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Insights into the crustal architecture from the analysis of gravity and magnetic data across Salem-Attur Shear Zone (SASZ), Southern Granulite Terrane (SGT), India: an evidence of accretional tectonics

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The gravity and magnetic surveys were carried out across E-W trending Salem-Attur Shear Zone (SASZ), Southern Granulite Terrane (SGT), India. The study envisages detail crustal architecture/ fabric across the SASZ from the analysis of potential field data. The Bouguer gravity map shows a circular gravity high closure over ultramafics complex of Chalk hill. Gravity model indicates that the complex is a spherical plug type body with depth extension of ~7-8 km. The SASZ is reflected by dominantly E-W trending elongated isogals with low gravity values and depth extension of 3-4 km. The gravity high anomaly at the southeastern part of the SASZ indicates a high-density crustal unit that might have accreted along the southern margin of the shear zone. The magnetic map shows a high anomaly zone in the north-western block of the study area and bordered by a predominantly low anomaly zone at the southeastern boundary. The gravity-magnetic joint modelling reveals that a plane in south of the SASZ separates two upper crustal unit of contrasting density and susceptibility. The study indicates evidence of accretional tectonic in the southern margin of Dharwar Craton (DC) through arc magmatism. The SASZ has a shallow vertical extension (~4 km) and is characterized by diamagnetic rock.

Introduction

The Southern Granulite Terrane (SGT) provides a critical window to understand the tectonic evolution of Precambrian crust as it preserves the geological records of continent reconstruction, subduction-collision and terrane accretion (Sato et al., 2011; Praveen et al., 2014; Samuel et al., 2014; Santosh et al., 2015; Ratheesh-Kumar et al., 2016; Santosh and Li, 2018; Santosh, 2020). The SGT consists, collage of

Neoarchean to Neoproterozoic terranes/ tectonic blocks, which are characterized by distinct lithological assemblages, grades of metamorphism and isotopic age (Behera et al., 2019). The Meso to Neoarchean terrane adjacent to Dharwar Craton is termed as Northern Granulite Block (NGB; Clark et al., 2009; Brandt et al., 2014; Collins et al., 2014; Ratheesh-Kumar et al., 2016; Li et al., 2018; Chetty, 2017; Kumar et al., 2020a), which is made up of orthogneisses, metasedimentary rocks and charnockites. The NGB includes several crustal blocks (Fig. 1) such as Coorg Block (CB), Nilgiri Block (NB), Bili-giri Rangan Block (BRB), Shevaroy Block (SB) and Madras Block (MdB). The present study area includes Shevaroy Block (SB), and Namakkal Block (NkB) traversed by the Salem-Attur Shear Zone (SASZ; Fig. 1). The lithological assemblages of the study area formed between 3.2 to 2.6 Ga (Behera et al., 2019). Some studies indicate the SASZ, as the northern frontier of the suture zone named as Palghat Cauvery Shear System (PCSS; Bhaskar Rao et al., 2003; Collins et al., 2007; Clark et al., 2009; Santosh et al., 2009, 2012). However, Behera et al. (2019), opined that the SASZ might not be a suture, but represent intra-terrane shear zone within a single Archean-Paleoproterozoic SGT. The geophysical signatures addressing crustal architecture in this important tectonic line is little known.

The Salem-Attur Shear Zone forms the north-eastern boundary of the PCSS or Cauvery Shear Zone (CSZ), which is a suture zone and separates NGB in the north and Madurai Block (MB) in the south (Chetty et al., 2003; Santosh et al., 2012; Collins et al., 2014). The MB (Fig. 1) occurs immediately south of the PCSS that extends up to Achankovil Shear Zone (ASZ) and includes Archean to Neoproterozoic charnockite-granite association along with gneiss, calc-granulite and quartzite (Bhattacharya et al., 2014). In the south of the ASZ, the Trivandrum Block (TB) occurs, which comprises dominantly of metasedimentary gneisses of Paleoproterozoic age and Neoproterozoic granitoids and syenites (Collins et al., 2014).

The geophysical studies, especially gravity and magnetic studies have immensely facilitated in understanding imprints of the ancient

tectonics (Gibb et al., 1983; Mishra and Kumar, 2005; Williams et al., 2006; Kumar et al., 2009). The geophysical methods have important advantage of providing continuity of information if not available in post tectonic cover (Williams et al., 2006). Distinct gravity signatures (paired negative and positive gravity anomalies) are observed over the

cratonic convergence and sutures at Precambrian age in Canadian Shield (Gibb and Thomas, 1976; Gibb et al., 1983). The geophysical studies in SGT have provided some key insights into crustal architecture and tectonics. Based on the signatures observed in gravity-magnetic anomalies, Proterozoic collisional tectonics across the PCSS/CSZ was

Figure 1. Generalized geological map of Southern Granulite Terrane (SGT) highlighting the study area. WDC: Western Dharwar Craton; EDC: Eastern Dharwar Craton; FL: Fermor Line (Transition Zone); CB: Coorg Block; NB: Nilgiri Block; BRB: Billigiri Rangan Block; SB: Shevaroy Block; MdB: Madras Block; NkB: Namakkal Block; MB: Madurai block; TB: Trivundram Block; CC: Closepet Granite; MSZ: Moyar Shear Zone; BSZ: Bhavani Shear Zone; MBSZ: Moyar-Bhavani Shear Zone; CBSZ: Cauvery-Bhavani Shear Zone; MeSZ: Mettur Shear Zone; PCSZ: Palghat-Cauvery Shear Zone; ASZ: Achankovil Shear Zone; KKPTSZ: Karur Kambam Painavu Trichur Shear Zone (Map compiled after GSI, 1998; Naganjaneyulu and Harinarayana, 2003; Reddy, 2003; Ghosh et al., 2004; Rao and Prasad, 2006; Yellapa et al., 2014; Samuel et al., 2014; Plavsa et al., 2015). MT-Profile modified from Naganjaneyulu and Harinarayana (2003).

inferred by Mishra and Kumar (2005). Another study by Singh et al. (2006) inferred a faulted contact between SGT and Eastern Dharwar Craton (EDC), also mantle upwarp beneath the PCSS. This study also indicated a possibility of Himalayan type geodynamic event for evolution of SGT (Singh et al., 2006). The gravity study reveals, no difference in crustal density across the ASZ (Kumar et al., 2009). The magnetotelluric (MT) and seismic signatures are interpreted in terms continent-continent collisional tectonics along the Moyar-Bhavani Shear Zone (MBSZ; Fig. 1; Reddy et al., 2003; Rao et al., 2006; Nagajene-yulu and Harinarayana, 2003; Patro et al., 2014). A recent study indicates that the Nallamalai Shear Zone (NLSZ; Fig. 1), in the north-eastern part of SGT, separating two blocks (Shevaroy Block & MdB), is an oceanic suture, which preserves the antiquity of paleo-ocean, ocean-basin cessation (Li et al., 2018).

Most of the geophysical studies mentioned above are based on the large-scale data, which lacks the analysis of high-resolution data set to address the crustal architecture of individual blocks and intervening structural or orogenic belts (Santosh, 2020). The geophysical signatures of the SASZ can provide an estimate of spatial and vertical subsurface geometry. Again the contrast of geophysical signatures across the SASZ is not available, which can enable to infer about the structure and paleo-tectonics of the study area. In the present study, we have acquired high-density gravity-magnetic data. It leads to high-resolution potential field maps followed by detail analysis of their derivative maps (Vaish and Pal, 2015; Kumar et al., 2019; Ganguli et al., 2019, 2020a,b) and joint gravity-magnetic modelling to address the critical issues. The collected rock samples provide information about density and susceptibility values which facilitate for understanding and the correlation of gravity-magnetic signatures.

