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Crustal structure and tectonics of the northern part of the Southern Granulite Terrane, India

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Abstract

Deep seismic reflection studies investigating the exposed Archean lower continental crust of the Southern Granulite Terrane, India, yield important constraints on the nature and evolution of the deep crust, including the formation and exhumation of granulites. Seismic reflection images along the Kuppam–Bhavani profile reveal a band of reflections that dip southward from 10.5 to 15.0 s two-way-time (TWT), across a distance of 50 km. The bottom of these reflections beneath the Dharwar craton is interpreted as the Moho. Further south, another reflection band dipping northward is observed. These bands of reflectivity constitute a divergent reflection fabric that converges at the Moho boundary observed at the Mettur shear zone. Reflection fabrics that intersect at a steep angle are interpreted as a collisional signature due to the convergence of crustal blocks, which we infer resulted in crustal thickening and the formation of granulites. Anomalous gravity and magnetic signatures are also observed across the Mettur shear zone. The gravity model derived from the Bouguer gravity data corroborates seismic results. The tectonic regime and seismic reflection profiles are combined in a 3-D representation that illustrates our evidence for paleo-subduction at a collision zone. The structural dissimilarities and geophysical anomalies suggest that the Mettur shear zone is a suture between the Dharwar craton in the north and another crustal block in the south. This study contributes significantly to our understanding of the operation of Archean plate tectonics, here inferred to involve collision and subduction. Furthermore, it provides an important link between the Gondwanaland and global granulite evolution occurring throughout the late Archean.

Keywords: granulite facies metamorphism; collision fabric; subduction; shear zone; suture; seismic reflection

1. Introduction

Granulite terranes, high-grade metamorphic rocks rich in orthopyroxene, are distributed in various tectonic environments throughout the globe and span the Earth's geological history from the Archean to the present. The Southern Granulite Terrane (SGT) of the Indian shield, the Kapuskasing structural zone of Canada and the Arunta Block of Australia are a few examples for the Archean high-grade granulite terranes [1]. Granulite terranes are also found in many Proterozoic and Phanerozoic collisional belts such as the Aravalli–Delhi fold belt and the Eastern Ghat Mobile Belt (India), the Grenville Front Tectonic Zone (USA), the Alps of Europe, and the Himalayas of Asia.

There is strong evidence that a large part of the lower crust in Precambrian regimes contains granulite facies

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rocks based on studies from the exposed crustal cross sections [2] and xenoliths [3]. However, the surface exposure of granulite facies rocks is exceedingly small, especially compared with the total area of the lower continental crust. This poses challenges to understanding the evolution of the lower crust.

The present study is focused on understanding the structure and tectonics of the Southern Granulite Terrane, located south of the low metamorphic grade Dharwar craton, in the southern part of the Indian shield. The SGT is one of the most extensive Archean high-grade granulite terranes of the world, having an area of several thousand kilometers. The exposed granulites of the SGT act as a window, providing a unique opportunity to understand the nature of lower continental crust. Charnockite, a pyroxene (hypersthene)-bearing anhydrous rock of granitic composition, is the most abundant granulite facies rock in the region. A particularly unique feature of the terrane is the presence of a number of granulite massifs surrounded by shear zones.

The exploration of Earth's lower continental crust is an exciting component of modern geophysical research. The SGT with its exposed late Archean lower crust, is particularly valuable in providing key information about the formation and exhumation of granulites as well as an accurate representation of the deep continental crust. Further investigation of similar terranes scattered around the world may yield an important link between Gondwanaland and the global granulite evolution during the late Archean.

Recently, the SGT was investigated using crustal seismic reflection and refraction profiles [4] along a 300-km long N–S transect (Fig. 1). The transect extended across the southern part of the Archean Dharwar craton, traversing shear zones, alkali complexes, charnockites, and various gneisses of the region. Seismic reflection data were reprocessed along two profiles, the Kuppam–Bommidi and the Vellar–Bhavani sections (Fig. 1), to improve the seismic images. Further, the seismic images are used to constrain the gravity modeling that is carried out along these profiles. The structure derived from the present study is used to demarcate the boundary of the Dharwar craton, which is fundamental for understanding the evolution of the SGT. A new perspective on the deep crust is achieved by combining surface geological information with seismic reflection profiling. The present study addresses the question of the possible operation of plate tectonic processes, involving collision and subduction, during the Archean. It also further enhances our knowledge of deep crustal processes related to granulite formation and exhumation.

2. Tectonic framework

The study area consists of the Archean low-grade granite–greenstone belts of the Dharwar craton to the north juxtaposed against extensive high-grade charnockite massifs and pyroxene granulites to the south (Fig. 1). The tectonic relationship between these crustal domains is not well understood. Many of these charnockite massifs (>1000 m) are surrounded by lowland shear zones (<300 m) of late Neoproterozoic age [5]. Two major shear zones, the Moyar–Bhavani (MBSZ) and the Palghat–Cauvery shear zones, divide the entire region into three main blocks: the northern, the central and the southern blocks (Fig. 2, inset). Granulite facies metamorphism occurred at c. 2500 Ma in the northern and central blocks, and at c. 550 Ma in the southern block [6].

The northern block consists of the Dharwar craton, with greenschist to amphibolite facies, low-grade metamorphic rocks dating from 3500–2500 Ma, and granulite massifs in the southern tip. The northern block is separated from the central block along the MBSZ. The MBSZ branches into several arcuate shears in the NE–SW direction; prominent among them is the Mettur shear zone (MESZ). The region between the MBSZ and the Palghat–Cauvery shear zone is referred to as the central block. This block consists of two segments: the western Nilgiri block (N) and the eastern Salem–Madras block (SM, Fig. 2, inset). The region between these segments is covered by shear zones and gneisses. The southern block lies south of the Palghat–Cauvery shear zone.

Granulites are formed at temperatures and pressures ranging from 700 to 900 °C and 5 to 12 kbar, respectively [7]. Petrologic, geothermic and barometric measurements from the metamorphic belts of the region indicate paleopressure–temperature (*P*–*T*) conditions in the range of 5.0–7.0 kbar and 700 ± 30 °C in the northern Dharwar block, 8–10 kbar and 760 ± 40 °C in the central block, and 5–7 kbar and 700 ± 20°C in the southern block [8–10]. The high-pressure granulitic metamorphism in the central block suggests that it is distinct from the blocks in the north and south. An increase in pressure from the Dharwar craton to the central block indicates that the exposed granulite rocks of the central block were formed at depths of approximately 20–30 km. The temperature range of granulite metamorphism suggests the necessity of a thermal anomaly for their formation rather than ambient conditions of the Precambrian lower crust [11]. *P*–*T* conditions of the metamorphic rocks provide useful constraints in formulating an appropriate tectonic model for high-grade granulite terrane. The region was intruded by mafic/ultramafic rocks,

