Research Article

Crustal Density and Susceptibility Structure beneath Achankovil Shear Zone, India

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1. Introduction

The crustal structures of shear zones in the southern part of India have attracted wide attention owing to their vital role in reconstructing the Precambrian evolution of Southern Granulite Terrain (SGT). The SGT is by far the largest exposed Precambrian deep continental crust consisting of multiple deformed Archean and Neoproterozoic high-grade metamorphic and magmatic rocks which are dissected by several shear/suture zones [1, 2]. The crustal structure and nature of large scale geological or tectonic features in southern part of SGT are not fully understood. The key to unraveling the evolution of South India, and its role in the amalgamation of Gondwana supercontinent, lies in the exposed lower crustal section of the SGT which is associated with several shear and suture zones [2–5].

The Achankovil Shear Zone (AKSZ) forms the southern tip of the SGT and separates the Madurai Block (MB) to the north and the Trivandrum Block (TB) to the south. The AKSZ plays a crucial role in Gondwana correlations and global tectonics. It provides an opportunity to understand the tectonic and geodynamic evolution of Western Ghats Escarpment (WGE), SGT and its associated lithological blocks, viz., Trivandrum and Madurai Blocks. It is also believed that the final amalgamation of Gondwanaland took place during the Pan-African, and Madagascar is placed against India in the Gondwana assembly. Such assemblage discrepancies in the SGT and their connection to Madagascar for the Gondwana reconstruction is of immense interest as the crustal architecture are still debated in terms of physical parameters (density and magnetization) and geological history.

Most of the geophysical studies in SGT involve a single transect of Vattalkundu-Kanyakumari profile [6–11] except for velocity analysis with limited seismic data from two stations by [12]. The seismic tomography and reflection studies...
brought out a high velocity upper crustal layer and upwarping below the Madurai Block. Analysis of receiver function data revealed an average crustal thickness of 43 km and 35 km beneath the Madurai and Trivandrum Block, respectively [13]. Gravity modeling across AKSZ along transects constrained with seismic results depicted a three-layer crustal model with Moho depth ranging from approximately 41 to 34 km from northwest of Vattalkundu and southeast of the Kanyakumari, respectively [7, 14]. These results together with an integration of seismic, gravity, and heat flow data suggest a highly dense and moderately conductive mantle material brought up to the mid-lower crust [10, 15]. However, the tectonic model proposed by [6] represents large compositional changes of subsurface rocks accompanied by velocity heterogeneities with crustal thinning (36–44 km) and Moho up warping from north to south. This study also successfully imaged anomalous zone of exhumation near AKSZ having transgression of exhumed rocks at mid-to-lower crustal level (20–30 km) with significant upwelling and mantle upwelling forming a complex metamorphic province.

Although SGT consists of a variety of magmatic and metamorphic lithologies, only qualitative interpretation from magnetic data is endeavored to differentiate the crustal structures among its various fragments (Ram Babu and [16, 17]). The joint interpretation of the AKSZ with gravity and magnetic datasets is lacking and has not been attempted earlier. Therefore, a detailed study of the region using multiprofile modeling is desirable to understand: (i) the three-dimensional heterogeneous crustal properties and refined architecture of the AKSZ and to understand its evolution, (ii) the geometrical variation of the AKSZ from NW-SE direction, (iii) the impact of the Western Ghat Escarpment over the geometrical variation of the AKSZ, (iv) the role of magnetization in defining the crustal layers of various lithologies, (v) the role of remnant magnetization in the SGT terrain, and (vi) the possible extension of the AKSZ in Madagascar. In the present study, the crustal structure using multiprofile modeling utilizing gravity and magnetic datasets is discussed, and a three-dimensional crustal signature from multiple profiles stacking is proposed.

2. Geology of the Study Area

The SGT is a collage of several Precambrian high-grade crustal blocks with contrasting geological and geochronological signatures separated by brittle–ductile shear/suture zones [18–24]. The Salem Block, the Madurai Block, the Trivandrum Block, and the Nagercoil Block are the four distinct crustal domains in SGT which archive the multiple magmatic, metamorphic, and deformation history of the SGT [4, 20, 25–29]. The Madurai Block in the north is separated from the Trivandrum Block by a 8–10 km wide NW-SE trending AKSZ [30, 31].

