Tectonic restoration of the Achankovil Suture Zone, South India: correlation with Ranotsara Shear Zone, Madagascar

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The total magnetic intensity (TMI) image of the southernmost part of the Indian peninsular shield exhibits a conspicuous NW–SE trending mega lineament of 200 km, associated with Achankovil Suture Zone (AKSZ) across the Southern Granulite Terrain (SGT) that evolved during East African Orogeny. This crustal scale anomaly of 200 nT amplitude, is significant to understand the regional tectonics and the possible linkage between AKSZ and Ranotsara Shear Zone (RSZ) of Madagascar. The structural trends are inferred from magnetic data surrounding AKSZ and RSZ to reconstruct the Gondwana fragments of the SGT and south Madagascar. The aeromagnetic images of conjugate rifted fragments of this part of India and Madagascar are connected well on both sides: the Madurai block with Antananarivo domain and Trivandrum block with Anosyan domain, north and south of AKSZ–RSZ respectively. Magnetic modelling across AKSZ reveals a hidden subsurface basic body suggesting a deep geofracture. We infer the sequence of tectonic development of the AKSZ as: (i) the subduction–accretion process in amalgamation of continental fragments to form Gondwana supercontinent during the Late Neoproterozoic and (ii) Pan-African exhumation of anomalous sub-crustal material.

Keywords: Aeromagnetic data, lithological units, magnetic anomaly, suture zones, tectonic restoration.

DURING the amalgamation of the Gondwana supercontinent, the East African Orogen largely affected the continental blocks, causing extensive granulite metamorphism. The Southern Granulite Terrain (SGT) falls in the southern part of the Indian subcontinent as a wedge. It is one of the oldest cratonic blocks among the widespread granulite terrains of east Gondwana that experienced high-temperature metamorphism. SGT is constituted by charnockite massifs formed due to the African Orogen and exhumed later to the surface during Pan-African rifting[1]. SGT is divided into various crustal blocks separated by several shear/suture/collisional zones[2], which are speculated to continue in other continental fragments, viz. Madagascar, Sri Lanka and East Antarctica. SGT is an ideal tectonic setting to study the deeper crust that has undergone tectonic rejuvenation through geological times from Neoarchaean to Neoproterozoic and tectonic rejuvenation possibly related to the Gondwana Supercontinent amalgamation and separation. Fit of shear zones and geochronological belts in the mirrored margins of the rifted continents are useful in reconstructing the Gondwana Supercontinent.

Amongst all the shear zones in SGT, the southernmost is the Achankovil Suture Zone (AKSZ), which is marked as a prominent lineament on the LANDSAT imagery that delineates the khondalites of the Trivandrum Block (TB)

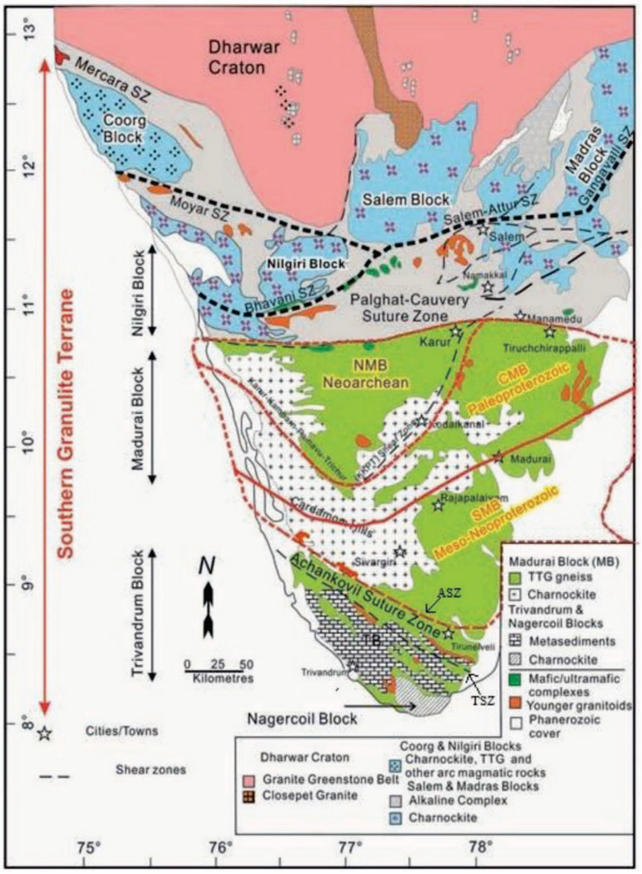

Figure 1. Geological map of Southern Granulite Terrain (SGT)[4]. The present study area lies from the southern tip of India to 10°N lat.

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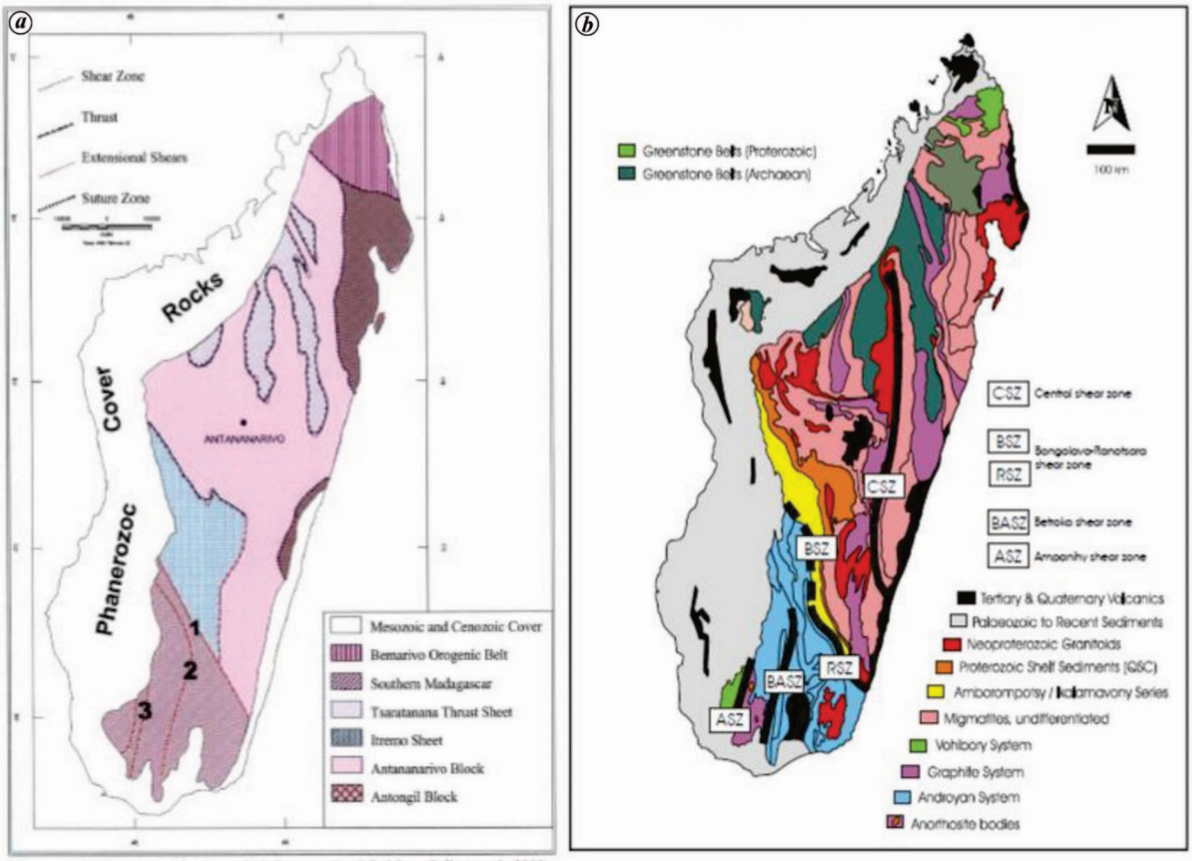

Figure 2. ***a***, Tectonic blocks (after from Collins *et al.*[19]). ***b***, Generalized geology map of Madagascar (Besairie[48]).

in the south from the charnockites of the Madurai Block (MB) in the north[3]. Figure 1 shows the geological map of SGT[4]. It is also inferred as developed during the East African Orogeny. AKSZ is 10–20 km wide and more than 150 km long, characterized by NW trending lineaments and a change in regional structural trends. AKSZ is interpreted by several researchers as a shear zone between MB and TB developed during late Neoproterozoic–Cambrian[5,6], while few others infer that it represents a suture zone related to subduction or collisional event[7–10].

Similar to SGT, Madagascar is also constituted of a mosaic of blocks bounded by several shear zones forming a network resembling that of SGT with lithological and structural similarities between various blocks of SGT and Madagascar. Figure 2 shows the simplified geological units/blocks of Madagascar. Among these, the NW–SE trending Ranotsara Shear Zone (RSZ) is reported to have a sinistral sense of movement similar to that of AKSZ[11]. Based on geological, structural or geochemical studies, several researchers have proposed the India–Madagascar fit by inferring AKSZ as an extension of RSZ of southern Madagascar in predrift times[12–17], while a few others have correlated AKSZ with the Tranomaro shear zone of Madagascar[18–21].

Geophysical data provide clues about subsurface geology and structure. While remote-sensing techniques reveal the surface geological and morphological features and their continuity, the magnetic methods greatly aid in deciphering the subsurface geological structure and lithological variations. The crustal-scale magnetic anomaly, with an amplitude of about 200 nT at a flight height of 2100 and 2850 m, is of considerable significance. Therefore, an interpretation of the available aeromagnetic data to understand the geophysical nature of this lineament, which is significant in the geology and tectonics of the southernmost part of the Indian Peninsular Shield and its possible linkage to RSZ of Madagascar. In this study, we have used the available regional aeromagnetic data to comprehend.