The present study brings out detail gravity and magnetic signatures of the SASZ, its geometry, depth persistence, shallow and deeper crustal architecture and tectonics across SASZ. Our results reveal the presence of a high density mafic crustal unit at the southern margin of the SASZ. The study also reveals spatial as well as vertical extensions of the Salem mafic-ultramafic complex, popularly known as Chalk hill, which is reported to be Alaskan-type complex developed in rift-related setting (Yellappa et al., 2019; He et al., 2015). The present study is leading to propose an accretionary tectonic model across the SASZ.

Regional Geological Setting

The Archean Dharwar Craton (DC) borders the SGT in north, which is predominantly represented by a granite-greenstone terrane (Fig. 1). The SGT is a collage of tectonic units/blocks, each of which is characterized by distinct protolith, lithological assemblage and isotopic age. The tectonic units/blocks are dissected by crustal-scale shear/suture zones (Santosh et al., 2009; Collins et al., 2014; Behera et al., 2019). From north to south, the tectonic units/blocks are (i) Northern Granulite Block (NGB), (ii) Palghat Cauvery Shear System (PCSS), (iii) the Madurai Block, and (iv) The Trivandrum Block.

The NGB consists of orthogneisses, charnockites, mafic granulites and high-grade metasedimentary rocks; which represents deep exposure of either Mesoarchean crust or Neoproterozoic arc terrane (Brandt et al., 2014). Elevated lands are generally occupied by large charnockitic massifs. The NGB is made up of Coorg Block, Biligiri Rangan Block

(BRB), Shevaroy Block (SB) and Madras Block (MdB); which was metamorphosed to granulite facies in late Archean to early Proterozoic (Collins et al., 2014). The Coorg Block, the oldest block of the SGT (Fig. 1, Santosh, 2020), at the western fringe of NGB is reported to be an exotic (Santosh et al., 2015) micro-continent; which comprises charnockites, gneisses and granulites (>3.3-3.1 Ga). The Mettur Shear Zone (MeSZ) separates the BRB in the west and Shevaroy Block (SB) in the east. Two stages of the magmatic event (3.3-3.1 Ga & 2.5 Ga) are recorded in BRB; which is dominantly made of charnockites, gneisses and granulites (Ratheesh-Kumar et al., 2016). The SB block consists of charnockites and gneisses; which recorded magma emplacement at 2.76-2.53 Ga (Glorie et al., 2014; Clark et al., 2009). The Nallamalai Shear Zone (NLSZ) separates the Madras Block (MdB) from the SB. The MdB consists of charnockite, migmatite, granite, gneiss, charnockite and granodiorite; shows emplacement during 2.58-2.53 Ga (Li et al., 2018). The Nilgiri Block (Fig. 1) is a discrete tectonic block that evolved through Neoproterozoic arc magmatism in a convergent margin setting (Samuel et al., 2014). The SASZ, which separates the Shevaroy Block (SB) and Namakkal Block (NkB, Li et al., 2018), is interpreted as strike-slip shear zone (Drury and Holt, 1980; Chetty et al., 2003) with basal decollement and along which PCSS is thrust over NGB (Biswal et al., 2010; Behera et al., 2019). The NkB is bordered by the SASZ at the north, the Cauvery-Bhavani Shear Zone (CBSZ) at the west and the Palghat Cauvery Shear Zone (PCSZ), at the south (Fig. 1). The NkB is dominantly comprised of charnockites, gneisses and intruded by ultramafic, ultrabasic, granites of Neoproterozoic to Neoproterozoic ages (Behera et al., 2019).

The PCSS is an east-west trending 70×400 km² major tectonic unit characterized by an anastomosing network of shear zones (Brandt et al., 2014; Chetty et al., 2017), which is bounded by Paleoproterozoic Moyar-Bhavani Shear Zone (MBSZ) and its eastward extension the SASZ, in north and Neoproterozoic PCSZ in south. The lithological assemblage consists charnockitic gneisses associated with biotite, hornblende-bearing migmatitic gneisses, which was intruded by ultramafic, ultrabasic and granite rocks of Neoproterozoic to Neoproterozoic ages. The north-western segment of the PCSS represents a discrete Meso to Neoproterozoic “oceanic domain; while the southern part, the PCSZ, is either Neoproterozoic suture or a zone of late-Neoproterozoic reworking of older Madurai block (MB) basement (Brandt et al., 2014).

The Madurai Block (MB) occurs immediate south of the PCSS, which is the largest crustal block of southern India. The MB block is divided into two sub-blocks (Neoproterozoic Western sub-block and Meso-Neoproterozoic eastern sub-block). It dominantly comprises of charnockite massifs intercalated with tonalitic/granodioritic gneisses, elongate narrow belts and slivers of metasedimentary rocks including quartzites, metamorphosed carbonates, iron formations and pelites (Behera et al., 2019; Santosh et al., 2009).

The southern boundary of the MB is marked by the Achankovil Shear Zone (ACSZ), which juxtaposed the MB with the Trivandrum Block (TB). The ACSZ is a well-defined lithological and isotropic boundary with prominent magnetic signature (Harris et al., 1996; Bartlett et al., 1998). The TB comprises dominantly of metasedimentary gneisses and khondolites. The subordinate lithologies include charnockites, calc-silicate rocks and pyroxene granulites (Santosh et al., 2009). In summary, the northern part of SGT preserves the Mesoarchean imprints. Towards the central part, the basement is prominently of

Neoproterozoic to Paleoproterozoic age; while at the southern part, Paleoproterozoic rocks dominate (Santosh, 2020).

The SGT is mainly covered by ground gravity-magnetic, aeromagnetic, seismic and magneto-telluric (MT) surveys (Reddy et al., 2003; Nagajeneyulu and Harinarayana, 2003; Harinarayana et al., 2003, 2006; Mishra and Kumar, 2005; Mishra, 2011; Singh et al., 2006; Rao et al., 2006; Kumar et al., 2009; Patro et al., 2014). Based on the aeromagnetic and gravity signatures in conjunction with geochronological data, Mishra

and Kumar (2005) inferred two stages of compressive regimes during Neoproterozoic and late Proterozoic in the PCSS. The analysis of gravity gradient data shows the absence of first-order gravity maxima along the PCSZ; which suggests the PCSZ to be an intra-cratonic litho-tectonic feature (Kumar et al., 2009). The electrical structure derived from MT survey suggests that the SGT is characterized by high-resistivity upper crustal column overlying less-resistive lower crustal column (Patro et al., 2014). The model further reveals the presence of three subsurface

Figure 2. Geological map of the study area. (Source: Geo Data Division, Geological Survey of India, Southern Region, Hyderabad); A-A' profile selected to study the gravity and magnetic response over geology and for gravity-magnetic modelling. Brown dashed lines are deep seated fault (modified from Grady, 1971). The Salem-Attur Shear Zone (SASZ), Sweta-Nadi Shear Zone and faults (black dashed line) are modified from Behera et al. (2019).

conductive feature reaching up to upper mantle depths beneath the PCSS. The MT study (Naganjaneyulu and Harinarayana, 2003) across the study area (Fig. 1) reveals low resistivity values though out the upper crust in south-eastern part of the area over charnockites and comparatively higher resistivity values in north-western part of the study area over granite gneiss.