AKSZ forms the southern tip of the SGT and separates the Madurai Block to the north and the Trivandrum Block to the south (Figure 1(a)). In the past few decades, a number of studies have been carried out in AKSZ which interpreted it as a magnetic lineament [32, 33], a dextral or Sinistral Shear Zone [31, 34, 35], a zone of coaxial deformation [36], subduction zone [28, 37, 38], a collisional suture [15], reworked margin of the Madurai Block [39], a sedimentary/ back-arc basin [40], and a single/two different shear zones [2, 34, 37, 41]. The Achankovil Zone consists of a variety of magmatic and metamorphic lithologies including garnet–biotite gneiss, garnet–cordierite gneiss, khondalites, charnockite, two-pyroxene mafic granulite, calc-silicate, and quartzite [2, 23, 29, 39]. The high-grade metamorphic rocks in AKSZ are intruded by felsic plutons, mafic dykes, and mafic to ultramafic bodies [42–44].

3. Data Utilized

In the present paper, open source data sets are exploited to delineate the crustal structure of AKSZ, with an emphasis on the deeper parts of the crust. The topography data used for the analysis is taken from a high-resolution digital elevation data obtained by SRTM 90 meter elevation data (https://gdex.cr.usgs.gov/gdex/). Regional gravity anomaly grid data is obtained from the WGM2012 model developed by BGI for the World Gravity Map (WGM2012) project (http:///cgi.obs-mip.fr/data-products/Gravity-atabases/Land-Gravity-data). Magnetic anomaly map of the study region is extracted from the World Digital Magnetic Anomaly Map (WDMAM) sponsored by IAGA (International Association of Geomagnetism and Aeronomy) and CGMW (Commission for the Geological Map of the World) (http://www.wdmam.org). Furthermore, our density and susceptibility model is based on geological and tectonic mapping, magnetic basement depth, and model of the crustal interfaces available from various published results (discussed in Sections 1 and 2). These were used in the modeling process to construct the geometry of the initial model.

3.1. Topography Variations. The topography of the southern SGT has different segments varying from the central part of the region to either side of the east and west directions (Figure 1(b)). The maximum and minimum topographic variations observed in the map range from -0.5 to 1765 m, respectively. In the central portion of the map, the north to south direction has higher elevation varying from ~1100 to 1765 m due to Western Ghats Escarpment. In the northeast southwest direction, the elevation gradually decreases to a minimum of ~0.5 m at the coast. Most of the topographic features are oriented in northwest and southeast directions. The AKSZ depicts a discontinuity in topographic features which might be caused by crustal upliftment.

3.2. Features of Gravity and Magnetic Anomaly. Gravity anomaly map generally emphasizes the image of the subsurface, despite issues related to signal superposition, in terms of contrasting density variations existing between different geological boundaries. The gravity field in any region depends on several factors such as crustal thickness, mean crustal density, mean surface elevation, and density inhomogeneities which lead to some important inferences regarding the subsurface mass distribution in the near-surface/subsurface lithology. In this study, we relied on the Bouguer
anomaly data over the study area as retrieved from the global database (of BGI; Figure 2(a)) that clearly shows a linear trend of positive anomaly elongated in the NW-SE direction. The Bouguer anomaly map, when correlated with the surface geology, free-air anomalies, elevation, and rock density data, leads to some salient inferences regarding the subsurface mass distribution. The clear feature is increasing Bouguer values from northern to southern parts of the region. The northern part of the Madurai Block having low-grade charnockite massifs shows low gravity anomaly, especially in Kumily and Idduki regions which have strong negative anomaly ranging from -108 to -80 mGal. This may be due to the crustal roots of elevated regions (~830 to 1766 m). On the other hand, the southern part of the Trivandrum Block which has high-grade khondalites shows high gravity anomaly ranging from -33 to 13 mGal.
Moderate gravity variations superimposed over the central gravity low and coastal high characterize the southcentral part of the region. Particularly, the AKSZ is conspicuously devoid of any significant paired gravity anomaly typical of the ancient suture zones. An inverse correlation of anomaly and topography in the MB validates its isostatic state; however, non-isostatic relationship is noted in the AKSZ block. The magnetic anomaly of the satellite data can provide long-wavelength coverage and valuable information for interpretation of crustal geologic character, major structures, tectonic development, crustal thickness, and deep-seated crustal properties. Qualitatively, the magnetic map of the study area (Figure 2(b)) indicates that the major magnetic anomalies range from -60 to 260 nT along the strike of the AKSZ. From the anomaly map, it seems that the boundaries of a few crustal blocks correlate fairly well with magnetic anomaly strike. There are a number of positive and negative magnetic variations in the northern block (of the low-grade charnockite complex) having anomaly range ranging from -60 to 44 nT. A NE-SW trend having moderate positive anomaly around 44 nT divides the MB in the north and south direction that exhibits a similar signature in the gravity anomaly map (Figure 1(a)). On the contrary, positive anomaly of 45 to 260 nT in the southern block (TB) may be attributed to high-grade khondalites or due to magnetic basement structure and composition. However, the magnetic anomaly trend changes from NE-SW to NW-SE near the AKSZ which might be a crustal boundary between MB and TB. The dissimilarity in magnetic characteristics of these two blocks can be attributed to the distinct metamorphic history.