We used magnetic data to ascertain the possible link between Madagascar and India by correlating the magnetic trends on either side of the rift margins – the west coast margin of India (WCMI) and the east coast margin of Madagascar (ECMM) – to find the conjugate relationship/fit between India and Madagascar.

Geological setting of the study area

SGT comprises the southern part of India to the south of the Palghat–Cauvery Shear Zone. It is one of the largest Precambrian terrains with exposed deep crustal sections, mainly composed of high-grade metamorphic rocks (of granulite facies), Neoarchean granite–gneisses and Neoproterozoic granitoids. Granulite facies of rocks are further divided into charnockites and khondalites. SGT has been divided into several crustal blocks (based on their evolution and structure) intersected by crustal-scale shear zones such as the Cauvery Shear Zone system and AKSZ. The present study area constitutes a part of the SGT containing three continental blocks, namely the Madurai Block (MB), the Trivandrum Block (TB) and the Nagercoil Block (NB) (Figure 1). MB is the largest crustal block in SGT. Massive charnockites are dominantly found in MB, whereas TB is composed of metasedimentary rocks of khondalites, leptynites and minor amounts of charnockite. NB is composed of charnockites.

MB is composed of massive charnockites, tonalitic/granodiorite gneisses with limited metasedimentary rocks such as quartzites, carbonates, iron formations and pelites. In TB, regional-scale garnet–biotite gneisses are intruded by charnockites[17,22]. In the Neoproterozoic ductile shear/suture zone, AKSZ separates the Pan-African TB (sometimes referred to as Kerala Khondalite Block (KKB) in the literature)[6] from higher metamorphic-grade rocks of MB situated to the north of it. In fact, two individual shear zones, namely the Achankovil Shear Zone (ASZ) and Tenmalai Shear Zone (TSZ), form the northern and southern boundaries of the suture zone AKSZ. Both massive and arrested charnockites appear along AKSZ, while calc-granulites, quartzites and ultramafics appear parallel to it[6]. In all these crustal blocks, charnockites are the dominant basement rocks. The rocks within the shear zone include quartzofelspathatic garnet–biotite gneiss, cordierite gneiss, charnockite, granite and rare ultramafic rocks[23]. AKSZ is primarily defined based on the evidence of intensive shearing with a sinistral sense of shearing between the crustal blocks across it. It is also differentiated based on the variations in rock type and the sharp change in trend of the structures to the north and south of the shear. Northeast-trending structures are inferred towards the north of the belt, while northwest-trending structures are identified within and to the south of it[3]. A detailed study of the geology and structure of this important shear zone has already been made[5].

Relatively younger ages (1500–1300 Ma) were inferred for AKSZ from radiometric data compared to the older crustal age (3000 and 2000 Ma respectively) of MB and TB[24]. Ganitoids related to Neoproterozoic–Cambrian felsic magmatism are found in and along AKSZ. These granitoids show similar ages of magmatism and metamorphism of the East African Orogen related to several collisional–extensional events forming the Gondwana supercontinent. The emplacement of several plutons in the SGT at different ages indicates multistage evolution through Neoarchean to Neoproterozoic periods. Granites with younger ages (590–560 Ma) have also been reported within the AKSZ (Yellappa and Mallikharjuna Rao[25] and references thereafter). In MB, the granite plutons range in age from 550 to 850 Ma. AKSZ plays a key role in the eastern Gondwana supercontinent by juxtaposing the terrains of MB and TB. There have been speculations regarding AKSZ – whether it is simply a shear or a suture related to the subduction zone or a collisional suture.

Data and methodology

Aeromagnetic data

As part of the country-wide coverage by aeromagnetic surveys, the Geological Survey of India undertook regional aeromagnetic surveys covering up to 25°N lat. starting from the south and excluding the major portion occupied by Deccan flood basalts. The aeromagnetic anomaly map up to 12°N lat. was published with an interpretation of the magnetic basement using power spectral analysis[26]. The coverage had a line spacing of about 4000 m, with most lines oriented along the N–S. The block in the west (up to 77°E long.) was flown along lines oriented in the N25°E direction at a height of 7000 ft amsl. The central block between 77°E and 78°E long. was flown along the N–S lines at a height of 9500 ft amsl. The eastern part between 78°E and 80°E long. was flown at 5000 ft amsl.

Figure 3 provides details of the blocks. Based on these data, a composite image with a mean altitude of 7000 ft amsl, was prepared using the mathematical techniques of upward and downward continuation. Figure 4 presents the resulting total magnetic intensity (TMI) anomaly image of the southernmost part of the Indian Peninsular Shield up to 10°N lat. The pink to red colours in the image represent TMI highs, and the blue colour represents lows. An interpretation of the available aeromagnetic data might throw some light on the geophysical nature of this lineament, which is significant in the geology and tectonics of the southernmost part of the Indian Peninsular Shield.

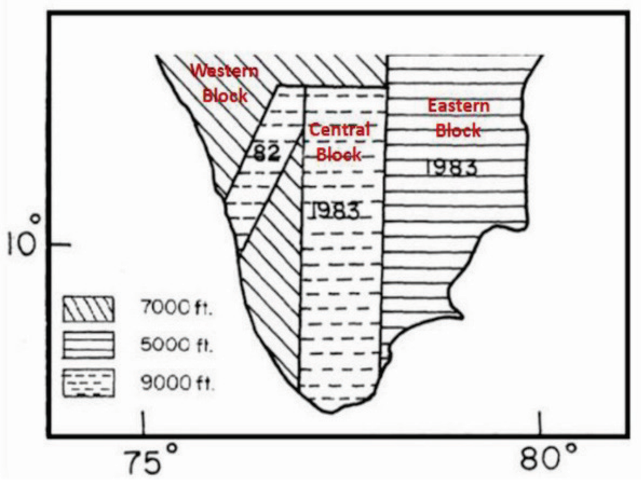

Figure 3. Flight parameters of aeromagnetic data coverage.

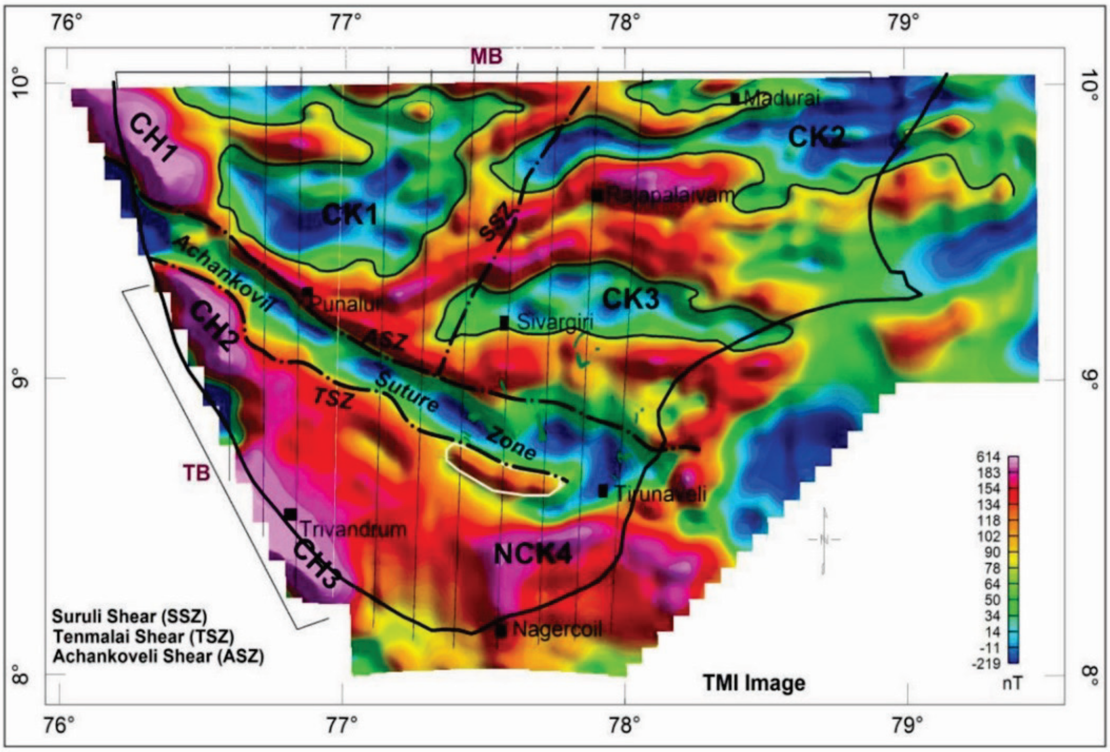

Figure 4. TMI image of the study area (CH1–CH3, Coastal TMI highs; CK1 and CK2, TMI lows inferred as charnockite; NCK, Non-magnetic charnockite; TB, Trivandrum Block; MB, Madurai Block; WMB, Western part of MB; EMB, Eastern part of MB. Profile P of the model shown in Figure 7).

Qualitative analysis of the anomalies

Regional aeromagnetic anomaly maps provide valuable information on the subsurface susceptibility distribution, which depends on the distribution of magnetite mineral content (it varies in a wide range). So, the magnetic method is one of the best geophysical tools to provide clues about subsurface geology and structure. Aeromagnetic data extensively aid in the mapping of geological features, the structural framework of the terrains defined by faults/fracture patterns, folds, dykes that are often concealed under sedimentary cover and also help in narrowing down the search of mineralized zones[27–30]. The aeromagnetic anomaly patterns reflect dykes, fault/fracture/shear systems, along with the patterns of greenstone belts. Major tectonic and structural lineaments that can be identified from the aeromagnetic data help understand the geodynamic aspects of regional crustal-scale contacts and the structure of the crust.