The seismic study across the PCSS shows a four-layer velocity structure with 6.1, 6.5, 6.0 and 7.1 km/s with prominent Moho up-warp beneath the PCSZ (Reddy et al., 2003). The seismic tomography study indicates average crustal thickness for SGT is 36 km and seismic velocity is 6.4 km/s (Rai et al., 1993). The study from flexure inversion analysis reveals (Ratheesh-Kumar et al., 2016) that the NB has an average crustal thickness of ~41 km, the BRB has an average crustal thickness of 38 km; while the PCSZ is marked by a distinct zone of a lower crustal thickness (~32 km). The variation in crustal thickness is not evident across the SASZ and derived thickness from flexure inversion analysis is ~33 km (Ratheesh-Kumar et al., 2016). The isostatic study indicates that crustal thickness around the SASZ is ~35-36 km (Kumar et al., 2009). The seismic study in northern part of the SASZ (near Bomidi, Fig. 2) indicates a four-layer velocity section with Moho depth of ~42 km.

The density values of the rock samples in the western part of SGT across Bavali Shear Zone were reported earlier (Radhakrishna et al., 2003), but the density and susceptibility values of the rock samples from the study area is not yet reported. In fact, susceptibility values of the rock samples from SGT in published literature are very few.

Geological Set Up of Study Area

Physiographically, the study area (Fig. 1) represents an undulating terrain encompassing Shevory hill (1630 m, maximum elevation), Kolli hill (1415 m, maximum elevation) and other hillocks like Chalk hill, Kanjamali hill. Geologically (Fig. 2), the area is covered by rocks of the age group from Archaean to Neoproterozoic. The Charnockite group of rocks and Peninsular Gneissic Complex (PGC) are two prominent geological units in order of abundance. The Charnockite Group consists of charnockite, banded magnetite quartzite (BMQ), amphibolites, and pyroxene granulites. While, Peninsular Gneissic Complex (PGC) consists of hornblende biotite gneiss, hornblende gneiss, and biotite gneiss (GSI, 1995). The mafic-ultramafic complex near Salem (Fig. 2), in Shevaroy Block, which outcrops as semi-circular to elongated body, is formed by altered ultramafic rocks like dunites, peridotites, pyroxenites, gabbros, amphibolites and quartzo-feldspathic alkaline rocks of Neoproterozoic age (Yellappa et al., 2019). The complex is known as Chalk hill of Salem (Fig. 2), which is located 7 km NE of Salem town on the Salem–Bangalore highway. The complex is compared with Alaskan-type complex and is well known for its magnesite potential (Yellappa et al., 2019). The shonkinites in the vicinity of the ultramafic complex reported with crystallization age of ~820 Ma and alkaline magmatism associated with it took place along an aborted rift (He et al., 2015). The Kanjamalai Mafic Complex (KMC) is another small but crucial geological unit. It is a mafic relic semi-circular elevated body comprising garnetiferous mafic granulites and other high-grade gneisses interfolded with BMQs (Mohanty and Chetty, 2014). There are granites that occur extensively as broad intrusive at both the sides (north and south) of the hill. The reported age of this complex is late

Archean (2500 Ma). The KMC is suggested to be dismembered from other mafic/ultramafic complexes of the NGB and originated from depleted mantle source at Neoproterozoic in MORB setting (Noack et al., 2013). Existence of a possible detachment zone in the north-western part of the KMC separating contrasting litho-structural unit is also reported (Mohanty and Chetty, 2014). In the south-western part of the study area, an anorthosite band is exposed, which is a part of Sittampundi Anorthosite Complex (SAC). The Neoproterozoic SAC is located at ~80 km SSW of Salem town (Fig. 1 & 2) which largely preserve the igneous stratigraphy. From the base to upward, the complex comprised of dunite, pyroxenite, anorthosite and meta-gabbro (Mohan et al., 2013). In the north-western part of the study area, small granitic bodies occur, which are part of the Sankaridurg granite (Chetty et al., 2016) emplaced between 0.6-0.4 Ga (Behera et al., 2019). A diverse sequence of mafic and ultramafic assemblages, gneiss, charnockite, pyroxene granulites, and banded magnetite quartzites are exposed along the SASZ. Majority of the rock types around the SASZ are highly deformed and converted into mylonites (Yellappa et al., 2019). The Sweta Nadi Shear zone, trending in ENE-WSW direction, which is running through the southern part of the study area, reported by Behera et al. (2019) but details are not available. The geophysical studies addressing the shallow crustal structure of Shevaroy Block, the SASZ or Nammakal Block (NB) is hardly available in public domain.

Methodologies and Principle

Gravity Data Acquisition and Processing

We have acquired high-resolution gravity and magnetic data along all the accessible roads available in 1:50,000 scale topographical map of the study area. A total of 1700 observations were performed in 4320 km² area (Fig. 3). The station positions and elevations were determined using differential GPS (DGPS) instrument. Post-processing technique was applied to obtain the elevation of each station which resulted in mm level accuracy. Highly rugged hilly terrain and dense forest at places hindered station occupancy. CG-5 gravimeter and GSM-19 Proton Precession Magnetometer were deployed for simultaneous measurement of gravity and magnetic data along with station elevations through DGPS. All the gravity stations were tied with IGSN-1971 gravity base established at Salem, Tamil Nadu by Geological Survey of India (GSI). We had applied linear drift correction on gravity data on a daily basis. After applying Free-air correction, we have used the standard crustal density of 2670 kg·m⁻³ for Bouguer corrections. The latitude correction was performed using International gravity formula (1980). The terrain correction was necessitated due to the fact that the area covers two major hills and characterizes undulating landscape. The GEOSOF software was used for terrain correction. The Shuttle Radar Topography Mission (SRTM) data (<https://gdex.cr.usgs.gov/gdex/>) was used to prepare regional elevation grid. Local elevation grid was prepared by merging the elevation of each gravity station with SRTM data. The corresponding values of terrain correction for each station were assigned to the measured gravity values (Mishra, 2011; Kumar et al., 2011). The corrected gravity data were gridded with a cell size of 1000m using minimum curvature technique (Radice et al., 2017).

Figure 3. Gravity-magnetic stations overlaid on topographic map of the area. White dot represents gravity and magnetic stations.

Power Spectrum Analysis of Gravity and Magnetic Data

Generally, potential field (gravity & magnetic) data represents the superposition of the anomalies of various frequencies associated from the sources at different depths. The power spectrum analysis of the

gravity and magnetic data has been found very useful for assessing the approximate depth of the causative bodies (Spector and Grant, 1970; Blakely, 1996; Ganguli et al., 2020 a, b; Kumar et al., 2020b; Sahoo and Pal, 2020). The power spectrum of potential field data provides a correlation between finite depth sources of the bodies and finite range of wavelength using the relationship $P(w) = A \exp(-2|w|h)$, where $P(w)$ is

the power spectrum, A is the constant for randomly distributed source, w is the wave-number; h is the depth to the source (Ganguli et al., 2019).

The slope of the logarithm power spectrum as a function of wave-number provides the depth to the of causative sources. The slope at smaller wave-numbers provides the depth of deeper source and subsequent slopes at higher frequency estimate the depth to the shallower sources.

Residual and Regional Analysis of Gravity Data

Residual of gravity data was carried out to analyze the gravity response of shallow causative sources. The wavenumber analysis was applied to extract the regional and residual component from Bouguer gravity (Spector and Grant, 1970; Mishra, 2011; Ganguli et al., 2020a,b).