4. Petrophysical Properties and Data Constrain

In order to obtain an enhanced interpretation of the geological structure for potential field data, petrophysical properties of major rock types play a crucial role in modeling. The determination of density, susceptibility, remnant magnetization, and magnetic component values of rocks mainly contribute to lateral contrasts of surface rocks, deep subsurface bodies, or a combination of both. The information on magnetic susceptibility of rocks in the SGT is limited to some paleomagnetic studies [45–48] which is hardly comparable to the bulk susceptibility in the crust of individual SGT blocks. However, in magnetic modeling, we mainly refer to average estimates of bulk susceptibility of crustal materials [45]. In the AKSZ and its surrounding regions, magnetization is mostly related to the presence of prograde-retrograde charnockites and khondalites [16]. In contrast, high amplitude magnetic anomalies are noted in locations with no evidences of Alkali plutons in the TB (Figure 2(b)).

The studies pertaining to the palaeomagnetism and rock magnetism from the charnockite belts of South India [49] allow us to define the average susceptibility value in the AKSZ and its surrounding region (0.021 to 0.024 in SI unit). In order to carry out modeling, the magnetic field is reduced to pole to decipher the preserved remnant magnetization [50–52], as any remanence present in the area will generally show weak signature of magnetic field as also noted as a NS trend in RTP map (Figure 2(c)). This is also corroborated by previous studies in SGT which specifies a remanent magnetization ranging from 0.240 to 0.243 A/m [49, 53]. Previous studies from SGT have reported a wide variety of igneous and metamorphic rocks with estimated susceptibility values from charnockite and noted a linear relationship between the magnetic content and susceptibility values [54–56].

These petrophysical properties are used as a priori information in the initial model taken from the 2D-study carried out along a single transect of Palani to Kanyakumari [6, 7, 57]. We used the seismic Moho points to constrain the depth to Moho and different thickness of crustal layers from radial spectrum of potential field data. The model parameters used in the present study are summarized in Tables 1 and 2. Furthermore, we used earth magnetic field parameters of average inclination (I), declination (D), and total field intensity (M) for all the profiles from IGRF 2015 model and given in Table 3.

5. Methods and Theories

5.1. Spectral Depth Estimate. The radially averaged power spectrum technique is used to detect depths of the causative sources of the potential filed data. Being a frequency domain approach, power spectrum is a function of wavelengths in both the X and the Y directions. Spectral analysis is capable of separating the information from different sources at varying depths and yields the average depth to the sources with uncertainty in the order of the 10% [58] especially in case of deeper bodies. To calculate the sources of depth for gravity and magnetic data, a simple relation between power spectrum and depth values is expressed by [59]

$$\log E(k) = 4\pi h k & \delta h = -\frac{s}{4\pi},$$

where “h” is the depth in kilometer, “s” is the slope of the log(energy) spectrum, and k is the wavenumber in cycles/kilometer. Here, we applied 2-D radially averaged power spectrum technique to both gravity and magnetic data for calculating the energy spectrum and determine the average

| Layers          | Density (g/cc) | Susceptibility (cgs) |
|-----------------|----------------|----------------------|
| Madurai Block   |                |                      |
| UC1_MB          | 2.50           | 0.0028               |
| UC2_MB          | 2.62           | 0.0033               |
| MC_MB           | 2.80           | 0.0035               |
| Trivandrum Block|                |                      |
| UC1_TB          | 2.66           | 0.0030               |
| MC_TB           | 2.68           | 0.0037               |
| Achankovil Shear Zone |  |                      |
| AZ              | 2.71           | 0.0031               |
| LC              | 2.92           |                      |
| UM              | 3.21           |                      |

Table 1: Physical properties used for individual modeling.
depth level to the gravity and magnetic source in the study area using Oasis Montaz (Geosoft software). These average depths can be determined from the slope of the plot between log power spectrum and wavenumber. The logarithmic plot of spectrum amplitude of the magnetic and gravity anomaly due to multiple layers would result in multiple straight line segments. Slope at smaller wavenumbers give the depth of deeper source; on the contrary, the higher frequencies estimate the depth to the shallower sources. The radially averaged power spectrum for both gravity and magnetic data is shown in Figure 3, which illustrates the estimated average depth levels to the deep and shallow depth segments in the study area. The 2-D power spectrum of gravity data (Figure 3(a)) can be interpreted as the least squares fit of the randomly distributed points of two linear slope segments and has been used to estimate averaged deeper and shallow sources depth of the density interfaces at 21.50 km and at 7.10 km, respectively. However, the estimated average depth of the magnetic source (Figure 3(b)) is 20.02 km and 6.40 km. The estimated depths from both the data sets are within the range of 0.3% of error limit.