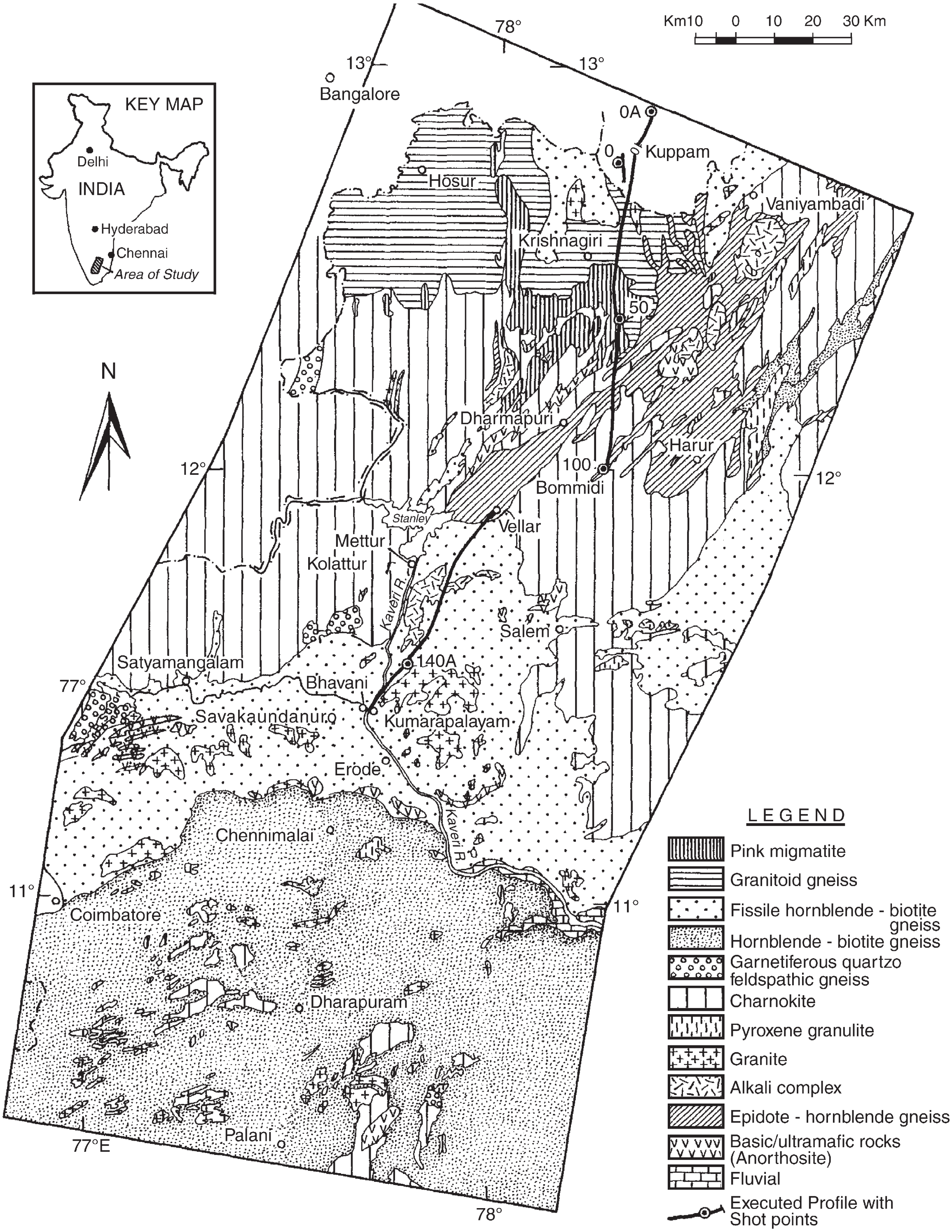

Fig. 1. Simplified geological map of the Southern Granulite Terrane (based on the map of the Geol. Survey of India, 1995) showing the locations of the Kuppam–Bommidi and Vellar–Bhavani profiles across the Mettur shear zone (Fig. 2). Note the prominent alkaline complexes north of SP140A and Bommidi, and the granitic intrusions south of SP140A. Also note mafic/ultramafic rocks and anorthosites (NE–SW direction) north and south of Dharmapuri along the Mettur shear zone.