The regional anomaly map brings out the deeper crustal fabrics. Upward continuation filter at a different height, i.e., 5 km, 10 km, 15 km, and 20 km was applied to understand the depth persistence of various anomalies and deeper crustal fabrics. The resulting gravity field from an upward continuation level of 'Z' retains anomalies from sources below a depth of $Z_0=Z/2$, whereas sources above are more attenuated (Jacobsen, 1987; Lyngsie et al., 2006).

Horizontal Derivative of Gravity Data

The horizontal derivative map of the potential field data is useful in delineating the boundaries of abrupt lateral changes in density (Blakely et al., 1996; Pal et al., 2015, 2016; Narayan et al., 2017; Kumar et al., 2020b, c). In the process, short-wavelength anomalies are enhanced, and the gradient is located directly over the edges of the density discontinuity. The horizontal gradient map is rather simple to interpret and requires no assumption about the source parameters (Pal and Majumdar, 2015; Sahoo and Pal, 2019; Chouhan et al., 2020a, b).

Magnetic Data Acquisition and Processing

The acquired ground magnetic data were corrected for diurnal effect and IGRF variation (2015 epoch). The magnetic data was gridded by applying minimum curvature algorithm with the grid cell size of 1000 m. The amplitude and anomaly pattern of magnetic anomaly map or Total Intensity Magnetic (TMI) map is a function of i) susceptibilities of the rock units, ii) magnetic latitudes of their occurrence, and iii) the orientation of the elongated axis of the geological body with reference to the magnetic meridian. The magnetic response of a magnetic-body near the magnetic equator will appear quite different from magnetic signatures at middle latitudes or poles. Average magnetic inclination value for the study area is 9.8° ; hence the survey area is near to the magnetic equator, and the geomagnetic field is mostly horizontal. In case of induced magnetization, a magnetic source close to the magnetic equator opposes the earth's geomagnetic field, and a negative (low) anomaly is observed (Dobrin and Savith, 1988; Mishra, 2011). To negate the complexities due to the bipolar nature of the anomaly, we have used Reduced to Equator (RTE) transformation operator. The RTE magnetic anomaly (MARTE) map is shown in Fig. 6. In general, for the present survey area, the lithounits with ferromagnetic mineral content (high susceptibility) will give a magnetic low, and lithounits with diamagnetic mineral content will provide a magnetic high (Ganguli et al., 2019, 2020a,b).

Euler Deconvolution

A comprehensive treatment of Euler Deconvolution (ED) is provided by Blakely (1996), Reid (1990), Reid & Thruston (2014). The technique mainly responds to gradients in the potential field data. It effectively traces the edges and estimates depths of the causative sources without any prior information of the source magnetization or remanence (Kumar et al. 2018, 2019; Horo et al., 2020).

The Euler homogeneity equation can be expressed for the potential field as follows.

$$(x-x_0)\frac{\partial T}{\partial x} + (y-y_0)\frac{\partial T}{\partial y} + (z-z_0)\frac{\partial T}{\partial z} = -N(B-T)$$

Where (x_0, y_0, z_0) are the coordinates of the source location; Total field T is measured at the observation point (x, y, z) and B is the background field; N indicates the structural index (SI) and relates to rate of change of potential field with distance (Reid et al., 1990), which characterizes source geometry. The source points resulting from solutions of ED are positioned at the border of density/susceptibility inhomogeneities.

The ED is solved within a grid of gradient values and field values. The SI varies from 0 to 3. The window size (WS), structural index N , and depth tolerance (d) are three important parameters for estimating best source locations.

Gravity-Magnetic Modelling

The gravity-magnetic joint modelling was attempted along the profile A-A' (Figs. 2 & 5) as it cut across the majority of the significant gravity-magnetic anomalies and geological features. The strike length of the profile selected for modelling is 92 km, and the maximum wavelength of the gravity anomalies is ~ 25 km. So we have considered 20 km vertical crustal section; because it appears that the causative sources of the anomalies are confined within 20 km. In joint gravity-magnetic modelling, it is assumed that gravity-magnetic anomalies have the same source. The aim of simultaneous determination of density and magnetization distribution is to derive geologically realistic model and reduce the non-uniqueness of the model (Gessner et al., 2016; Singh et al., 2014; Tiwari et al., 2006). The gravity-magnetic joint model is initially constrained using available geophysical and petrophysical data (de Castro, 2011), to reduce the ambiguity and to produce a realistic geological section. The magnetic data is dominated by high-frequency anomalies than gravity data, so more emphasis was given on magnetic anomalies to arrive at shallow crustal configurations. Here, we have considered induced type magnetization as RTE map indicates mainly induced type magnetization. A north-south oriented seismic line (Fig. 1) which terminates at Bonmidi (Fig. 2) shows a four-layer crustal section (Reddy, 2003). The initial crustal configuration is derived from the above mentioned seismic section. The upper crustal and mid-crustal velocity values are 6.15 km/s and 6.55 km/s with an interface at ~ 12 km. The density values of the crustal layer are determined using nonlinear velocity density regression analysis of Christensen and Mooney (1995). The density and susceptibility values of the shallow crustal rock units were assigned according to data collected in the present study on petrophysical parameter and outcrop geology. This was followed by forward modelling performed using GM-SYS, 2004 software in which

interactively crustal model is adjusted, and corresponding real-time response of the combined gravity-magnetic data is observed. Different sources were introduced in the upper crust for better fitting between the observed and calculated magnetic anomalies (de Castro et al., 2014; Pilkington, 2006). After obtaining a satisfactory fit, the final results were derived by applying an optimization scheme within the logical limits of geology and tectonics. The calculations of gravity-magnetic model responses were adapted from Talwani et al. (1959), and Talwani and Heirtzler (1964). The optimization algorithm adopts a 2D flat earth model, which uses USGS SAKI implementation (Webring, 1985) of the Marquardt inversion algorithm (Marquardt, 1963) to linearize and invert the data sets. The density and magnetization can be inverted jointly or separately, keeping the other fixed, during the iteration process. The model geometries were kept fixed during the inversion process. The RMS errors between computed and observed data are approximately 1.2 and 19.285 for gravity and magnetic data, respectively. A relatively poor fit for magnetic data is expected as the magnetic field is characterized by the complex vectorial character in comparison to scalar behaviour of gravity field (Bauer et al., 2003; Ramadass et al., 2006; de Castro, 2014).

Collection of Rock Samples

During the gravity-magnetic survey, we collected a total of 280 rock samples from various demonstrative lithological units of the study area for density and susceptibility measurements (Table 1). However, few specimens of charnockites, banded magnetite quartzite, granite gneiss with skewed density and susceptibility values are omitted.

Results

Density and Susceptibility of the Rock Samples

The lithounits of the study area are of Archean to the Proterozoic age. The average density of the rock samples for the study area varies from

2670-3250 kg·m⁻³. The density values for the rest of the lithounits are more than 2800 kg·m⁻³ except granite gneiss, and this is a typical signature of high-grade metamorphic terrain (Table 1). Charnockite is the most abundant lithological unit of the area with an average density of 2830 kg·m⁻³, but the susceptibility of the rock unit varies widely. The samples representing banded magnetite quartzite (BMQ) registered the highest density (an average density of 3.25 gm/cc) and highest susceptibility values (0.0062-0.0078 CGS unit). The granite-gneiss exhibit low-density (an average density of 2670 kg·m⁻³) and lowest susceptibility values (0.000003-0.00055 CGS unit). The measured density values of dunites are on the lower side than the expected, probably because the exposed dunites are serpentinized.