5.2. Subsurface Characterization from Computed Gravity Gradient Anomalies. Subsurface mass density can be analyzed by using gravity field, and the gravity field from any mass body having a particular density is most easily understood in terms of its gravity scalar potential field \( \phi(r) \) at \( r \) is given by,

\[
\phi(r) = G \left( \frac{\rho(r')}{|r' - r|} \right) d^3r',
\]

where \( \rho(r') \) is the mass density at position \( (r') \), and \( G = 6.668 \times 10^{-11} \text{ Nm}^2\text{kg}^{-2} \) is the gravitational constant. Gravity

| Layers         | Density (g/cc) | Susceptibility (cgs) | Remanent magnetization (emu/cc) | Inclination (°) | Declination (°) |
|----------------|---------------|----------------------|-------------------------------|----------------|----------------|
| Madurai Block  |               |                      |                               |                |                |
| UC1_MB         | 2.74–2.90     | 0.0031–0.0034        | 0.00017–0.00020               | -23–10         | -24–100        |
| UC2_MB         | 2.52–2.69     | 0.0029–0.0034        | 0.00018–0.00022               | -11–46         | -19–161        |
| UC3_MB         | 2.68–2.74     | 0.0028–0.0033        | 0.00020–0.00022               | 18–85          | -26–171        |
| UC4_MB         | 2.78–2.82     | 0.0032–0.0034        | 0.00015–0.00021               | -19–25         | -12–146        |
| UC5_MB         | 2.81          | 0.003                | 0.00020                       | 55             | 95             |
| MC_MB          | 2.71–2.78     | 0.0020–0.00047       | 0.00020–0.000040              | 8–77           | 3–126          |
| Trivandrum Block|               |                      |                               |                |                |
| UC1_TB         | 2.70–2.76     | 0.0023–0.0033        | 0.00020–0.00025               | 11–38          | -151–104       |
| UC2_TB         | 2.50–2.80     | 0.0023–0.0035        | 0.00020–0.00025               | 35–60          | 54–174         |
| MC_TB          | 2.76–2.80     | 0.0027–0.0036        | 0.00020–0.00030               | -35–67         | -154–143       |
| Achankovil Shear Zone |   |                     |                               |                |                |
| AZ             | 2.70–2.76     | 0.0022–0.0037        | 0.00020–0.00023               | 10–42          | -101–165       |
| Deeper layers  |               |                      |                               |                |                |
| LC             | 2.92          | 0                    | 0                             | 0              | 0              |
| UM             | 3.21          | 0                    | 0                             | 0              | 0              |

Table 2: Physical properties used in multi-profile modeling.

| Profiles | Magnetic field (nT) | Inclination (°) | Declination (°) |
|----------|---------------------|----------------|----------------|
| Profile-P1-P1'   | 40443.50            | 4.60           | -1.81          |
| Profile-P2-P2'   | 40544.61            | 5.35           | -1.75          |
| Profile-P3-P3'   | 40554.67            | 5.04           | -1.77          |
| Profile-P4-P4'   | 40568.40            | 4.86           | -1.77          |
| Profile-P5-P5'   | 40556.58            | 4.54           | -1.80          |

Table 3: Earth magnetic field components for profile modeling.

\[
g(r) = \nabla \phi(r) = \frac{\partial \phi}{\partial x} \hat{i} + \frac{\partial \phi}{\partial y} \hat{j} + \frac{\partial \phi}{\partial z} \hat{k}. \quad (3)
\]

Gravity gradient is used to describe how a particular component of gravity varies with position [60] as given below.

\[
g_x(r + \delta r) = g_x(r) + \frac{\partial^2 \phi}{\partial x^2} \delta x + \frac{\partial^2 \phi}{\partial y \partial x} \delta y + \frac{\partial^2 \phi}{\partial z \partial x} \delta z = g_x(r) + T_{xx} \delta x + T_{xy} \delta y + T_{xz} \delta z. \quad (4)
\]