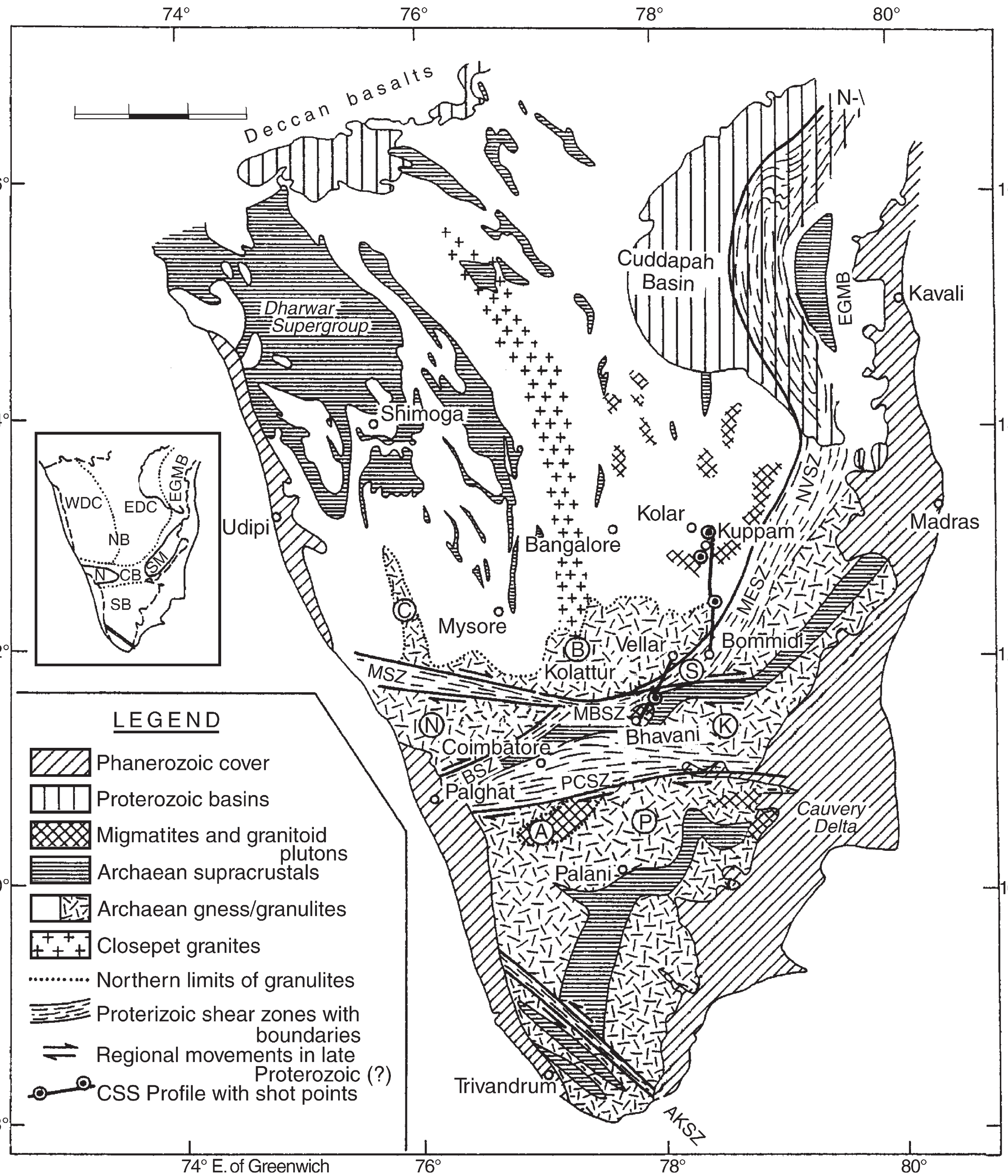

Fig. 2. Simplified tectonic map of South India along with the locations of the Kuppam–Bommidi and Vallar–Bhavani profiles (modified after Drury et al. 1984). *Proterozoic shear zones:* MBSZ—Moyar–Bhavani Shear Zone; PCSZ—Palghat–Cauvery Shear Zone; MESZ—Mettur Shear Zone; NVSZ—Nallamalai–Velikonda Shear Zone; AKSZ—Achankovil Shear Zone. *Granulite massifs*: A—Anaimalai; B—Billigirirangan; C—Coorg; K—Kollimalai; N—Nilgiri; P—Palani; S—Shevroy. *Inset abbreviations*: EGMB—Eastern Ghat Mobile Belt; WDC—Western Dharwar Craton; EDC—Eastern Dharwar Craton; NB—Northern Block; CB—Central Block; SB—Southern Block; SM—Salem–Madras Block. The Moyar Shear Zone (MSZ) and Bhavani shear zone (BSZ) in the west merge together and form the Moyar–Bhavani shear zone (MBSZ).

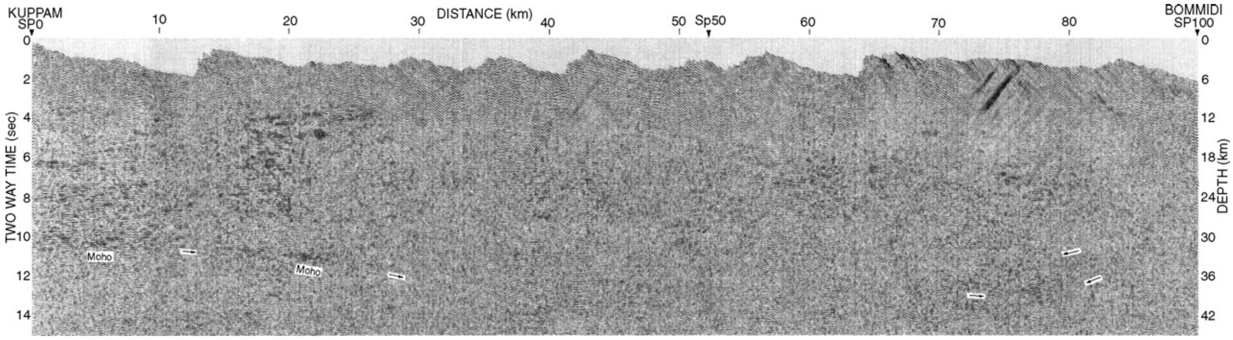

Fig. 3. Seismic stack section from the Kuppam–Bommidi profile. A prominent south-dipping reflection band can be observed in the Dharwar craton (vertical to horizontal ratio—1:2.5). See also Fig. 11. The base of the reflection band is interpreted to be the Moho. Other reflections are shown by arrows.

anorthosites, granites, and alkaline complexes from the Archean to the Neoproterozoic [12,13].

3. Previous studies

The region consists of a mosaic of Archean/Proterozoic crustal blocks accreted over the past 3 Ga [14]. Early work in the SGT was generally completed on a regional scale. Drury et al. [5] used Landsat imagery and geological data to suggest a tectonic model that explains the crustal evolution in the region. They proposed northward subduction (at the Palghat–Cauvery shear zone) and the collision of a southern cratonic block with the Dharwar craton. This provides a reasonable explanation for the late Archean crustal shortening, thickening, and metamorphism in the region. Srinagesh and Rai [15] suggested another model for the region using seismic tomography. This approach incorporated continent–continent collisions leading to the subduction of the Dharwar craton beneath an ancient cratonic block in the south. However, due to a lack of suitable geographic coverage, these studies were unable to provide the actual boundary between the crustal blocks. Using aero-magnetic data, Reddi et al. [16] suggested that the SGT is a mosaic of independent crustal blocks related to vertical movements by a number of up-thrown (horst) and down-faulted (graben) block structures in the region. Thakur and Nagarajan [17] speculate that the exposure of granulites in the SGT may be the result of vertical tectonics. Mesozoic rifting along the continental margins of the Indian peninsula may have resulted in crustal extension and magmatism, and uplift of some material deep in the crust to the surface. More

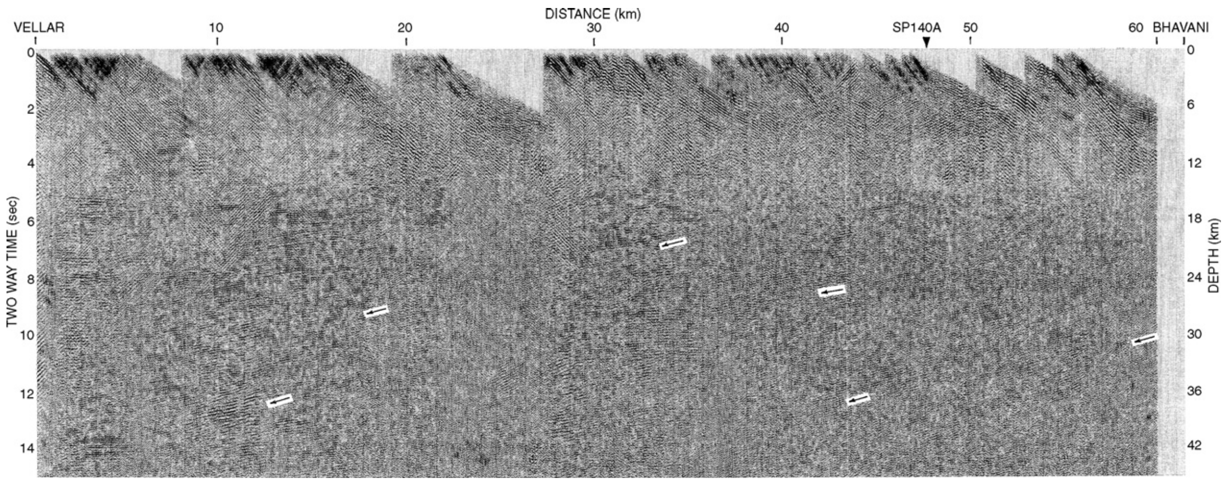

Fig. 4. Seismic stack section from the Vellar–Bhavani profile. A prominent north dipping reflection band can be observed, see also Fig. 11. (Vertical to Horizontal ratio—1:2.5) Arrows show prominent reflections.

recent studies [4] determined a maximum crustal thickness of 46 km but did not address the evolution of the granulite terrane.