Based on the measured physical properties (density and susceptibility) from the collected rock samples, a map showing the distribution of susceptibility and density was prepared for a corroborative understanding of the physical properties (Fig. 4). The susceptibility map shows moderate to high susceptibility zone encompassing Salem, Shevaroy hill, Pallipatti in NNE-SSW direction, but this zone is represented by low to moderate density rocks. At Kanjamalai hill high susceptibility zone is associated with high-density lithounits. At Kolli hill low to moderate susceptibility zone is associated with moderate to high-density lithounits. At the south-western part, high-density rocks occur with low susceptibility values. Geologically charnockite is the dominant lithounits in both Shevaroy and Kolli hills, but the charnockites of Shevaroy hill show moderately high susceptibility; whereas, for Kolli hill it shows low to moderate susceptibility values. It may be noted that the magnetic character of rock is determined by several factors; but most important are 1) the bulk geochemistry of the rock including the amount of Fe content with different oxidation state, and 2) thermal-heating history; which lead to variable susceptibility of the same rock type.

Bouguer Gravity

The Bouguer gravity anomaly primarily reflects subsurface density contrast and in turn, reveals subsurface geology and structure. The

Table 1. Density and susceptibility values of the representative rock samples of the study area. BMQ: Banded Magnetite Quartzite, HBG: Hornblende Biotite Gneiss, HG: Hornblende Gneiss

Sl. No	Rock types/mineral	No. of samples	Density, D, (gm/cc)		Magnetic susceptibility (S) range in CGS units ($\times 10^{-6}$)
			Range	Average	
1	Charnockite	136	2.70-3.16	2.83	10-2853
2	BMQ	04	3.02-3.51	3.25	6200-7800
3	Mafic Granulite	50	2.75-3.39	3.03	11-1908
4	Meta Gabbro	16	2.82-3.40	3.07	15-1981
5	Pyroxenite	05	2.99-3.28	3.16	53-218
6	Gabbro	03	2.1-3.17	2.94	37
7	Dolerite	03	3.00-3.10	3.04	967-1771
8	Granite Gneiss	22	2.56-2.75	2.67	3-550
9	HBG	12	2.68-3.12	2.84	6-908
10	HG	07	2.65-2.93	2.80	8-338
11	Dunite	02	2.73-3.07	-	97-280
12	Magnetite	01	2.57	-	
13	Ultramafite	06	2.91-3.25	3.14	12-1190
14	Amphibolite	04	3.09-3.16	3.12	17-1311

Figure 4. Circular dots indicate location of rock samples collected from the study area for understanding the variations of the density and susceptibility. Susceptibility image map is generated using susceptibility values of all the samples. Circular dots with different colours are used to indicate density variation at all the sample locations, which are overlaid on the susceptibility image map for combined representation.

Figure 5. Bouguer Gravity map of the study area. The warm colour indicates gravity high zones and the lighter colour indicates gravity low zones. GH-2: gravity high zone; GMH1, GMH2: gravity moderate to high zone; GL1: gravity low; GLL1: gravity low linear; GCH1: gravity high closure; GG1: gravity gradient. A-A' profile selected to study the gravity and magnetic response over geology, and for gravity magnetic modelling. The SASZ and Sweta Nadi shear zone are modified after Behera et al. (2019). The black dashed line indicates fault, which are modified after Behera et al. (2019). See the circular gravity high over Chalk hills, and NEE-SWW trending gravity liner low corresponding to the SASZ.

gravity anomaly map (Fig. 5) shows an overall variation of 75 mGals with the lowest value occurring in the south-western part of the study area (-116 mGals) and highest value happening near Chalk hill (-41 mGals). Based on the gravity values and anomaly pattern, gravity map is classified into the high, moderately high and low anomaly zone.

The moderate-high gravity anomaly zone of broad elliptical shape marked as GMH1 (Fig. 5) is observed over the elevated land of the Shevaroy hill, which is represented by charnockite group of rocks. A circular gravity high (GCH1) surrounded by GMH1 at Chalk hill is the distinct anomaly pattern. It demarcates the boundary of the altered ultramafic unit, which is veined by secondary magnesite deposit. Anomaly pattern suggests a circular plug-like body which might have emplaced on the basement through weak planes developed due to shearing/rifting. It is further interesting to notice that GCH1 almost occurs at the junction of two deep-seated faults (Grady, 1971); however, those faults do not find signatures in isogals pattern.

A prominent linear gravity low to moderate (GLL1, Fig. 5) anomaly zone running in ENE-WSW direction suggests a high strain sheared zone which indicates sheared gneisses and may represent gravity expression of the Salem-Attur Shear Zone (SASZ). The GLL1 takes a northward swing from Bellur and has a width of ~12-13 km. However, the northern extension of the GLL1 shows moderate gravity anomaly values which indicate less sheared rocks. There are pockets of some circular high-frequency closures within the GLL1, which are probably pre/post-shearing emplacement of moderate to high-density rock units.

A low gravity anomaly (GL1, Fig. 5) with gravity value ranging from -100 to -116 mGals at the south-western part indicates the occurrence of a low-density granitic pluton as the plutons are generally associated with moderate to large (negative) gravity anomalies (Ranganai et al., 2019). The pluton is the extension of neighboring Sankaridurg granitoids (Chetty et al., 2016). The abrupt termination of NNE-SSW isogals associated with the GLL1 at the eastern part of the GL1 suggests that granitic emplacement was a post shearing event, probably related to 600 Ma tectonic event (Ghosh et al., 2004). Another gravity low 'GL2' is the northward continuation of GL1 and indicates northward extension of the same granitic plutons. The depth extension of gravity plutons represented by gravity lows is greater than the depth extension of the shear zone as revealed by wavelengths and amplitude of the isogals.

The Kanjamali Mafic Complex (KMC), bears no significant signature in the gravity map (Fig. 5). Probably, the high-density mafic granulites have minimal depth extension, and gravity low caused by the occurrence of granitoids at both sides of the hill masked the signature of the mafic bodies. It may also indicate that the base of the KMC is occupied by granitoids. However, the isogal pattern across the KMC abruptly changes as NE-SW trending isogals suddenly changes to N-S trending isogals.

A linear increase of gravity values is observed across Kolli hill from NW to SE as represented by moderate to the steep gradient of gravity contours (GG1) at the southeastern part. The gravity contour trends in NEE-SSW direction and sensitive to the trend of GLL1. Some geologically demarcated fault also follows the same trend (Behera et al., 2019). The moderate to high gravity at the southeast region is marked as GMH2. Based on the difference of isogals pattern and values between GMH1 (Shevaroy hill) and GMH2 it is suggested that Kolli hill represents a distinct high-density crustal unit. The anomaly pat-

tern and amplitude of gravity high GH2 at the southeast corner of the study area indicate the occurrence of a high-density body at the very shallow crustal level. Apart from above mentioned broad anomalies, few high-frequency anomaly patterns are representing shallow causative source in gravity map, will be discussed in the context of residual gravity anomaly map.