Therefore, the full gravity gradient tensor \( T_{ij} \) can be illustrated by

\[
T_{xx} \quad T_{xy} \quad T_{xz} \\
T_{yx} \quad T_{yy} \quad T_{yz} \\
T_{zx} \quad T_{zy} \quad T_{zz}
\]

where, \( i \) & \( j = x, y, z \).
Full gravity gradient tensor given in equation (5) is a symmetric tensor, since the order of differentiation of a scalar quantity is irrelevant and because gravity is a central force obeying Laplace equation in free space, the sum of the diagonal components is zero for an inertial frame of reference. Thus, there are only five independent components and one dependent component of the gravity gradient tensor \(T_{xx}, T_{xy}, T_{xz}, T_{yy}, T_{zz}, \text{ and } T_{zy}\). Each independent component and combination of these provides significant subsurface information individually [60–62]. In present study, only vertical gradient components like \(T_{zz}\) and \(T_{zy}\) and THZ (total horizontal components, detail is given by [60]) have been computed which enhances details of the shallow structures (Figure 4) better than gravity anomaly itself (Figure 2(a)) and maps lateral density variations in the subsurface.

Three major units can be differentiated from the vertical gravity gradient \(T_{zz}\) in the region: (1) long wavelength linear trend of positive anomaly in the east can be associated with the shallow crustal thickness, (2) the migmatite group of high-grade metamorphic rocks of high density are interpreted to be the source of prominent positive anomalies in the eastern part of the region, and (3) charnockite and laterite bauxite are interpreted to be the source of prominent positive anomalies in the central part of the region which cannot be directly interpreted from the gravity anomaly (Figure 2(a)). Moreover, Western Margin Fault (WMF) in the west is easily marked with linear trend of positive anomaly. The AKSZ shows positive trend of anomalies suggesting the presence of two different crustal blocks (MB and TB). A new set up of faults F1, F2, F3, and F4 is seen clearly with several folds C1, C2, and C3 in the northeast part of the region [34], where fault F1 connects the AKSZ and TF (Tennimalai Fault) and the faults F2, F3, and F4 cut across the basement of the MB. Furthermore, a particular trend can be observed along Western Ghats Escarpment (WGE) that crosses the major units of the MB, TB, and NB. However, NB and TF are not demarcated easily from the vertical gradient \(T_{zz}\) but can be easily noticed in horizontal gradient \(T_{zy}\) (Figure 4(c)). The crucial feature of the Charnockite Block shown in white shaded boundary, NB, F4, and TF, presents a clear demarcation in horizontal gradient map \(T_{zy}\) (Figure 4(c)). However, WMF, WGE, F2, F3, and folds like C1, C2, and C3 underscore their presence and confirm the vertical gradient signature in all horizontal gradient maps \(T_{zy}, T_{zy}, HGz : \) Figures 4(b)–4(d)).

5.3. 2-D Joint Modeling of Gravity and Magnetic Data. The joint gravity/magnetic model can be considered to better reflect the geology of the study area as compared to the independently generated 2D gravity and magnetic models. In this study, Oasis Montaj Geosoft modeling program called GM-SYS is used for intuitive, interactive, and real-time calculation of the profile residual gravity/magnetic response with change of density, susceptibilities, and undulating geometries of layers. The adopted approach of joint modeling is illustrated as flow chart (Figure 5). This modeling process is nonunique, therefore, needs to be constrained with the present as well as earlier geological and geophysical knowledge. This method is an established procedure of estimating profile geometries of the interfaces since [63]. The initial model consists of four lithologic horizons, namely, upper crust (UC), middle crust (MC), lower crust (LC), and upper mantle (UM) followed by their respective parameters (Table 1, Figures 6(a) and 6(b)). The initial model geometry is taken from the previous studies, and depth of layers is constrained using power spectrum method and later modified using the adopted approach.

5.3.1. Uncertainty in Model Parameters and Subsurface Geometries. Since, individual gravity and magnetic modeling processes are nonunique, therefore, they have uncertainties in model parameters (density/susceptibility) and their subsurface layers due to the ambiguous nature of potential fields. The gravity modeling along the profile P3-P3’ is taken initially for the uncertainty analysis and shown in Figures 6(a)–6(c). The approximated model using only gravity
data shows an error of 11.40 mGal with several unmatched high frequency anomalies. However, the same subsurface model using magnetic data produces an error of 37.65 nT with huge discrepancies along the profile as shown in Figure 6(a) and 6(b). This may be due to the combination of either density or susceptibility or due to subsurface geometries (Figure 6(c)).