4. Seismic reflection study

Seismic reflection data were acquired along the 90-km-long Kuppam–Bommidi and the 65-km-long Vellar–Bhavani profiles (Fig. 1) using digital seismic recording equipment (DFS-V) and a 4 ms sampling interval. Shot holes of 18 m depth with 35 kg explosives were used as seismic sources. The shot and receiver spacing was set at 100 m. Using 120 channels, the source–receiver geometry theoretically provides 60-fold subsurface coverage (if all receiver locations were able to be used as shot points, the multiplicity of data on any given subsurface point would have been equal to half of the number of recording channels). However, due to logistical problems in data acquisition, shots could not be fired at every 100 m interval, which led to lesser multiplicity. The two-way time (TWT) provides the vertical time taken by the seismic waves to travel from the surface to the reflector and back. The reflector could be at any depth in the subsurface down to the Moho, or even beyond. This TWT is converted into approximate depth using the average crustal P-wave velocity of the region. This is used throughout the text to visualize the depth to various reflectors.

The reflection processing sequence included demultiplexing, editing, spherical divergence corrections, deconvolution, static corrections, geometry generation, CDP sorting, iterative velocity analysis, a normal move out (NMO) correction, stacking, and F-X based random noise attenuation [18–20]. Since shear waves and ground roll were common, velocity filtering was performed in the F-K domain over all shot domain data in order to reduce noise. Enhancing signal strength and increasing the continuity of various reflectors required post-stack trace mixing. This was applied along with coherency filtering. The crustal velocity–depth model derived from the refraction/wide-angle-reflection data [4] was used to derive the TWT-stacking velocity functions. Such a model provides a more accurate estimate of the deep crustal velocity structure for a region than that derived from short-offset near-vertical reflection data. The use of such a velocity model provides a proper normal move out (NMO) correction, and therefore improves the quality of the seismic section and structural details.

Stack sections along the Kuppam–Bommidi and Vellar–Bhavani profiles are presented in Figs. 3 and 4, respectively. The corresponding seismic reflectivity of

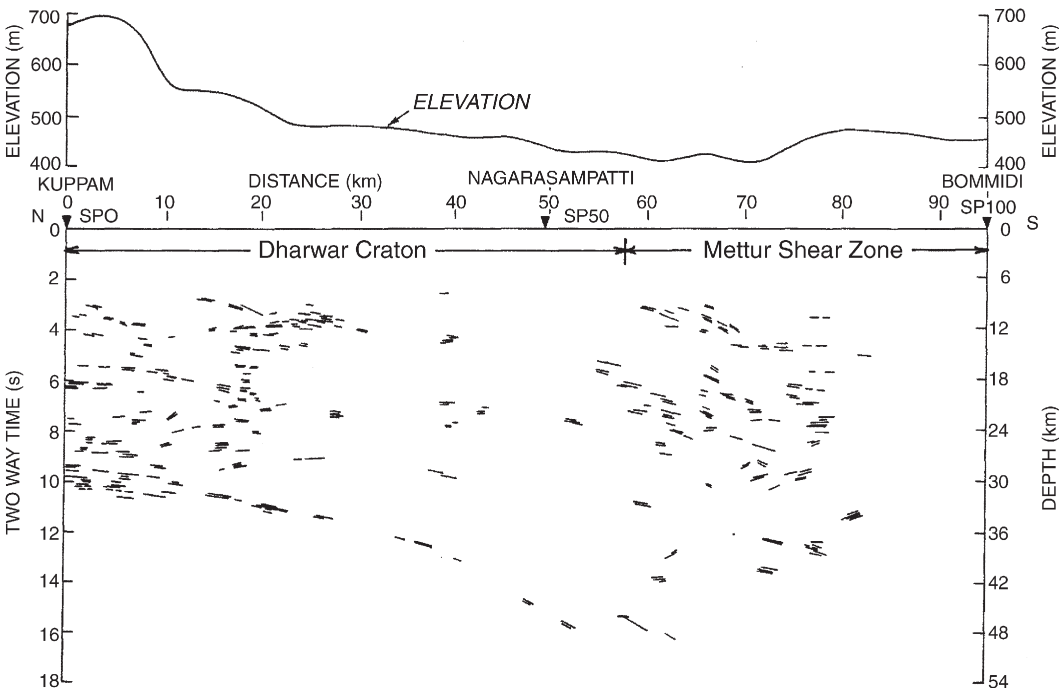

Fig. 5. Line drawing of the seismic reflection section along the Kuppam–Bommidi profile along with elevation. A deep crustal reflection band representing the Moho is observed only in the Dharwar craton.

the crust is presented as line drawings in Figs. 5 and 6. Elsewhere in the world, it is generally found that the reflectivity is rather weak in Archean terranes [21]. However, in this Archean region, moderate reflectivity is observed, which may be due to the rejuvenation of old fault zones during subsequent tectonic activity. The reflectivity patterns reveal some important events of the region which are very useful for understanding the tectonic evolution of the region and are discussed below.

A band of reflectors in the interval between 5.0 and 10.5 s TWT (~ 15–34 km depth), observed at SP0 (Kuppam), dips gently towards the south (Fig. 3). The reflections can be observed to a distance of ~ 10 km, after which the reflectivity is weak. However, the bottom of the reflection band, probably the Moho, is detected up to SP50. This band observed at 10.5 s TWT (~ 34 km depth) at SP0, shows a steep southward dip to 15 s TWT (~ 45 km depth) near SP50. This band could not be traced further south. Next, the reflectivity abruptly increases from SP50 to shallow crustal depths in the south (2–8 s TWT, ~ 6–24 km depth). A similar south-dipping reflection band is also observed near SP50 at 5–9 s TWT (~ 15–27 km depth). A small, domal feature with relatively good reflectivity is observed near SP0 between 3 and 4 s TWT (~ 9–12 km depth). Poor reflectivity at several places could be due to lower fold, vertical intrusions, or complex structural, lithological and metamorphic variations.