Magnetic Anomaly

The magnetic anomaly map shows several distinct moderately-high to high zones and moderately-low to low zones (Fig. 6). The north-western part is represented by medium to high anomaly (MH-I) zone with NE-SW strike, which indicates the presence of para to the diamagnetic lithounit. The geological map shows that the area enclosed by the MH1 is represented by granite-gneiss. The most prominent moderate to high anomaly zone running in ~E-W direction is marked by MH-II. This zone follows the trend of SASZ. The MH-II is dotted by few high-frequency, low-magnetic anomalies suggesting the presence of mafic lithounits within gneisses. The KMC is manifested as a low-magnetic enclosure within MH-II. The petrological analysis of the rock sample from KMC shows that ortho and clinopyroxenes are the dominant minerals (Noack et al., 2013). It suggests that rock units comprising pyroxene minerals predominantly explain the low-magnetic anomaly in the study area. The ultramafic complex of Chalk hill is manifested as moderate to high amplitude anomaly. The chemical analysis of dunites from Chalk hill shows that SiO₂ and MgO are dominant oxides (Yellappa et al., 2019). It suggests that high anomalies are the manifestation of rock with poor Fe content. The magnetic low zone ML-I is mainly attributed to charnockites. The high amplitude closures are indicative of the presence of mafic/ultramafic rocks within charnockites. The ML-II is similarly attributed to mafic charnockites. The zone represented by MH-III is the manifestation of exposed granite gneiss. A moderate to low anomaly ML-III is another prominent anomaly zone. The magnetic low 'ML-III' is caused by the presence of mafic to ultramafic unit as it corroborates well with GH2 (Fig. 5), though it may be concealed as the mafic/ultramafic rocks are not apparent in the geological map (Fig. 2). The other smaller magnetic high anomalies mostly represent silicic lithounit such as granite gneiss, and moderate anomalies represent hornblende biotite gneiss or hornblende gneiss. The smaller order magnetic lows are the manifestation of mafic units.

Power Spectrum Analysis of Gravity and Magnetic Data

The analysis of gravity power spectra indicates that 15 km and 2.0 km are the cut-off wavelengths (Fig. 7a), which can be used for separating deeper and shallower source, respectively. A Butterworth band-pass filter, using a passband wavelength of 15 km and 2.0 km, has been applied to gravity data to eliminate the effect of large-scale deeper causative sources and near-surface noise. The power spectrum of gravity delineates three slope sections that indicate depths of the density interfaces at 8.0 km, 3.0 km, and 1.0 km (Fig. 7a). The deepest interface probably represents the depth of the ultramafic complex at Chalk hill. The second density interface may be indicating depth extension of the mylonites of the SASZ and third interface may be indicating the depth of some mafic units.

Figure 6. Reduced to Equator (RTE) magnetic anomaly map. MH-I to MH-III are magnetic high; ML-I to ML-III are magnetic low; white lines are tentative boundaries of different zones. The SASZ is marked after Behera et al. (2019). The black dotted lines indicate fault also marked after Behera et al. (2019).

Figure 7. Radially averaged power spectrum of (a) gravity data and (b) magnetic data. h_1 , h_2 are depth to the density/magnetic interfaces. See text for details.

Figure 8. Residual gravity map. GRH-1 to GRH-19 indicate residual gravity high zones; GRLL1 to GRLL9 indicate gravity residual low linear interpreted as minor shear. The Salem-Attur Shear Zone (SASZ), Sweta-Nadi shear zone and faults (black dashed line) are modified from Behera et al. (2019).

The power spectrum of magnetic delineates two linear slopes (Fig. 7b) that indicate the depths of magnetic interfaces at 3.0 km and 1.0 km. The first interface may be indicating average depth extension of KMC and the second interface may be stating the depth to some local mafic rock units.

Residual Gravity Anomaly

The boundaries of residual gravity highs and the axis of the linear gravity lows are marked in Fig. 8 with the dashed line. Most of the anomalies are not apparent on the Bouguer gravity map (Fig. 5). We have interpreted linear gravity lows as the shear, and many of them show good corroboration with the geological marked shear zones. The circular residual gravity low (GRLL2) anomaly may represent an occurrence of low-density granitoids surrounding the Chalk hill. The linear anomalies GRLL3, GRLL4 running through Kanjamalai hill and south of Bellur follows the geological trend of SASZ. At southeastern part, near Kolli hill, the eastern flank of GRLL7, GRLL8, and GRLL9 are in good corroboration with the geologically marked shear zone. The other shear brought out from the residual gravity map includes GRLL1 and GRLL9.

The circular residual gravity closure (GRH3, Fig. 8) is also well represented in the Bouguer gravity map (GCH1, Fig. 5). It indicates the deeper causative source of the anomaly. The other high(s) marked as GRH1, GRH2 etc., probably represent high-density mafic units which cannot be directly correlated with the exposed geology as in many cases mafic bands are concealed. The GRH8 anomaly zone reflects the high-density mafic unit of Kanjamalai hill, which indicates very shallow depth extension of the mafic units. The anomaly GRH9 may indicate the presence of an assemblage of high-density lithounits like pyroxenite/meta gabbro under the exposed anorthosite (Fig. 4). It is interesting to notice that GRH9 and GRH10 occur along the north-south trend, which may indicate the extension of the SAC. Another residual gravity high band in NE-SW direction encompassing GRH12 is a conspicuous feature of the residual gravity anomaly map. The trend well corroborates with the geologically marked Sweta-Nadi shear Zone. It may indicate disposition of high-density lithounit along the shear zone. A very thin band of banded magnetite quartzite and pyroxene granulite are exposed with NW-SE trend (Fig. 2), in the area enclosed by GRH16. It indicates the occurrence of pyroxene granulite or BMQ within the area encircled by GMH16. The GRH13 is a prominent residual gravity high band in the south of Kolli hill, which indicates the occurrence of high-density rock unit as the majority of the rock samples pertinent to GRH13 shows density values 2.8 gm/cc or more (Fig. 4).

Regional Gravity Anomaly

The regional gravity maps (Fig. 9) depicts enhance response from the sources below 2.5 km, 5 km, 7.5 km, and 10 km, respectively. Fig 9(a) represent 5 km upward gravity map where signatures of NEE-SWW trending gravity low are present but subdued in the surface map (Fig. 5). The map shows (Fig. 9) that the circular gravity high (GUP-5, GUP-10, Fig. 9a & b) at Chalk hill dies out at 15 km upward continued map (GUP-15). It indicates that the ultramafic unit is hosting magnesite deposit of limited depth extension which extends maximum up to the ~7.5 km. The SASZ represented by linear gravity low

is also not traceable at GUP-15. It suggests SASZ does not continue up to mid-crustal depth. The gravity high at the southeastern part and gravity low at the north-western part of the study area is easily traceable up to 20 km upward continued map (GUP-20), which suggests the continuation of the anomaly sources up to mid-crustal depth. Further, GUP-15 and GUP-20 suggest the systematic variation of upper crustal density along NW-SE direction; where NW part is represented by the low-density acidic rock in the middle to lower crust, and SE part is represented by the high-density mafic rock in the upper to lower crust. The part of the anomalies (both low and high) may also be attributed to the variation of crustal thickness as it appears from the GUP-20 that at the southeast part crust is thinner compared to the north-west part. The regional trend of the anomalies is in a NE-SW direction. The moderate gradient of isogals in the central part of the GUP-15 and GUP-20 may indicate that the contact is faulted or thrust.

Horizontal Derivative of Gravity Data

The horizontal derivative of gravity data has been computed by using Geosoft software and map is presented in Fig. 10. The most striking feature of the map is the linear gravity gradient observed in ENE-WSW and NNE-SSW directions. The trend in the eastern part of the study area follows the trend of the SASZ, but from the central part, it swings towards the north-west. It indicates that there is abrupt lithological discontinuity along the area marked by the white dashed line in Fig. 10. It incorporates mafic/ultramafic hill like Kanjamalai hill and Chalk hill.