5.3.2. Improved Subsurface Modeled Geometry. The initial density-susceptibility structure of the southern part of SGT crust is modeled using GMSYS-2D by defining three crustal and one upper mantle layers with combination of various density and susceptibility contrasts along 5 different parallel profiles (Figure 1). The final joint gravity and magnetic model response in terms of the subsurface model are taken to be acceptable with a root mean square error (RMS) of 1.70–3.06 mGal and 1.67–4.89 nT, respectively (Figures 7–11). The joint model offers a good fit between observed and calculated gravity and magnetic anomalies along the profile. The modeled results were controlled with the qualitative analysis predictions and geometrical interpretations (Sections 6.1 and 6.2). Additionally, the density of crustal blocks used along a single gravity profile by [7] was also taken into account when estimating the density of different blocks for this study. The multiprofile
modeling is constrained with seismological Moho, electrical resistivity information, and available geological observations. The lithological associations in the AKSZ and its structural geometry are also uncertain and a matter of debate. Most of the previous workers suggest AKSZ to be a crustal scale geometry using a single profile that may causes a gap in understanding the detailed geometrical variations. Integrating gravity data with magnetic model allows delineating the geometry of shallow structures, since susceptibility contrast of some layers in MB and TB is minor, unlike their density contrast. Deep magnetization is supposed to be limited by 580°C. Curie isotherm depth is the limit where rocks lose their ability to the ferromagnetic property.

**6. Results and Discussion**

In order to establish the crustal structure of AKSZ and its adjacent blocks, five profiles, viz., P1-P1', P2-P2', P3-P3', P4-P4', and P5-P5', are considered and the locations of these five profiles aligned in the NE-SW direction are shown in Figures 1 and 2, respectively. The gravity and magnetic anomaly along the selected profiles are taken perpendicular to the geological strike of AKSZ with a profile interval of around 20 km and a sampling interval of 2 km. Using geologic information, a range of densities and magnetic susceptibilities (Table 1) for the rock units were considered from previous studies (Section 4), and initial subsurface models were constructed. This was followed by demarcating shear zone locations on each profile (Figures 1 and 2). Long-wavelength anomalies were matched first, followed by smaller wavelength features of the observed data curves. The geometry, depth, and properties of the crustal rocks such as density and magnetic susceptibility values vary within 10% of initial values in order to obtain a good match between the observed and the calculated curve. Furthermore, the selected profiles were taken in such way that total length of the modeled sections is 5 times of the modeled depth and extended to infinite in both directions in order to reduce the edge effects and neglect the consequence of spherical surface of the Earth.

The developed model of the southern part of SGT is composed of three layers representing two upper magnetic crust layers, one lower magnetic crust up to Moho (varying from 38 to 45 km) and a nonmagnetic upper mantle beneath the region (Table 4). All the modeled cross-sections along the profiles differ only within the top two layers of the upper heterogeneous crust whereas similar Moho variations are

![Flowchart of adopted approach in 2D gravity and magnetic joint modeling.](http://pubs.geoscienceworld.org/gsa/lithosphere/article-pdf/doi/10.2113/2021/6017801/5421904/6017801.pdf)
Figure 6: (a, b) Gravity and magnetic modeling along the profile P3-P3' (can be seen in Figure 1). (c) Calculated uncertainty along the profile P3-P3'. UC: upper crust; MC: middle crust; LC: lower crust; UM: upper mantle; MB: Madurai Block; TB: Trivandrum Block; AZ: Achankovil Shear Zone.
Figure 7: 2D joint modeling of the gravity and magnetic anomalies across the Achankovil Shear Zone (AKSZ) along profile P1-P1′ as shown in Figure 1(a). The diamond symbol showing seismic Moho depth. Petrophysical properties are given in Table 2. UC: upper crust; MC: middle crust; LC: lower crust; UM: upper mantle; MB: Madurai Block; TB: Trivandrum Block; AZ: Achankovil Shear Zone.

Figure 8: 2D joint modeling of the gravity and magnetic anomalies across the Achankovil Shear Zone (AKSZ) along profile P2-P2′ as shown in Figure 1(a). The diamond symbol showing seismic Moho depth. Petrophysical properties are given in Table 2. UC: upper crust; MC: middle crust; LC: lower crust; UM: upper mantle; MB: Madurai Block; TB: Trivandrum Block; AZ: Achankovil Shear Zone.
Figure 9: 2D joint modeling of the gravity and magnetic anomalies across the Achankovil Shear Zone (AKSZ) along profile P3-P3′ as shown in Figure 1(a). The diamond symbol showing seismic Moho depth. Petrophysical properties are given in Table 2. UC: upper crust; MC: middle crust; LC: lower crust; UM: upper mantle; MB: Madurai Block; TB: Trivandrum Block; AZ: Achankovil Shear Zone.