Magnetic trends are defined as the axis of elongated highs, lows and high–low pairs of bipolar anomalies. These trends represent shallow-to-deep structural features such as the axis of a major fold or an elongated intrusion in the metamorphic or crystalline part of the crust. In sedimentary regions, the magnetic anomaly trends are usually parallel to the trends in the underlying crust. These trends help identify geologic terranes and crustal blocks with a different geological and tectonic history from the adjoining blocks. Structural features like faults, fractures and other lineaments are identified based on the trend of aeromagnetic anomalies with their linearity, abrupt truncation of the anomaly trends along a line, flexures in the contour pattern, alignment of sets in the continuity of anomaly patterns, offsets in the linear magnetic features, alignment of highs/lows or their termination abruptly along a line, etc. Magnetic trends have been studied to identify structural provinces in this region. Each province has a characteristic geological/structural fabric distinguishable from one another that is described in the interpretation.

Quantitative analysis

Modelling the aeromagnetic data along with other quantitative interpretation techniques would reveal the physical properties of the anomalous subsurface, thereby enabling a meaningful geological/structural evaluation of the subsurface. In 2002, an attempt was made through 1D inversion of aeromagnetic profiles across the belt to obtain the physical parameters such as dip, depth to the top of the magnetic body and its susceptibility[31]. Quantitative interpretation of the aeromagnetic profiles revealed the depth of the causative varying between 500 and 1000 m. The susceptibility contrast evaluated over AKSZ was higher than the adjoining khondalites. The parameters of the source (depth and susceptibility) suggested it to be a basic intrusive that might not have reached the surface (as there were no surface indications). As the lithology and structural trends of rock units on either side of this lineament differ, ACSZ might represent a suture zone along which basic material might have been intruded and not reached the surface. However, it is certain that the magnetic character of this zone is entirely different from its adjoining formations. Our results can be constrained by other gravity and magnetotellurics studies to understand the physical properties and geological characteristics of the intrusive. Later, several magnetotellurics (MT), gravity and deep seismic reflection (DSS) studies were conducted[4,10,32,33]. In this work, we attempted magnetic modelling across the Achankovil shear zone (ACSZ) and the surrounding region to examine the source characteristics in detail using 2.5D modelling.

2.5D modelling

This is a pseudo 3D modelling that employs limited strike length with little influence or contribution from the strike side of the body. It is a model midway between the 2D model, which deals with two-dimensional variation, say *X*- and *Z*-directions and the 3D model, which shows three-dimensional variation, i.e. *X*-, *Y*- and *Z*-directions. It is used to model the body most realistically by accommodating contributions from its strike side (say *Y*-direction). 2.5D modelling was carried out using GM-SYS (GEOSOFT 2004) package, interactive computer programing software. The magnetic response was computed based on the gravity and magnetic algorithms for an infinitely long prismatic body[34–36]. Shuey and Pasqulae[37] developed a 2.5D profile modelling with a finite strike length. The GM-SYS package used was developed by integrating these algorithms.

Interpretation of aeromagnetic image

The geomagnetic inclination of the study area is about 4°. At these low magnetic latitudes, for normal induction, the magnetic anomaly over a source of higher susceptibility contrast shows a low in TMI anomaly. The general practice to remove the effect of inclination is to apply the reduced-to-equator (RTE) operator on TMI data at latitudes close to the equator.

Thus,

$$L(\theta) = \frac{(\sin(I) - i\cdot\cos(I)\cdot\cos(D-\theta))^2 * (-\cos^2(D-\theta))}{(\sin^2(I_a) + \cos^2(I_a)\cdot\cos^2(D-\theta)) * (\sin^2(I) + \cos^2(I)\cdot\cos^2(D-\theta))},$$

I_a = default is 20. $I_a = 20$, if $I > 0$; $I_a = (-20)$, if $I < 0$. If $|I_a|$ is specified to be less then $|I|$, it is set to I. Where $L(\theta)$ is the TMI RTE, I the geomagnetic inclination, I_a the inclination for amplitude correction (never less than I) and D is the geomagnetic declination.

Figure 5 *a* shows the RTE image. There is no distinguishable difference between TMI and its RTE. However, for a change in inclination from 0° to 4° in the study area, we computed the TMI anomaly of a tabular magnetic body with a fixed depth (250 m) and width (350 m) with a susceptibility of 0.03 SI units (Figure 6), using MAGMOD forward modelling code[38]. We found that there was no recognizable change in the shape of the anomaly. So, in our interpretation, we presume that a high magnetic source produces a low of the same anomaly shape (and vice versa) over the entire region without remanence.

The anomaly values in the region varied between –220 and 614 nT. The TMI image of the study area showed a predominant linear low (marked as AKSZ in Figures 4 and 5) aligned in the NW–SE direction and extending from the west to the east coast. The length of this linear low anomaly was about 200 km, with width varying between 15 and 25 km along its strike. The amplitude of the anomaly varied between 150 and 200 nT. The location of the magnetic linear low coincided with the surface expression of AKSZ, and the predominant low indicated that the source was associated with higher susceptibility.

To the north of AKSZ in MB, TMI anomaly lows (CK1–CK2) were spread as broad zones containing a few linear lows within these zones (short, broken lines in Figures 4 and 5). Whereas towards the south of it, TB was characterized by closely spaced linear highs (long broken lines in Figures 4 and 5), although levelling errors in the N–S direction (located between Trivandrum and Nagercoil) obliterated some of the linear highs in this zone. A few predominantly high anomalies (coastal highs CH1–CH3) with long wavelength (almost double) compared to the other anomalies over the remaining part of the study area were observed over quaternary sediments along the west coast on either side of AKSZ.

The most striking observation was that the wavelength character to the north of AKSZ was more or less uniform throughout the region with long, linear, high anomalies of similar widths (long broken lines in Figure 5 *b*).

Lithological units contributing to magnetic anomalies

The region indicated by magnetic low CK1 coincided with massive charnockites. Both AKSZ and charnockitized areas (charnockite exposures to the north) showed high magnetic properties (at these latitudes). Charnockite units have been inferred as possessing high magnetic character with higher susceptibility values[39,40]. The similar magnetic low zones CK2 and CK3 may also represent exhumed charnockites at sub/mid-crustal levels in the eastern MB below the metasedimentary rocks. Charnockite blocks are defined by boundaries of curvilinear magnetic highs indicating decreased

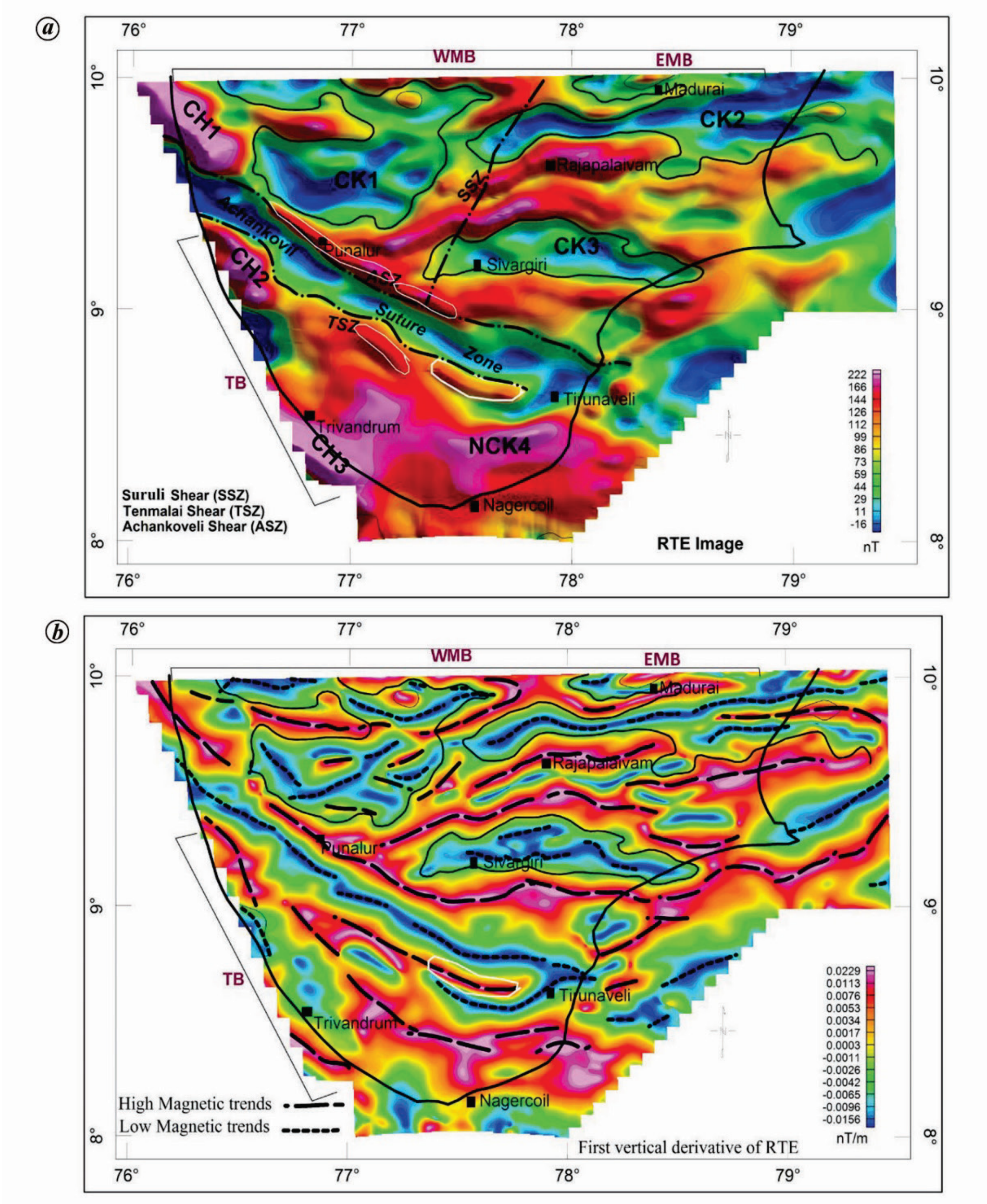

Figure 5. *a*, RTE image. *b*, First vertical derivative of RTE image.

