can be very well correlated with charnockites that are intruded by alkali plutons. However, the region occupied by charnockites of Biligirirangan hills does not show any magnetic sources or high frequency anomalies except for the edges where it is associated with Closepet granite intrusion (Fig. 3). It is worth mentioning that there are no alkali plutons or dykes reported form Biligirirangan region. Thus it can be inferred that charnockites that have been later intruded by alkali plutons are associated with magnetic sources while those not associated with later intrusives do not show considerable magnetic anomalies. Also, several patches of exposed charnockites mapped in the Madurai block do not depict any magnetic signatures. This may imply that the charnockites in the Madurai block have undergone retrograde metamorphism thereby losing its magnetite content. The measured susceptibility of the sampled charnockites (Ramachandran, 1990) in the Madurai block reflects retrogressed characteristics. All the Group II charnockites of high susceptibility mapped by Ramachandran (1990) are associated with location of the alkaline plutons (see Fig. 7).

Toward the south of the PCSZ, the Anamalai hills bounded by Karur–Kambam–Painvu–Trichur shear zone are associated with magnetic sources. The lithology of this region includes granitic gneiss which cannot give rise to such high amplitude anomalies. The vertical derivative map depicts E–W signatures in this region. Hence it is inferred that this region has been affected by later thermal event that may have resulted in the formation of secondary magnetite in the subsurface from the available iron oxides in the retrograded country rock. Thus from the present study it can be interpreted that magnetic mineralogy (magnetite content) of the protolith that has undergone tectono-thermal alteration due to sporadic younger intrusive is considerably different from that which has not been associated with intrusives. The characteristics of the protoliths are altered by sporadic younger intrusives that tend to increase the magnetite content of the protolith due to prograde metamorphism thereby increasing the magnetization that can be easily mapped using the aeromagnetic data.

Fig. 5 depicts that the region to the north of the orthopyroxene isograd is essentially devoid of any significant magnetic sources at depth with the exception of iron ore and intrusive. If there are granulite facies rocks at deeper crustal levels within the Dharwar craton, their signatures would have been evident in the magnetic sources map. Hence from Fig. 6, we infer that north of the orthopyroxene isograd, within the Dharwar craton, there is no conversion of greenschist/amphibolites facies rocks to granulite facies within crustal depths. This implies that the region did not experience very high geothermal gradient to reach the granulite facies metamorphism. This is supported by the observation that the average heat flow decreases (Roy and Mareschal, 2011) from south to north (8°–16°N) while the magnetic crustal thickness (Rajaram et al., 2003, 2009) increases. To confirm these results detailed investigations need to be carried out.

5.2. *Tectonic activity and magnetic anomalies*

Terrane boundary can be regarded as major petrophysical discontinuity, along which discrete crustal domains with marked difference in geophysical characteristics (like trend, physical properties), stratigraphy, tectonic history, etc. are welded together during different periods of their evolutionary history. An attempt was made by Kumar et al. (2009) to divide the Peninsular Indian shield into different domains based on the horizontal bouguer gravity gradient analysis. From the present analysis we have identified three major trends associated with the aeromagnetic image map and its transformations. These are the NW–SE trends of the eastern Dharwar and Bastar craton, NE–SW trends over the western Dharwar craton, EW trends over the region south of orthopyroxene isograd and NE–SW related to the EGMB. There is a marked difference in magnetic anomaly trends and the distribution of magnetic sources within the eastern and western Dharwar cratons. The gneisses in WDC are dated at 3000–2600 Ma while the EDC mainly consists of relatively younger gneisses dated at 2600 Ma (Radhakrishna and Vaidyanadhan, 1997). Granitic intrusive is abundant in the EDC whereas there are very few granitic intrusions in the western block. DSS studies (Kaila et al., 1979) found that the WDC is thicker than the EDC. Integrating these results it can be inferred that WDC and EDC represent two different terranes with the location where the trend of the magnetic anomaly changing from NE–SW to NW–SE be considered as the terrane boundary and this boundary matches with the Chitradurga boundary shear dividing the Dharwar craton into western and eastern parts. A similar change in trend from NW–SE to NE–SW can be observed between pertophysically different Bastar craton and Eastern Ghat mobile belt suggesting a terrane boundary that coincides with the location of Sileru shear zone. Such difference in anomaly trend is not visible in the region between orthopyroxene isograd and Achankovil shear zone. Applying the principle of Wellman (1985), i.e. the trends oblique to the terrane boundary is older while that parallel to the boundary to be younger it can be inferred that the western Dharwar craton is older compared to eastern Dharwar craton which is true as per the age information from these cartons, eastern Dharwar craton is older than the EGMB and the region south of the orthopyroxene isograd is younger compared to western Dharwar craton and eastern Dharwar craton.