A prominent north-dipping reflection band is observed in the interval between 3 and 10 s TWT (~ 9–31 km depth) near Bhavani in the south, the bottom of which extends to 14 s TWT (~ 42 km depth) near Vellar in the north (Fig. 4). From 20–40 km, the intrusion of alkaline complexes makes this reflection band discontinuous (north of SP140A, Fig. 1). A horizontal reflection band is observed at 14 s TWT (~ 42 km depth) at 0–12 km distance (Fig. 4). Most of the dipping reflections terminate at ~ 14 s TWT (~ 42 km depth) beneath Vellar. This horizontal reflection band (14 s TWT, ~ 42 km depth) may represent the reflection

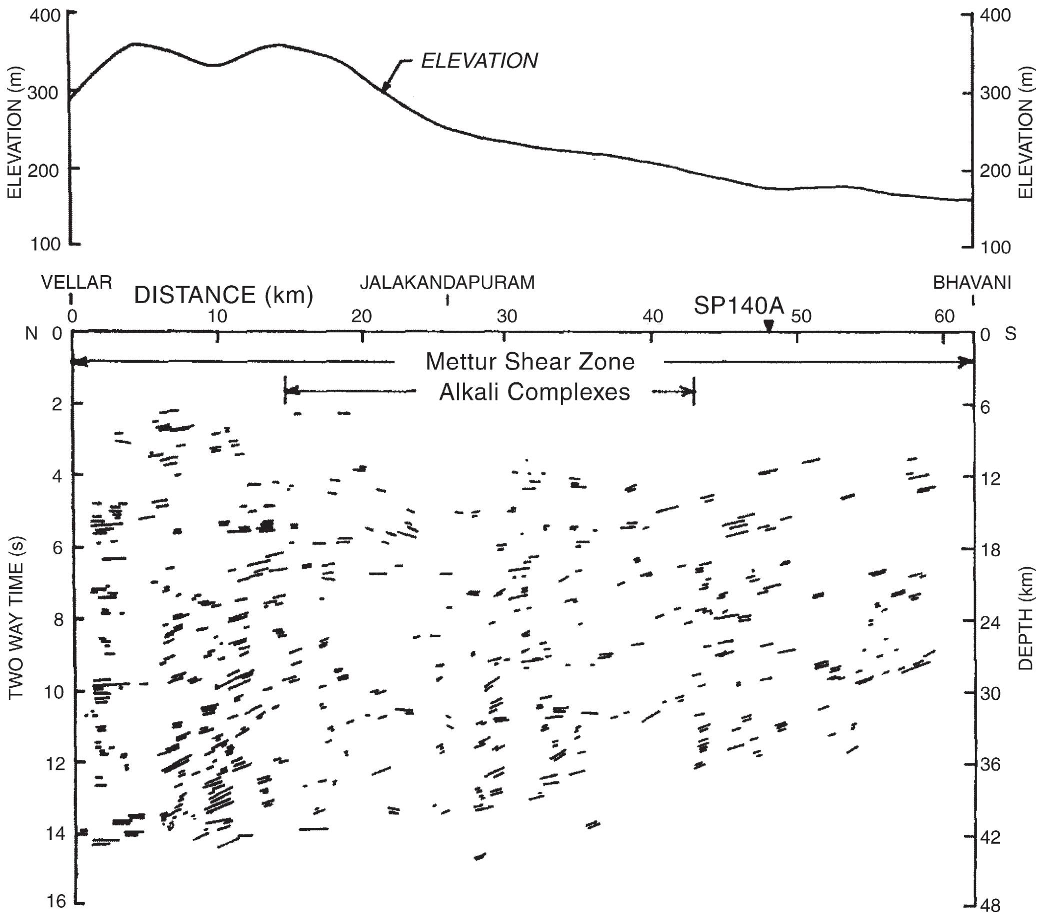

Fig. 6. Line drawing of the seismic reflection section along the Vellar–Bhavani profile along with elevation. Most of the reflections dip to the north. The actual locations of the alkali complexes can be seen in Fig. 1.

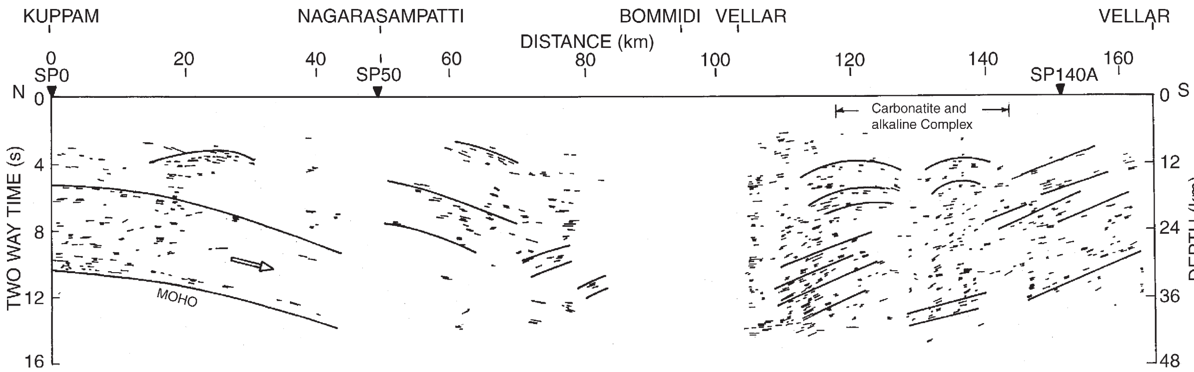

Fig. 7. Tectonic interpretation of the seismic reflection study. SP0, SP50 and SP140A represent the shot point locations used in the refraction study. The blank between 80 and 100 km distance denotes a data gap.

Moho, which coincides with the refraction Moho at a depth of ~ 42 km [4].

5. Geological interpretation

The most prominent feature of the reflection study is the dipping reflection band beneath Kuppam and extending from 10.5 to 15.0 s TWT across a distance of 50 km. Generally, it is observed that the base of the reflections in the lower crust represent the Moho [22,23]. This is because the seismic reflection coefficient at the Moho is relatively higher than other deep crustal boundaries due to the large acoustic impedance (velocity × density) contrast. We interpret the base of the south-dipping bright reflection band from Kuppam at 10.5 s TWT to represent the reflection Moho at a depth of ~ 34 km. The Moho extends to a depth of 15 s TWT (~ 45 km depth) near SP50. The up-dipping trend of the Moho (Fig. 3) towards SP0 suggests shallowing of the crust at the northern end. Earlier studies using controlled-source seismic and receiver functions indicate a crustal thickness of ~ 34 km for the northern part of the eastern Dharwar craton [24–26]. The northern part of the seismic profile, to a distance of ~ 50 km, is located at the southern end of the eastern Dharwar craton (Fig. 2, inset). Thus, there is good agreement between the crustal thickness at SP0 (Kuppam) inferred from the present reflection study and other seismic studies in nearby areas. This supports our view that the dipping reflection band represents the Moho (Fig. 6). A crustal thickness of 34 km at the Archean eastern Dharwar craton (in the north) is similar to the global average for Archean terranes [27]. The increase in crustal thickness towards the south is indicative of the southernmost tip of the Dharwar craton. The presence of a well-defined, dipping Moho indicates that subsequent tectonic events have neither modified the lower crust nor destroyed the reflectivity in the Dharwar craton, highlighting the unique tectonics of this region. This is indicative of the thermal and tectonic stability of the region. The low mantle heat flow (11–161 mW/m^2) and thick lithospheric root further constrain the stability of the region. A strongly-dipping Moho is also observed in the Opatica belt in the Archean Superior Province of the Canadian shield [28], the Proterozoic orogenic belt of the Baltic Shield [29] and in the Phanerozoic Swiss Alps [30].