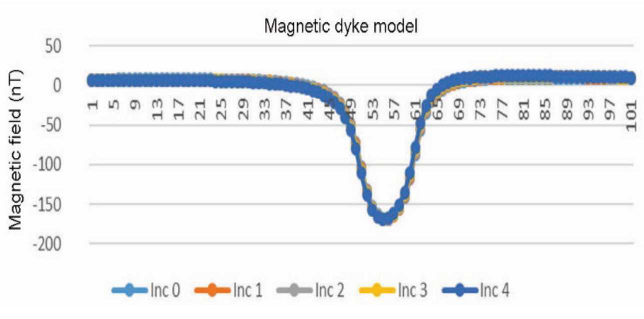

Figure 6. TMI anomaly over a tabular body for magnetic inclinations varying between 0° and 4°.

magnetite content along the peripheral zones. The strong linear lows with short, broken lines may represent the thickest portion/rooted zone of exhumed charnockites (Figure 5 *b*). The linear highs (long broken lines) infer the khondalite trends to the south of AKSZ, thus indicating the low magnetic nature of khondalites compared to charnockites. An isolated charnockite unit belonging to NB was associated with a magnetic high in TMI (nonmagnetic charnockite denoted as NCK4), indicating its nonmagnetic nature.

It has been inferred that the Nagercoil charnockites are relatively older than those in MB[41]. They were formed during the Columbia amalgamation and metamorphosed to high grade during the assembly of the Gondwana supercontinent[42]. These differences in age (indirectly, the origin and/or the intensity of metamorphism) could be one of the probable reasons for variation in the magnetic characteristics of charnockites of MB and NB. In a way, magnetic data help differentiate between units of the same lithology in age/origin/grade and assist in detailed geological mapping.

The coastal magnetic highs (CH1–CH3) cover the Phanerozoic sediments, align parallel to the west coast and are truncated by the scarp fault of the Western Ghats. These highs indicate the nonmagnetic nature of the sources below. Also, their linearity all along the coastal tract in the study area deserves attention since it may have tectonic significance. This will be discussed in later sections.

The magnetic low associated with AKSZ was broadened at its southeast end and seemed like it was taking a *U*-turn. Here, a small, linear magnetic high coincided with a granitoid body (shown as a white polygon in Figure 4). The granitoid intrusion, being acidic, was also nonmagnetic in nature and hence gave rise to a magnetic high. This observation led us to map the other granitoids using these data. The AKSZ magnetic low was aligned on either side over some distance in the central part by small, linear magnetic highs, and some of them randomly coincided with known granitoids in the region. The others were inferred from data analysis.

Structural framework from anomaly trends

While remote-sensing techniques reveal the surface geological and morphological features along with their excellent continuity, the magnetic methods greatly aid in deciphering the subsurface geological structure and lithological variations. For structural interpretation from remote sensing and other methods, the analysis of magnetic data is unique. However, there are certain limitations in deciphering source parameters due to dependency on the inclination of the magnetic field. We used RTE and its first vertical derivative images to map the trends (Figure 5 *a* and *b*).

The study area can be divided into two major zones of different magnetic trends separated by AKSZ. (Here, we used long broken lines to represent magnetic high trends and short, broken lines for magnetic low trends.) To the south of AKSZ (over KKB), the trends were parallel to AKSZ. To the north of it, the magnetic linears were oblique to the trend of AKSZ, extending from SW–NE to E–W. Nevertheless, the NW–SE structures identified from the remote sensing data in the eastern part of MB and further east below the Cauvery basin were absent in the magnetic data. Instead, we noticed two distinct trends in MB itself, separated by a shear known as the Suruli Shear Zone, trending near N–S to NNE. To the left of this shear, the predominant trend was WNW–ESE, and to the right, the trends were in ENE–WSW to almost E–W. We also noticed an NNE–SSW drag/displacement between these two sets of trends along this shear. Hence, we inferred this shear as a subsurface fault along which the eastern (metasedimentary rocks) and western (charnockite massifs) parts of MB were displaced. This fault happened to be the eastern boundary of the massive charnockite massif. Here, we emphasize that these regional magnetic trends represent the regional subsurface structures rather than morphological impressions. The major structure extending near N–S was observed from these data, though there was a preponderance of E–W anomalies reported by Johnson and Aisengart[43]. We conclude that the N–S magnetic bodies cease to produce anomaly at low latitudes, but the N–S structures do not.

Extension of AKSZ in the northwest direction below the coastal sediments of the west coast was prominently and consistently seen from the magnetic data, indicating its definite extension into the adjoining neighbouring Gondwana fragments. Though AKSZ was mapped up to the Western Ghats highlands only in the geology map, the TMI low anomaly of AKSZ showed remarkable continuity cutting across the prominent TMI highs aligned over the Western Ghats and continuing further west. Knowledge of the nature of AKSZ is poor in this area (not mapped) due to a thick cover of alluvium and laterite. The continuation of the AKSZ anomaly across and beyond the Western Ghats into the west coast indicates that the Western Ghats formation could not significantly obliterate the AKSZ anomaly. However, the amplitude of the AKSZ anomaly was less over its overlapping region with the Western Ghats. From the magnetic data, the southeast extension of the AKSZ anomaly across the Cauvery basin was identified just up to the east coastline but not beyond.

Phanerozoic sediments along the west and east coast (Cauvery basin) differed distinctly in their magnetic character. The western sediments were evidently demarcated by magnetic highs aligned parallel to the coast. They seemed to be fault-bounded (Kerala lineament); the western margin of the Cauvery basin could be easily demarcated, but the data do not indicate a faulted margin.

Depending upon the trends, the present study area can be classified as AKSZ, TB, East MB, West MB, NB, coastal sediments and Cauvery basin. As the lithology and structural trends of rock units on either side of AKSZ are different, this lineament might represent a suture zone along which mafic material might have intruded/come up/and not reached the surface. However, the magnetic character of this zone is entirely different from its adjoining formations.

1D and 2.5D modelling

1D inversion of the aeromagnetic profiles revealed the depth of the causative source varying between 500 and 1000 m. As the width (>10 km) of the source appeared to be much larger than its depth (depth to top), the lateral boundaries could be mapped easily as the trace of the

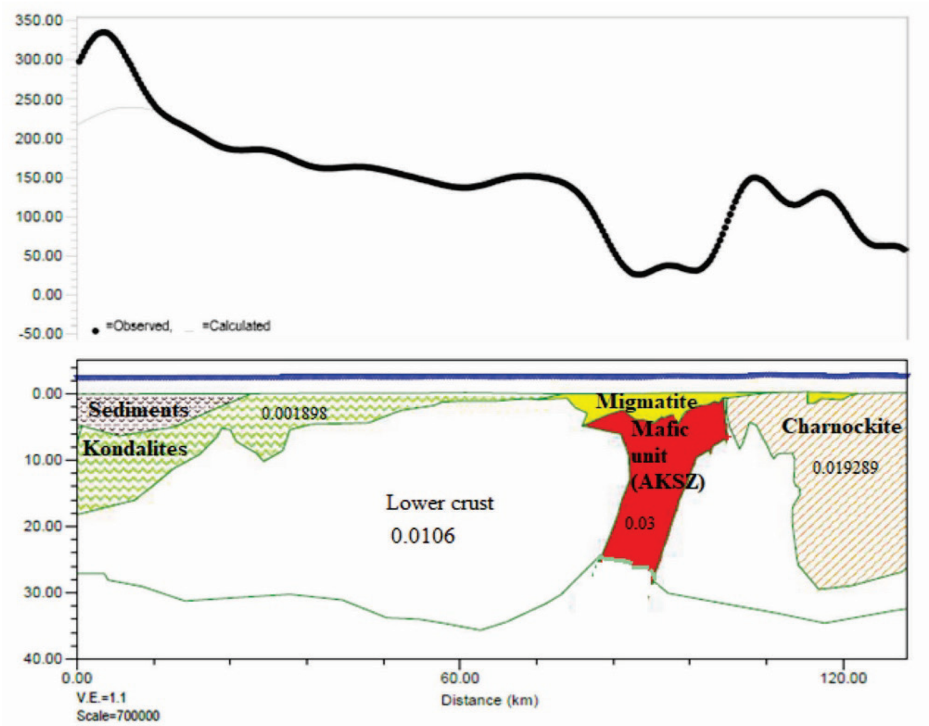

Figure 7. 2.5D model cross-section below one of the profiles.

Table 1. Parameters of the mafic source from 1D modelling

Profile number	Depth to top (below ground surface)	Dip	Susceptibility X10-6
1	1.57	140	1525
2	2.61	140	1300
3	1.03	130	1040
4	2.02	120	1190
5	1.54	90	1110
6	2.1	140	1100
Average	1.8	125	1200

maxima of the analytic signal. The susceptibility contrast of the basic body modelled through 1D inversion was 1200×10^{-6}. The dip of the structure estimated from modelling was about 120°N. The parameters suggest it to be a basic source with a tabular shape (similar to the intrusive) that might not have reached the surface. Table 1 shows the interpreted model parameters.

To provide a synoptic view of this magnetic feature throughout its length from the west to the east coast, we took ten profiles across AKSZ and modelled them using 2.5D modelling code (GMSys). Figure 7 shows the modelled section along one of the profiles and the resultant combined image forming a rough, three-dimensional configuration of the magnetic source. Susceptibilities used for various lithological units are also shown in the model. The south-dipping magnetic source block fitted the anomaly over AKSZ. Charnockites were equally magnetic but for a small variation in susceptibility value. We chose the surface of the mafic source (below AKSZ) from all the profiles and made a three-dimensional representation of the source (Figure 8). The magnetic source body clearly showed a general southward dip and top depth varying around 2 km from the ground surface. Its thickness (from top to bottom) and width showed a general increase from NE to SW (though varying relatively in a small percentage). Charnockites were also highly magnetic, but the mafic source below AKSZ exhibited higher and uniform amplitudes. (Note that the depth to the bottom of the body can be extended further, but does not contribute to the anomaly once it reaches Curie temperature isotherm at that location.)