There is an ongoing debate whether plate tectonics was active during the Precambrian times and if its signatures can be deciphered. Recently Santosh et al. (2009) have discussed in detail a plate tectonic model of subduction–collision–accretion for the evolution of the Palghat Cauvery shear zone and the Madurai block during the final stages of the amalgamation of the Gondwana supercontinent. The PCSZ was proposed as a trace of Mozambique ocean suture in southern India (Collins et al., 2007) which was later confirmed by the plate tectonic models (Santosh et al., 2009). PCSZ and AKSZ do not depict distinctive gravity gradient signatures; therefore Kumar et al. (2009) concluded that PCSZ and AKSZ are only lithological/morphological boundary rather than terrane boundaries or elements of ancient geo-sutures. This would be related to the fact that the density difference of the adjacent blocks is marginal and hence not reflected in the gravity data. The magnetic data, on the other hand, can play a very crucial role as the susceptibility contrast can be very significant as in the case of granulites and khondalites. Here we make an attempt to check whether any characteristic magnetic signature is associated with the PCSZ which is confirmed as a Cambrian orogenic suture. The location of the Palghat Cauvery shear from the geology and tectonic map (Fig. 1) is shown as white line in Fig. 8c and d which coincides with the EW linear high in the western and central part. The PCSZ interpreted from the present study is demarcated in black (Fig. 8c, d); it may be noted that it is displaced southwards and continues underneath the Cauvery basin. The location of the extruded thin layer of the core of the collision orogen (white dashed lines) and the high pressure–ultra high temperature outcrops (white filled circles) as identified by Santosh et al. (2009) is also superposed on Fig. 8c and d. This exactly falls on a part of the EW trending high associated with the PCSZ. Hence we infer that the EW trending high associated with the PCSZ is a reflection of the HP–UHT assemblages of extruded metamorphic belts within the PCSZ which may have very high susceptibilities. This requires further studies including sampling and analysis of the rock magnetic properties. Through combined modeling of magnetotelluric and gravity data Naganjaneyulu and Santosh (2010) have suggested the presence of south dipping retrogressed eclogites at the lower crustal levels formed as result of the subduction process. Studies (Xu et al., 2009) have shown that retrogressed eclogites are having susceptibilities that are comparable or much higher than that of the granulites and these should show signatures on the magnetic data. The magnetic high associated with the PCSZ is seen even in the tilt derivative of upward continued map (Fig. 8c, d) depicting deeper features thus suggesting the presence of high susceptibility material in the deeper layers that may be related to eclogites at depth. The location of the maxima associated with the PCSZ (depicting the depth to the top of the magnetic source) of the tilt derivative shifts from north to south as the level of upward continuation increases suggesting the southward dip of the HP–UHT metamorphic belt. Contrary to the previous belief that the Madurai block comprises charnockite massifs, recent study revealed several narrow linear belts of metasedimentary packages (Sajeev et al., 2006) including high pressure–ultra high temperature (HP–UHT) assemblages associated with linear belts of metamorphosed clastic sediments, quartzites, banded iron formations and mafic/ultramafic bodies that represent an accretionary setting during the final collissional orogeny (Santosh et al., 2009). The identification of the sea-floor magnetic anomalies has played a very significant role in the acceptance of the plate tectonic theory; in the present paper we attempt to identify in the aeromagnetic data signatures, if any, of the plate tectonic model suggested for the evolution of the Madurai block during the Precambrian times. We have identified several EW trending linear bands of magnetic highs (L; Fig. 8c, d) between the Palghat Cauvery shear zone and the Achankovil shear zone, running from west to east coast, up to the intermediate and deeper levels. This possibly represents the linear belts of metamorphosed clastic sediments, BIF and mafic/ultramafic bodies within the Madurai block. Thus the present study supports the subduction and the accretionary process related to the formation of the PCSZ and Madurai block, respectively.

The PCSZ and AKSZ depict high amplitude magnetic anomaly zones while the Chitradurga boundary shear and Sileru shear just represent a change of magnetic anomaly trend on either side i.e. the magnetic characteristics of PCSZ and AKSZ are very different from Chitradurga boundary shear and Sileru shear. Hence based on the magnetic anomalies we interpret PCSZ and AKSZ to be suture zones while Chitradurga boundary shear and Sileru shear are terrane boundaries.

6. Conclusions

From the analysis of the reconnaissance scale aeromagnetic data up to 19°N latitude we were able to bring out the following: (a) five different blocks related to Western Dharwar craton, eastern Dharwar craton, EGMB, Madurai block and Kerala khondalite block based on orientation, amplitude, continuity and texture of the magnetic anomalies; (b) Palghat Cauvery and Achankovil shears are suture zones; the Chitradurga boundary shear and Sileru shear are boundaries between two different tectonic blocks; (c) from the mapped charnockites within the Madurai block, the prograded charnockites could be distinguished from the retrograded charnockites; (d) within the Dharwar craton, due to low geothermal gradient the greenschist/amphibolites facies rocks are not metamorphosed to charnockites at crustal depths; (e) linear west to east trending magnetic anomalies seen within the PCSZ are attributed to the HP–UHT extruded and subsurface metamorphic belts formed as a result of subduction while that within the Madurai block are related to the linear belts of metamorphosed clastic sediments, BIF and mafic/ultramafic bodies formed as a result of accretionary processes.

High resolution aeromagnetic data have been utilized for the structural interpretation thereby building the deformational history of different geological terranes (Aitken and Betts, 2009). The present analysis is based on reconnaissance scale (1:250,000) aeromagnetic surveys and does not have the ability to resolve very detailed scale structural interpretation for example flower structure interpreted from structural geologic studies in the PCSZ (Chetty and Bhaskar Rao, 2006). Utility of the magnetic data would increase several folds if high resolution aeromagnetic data are available over this region in India.

Acknowledgments

We wish to thank Dr. L.K. Das for valuable discussions. We also wish to thank the reviewers whose comments on an earlier draft of the manuscript have helped to improve the presentation of the paper.

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