Euler Deconvolution

For the present study, we seek to estimate the edges of the spherical type of source at Chalk hill, which is causing high gravity closure. The solutions derived from gravity data are presented in Fig. 11(a). The solutions indicate that ultramafic units comprising Chalk hill is a sphere-like structure with the edge of the source ranges from 4-8 km.

From magnetic data, we obtained a good cluster of solutions for structural index (SI) '3', which designates spherical geometry (Fig. 11b). The tightest clusters of solutions were found to be associated with the KMC. It suggests that the KMC is a magnetically spherical structure with depth to the edge of the source varies from 2.5 to 5 km. The other solution sets are observed at the northeast of Shevaroy hill, north of Bellur, south of Kolli hill, and in few other places. This solution sets suggest the occurrence of the magnetically anomalous sphere-like structure.

Analysis of Gravity and Magnetic Signatures Along a Profile

Profiles A-A' is selected in the NNW-SSE direction, which cuts across the geological units to analyze the gravity and magnetic anomaly responses over different lithounit along the profile AA' (marked in Fig. 2 and 5). The Fig. 12 depicts the variation of gravity, residual gravity, regional gravity and magnetic anomalies along the profile.

The gravity anomaly in profile A-A' shows a total variation from -100 mGal to -43 mGal. Two distinct feature observed in the profile, a gravity high (GH1) at Chalk hill and a gravity high gradient (GHG1) at the southeast part of the profile. Wavelength and amplitude of the

Figure 9. Regional gravity map. Gravity map upward continued (a) to 5 km (GUP-5), (b) to 10 km (GUP-10), (c) to 15 km (GUP-15), (d) to 20 km (GUP-20).

Figure 10. Horizontal gradient of gravity data. White line encircles the maxima. See the ENE-WSW to NNE-SSW trending gravity maxima.

anomaly GH1 suggest the occurrence of the high-density body at the surface and of limited depth extension. GHG1 suggests contact between the comparatively low-density crustal unit and the high-density crustal unit, which may be associated with a fault. It also suggests that crust may be tilted towards NW. The high-frequency components in the gravity profile are amplified in the residual gravity profile. Residual gravity profile shows high over Chalk hill, which reconfirms the fact that maximum component of GH1 is contributed from the shallow source. At SE part of the profile, a residual gravity high is observed. It indicates

the occurrence of the high-density unit at this place. Upward continuation to 15 km is considered as regional gravity profile as it is devoid of any high or moderate frequency component. The profile shows moderate gradient ($m_1=28^\circ$) at NW part of the profile, high gradient ($m_2=37^\circ$) at the southeast part of the profile and very gentle gradient at the central part of the profile, with gravity value ranging from -104 mGal to -63 mGal. The steeper gradient in southeastern part suggests a change in upper-crustal lithology and the causative source of Bouguer gravity high at SE part is deeper. The seismic study shows crustal thick-

Figure 11. Euler solution from (a) gravity data with Structural Index (SI) 2, window size (WS) 10, depth of tolerance (DT) 5%; and from (b) magnetic data, with SI 3, WS 10, DT 8%.

ness in the northern part of the study area near Bommidi is ~41–42 km (Reddy, 2003). The Moho depth variation across the area inferred from the isostatic study is 36 km to 40 km with relatively thicker crust in the northern part of the area (Kumar et al., 2011). Upward continuation to 15 km (Fig. 10) was used for estimating crustal thickness using the formula $T = 31.6 - 0.078 \Delta g$, (Qureshy, 1967; Radhakrishna, 2003). It shows that crustal thickness varies from 40 km to 36 km from NW to SE, which may be due to thrusting of the SW part over the NW part. The magnetic profiles show high over gneiss and low over mafic rock units. However, GH1 is not associated with any definite magnetic signature.

Gravity-Magnetic Joint Modelling

The gravity-magnetic joint model (Fig. 13) shows that the ultramafic unit hosting magnesite deposit at Chalk hill has depth extension of ~7.5 km with a density (D) of $3130 \text{ kg} \cdot \text{m}^{-3}$ and susceptibility (S) value -0.0141 SI unit. Here, it is to inform that depth extension of the gravity anomaly GH1 is mainly constrained from the results of Euler Solutions (Fig. 11(a)). The initial density value is assigned from the measured density value of dunite (3.07 gm/cc).

At southeastern part, the model brought out the unexposed contact

of two crustal units with different density and susceptibility. The upper crust up to Kolli hill (block-13) with D value of $2762.7 \text{ kg} \cdot \text{m}^{-3}$ and S value of 0.0009 SI unit, probably represents silicic moderate-density rock units. While the crustal unit, towards the SE part of the profile starting from Kolli hill (block-12) probably represents basic high-density rock unit (D: $2801.8 \text{ kg} \cdot \text{m}^{-3}$ S: 0.0039 SI unit). A high-density rock (block-10) at SSE part of the profile represents a mafic unit, probably meta gabbro. The low-density unit (block-6) at the eastern part of GH1 probably represents mylonites, and it extends up to ~4 km depth. This is the depth extension of the SASZ, which have an average width of 18 km. Some mafic rock unit with density $2870.0 \text{ kg} \cdot \text{m}^{-3}$ intrudes the SASZ. At the western part of the profile, the low-density unit ($2671.4 \text{ kg} \cdot \text{m}^{-3}$) probably designates granites or sheared gneiss.

Discussions

Gravity-Magnetic Signatures of the SASZ and Blocks Across it

The present study area is placed in a significant tectonic environment between two crustal blocks, Shevaroy Block (SB) at north, and

Figure 12. Gravity and magnetic responses over different geological lithounits along the profile AA', m_1 , m_2 slope; GH1- Gravity high; GMG1- Gravity moderate gradient; GHG1- Gravity high gradient. Moho depth calculated using the relation $T = 31.6 - 0.078 \Delta g$ (Qureshy et al., 1967).

Namakkal Block (NkB) at the south, which is divided by the SASZ. The gravity map shows that the SASZ represents a distinct anomaly pattern. The shear zone is narrow parallel, planar, sub-parallel domain, where strain is concentrated relative to their surrounding regions (Ramsey, 1980). The SASZ, an imbricate thrust with varying dips, preserves a dextral sense of movement, but individual domain exhibits variation in the sense of movement from the bulk sense and strain progression towards central part (Chetty, 1996; Bhadra, 2000; Kumar and Prasannakumar, 2009; Behera et al., 2019). Our study shows that the SASZ is reflected in gravity map (Fig. 5) as a moderately low zone (GLL1) with elongated isogals trending in ENE-WSW direction. The low linear anomalies delineated from residual gravity map are predominantly trending in NE-SW directions (Fig. 8). The magnetic map shows magnetic highs along the shear zone with pockets of magnetic lows. However, NNE part of the shear zone is represented by magnetic low (ML-I). It indicates that the SASZ is predominantly composed of nonmagnetic rock units with mafic intrusive up to Bellur. The isogals pattern of the GLL1 (Fig. 5) indicates that the northern part of the SASZ starting from Bellur is less sheared and characterized by mafic rocks. The maximum vertical extension of the shear zone as revealed by gravity modelling is ~4 km. It seems that the evolution of the SASZ is a manifestation of thin-skin tectonism.