Discussion

SGT

Though we have limitations of magnetic data at latitudes close to zero, the major advantage was that the magnetic anomalies do not have a bipolar nature, so interpretation becomes simpler. In the study region, the mapped magnetic highs either represented the contacts of rock units of large width/areal extent or granitic plutons possessing lower magnetite content (as evidenced by the direct correlation of highs with plutons). The elongated nature and strike direction of granitoids on either side of and within AKSZ clearly indicate that the shear systems acted as pathways for the emplacement of granitic plutons. Khondalites were also characterized by magnetic highs, showing low magnetic properties.

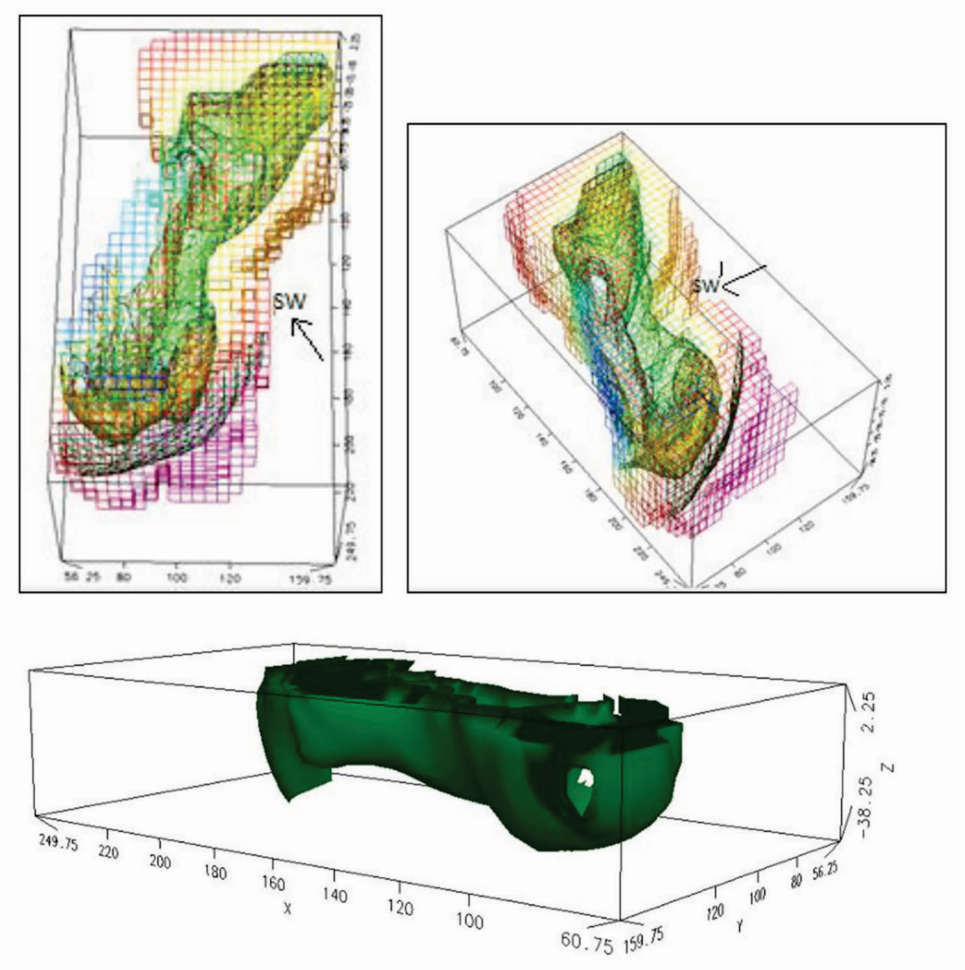

Figure 8. Three-dimensional representation of the surface of the mafic source below Achankovil Suture Zone (AKSZ).

While the massive charnockites of MB were magnetic in nature with associated TMI lows, the charnockites of NB were different from the others, as evidenced by the associated magnetic highs indicating their nonmagnetic nature. The difference between the magnetic character of charnockites belonging to MB and NB must be of different origins related to different tectonothermal events and/or age. It can be correlated with major lithological contrasts of pelitic migmatites in the south to charnockites in the north of AKSZ[44]. Charnockites of different magnetic characters on either side of AKSZ, also support the fact that these crustal blocks were not adjoining terrains during formation. The similarity in amplitude of anomalies on either side of the Suruli shear indicates the presence of charnockites in the eastern MB, existing below the exposed metasedimentary gneisses. Moreover, these linear magnetic anomalies continued across the Suruli shear with a displacement along the shear (clearly seen in Figure 4). This indicates lateral displacement (in the NNE–SSW direction, along the strike direction of the shear) between these two charnockite units located at different depths on either side of the Suruli shear. The northwestern half of ASZ and the Suruli shear seem to be controlling the southern limit of the charnockite massifs of MB. Movements along the sub-vertical faults along these shears must be responsible for the upliftment/exhumation of charnockite massifs. The massif charnockites in TB are limited in areal extent in comparison with the flight line spacing (4000 m) and hence could not be mapped.

The major structural trends derived from magnetic and satellite images/elevation data (SRTM) correlated with each other in AKSZ and TB (Figure 9 *a* and *b*). The regional strike of the rocks of MB is in the NE–SW, but in the magnetics, these are in the ENE–WSW direction and truncate along AKSZ[3,6]. However, other major regional structural trends derived from satellite data do not show much obliqueness to the AKSZ trends in MB, except for taking a twirl (at 9°, 77°) along the NNE–SSW direction demarcating the Suruli shear. In contrast, magnetic data in the western MB and eastern MB (on either side of the Suruli shear) have deciphered prominent trends that are oblique to the AKSZ trends. The trends shown from satellite images were absent in the magnetic data towards the north of AKSZ in MB, while the trends shown by magnetic data were absent in remote-sensing data. The magnetic method cannot identify

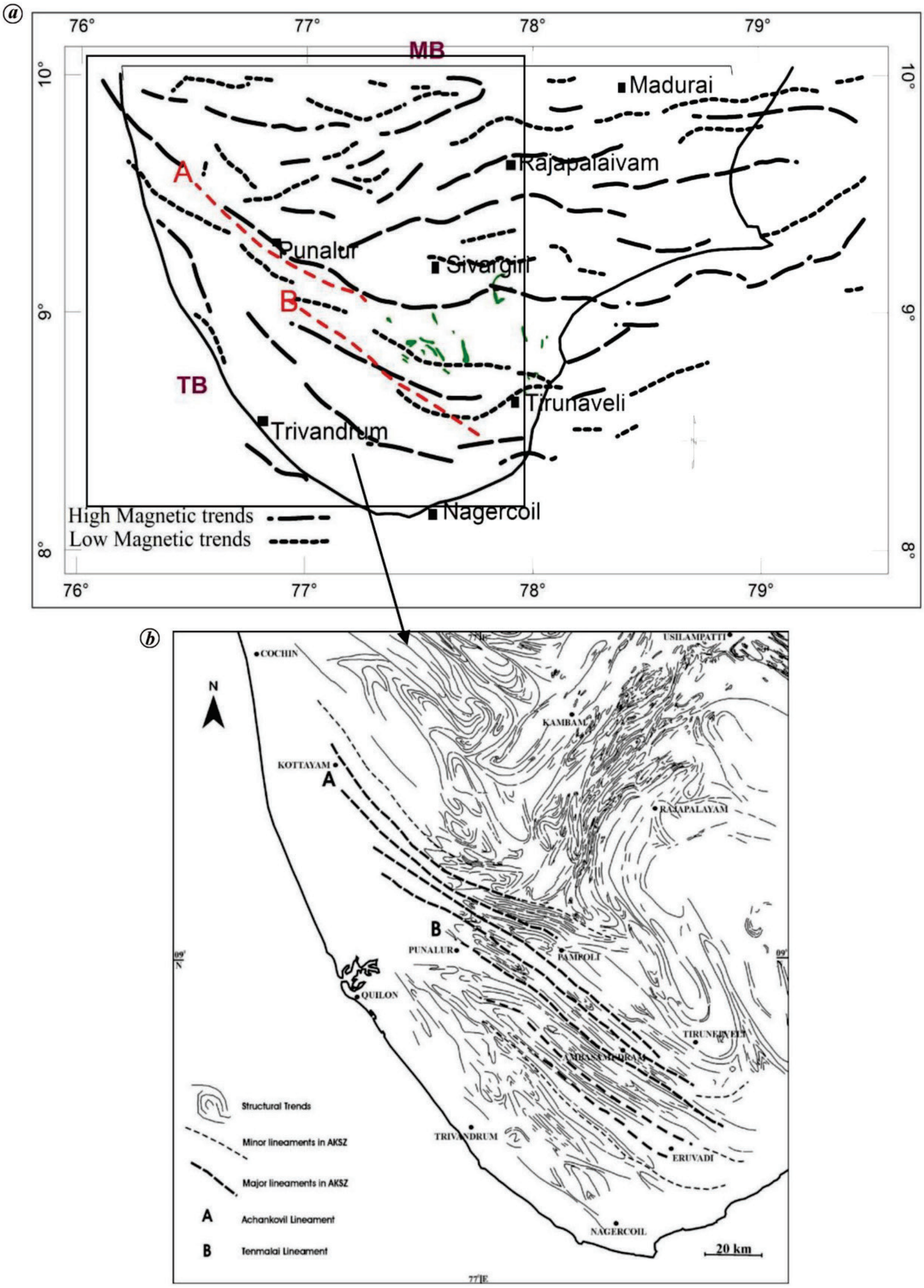

Figure 9. Structural trends derived from (***a***) magnetic data and (***b***) remote sensing/geological mapping[6].

the N–S features at low latitudes. Also, it cannot create false E–W features unless they are present in the subsurface structure. So, the dominant E–W trends in MB must be considered a regional subsurface fabric clearly unravelled by magnetic data. The magnetic anomaly trends indicate the subsurface geological trends and their relative ages. As the trends of MB are oblique to AKSZ, MB can be inferred to be relatively older than TB.