Figure 10: 2D joint modeling of the gravity and magnetic anomalies across the Achankovil Shear Zone (AKSZ) along profile P4-P4′ as shown in Figure 1(a). The diamond symbol showing seismic Moho depth. Petrophysical properties are given in Table 2. UC: upper crust; MC: middle crust; LC: lower crust; UM: upper mantle; MB: Madurai Block; TB: Trivandrum Block; AZ: Achankovil Shear Zone.
noted at depth. The use of only two layer crust model instead of three layer models fail to fit the regional gravity and magnetic anomalies. Therefore, the use of two upper layer crusts and one lower crust is an important prerequisite before addressing the lateral distribution of other geometrical and physical parameters. The various profiles for modeling have been selected with different susceptibility contrasts. The distribution of susceptibility contrasts in the entire crust is done initially by fixing the interface of lower and upper crust.

The 2D-forward density-susceptibility model was jointly constructed using published geophysical and geological constraints in order to reduce the uncertainty of the model and to access the result of each model parameter on the misfit. The Moho depth initially was constrained by the seismic Moho and later fine tuned by the long wavelength Bouguer gravity anomaly. A range of density values (susceptibility values discussed earlier) were used for the different crustal units as obtained from the global crustal velocity and local scale studies. Finally, the density and susceptibility value for each crustal block is adjusted to improve the anomaly fit.

6.1. Crustal Heterogeneities and Shallow Faults. Gravity and magnetic data along different profiles are shown with models in Figures 7–11. The observed gravity is the lowest (~ -13 mGal) at the northeastern part of profile, and it is maximum (~ -10.0 mGal) towards southwestern end. Similarly, the magnetic anomalies range from -60 to 240 nT (Figures 7–11). Joint modeling results along all profiles decipher almost similar Moho depth variations ranging from 35 to 41 km (Table 4). A heterogeneous two-layer upper crust is observed with low susceptibility in the MB, high susceptibility in the TB, and variable susceptibility in the AKSZ. A thick upper crust varying from 18 km to a maximum of 23 km is associated with a thin lower crust (18 km) in the MB. However, thin upper crust with an average thickness of ~20 km associated with thick lower crust of around 22 km (Figures 7–10) is noted in the TB. The difference in the crustal structures in TB and MB is also suggested based on detailed field based analysis of mesoscale structures and deformation kinematics [64]. The part of the lower crust

Table 4: Crustal variations from multiprofile modeling.

| Profile No. | Moho depth (km) | Lower crust (km) | Upper crust (km) |
|-------------|-----------------|-----------------|-----------------|
| P1-P1’      | 41-36 km        | 22-18 km        | 6-9 km          |
| P2-P2’      | 40-35 km        | 23-13 km        | 4-9 km          |
| P3-P3’      | 39-35 km        | 19-14 km        | 6-9 km          |
| P4-P4’      | 40-34 km        | 21-13 km        | 6-9 km          |
| P5-P5’      | 39-34 km        | 17-15 km        | 5-8 km          |
near the AKSZ almost reaches to 18 km from 22 km. The Moho varying from NE-SW is 41 to 35 km constrained from seismic Moho [65] from two stations (ELP -76.97, 9.6; depth: 38.30 ± 0.12 and MVK-76.558, 9.211; depth: 39.25 ± 0.50) along a profile 1 (Figure 7). On the other hand, Moho along profile 3 (Figure 9) is constrained using three stations (TKS-77.264, 9.023; depth: 37.15, TYD-77.09, 8.650; depth: 34.55 km, TRVM-77.00, 8.50; depth: 35 km). A combined high frequency signature of gravity and magnetic data can be easily perceived from profile 1 to profile 4 in upper crust of MB (Figures 7–10) which is absent in profile 5 (Figure 11). This newly fault named F4 was also interpreted in the previous section based on gravity gradients (black dashed line of F4 in Figure 4). Our study confirms that AKSZ is an upper crustal unit (from all five profiles) which differentiates the MB from the TB.

6.2. Geometrical Variation of AKSZ. The models along all the five profiles are almost consistent in the lower part of the crust (~20 to 50 km of depths) with a slight deepening towards north. The model further depicts an abnormal geometrical variation of the AKSZ in the upper crust. However, joint modeling along the profiles clearly indicates the uniqueness of AKSZ in form of density (2.70–2.76 g/cc), susceptibility values (0.0036–0.0042 SI units), and geometrical variations.

Additionally, to understand the regional crustal structure and the tectonic relation between the AKSZ and surrounding region, we developed a 3D representation using stacking of joint multi-profile models obtained from gravity and magnetic data sets in order to have a better understanding of AKSZ structural geometry (see Figure 12). Our results advocate that AKSZ is ~12-21 km wide to the west to east direction and is ~120 km long with NW–SE orientation. The vertical extent of AKSZ varies from ~17 km in northwest to ~13 km in southeast direction and corroborates its upper crustal nature. It further supports the results from the subsurface electrical structure wherein a sharp contrast in resistivity pattern can be observed below the AKSZ zone in the upper crust [66].