The geological study by Behera et al. (2019), suggests that the Shevaroy and Namakkal blocks share similar lithologies and common magmatic deformational histories as charnockite magmatism took place between ca 3.2-2.6 Ga. The blocks were contiguous before the Salem-Attur shear zone affected them at ca. 2.0 Ga and the Namakkal block

over-thrusted on to the Salem block in N-NNE direction. Clark et al. (2009) estimated the weighted mean age (zircon, U-Pb-Pb, isotopic data) of two charnockite samples from (50 km north of Salem, Fig. 2) Shevaroy Block as ~2482-2473 Ma. The charnockite samples from Kolli hill (in NkB; Fig. 2) indicate that the age (Sm-Nd isotopic analysis) of the samples varies from 2.6-3.2 Ga (Tomson et al., 2013). These two studies indicate that charnockite massif from Shevaroy and Namakkal block may have different magmatic history. The different pressure-temperature condition was reported at Shevaroy hill and Kolli hill (Raith et al., 1983) for the charnockite massifs. For Shevaroy hill, temperature-pressure was 680 °C and 7.5 kb, while for Kolli hill, it was 680 °C and 8.4 kb. It suggests that mafic rocks of Kolli hill are of deeper crustal origin.

The geochronological studies (Clark et al., 2009; Mohan et al., 2013; Santosh et al., 2012, 2013) suggest that the southern margin of the DC had witnessed subduction and arc accretion regime twice but widely separated in time. The northern part of the PCSS including NGB forms Neoproterozoic-early Paleoproterozoic subduction-accretion belt (Santosh et al., 2012); where multiple subduction systems had pulled the oceanic arcs toward the large continent with progressive closure of ocean basin (Santosh et al., 2013). The continental growth through late Archean arc magmatism in a convergent margin setting, is also suggested (Samuel et al. 2014) in the Nilgiri Block (NB). The tectonic model proposed by Santosh et al. (2013) also suggests that the rheologically weak southern margin of the DC underwent trans-crustal rifting due to extensional tectonics during Neoproterozoic partly in consequence of slab-pull force generated by down going oceanic lithosphere.

Figure. 13 Gravity-magnetic joint model along the profile AA'. Density and susceptibility values of the blocks are provided in the chart.

In the present study, gravity map shows that northern and the southern blocks of the SASZ are represented by two distinct anomaly domains (Fig. 5). Regional gravity map reveals that the north-western part of the gravity map is indicative of a dominant low and it is attributed to thick Dharwar crust. The map (Fig. 5) shows that the southeastern part of the area is represented by gravity high with isogals trending in the NE-SW direction. The gravity-magnetic modelling shows that comparatively denser mafic upper-crust is attributing for this high at the southern block of the SASZ. It indicates that a high density mafic crustal unit might have accreted to the southern margin of the SASZ through arc magmatism. The MT profile passing through the vicinity of the southeastern part of the study area (Fig. 1) shows a conductive upper crustal unit. The high-density crustal blocks, associated with high pressure, along the ancient active margins signify the up-thrusted high-grade metamorphic terranes accreted through continental collision (Fountain and Salisbury, 1981; Thomas, 1992). The gravity signatures (Fig. 5) at the southeastern part of the SASZ indicates that the rock unit of the Kolli hill probably represents high-density granulite body or continental fragment extending up to the mid-crustal depth. The isogals pattern

indicates that the continent fragment (we refer it as Kolli Block) at the south of the SASZ was probably thrust onto the Shevaroy Block. The analysis of the present study along with geochronological data suggest Shevaroy Block and Kolli Blocks are two different crustal fragments. The high-density mafic lithounits at the south eastern part (GRH12 & GRH13, Fig. 8) as observed from the residual gravity anomaly map may represent the slivers of oceanic realm. This inference may open up a debate regarding the possibility of considering the PCSS as an amalgamation of continental fragments.

The horizontal gravity map (Fig. 10) shows a strong gravity maxima in NE-SW direction encompassing the KMC and the Chalk hill. This may represent the geophysical signature of part of the trans-crustal rift zone as proposed by Santosh et al. (2014). The circular gravity high (GCHI, Fig. 5) representing the mafic-ultramafic complex (Chalk hill) near Salem is a prominent feature of the study area. It represents a high-density nonmagnetic unit and confined within the top ~8 km of the upper crust. In a recent study by Yellappa et al. (2019), suggests that the complex was formed during Neoproterozoic, which can be correlated with Alaskan-type complex. The Alaskan-type complexes are generally

uplifted fragments of the deep levels of island arcs formed as small intrusions in convergent plate margin settings. The gravity-magnetic joint modelling suggests that the emplacement of the mechanism was a forceful diapiric ascent that may be due to asthenospheric upwelling followed by rifting.

At northern part as discussed earlier, KMC is represented by moderate residual gravity high and a magnetic low. It indicates that KMC is predominantly magnetic inhomogeneity with very shallow crustal root or base of the KMC is formed by granites. Noack (2013) suggested that protoliths of KMC are derived from the Archean mafic-oceanic crust and ocean floor sediments. The model furnished by the author further proposed that KMC represent an accretionary wedge formed during Neoproterozoic–Paleoproterozoic subduction–accretion processes along the southern margin of the DC. The present study shows that the gravity-magnetic signature of the KMC does not have a spatial extension, so the tectonic significance of KMC is not well manifested in the present study.

Accretion of Terranes

In the SGT, numerous distinct crustal micro-blocks have been delineated (SGT, Ratheesh-Kumar et al., 2016). The micro-blocks were gathered along the multiple zones of ocean closure during Archean to Paleoproterozoic (Li et al., 2018). Study in the southeastern margin of Dharwar Craton indicates that two micro-blocks Shevaroy and Madras welded together along Nallamalai Suture Zone (NLSZ, Li et al., 2018, Fig. 1). The study suggests an eastward oceanic subduction and ocean closure along the NLSZ that welds the Shevaroy and Madras Blocks. The present research indicates the presence of distinct micro-blocks in terms of gravity-magnetic and conductivity (from MT study) in the southern part of the SASZ. We propose an amalgamation of a micro-block (Kolli Block) along the southern margin of SASZ, but its mechanism of the assembly to SGT needs further study.

The inference from the paleomagnetic study indicated that the Dharwar Craton (DC) and the SGT or Shevaroy Block forms a single crustal domain with high-grade rocks of SGT represent the deeper section of the DC (Dash et al., 2013). The present study shows a linear Horizontal Gradient maxima (Fig. 10), which implicates density inhomogeneity along NE-SW direction. It further suggests that this is an essential tectonic boundary separating the DC and SGT, which negates the proposition that the SGT is contiguous with the Dharwar Craton.

Conclusions

The comprehensive study using gravity and magnetic methods across the Salem-Attur Shear Zone (SASZ) delivers the following significant findings or valuable insights regarding shallow and deeper crustal architecture across the SASZ. The conclusions also provide substantial clues for deriving an evolutionary model of the Southern Granulite Terrane (SGT).

- An orderly increase of Bouguer gravity values is observed from NW to SE direction. The joint modelling of gravity-magnetic data reveals significant differences in upper crustal density and magnetization in the northern and southern part of SASZ. Crustal unit

represented by Kolli hill may have accreted along the southern margin of Dharwar Craton (DC). The SASZ has a shallow vertical extension (~4 km) and is characterized by diamagnetic rock.

- The ultramafic complex of Chalk hill appears as spherical plug type body with depth extension of ~7–8 km.

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