Other structural features observed in the region include a band of south-dipping reflections from Kuppam (SP0) to SP50 (Fig. 3), and another band of north-dipping reflections from Bhavani to Vellar (Fig. 4). These reflection bands constitute a divergent reflection fabric (pro and retro) and merge at the boundary of the Dharwar craton and the Mettur shear zone (Fig. 5). Such oppositely-dipping reflection fabrics (bivergent patterns) have been observed across the Phanerozoic, Proterozoic, and Archean fold belts in various parts of the world [31,32,28,33]. In general, such a reflection fabric is related to orogenic processes. This is found to be consistent with predictions from numerical and analog models of the continental collision process [34], thus representing episodes of collision. The tectonic interpretation of the reflection study is presented in Fig. 7.

In the absence of seismic and other geophysical data, it is generally believed that the increase in regional metamorphism, from amphibolite facies rocks equilibrated at pressures <7 kbar in the north (Dharwar craton) to granulite facies rocks equilibrated at pressures >7 kbar in the south (SGT), is gradational and shows no abrupt structural break. Also, it has been hypothesized that the two blocks (Dharwar and SGT) are continuous and together constitute a single crustal block. The increase in metamorphism from north to south is thought to be due to the northward tilt of this crustal block

(Dharwar and SGT) and the effect of differential erosion, thus exposing the lower crustal granulites in the south. However, the present study indicates a tectonic/structural break at the Mettur shear zone. These results, therefore, bring significant insight into understanding the tectonic evolution of the region.

The deeply-penetrating south-dipping reflection band from SP0 (Figs. 3 and 5) extending into the lower crust and upper mantle suggests that tectonically imbricated thrusting developed during a compressional environment. In such zones, reflections may originate from within shear zones [23]. This feature is observed from the southern boundary of the Dharwar craton to the Mettur shear zone in the south (Fig. 3). This may represent a paleo-subduction zone, and the Salem–Madras block (the southern part of the Mettur shear zone, Fig. 2, inset) might represent a volcanic arc system with calc-alkaline meta-igneous lithology. The swathes of Archean supracrustal rocks south of the MESZ represent the presence of a large marginal basin in the region [13]. Deeply-penetrating reflection bands in the lower crust and the upper mantle are also observed at the Archean and Proterozoic subduction zones of the Canadian and Baltic shields. The Archean layered meta-anorthosite bearing mafic–ultramafic complexes extending along the Mettur shear zone may represent dismembered ophiolites of the region (Fig. 1). As the subduction process continued, a collision took place between the Dharwar craton and a crustal block in the south, with an arc between them, during the late Archean period. The oppositely-dipping divergent reflection fabric observed in the region appears to represent this collisional episode. The deep-crustal granulites were exhumed during the subduction of the Dharwar craton and its subsequent collision. One of the deep faults identified by Grady [35] coincides with the subduction zone inferred in the present study. The 46 km crustal thickness at the Mettur shear zone derived from the refraction study [4] is therefore likely due to crustal shortening during the collisional event. With the above evidence, the Mettur shear zone is interpreted as a terrane boundary/suture zone.

Geological data in the region indicate that the Dharwar craton located to the north of the MESZ has rocks dating from 3580 Ma, whereas the protolith age of the Salem–Madras (Central Block, Fig. 2, inset) granulites located to its south is around 2550 Ma [36]. This evidence indicates that the region south of the MESZ has a very short or no prior crustal history of protoliths and formed syn-accretional granulites. Peucat et al. [37,38] are of the opinion that tonalitic gneisses and granulites might have formed simultaneously in the same subduction episode. They further suggest that the granulites north and south of the Mettur shear zone are distinctly different. This indicates that a juvenile crust might have developed in a volcanic arc environment of a subduction zone south of the Mettur shear zone, and further suggests that the Salem–Madras block has a different evolutionary history than the Dharwar craton in the north. As mentioned

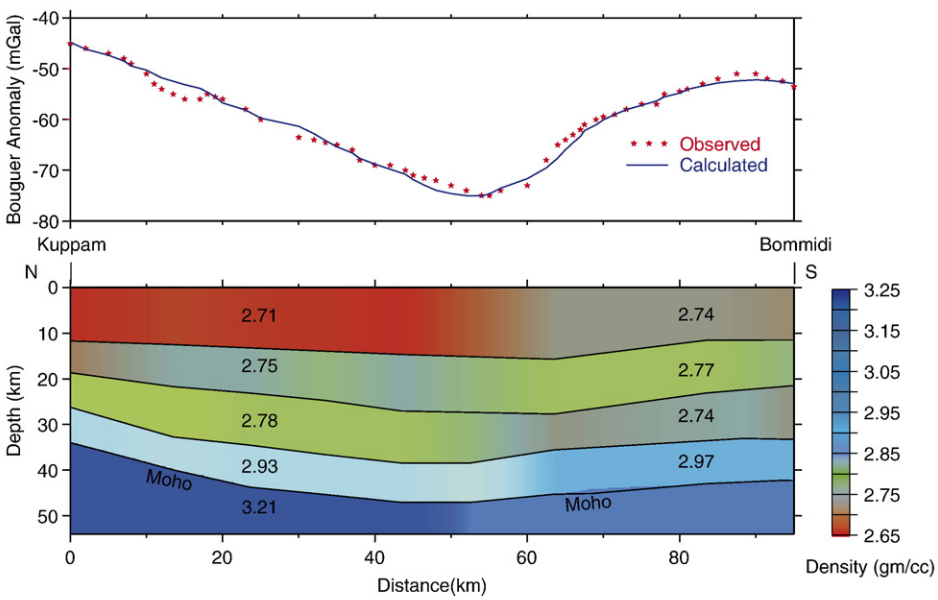

Fig. 8. Crustal density model along the Kuppam–Bommidi profile, derived from the reflection section and velocity models of the region. Observed and calculated Bouguer gravity anomalies are shown on the top. The side panel displays the color-scale index of the density range. Note the bipolar gravity anomaly of the region.

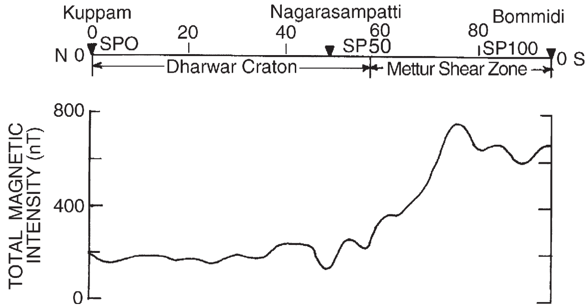

Fig. 9. Total magnetic intensity anomaly along the Kuppam–Bommidi profile. Note the abrupt change in magnetic signature across the Mettur shear zone, which constitutes the bipolar magnetic anomaly of the region.

earlier, these crustal blocks are separated by the Mettur shear zone. The N–S structural trends of the Dharwar craton are disrupted with the NE–SW trending MESZ.