AKSZ

Ultramafic rocks and mafic granulites are rarely found in AKSZ in order to produce magnetic anomaly of high amplitude consistently throughout its strike length[17]. It is impossible to ascertain the origin of the causative source of the regional extent (crossing the subcontinent boundaries) without any regional tectonics involved.

Magnetic modelling inferred a south-dipping mafic body (Figures 7 and 8). Rather, this body could be explained by a subsurface magmatic material formed due to partial melting of the subducted slab which was exhumed later (close to the surface) along with granulites of the area (exhumation of charnockite massifs is reported on a large scale during the Pan African rifting). It was also suggested through tomographic imaging studies of DSS data that AKSZ exhibits exhumation of anomalous material[32].

The distinct difference in subsurface structural trends of MB and TB clearly emphasizes that these blocks were accreted along the present AKSZ. The width of AKSZ varies between 15 and 25 km, much less than that reported by other studies (40 km)[10,33]. These studies have extended the width of AKSZ further north (of ASZ) by 15–20 km from their gravity modelling studies. Magnetic data do not show this extended width was reported by gravity studies. Cross-trends to AKSZ start sharply at ASZ, clearly defining the boundary of AKSZ. Moreover, there is no parallel feature to shear ASZ to the north of its present position. The maximum width is encountered at its southeastern margin (45 km) only over a small part where it takes an oxbow shape with an inferred granitoid intruded into the shear. It extends further south and north, taking an oxbow shape around Tirunelveli and has a width of over 45 km. The DSS profile goes across this zone; hence, the inference of the extended AKSZ is true to this part. The remaining major part of AKSZ is not beyond 25 km in width. The magnetic source is narrower according to the inference from DSS. Shearing could have taken place on either side over a zone, which was later intruded by granitoids. These granitoids, which exhibited magnetic highs (indicating less/nonmagnetic nature) could be the boundary of shears. Felsic magmatism in and around AKSZ has been reported[45]. However, there are no studies about mafic magmatism except for a small mafic body found near the Kakkaponnu area within AKSZ[23]. Mafic granulites have been observed within AKSZ[32].

Two possible basic factors responsible for the exhumation of the lower crust are vertical extension during synconvergent horizontal shortening and diapiric upwelling of the melt-dominant buoyant granitic crust during post-orogenic collapse and extension. The age of exhumation and peak metamorphism in MB and TB must be different, as they were separated by the crustal-scale shear zone (AKSZ), which was reported as a subduction–accretion boundary between these two blocks. Khondalites were inferred to be formed due to partial melting of igneous rocks in a subduction-related environment[9]. Rapid exhumation of granulites of TB was possible during post-orogenic collapse along AKSZ. The structural trend of khondalites of TB being parallel to AKSZ also supports the effect of AKSZ on khondalites in the subduction-related setting. Magnetic data analysis and modelling clearly show a compositional variation represented by the difference in susceptibilities in the rocks on either side and over AKSZ. Figure 10 shows an illustrative diagram of our inference of a mafic material that was exhumed to shallow crustal levels along with charnockites of MB.

Correlation with southern Madagascar

Several researchers postulated theories on the subduction of MB under TB along AKSZ[4,10,32,45]. Moreover, several studies reported that RSZ was a continuation of AKSZ. Hence, it is possible that the Anosyan Block, south of RSZ and TB and south of AKSZ, were possibly together as a single plate before and during the subduction–accretionary process and that the rifting of India and Madagascar took place later during the Gondwana break-up due to the Marion plume. We positioned the Madagascar TMI image[40] to the west of the SGT VDTMI image so that RSZ and AKSZ were aligned side by side (Figure 11 *a*). Vertical derivative of total magnetic intensity (VDTMI) was used for SGT because magnetic data over the terrain are regional, while data over this part of Madagascar are high-resolution. We used magnetic correlations to ascertain the possible link between Madagascar and India.

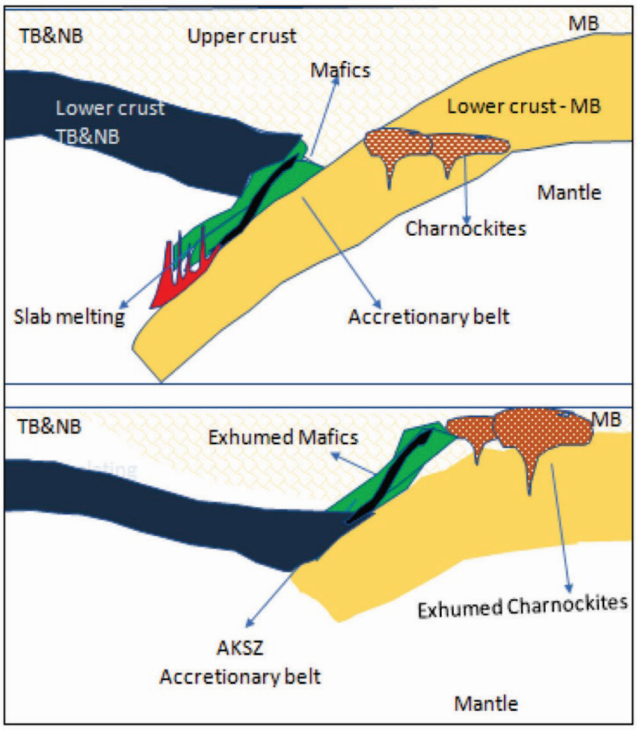

Figure 10. Illustrative diagram on the tectonic development of AKSZ.

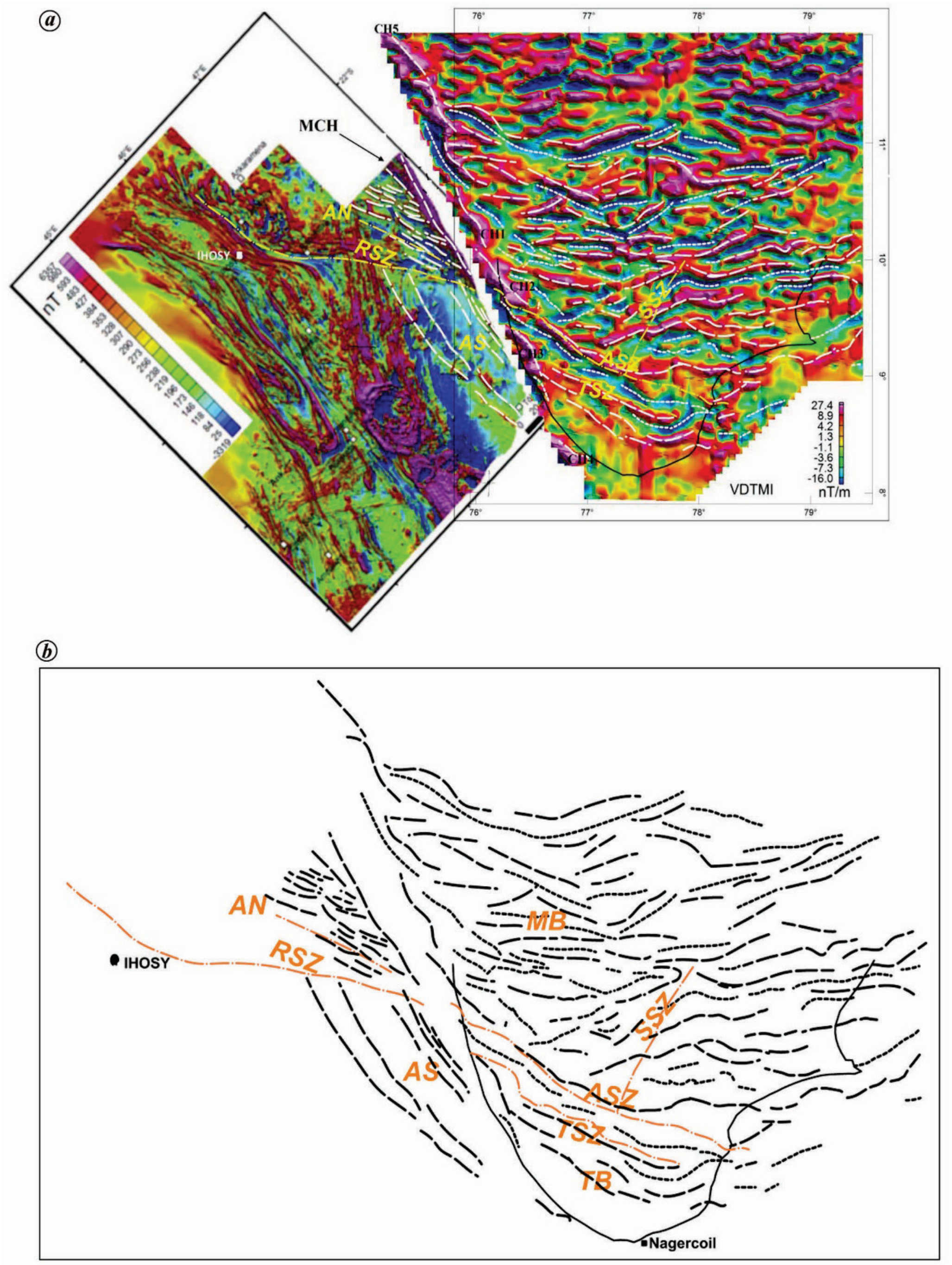

Figure 11. ***a***, Juxtaposed aeromagnetic maps of SGT and a part of southern Madagascar. Image over part of Madagascar is taken from Kumar *et al.*[33]. (Vertical derivative of TMI is considered over SGT to best highlight the structures since TMI over Madagascar is of high resolution.) ***b***, Juxtaposed trends of SGT and southern Madagascar. TSZ, Tan Shear; ASZ, Achankovil Shear; SSZ, Suruli Shear; RSZ, Ranotsara Shear; AS, Anosyan Block; AN, Antananarivo Block; CH1–CH5, Coastal magnetic highs along west coast margin of India (WCMI) and MCH, Coastal TMI high along east coast margin of Madagascar (ECMM).