6.3. India-Madagascar Connection. Several fascinating phenomenon, yet not studied systematically, have been observed in the intercontinental correlation. One of these is the Gondwana assemblages and its extension from the Middle East through Arabia, East Africa, and Madagascar into southern India, Sri Lanka, and eastern Antarctica [67–69]. The southern part of India consists of a collage of crustal blocks which are dissected by Late Neoproterozoic–Cambrian shear/suture zones [4, 28, 31, 70]. These shear/suture zones can be traced across continents and are crucial in establishing spatial relationships with other fragments of Rodinia and Gondwana supercontinents [4, 26, 36, 71]. Numerable studies have correlated India and Madagascar based on various geological aspects; however, limited studies [72] have focused on the geophysical correlation between the two terrains.

To further constrain the correlation based on geophysical results, we attempted to develop a density model constrain with the velocity model [73] along the profile AA’ (Figure 13(a)) which crosses the two major shear zone (RSZ and ASZ). Our results highlight the two layers of heterogeneous upper crust (2.70–2.76 g/cc) and one layer of lower crust (2.85 g/cc) as also deciphered in the southern SGT (Figures 13(b) and 7–11). The RSZ is characterized as an upper crust deformation with a Moho depth of around 38 km and shows a thin crust signature, whereas ASZ is characterized with abrupt structural changes till the depth of Moho (~42 km) and shows thicker crust (Figure 13(b)). A correlation is observed between AKSZ and RSZ based on the present modeling results which are also corroborated by previous geological studies in both the terranes wherein comparable rock types, metamorphic conditions, and zircon
ages have been reported (Figure 13(c)) ([64, 74] and references therein). A recent study by Tang et al. [74] suggested that the detrital zircon spectra from AKSZ and RSZ are comparable suggesting a probable link between the two shear zones. Therefore, a contiguous correlation between AKSZ and RSZ can be made based on the structural similarity, model parameters, and comparable detrital zircon ages. However, the observation made based on the very limited geophysical data sets is underdetermined and required detailed geophysical investigations to conclude for an impeccable correlation.

7. Conclusion

We developed a multiprofile density-susceptibility model from compiling the information using gravity and magnetic data sets to draw a conclusion regarding the evolution and tectonics of AKSZ and its surrounding blocks of the MB and the TB. The jointly developed density-susceptibility model illustrates the crustal density structure constrained with seismic Moho, electrical resistivity structure, and available surface geological information along five different profiles taken across the AKSZ. Modeling results reveal a three-layer crustal configuration with the depth to Moho varying from 41 km in the northeast direction to about 34 km in the southwest direction. Our results showed that AKSZ extending 12-21 km wide from the west to east direction and ~120 km long oriented towards the NW-SE direction. The vertical extent of AKSZ varies from 17 km in northwest to approximately 13 km in the southeast direction that confirms the upper crustal structure and support the subsurface electrical structure. Thus, the presented model reveals the geometrical variation of AKSZ from west to east part of the region. The AKSZ shows a deep and narrow zone
near to the Escarpment of Western Ghats and a wide and shallow structure in the far-east region. We suggest that earlier existed less sheared zone (paleotectonic lineament) would have significantly sheared due to the development of escarpment, and thus it indicates that the evolution of Western Ghats is a late geological event. In addition, the subsurface geological structures are interpreted using different combinations of gravity gradients and its individual components.

We combine gravity and magnetic data, with previously published geological information to reevaluate the crustal architecture, evolution, and possible extension of AKSZ into Madagascar. Modeling analyses indicate that the long wavelength trends of the magnetic anomalies originate at ~20 km depth of different SGT blocks (TB and MB), whereas the magnetic basement mapping shows that the prominent shallow magnetic features and furthermore associated with the newly identified faults at shallow depths that are corroborated with the gravity anomalies. The presence of khondalite outcrops in the Trivandrum Block implies that the high magnetization crust is the main source of positive magnetic anomalies. Furthermore, magnetic anomalies unveil, however, SGT that preserve the remnant of different block of crust in southern SGT. The NW-SE trending of AKSZ separating the two major lithological blocks (MB and TB) unveils different magnetic crusts individually.

Data Availability

Data utilized in this manuscript have been taken from global dataset and published literature. The required references are cited in the text.

Conflicts of Interest

There is no potential conflict of interest involved in the present manuscript.

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