Fluid inclusion studies of the region indicate the streaming of carbon dioxide as the main mechanism for granulite facies metamorphism [11,39]. The carbonic fluids released from the supracrustal rocks at the subduction zone, and mantle degassing at the volcanic arc environment, might have purged the water and transformed the amphibolite facies rocks into anhydrous granulites. Such an environment is the main source of fluids and might be responsible for the Archean high pressure–temperature granulite facies metamorphism (charnokite formation) of the region. These granulites have been thrust to the surface and found to be syn-accretional [37,38]. Harris et al. [6] studied the carbon–isotope composition in fluid inclusions from the charnokite of this region (−4% to −12%) and suggested

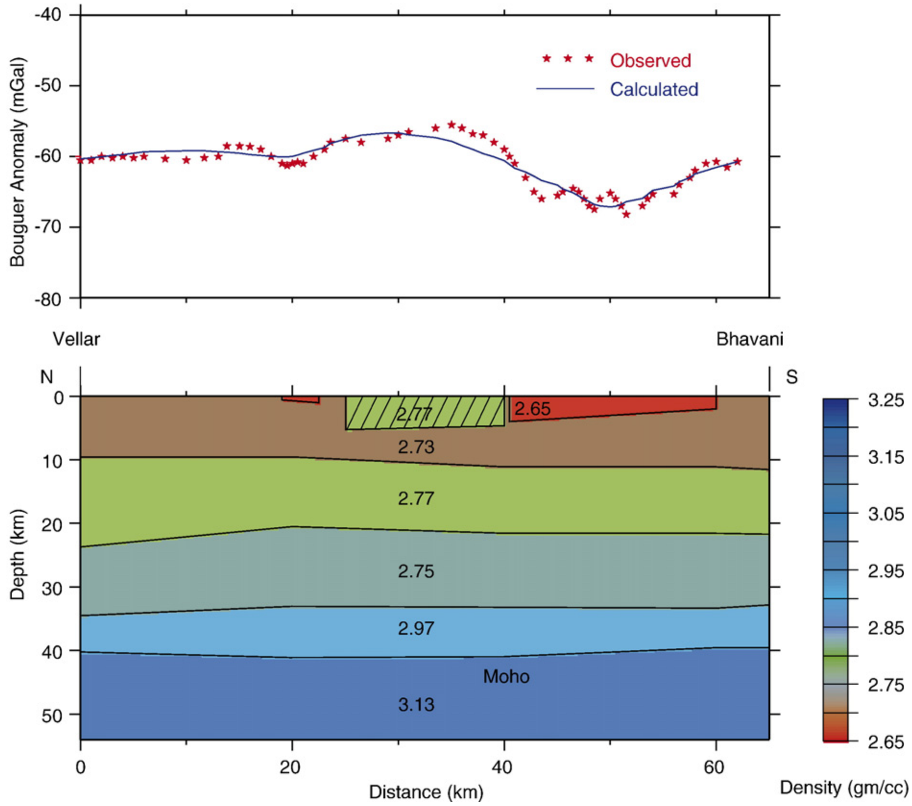

Fig. 10. Crustal density model along the Vellar–Bhavani profile, derived from the reflection section and velocity models of the region. Observed and calculated Bouguer gravity anomalies are shown at the top. The hatched portion represents carbonatites observed in the study region.

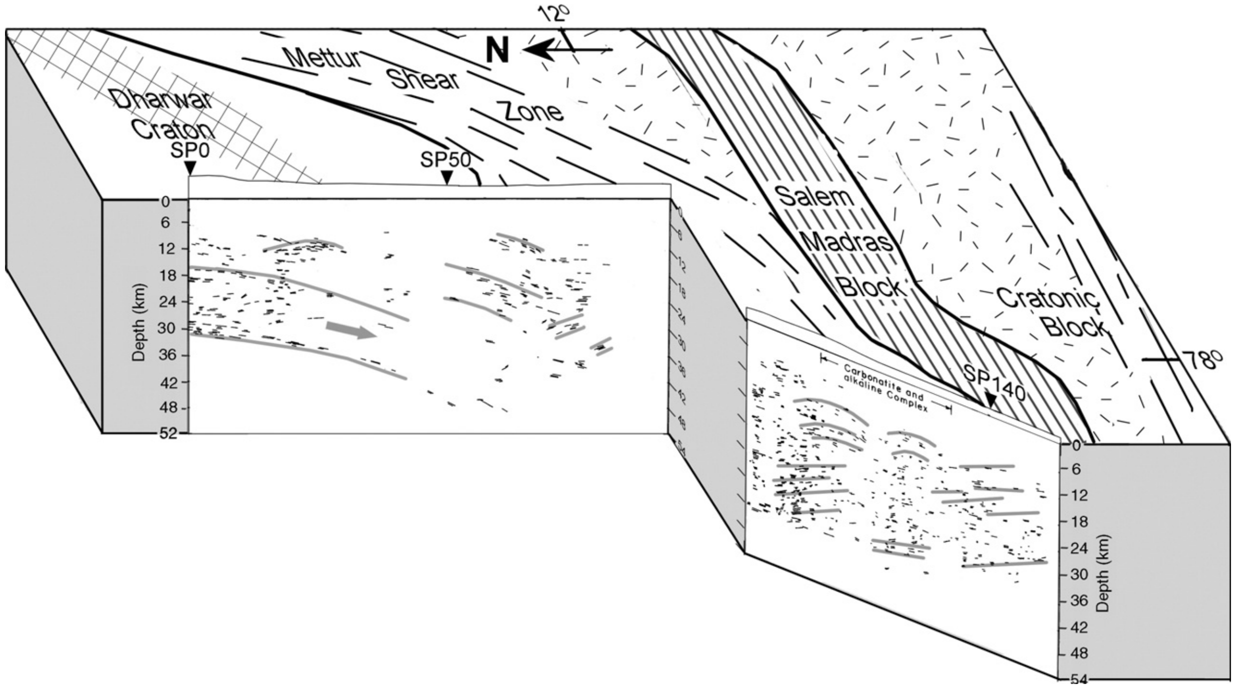

Fig. 11. 3-D representation of the tectonic regime and the seismic reflection images. It is evident that this is a collisional zone. We propose that paleo-subduction has occurred, with the Dharwar craton forced towards the south where it subsequently collided with the southern crustal block. Also note the evolution of a suture at the Mettur shear zone.

that the Archean granulite facies metamorphism is associated with the volatiles released at the subduction zone. This supports the presence of a subduction zone and the associated formation of charnokites at this zone. The evolution of the granulites in the region may thus be related to the collision process. Bohlen [40] suggests that the collision zones and volcanic arc environments provide appropriate *P*–*T* conditions for the formation of granulites.