We traced anomaly linears from Madagascar and SGT. At present, Madagascar and India are positioned at different magnetic inclinations, which may cause changes in the shape of the anomalies. In this study, we did not consider the polarity of magnetic anomalies since we do not have digital data to reduce them to poles and match each other. We only considered the linearity and widths of the anomalies while juxtapositioning the fragments.

Linear magnetic anomaly highs running parallel to continental margins were seen on ECMM and WCMI. These might represent linear anomalies produced by stretched continental crust during the last stages of rifting (before drifting)[46]. The high (marked as MCH), paralleling the east coast margin northeast of RSZ (Figure 11 *a*), coincided with that of India for a length of 160 km (around 10–11°N lat.). We do not have images further north over Madagascar, but along the west coast of SGT, this high continues further north along the coast (marked as CH5). This coastal high of Madagascar continues till the end of RSZ, stops at Ranotsara and the AKSZ conjuncture and continues (marked as CH2) along WCMI of TB, if we assume that RSZ is an extension of AKSZ. The most important observation is that the magnetic anomaly of AKSZ breaks this coastal high of WCMI. It clearly reveals that AKSZ is a continuation of RSZ.

The structural fabric on either side of AKSZ–RSZ was analysed to understand crustal fragments that participated in the geodynamic evolution of this part of the Gondwana supercontinent. Madagascar displayed two distinctly different lineament directions above and below RSZ. To the north of RSZ in the Antananarivo block, trends (NW to WNW) continued to MB of SGT in the same direction (Figure 11 *a* and *b*). Similarly, we noticed that the trends in TB were clear extensions of those in the Anosyan block (Figure 11 *a* and *b*). Structures on either side of RSZ were different, probably exhibiting a dissimilar history/age of pre-Gondwana times. Antananarivo and Anosyan blocks represent two of several continental fragments connected through a network of shears to form present-day Madagascar. With a close fit between the magnetic anomaly trends to the north and south, we suggest that RSZ and AKSZ were continuous/connected before rifting.

Charnockite massifs of MB were abruptly truncated along AKSZ, indicating that AKSZ is a crustal-scale feature. The charnockites of Antananarivo block of Madagascar also sharply terminated along RSZ to its north. The similarity in truncation of trends of charnockites along RSZ and the AKSZ also indicates their linkage.

Muller[47] reported that Madagascar never existed as a single continental fragment prior to the formation of Gondwana.

The Anosyan domain possessing weaker magnetic character may be analogous to TB[40]. The Anosyan block had smoothly varying, moderate-amplitude background anomalies imprinted by a few linears, which extend into KK of TB when placed conjugate beside each other. TB also possessed a moderate field with linears.

According to Martelat *et al.*[40], the magnetic data over the Antananarivo domain (lying north of RSZ) showed differences in geometrical pattern. Correlation studies from Pb–Pb zircon and monazite ages of different rock types of Madagascar with those obtained from TB (strong Mid-Neoproterozoic, less prominent Pan-African, few older than 2200 Ma) inferred identical ages of central Madagascar and MB (prominent Pan-African, lack of Mid-Neoproterozoic and absence of ages older than 2200 Ma)[17].

Felsic magmatism in the form of granitoids was present in AKSZ. Neoproterozoic granitoids were also noticed along RSZ just at its intersection with ECMM, where AKSZ can be connected to RSZ when juxtapositioned side by side with each other.

Several geochemical, geological and geophysical studies have inferred the southward subduction of MB below TB[4,10,32,45]. It is also called an ocean-closure event in which intervening oceanic lithosphere between two continental blocks can subduct either way beneath them. The same hypothesis may be followed with central and southern Madagascar, particularly between the Antananarivo and Anosyan blocks along RSZ.

The major inferences from this study are as follows:

(i) Discordance of structures in MB and TB on either side of AKSZ and in the Antananarivo and Anosyan blocks on either side of RSZ.
(ii) Continuation of structures from the Anosyan block into TB and the Antananarivo block into MB on either side of the RSZ–AKSZ.
(iii) Anomaly amplitude characteristics demonstrating that RSZ and AKSZ had formed a single shear zone before the India–Madagascar breakup.

Conclusion

In this study, the regional aeromagnetic data were utilized through modelling and qualitative analysis to understand the nature of AKSZ running across SGT, one of the largest high-grade metamorphic terrains of East Gondwana. Dissimilarity in structural trends and magnetic character on either side, as evidenced by this study, clearly indicates different tectonothermal events related to the origin and/or age of MB and TB. The crustal-scale magnetic anomaly revealed the mafic nature of the material with a width varying from 15 to 25 km, extending from a depth of a few hundred meters to almost 20 km below AKSZ over a length of about 200 km. We infer that this anomaly is probably due to the exhumed partially molten lower crustal material (molten slab/molten lower crust due to underplating/exhumed mafics along the subduction–accretionary boundary) from lower crustal levels along with charnockites that represent the deeper crust.

The magnetic trends on either side of the rift margins (WCMI and ECMM) were identified and correlated to find the conjugate relationship/fit between India and Madagascar. The magnetic linears on either side of ECMM–WCMI and AKSZ–RSZ were similar.

Comprehensive analysis of aeromagnetic data surrounding AKSZ in correlation with anomaly trends over its conjugate part in Madagascar revealed the probable sequence of tectonic development of this crustal-scale feature through time from the amalgamation of the Gondwana supercontinent till its rifting during Pan-African. The Antananarivo block and MB together, as a single continental fragment, accreted/subducted below the Anosyan block and TB

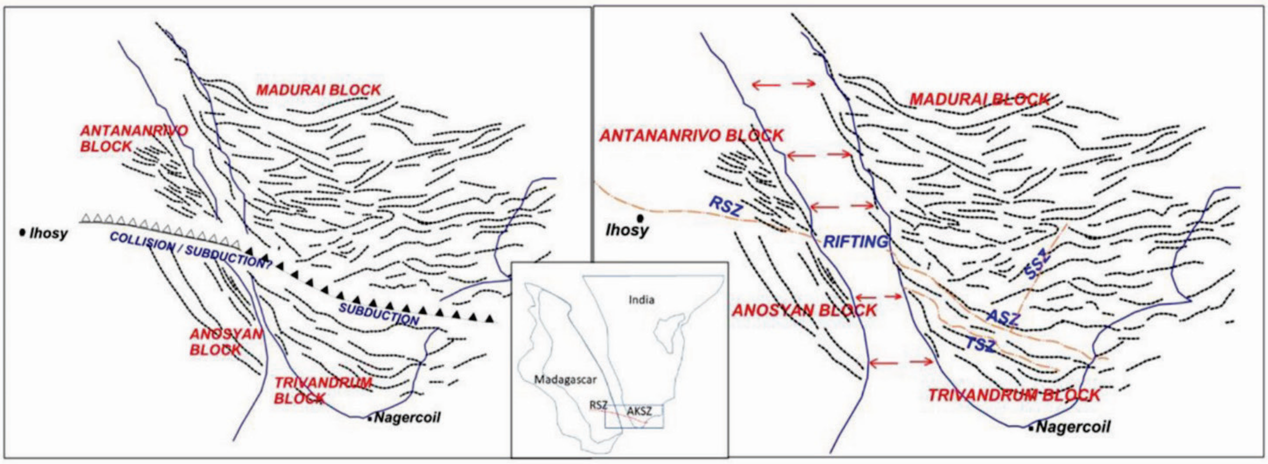

Figure 12. Status of AKSZ–RSZ with respect to Gondwana amalgamation and its Pan-African rifting.

(forming the southern continental fragment) during the Gondwana amalgamation, creating AKSZ–RSZ and rifted along WCMI–ECMM during Pan-African rifting (Figure 12). High-resolution aeromagnetic data may help map the subsurface lithology/mafic source along AKSZ and decipher/probe the structure more precisely. They may further aid in understanding the tectonic development and reconstruction of the palaeo-positions.