The Bouguer gravity value along the Kuppam–Bommidi profile changes from −45 mGal at Kuppam (located in the Dharwar craton) to −75 mGal at a distance of 55 km, and increases to a value of −50 near Bommidi (Fig. 8). Such an anomaly constitutes a positive–negative gravity pair which has been observed over many sutures/terrane boundaries in different parts of the world [41,2]. The total magnetic intensity data [42] along the Kuppam–Bommidi section shows a low value of 200 nT over the granitic gneisses of the Dharwar craton and a high value of 800 nT over the shear zone, thus constituting a bipolar magnetic anomaly (Fig. 9). Such an anomalous magnetic pair with a change in magnetic intensity of 600 nT is generally observed over the suture zones [43]. The magnetic high indicates the presence of mafic and ultramafic rocks in this part of the region. This further supports the presence of a magmatic arc, as suggested earlier.

Gravity modeling [44] is carried out for the Kuppam–Bommidi profile by converting the velocity model [4,24] into an initial density model using velocity–density relationships [27]. Further, the gravity model is constrained by the reflection stack section. The model is iteratively refined to derive a minimum misfit between the observed data and computed gravity response. A good match is found between the observed and computed data (Fig. 8). The gravity model displays distinctly different crustal blocks on either side of the MESZ. A dipping Moho is observed in the eastern Dharwar craton, which is similar to the reflection section (Figs. 3 and 5). A good correlation is found between the gravity and crustal thickness, as the crustal thickness increases while gravity decreases along this section. The Moho up-warp at the MESZ and subsequent crustal thinning corresponds to an increase of gravity values.

A gravity model is also derived for the Vellar–Bhavani profile by adopting a similar procedure to that of the Kuppam–Bommidi section. The final gravity model along with the observed data and computed response is presented in Fig. 10. The gravity model shows almost a constant crustal thickness along this section and matches very well with the gravity low observed along the seismic profile. The decrease of Bouguer gravity at the end of this section is due to the presence of a large number of granitic plutons (Fig. 1) with an estimated 2.65 g/cc density. The high density body (2.77 g/cc) observed in the shallow part, between 20 and 40 km distance, may correspond to carbonatites observed in the region (Fig. 1).

The presence of a dipping Moho, structural discontinuity, change in metamorphic conditions, age differences, variation in the crustal thickness, contrasting crustal evolution, and the bipolar gravity-magnetic signatures across the MESZ suggests it is a terrane boundary/suture zone formed during the late Archean. The present reflection study suggested a collisional suture at the MESZ for the first time. Earlier studies, mostly geological in nature, were confined only to the Moyar–Bhavani shear zone.

Signatures of collision and suturing of cratonic blocks similar to the present study are also observed in several parts of the world [23]. Seismic images from the Canadian shield indicate a Archean collision zone involving the Abitibi granite–greenstone belt and the plutonic arc-related Opatica belt [28]. A gently-dipping thrust fault extending to mid-crustal depths observed in the Archean Kapuskasing structural zone is found to be responsible for the exhumation of granulite facies rocks [45].

The other feature of the reflection study is a change in reflectivity character near SP140A (Fig. 5). The continuity of the north-dipping reflection band is obliterated by a small domal structure and is again noticed further north (Fig. 5). Such a reflectivity pattern could be due to the intrusion of the 750 Ma alkali complexes observed as a surface geological feature north of SP140A (Fig. 1). Widespread magmatic activity in the form of alkaline and granitic intrusions of the same period is also observed along the MESZ to the northeast up to a distance of 200 km. Since the collision/suture zones are rheologically weak, the later tectonic activities are generally confined to these zones. This is evidenced by the prominent 750 Ma tectonic activity along various parts of the suture zone. In addition to ophiolites, high pressure metamorphic rocks, post-collisional granites, carbonatites, and alkaline rocks in a region commonly indicate the locations of paleo-suture zones. Burke et al. [46] have identified the paleo-sutures in Africa with the presence of deformed alkaline rocks and carbonatites. The long chain of alkaline rocks and carbonatites observed all along the MESZ may indicate the location of a paleo-suture zone. The 750 Ma alkaline igneous activity observed in the region coincides with the rifting of the Rodinia supercontinent. The above observations represent evidence of global tectonic activity as observed over the south Indian shield.

Heat flow studies of the region [47] suggest similar surface heat flow values for the Dharwar craton and the SGT, but distinctly different mantle heat flow values. The estimated mantle heat flow for the SGT is in the range of 23–35 mW/m^2, whereas it is 11–16 mW/m^2 for the Dharwar craton. Ray et al. [47] have calculated the Moho temperatures for the SGT and the Dharwar craton to be 550–650 °C and 275–380 °C, respectively. They attribute the higher mantle heat flow to the enriched mantle in the region. The isotopic characteristics of the carbonatite (alkaline complexes of various ages) rocks of the SGT also suggest mantle enrichment in the region [48]. Such mantle enrichment can take place from the subduction of crustal material. This further supports the presence of a paleo-subduction zone in this region. High heat flow at the base of the crust in the SGT compared to the granite–greenstone gneissic terrane of the eastern Dharwar craton is consistent with the seismic section and gravity model, which indicate contrasting geophysical properties on either side of the MESZ. Fig. 11 presents a broad 3-D representation of the above observations across the study area.

The discontinuously elevated topography observed in the form of hills within the Salem–Madras block might have formed as a part of the much larger Archean juvenile terrane. Due to subsequent tectonic activity, either from the evolutionary process of the Eastern Ghat orogeny (1100 Ma) or from Neoproterozoic shearing along the Archean collision zone, this terrane may have bifurcated into small hill ranges (the Shevroy, Kalrayan, Kollimalai and Pachimalai hills) with shears/thrusts surrounding them (Fig. 2). This is supported by structural evidence as most of the shears extend NE–SW and seem to merge with the Eastern Ghat mobile belt.

6. Conclusions

The present study documents a deeply-penetrating, dipping band of reflections which extends from 34 to 46 km depth, and is observed only beneath the Dharwar craton. This reflection band is here interpreted to be the Moho. Seismic images further suggest collision of the Dharwar craton and another crustal block with a volcanic arc between them during the late Archean. The collision process thickened the crust at the Dharwar craton–Mettur shear zone boundary. The observed crustal reflectivity patterns, lateral variations in crustal thickness, gravity-magnetic signatures and geological attributes on either side of the Mettur shear zone characterize it as a suture formed during subduction and collision processes.

The carbonic fluids released from the supracrustal rocks of the subduction zone and volcanic arc environments are interpreted to be responsible for the formation of granulites. The deep crustal granulite rocks at the subduction zone were probably exhumed during the collisional process. The present study suggests that the tectonic processes involving subduction, collision and suturing are mainly responsible for the crustal evolution of the high-grade Southern Granulite terrane. The inferences drawn in the present study are derived from the first deep seismic reflection images crossing the Mettur shear zone.

The images from this reflection study provide evidence for the operation of plate tectonics over the Indian shield since 2500 Ma. A steeply-dipping Moho is identified for the first time over the Indian shield. A well-defined Moho in the Archean Dharwar craton, an unusual feature of the Archean terranes, indicates its thermal and tectonic stability. However, other evidence indicates that the Mettur shear zone has been affected by late Neoproterozoic tectono-magmatic activity [49].

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