1. Stern, R. J., Continental collision in Neoproterozoic East African Orogen: implications for the consolidation of Gondwanaland. *Annu. Rev. Earth Planet. Sci.*, 1994, **22**, 319–351.
2. Chetty, T. R. K., Proterozoic shear zones in Southern Granulite Terrain, India. In *The Archaean and Proterozoic Terrains of Southern India within East Gondwana* (eds Santosh, M. and Yoshida, M.), Gondwana Research Group Memoir, Field Science Publications, 1996, vol. 3, pp. 77–89.
3. Drury, S. A. and Holt, R. W., The tectonic framework of the South Indian craton: a reconnaissance involving LANDSAT imagery. *Tectonophysics*, 1980, **65**, T1–T5.
4. Dhanunjaya Naidu, G., Manoj, C., Patro, P. K., Sreedhar, S. V. and Harinarayana, T., Deep electrical signatures across the Achankovil shear zone, Southern Granulite Terrain inferred from magnetotellurics. *Gondwana Res.*, 2011, **20**, 405–426.
5. Sacks, P. E., Nambiar, C. G. and Walters, L. J., Dextral Pan-African shear along the southern edge of the Achankovil shear belt, South India: constraints on Gondwana reconstructions. *J. Geol.*, 1997, **105**, 275–284.
6. Guru Rajesh, K. and Chetty, T. R. K., Structure and tectonics of the Achankovil Shear Zone, southern India. *Gondwana Res.*, 2006, **10**, 86–98.
7. Santosh, M., Shaji, E., Tsunogae, T., Ram Mohan, M. and Horie, K., Suprasubduction zone ophiolite from Agali hill: petrology, zircon SHRIMP U–Pb geochronology, geochemistry and implications for Neoarchean plate tectonics in southern India. *Precambrian Res.*, 2013, **231**, 301–324.
8. Ramsay, J. G., *Folding and Fracturing of Rocks*, McGraw Hill, New York, USA, 1967, p. 568.
9. Rajesh, V. J., Arai, S., Satish-Kumar, M., Santosh, M. and Tamura, A., High-Mg low-Ni olivine cumulates from a Pan-African accretionary belt in southern India: implications for the genesis of volatile-rich high-Mg melts in suprasubduction setting. *Precambrian Res.*, 2013, **227**, 409–425.
10. Mandal, B., Vijaya Rao, V., Karuppannan, P., Raju, S. and Ganguli, S. S., Thick-skinned tectonics of the Achankovil Shear Zone, southern India, inferred from new deep seismic reflection image: constraints on the East African Orogen. *Precambrian Res.*, 2021, **356**, 106–110.
11. Chetty, T. R. K., *Proterozoic Orogens of India: A Critical Window to Gondwana*, eBook, Elsevier, Amsterdam, The Netherlands, 2017, pp. 364–365.
12. Windley, B. F., Razafiniparany, A., Razakamanana, T. and Ackermand, D., Tectonic framework of the Precambrian of Madagascar and its Gondwana connections: a review and reappraisal. *Geol. Rundsch.*, 1994, **83**, 642–659.
13. Kriegsman, L. M., The Pan-African event in East Antarctica: a view from Sri Lanka and the Mozambique Belt. *Precambrian Res.*, 1995, **75**, 263–277.
14. Markl, G., Metamorphic evolution of Pan-African granulite facies metapelites from southern Madagascar. *Precambrian Res.*, 2000, **102**, 47–68.
15. Cenki, B., Braun, I. and Brocker, M., Evolution of the continental crust in the Kerala Khondalite Belt, southernmost India: evidence from Nd isotope mapping, U–Pb and Rb–Sr geochronology. *Precambrian Res.*, 2004, **134**, 275–292.
16. Manimaran, G., Finite strain patterns and transpression regime of Achankovil Shear Zone, South India and their implications in Gondwana reconstructions. *Geosci. Front.*, 2014, **2**, 23–29.
17. Praharaj, P., Rekha, S. and Bhattacharya, A., Structure and chronology across the Achankovil terrain boundary shear zone system (South India), and its Madagascar connection in the Gondwanaland. *Int. J. Earth Sci.*, 2021; https://doi.org/10.1007/s00531-021-02029-5.
18. De Wit, M. J., Bowring, S. A., Ashwal, L. D., Randianasolo, L. G., Morel, V. P. I. and Rambeloson, R. A., Age and tectonic evolution of Neoproterozoic ductile shear zones in southwestern Madagascar, with implications for Gondwana studies. *Tectonics*, 2001, **20**, 1–45.
19. Collins, A. S. and Windley, B. F., The tectonic evolution of central and northern Madagascar and its place in the final assembly of Gondwana. *J. Geol.*, 2002, **110**, 325–340.
20. Collins, A. S., Madagascar and the amalgamation of Central Gondwana. *Gondwana Res*., 2006, **9**, 3–16.
21. Ratheesh-Kumar, R. T., Ishwar-Kumar, C., Windley, B. F., Razakamanana, T., Rajesh, Nair, R. and Sajeev, K., India–Madagascar paleo-fit based on flexural isostasy of their rifted margins. *Gondwana Res.*, 2015, **28**(2), 581–600.
22. Pradeepkumar, A. P. and Krishnanath, R., A Pan-African 'Humite Epoch' in East Gondwana: implications for Neoproterozoic Gondwana geometry. *J. Geodyn.*, 2000, **29**, 43–62.

23. Rajesh, V. J., Arima, M. and Santosh, M., Dunite, glimmerite and spinellite in Achankovil Shear Zone, South India: implications for highly potassic CO_2-rich melt influx along an intracontinental shear zone. *Gondwana Res.*, 2004, **7**(4), 961–974; doi:10.1016/S1342-937X(05)71078-9.
24. Bartlett, J. M., Dougherty-Page, J. S., Harris, N. B. W., Hawkesworth, C. J. and Santosh, M., The application of single zircon evaporation and model Nd ages to the interpretation of polymetamorphic terrains: an example from the Proterozoic mobile belt of south India. *Contrib. Mineral. Petrol.*, 1998, **131**, 181–195.
25. Yellappa, T. and Mallikharjuna Rao, J., Geochemical characteristics of Proterozoic granite magmatism from Southern Granulite Terrain, India: implications for Gondwana. *J. Earth Syst. Sci.*, 2018, **127**, 22; https://doi.org/10.1007/s12040-018-0923-6.
26. Reddy, A. G. B., Mathew, M. P., Singh, B. and Naidu, P. S., Aeromagnetic evidence of crustal structure in the granulite terrain of Tamil Nadu–Kerala. *J. Geol. Soc. India*, 1988, **32**, 368–381.
27. Grauch, V. J. S., Rodriguez, B. D. and Wooden, J. L., Geophysical and isotopic constraints on crustal structure related to mineral trends in North–Central Nevada and implications for tectonic history. *Econ. Geogr.*, 2003, **98**, 269–286.
28. Betts, P. G., Valenta, R. K. and Finlay, J., Evolution of the Mount Woods Inlier, northern Gawler Craton, southern Australia: an integrated structural and aeromagnetic analysis. *Tectonophysics*, 2003, **366**, 83–111.
29. Wennerstrom, M. and Airo, M. L., Magnetic fabric and emplacement of the post-collisional Pomovaara Granitic Complex in northern Fennoscandia. *Lithos*, 1998, **45**, 131–145.
30. Nabighian, M. N. *et al.*, The historical development of the magnetic method in exploration. *Geophysics*, 2005, **70**(6), 33–61.
31. Rambabu, H. V. and Prasanthi Laxmi, M., Aeromagnetic characteristics of the Achankovil Shear Belt, South India. In CSIR Diamond Jubilee Seminar on Frontiers of Geophysical Research, National Geophysical Research Institute, Hyderabad, 2003, pp. 86–89.
32. Behera, L., Crustal tomographic imaging and geodynamic implications toward south of Southern Granulite Terrain (SGT), India. *Earth Planet. Sci. Lett.*, 2011, **309**(1), 166–178.
33. Kumar, N., Singh, A. P., Rao, M. R. K. P., Chandrasekhar, D. V. and Singh, B., Gravity signatures derived crustal structure and tectonics of Achankovil shear zone, southern India. *Gondwana Res.*, 2009, **16**, 45–55.
34. Talwani, M., Worzel, J. L. and Landisman, M., Rapid gravity computations for two-dimensional bodies with application to the Mendocino submarine fracture zone. *J. Geophys.*, 1959, **64**, 49–59.
35. Talwani, M. and Heirtzler, J. R., Computation of magnetic anomalies caused by two-dimensional bodies of arbitrary shape. In *Computers in the Mineral Industries. Part 1* (ed. Parks, G. A.), Stanford University Publications, Geological Science, USA, 1964, vol. 9, pp. 464–480.
36. Won, I. J. and Bevis, M., Computing the gravitational and magnetic anomalies due to a polygon. Algorithms and Fortran subroutines. *J. Geophys.*, 1987, **52**(2), 232–238.
37. Shuey, R. T. and Pasqulae, A. S., End corrections in magnetic profile interpretation. *J. Geophys.*, 1973, **38**(3), 507–512.
38. PGW, Program Documentation-MAGMOD Version 1.4, Magnetic Interpretation Software Library, Paterson, Grant and Watson Ltd, Toronto, ON, Canada, 1982, p. 17.
39. Ramachandran, C., Metamorphism and magnetic susceptibilities in South Indian Granulite Terrain. *J. Geol. Soc. India*, 1990, **35**, 395–403.
40. Martelat, J. E., Randrianasolo, B., Schulmann, K., Lardeaux, J.-M. and Devidal, J.-L., Airborne magnetic data compared to petrology of crustal scale shear zones from southern Madagascar: a tool for deciphering magma and fluid transfer in orogenic crust. *J. Afr. Earth Sci.*, 2014, **94**, 74–85.
41. Gao, P., Santosh, M., Cheng-Xue, Y., Sanghoon, K. and Ramkumar, Mu., High Ba–Sr adakitic charnockite suite from the Nagercoil Block, southern India: vestiges of Paleoproterozoic arc and implications for Columbia to Gondwana. *Geosci. Front.*, 2021, **12**, 101–126.
42. Santosh, M., Tagawa, M., Taguchi, S. and Yoshikura, S., The Nagercoil Granulite Block, southern India: petrology, fluid inclusions and exhumation history. *J. Asian Earth Sci.*, 2003, **22**, 131–155.
43. Johnson, A. S. H. and Aisengart, T., Interpretation of magnetic data at low magnetic latitudes using magnetization vector inversion. *J. Geophys.*, 2014, **3**, 91–96.
44. Cenki, B. and Kriegsman, Leo M., Tectonics of the Neoproterozoic Southern Granulite Terrain, South India. *Precambrian Res.*, 2005, **138**(1–2), 37–56.
45. Santosh, M., Tanaka, M., Yokoyama, K. and Collins, A. S., Late Neoproterozoic–Cambrian felsic magmatism along transcrustal shear zones in southern India: U–Pb electron microprobe ages and implications for the amalgamation of the Gondwana supercontinent. *Gondwana Res.*, 2005, **8**, 31–42.
46. Reeves, C., The position of Madagascar within Gondwana and its movements during Gondwana dispersal. *J. Afr. Earth Sci.*, 2014, **94**, 45–57.
47. Muller, B. G. J., The evolution and significance of Bongolava–Ranotsara shear zone, Madagascar. Ph.D. thesis, Rand Afrikaans University, South Africa, 2000.
48. Besairie, H., 1 : 2,000,000 Geological Map of Madagascar (l sheet). Survey of Geological, Madagascar, 1973.

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