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Precambrian Research 124 (2003) 21–40
Precambrian Research
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# Nature of the crust below the Southern Granulite Terrain (SGT) of Peninsular India across the Bavali shear zone based on analysis of gravity data

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Received 5 November 2001; accepted 24 January 2003

**Abstract**

The Bavali shear zone is a major Proterozoic structure in the Southern Granulite Terrain (SGT) of Peninsular India. A detailed gravity survey has been carried out in order to delineate the crustal structure and tectonics of the shear zone and adjacent areas.

The Bouguer anomaly map of the region shows a number of features: (i) an E-W gravity gradient zone with an average gradient of 3.0 mGal/km in the west and 0.4 mGal/km in the east across the shear; (ii) a broad gravity low with a relief of 20 mGal in the Wynad plateau SE of the shear; (iii) a series of gravity lows in the southern part of the shear between Kannur and Vayittiri; (iv) a broad gravity high of 30–40 mGal encircling the charnockite province in the NW part of the shear, and; (v) a sharp localised gravity high closure of 40–50 mGal towards coast at Nileswaram.

Spatially filtered gravity anomaly maps clearly exhibit contrasting gravity signatures on either side of the shear zone with relatively higher gravity values within the northern block. Crustal thickness estimates, in general, vary from 36 to 41 km with a thinning of 2 to 3 km towards the north below the shear zone. Using two-dimensional crustal models determined from gravity anomaly profiles across the Bavali shear zone, it is interpreted that the shear zone extends downward close to a plane separating blocks of different crustal densities. The shear zone dips steeply towards the south and its downward extension meets with a slight Moho rise suggesting that the Bavali shear zone is a crustal-scale structure. Eastwards below the Wynad plateau, however, the shear zone becomes less prominent suggesting local variations in its geometry.

The models also point out the presence of a thick high-density body (2.98 g/cc) in the lower part of the crust below the northern charnockite province, which narrows towards the Wynad plateau region in the east. The presence of such a high-density body could be due to factors such as evolution together with the protoliths of overlying charnockitic rocks, a dense lower crustal residual fraction during anorthosite genesis, or emplacement during Pan-African/later anorogenic events. The models also indicate that the Wynad plateau region is characterised by a relatively homogeneous crust.


*Keywords:* Gravity anomalies; Crustal structure; Bavali shear zone; High-grade terrain; Southern India; Proterozoic

## 1. Introduction

Mid-crustal shear zones exposed in deeply eroded Precambrian orogenic belts transfer or accommodate large scale relative displacements between crustal

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doi:10.1016/S0301-9268(03)00047-0

blocks. Numerous structural investigations of regional geology and tectonics of major shear zones in Precambrian regions have been made by several workers (e.g. Bak et al., 1975; Daly, 1986; Coward and Park, 1987; Friend et al., 1988; Pili et al., 1997). Additionally, recent geophysical studies, particularly gravity and seismic investigations, combined with geology over certain major shear zones in other orogenic belts, have provided insight into the crustal dynamics, crust–mantle interactions and lithospheric structure associated with such zones (Fountain and Salisbury, 1981; Lambeck, 1983; Lambeck et al., 1988; Reston,

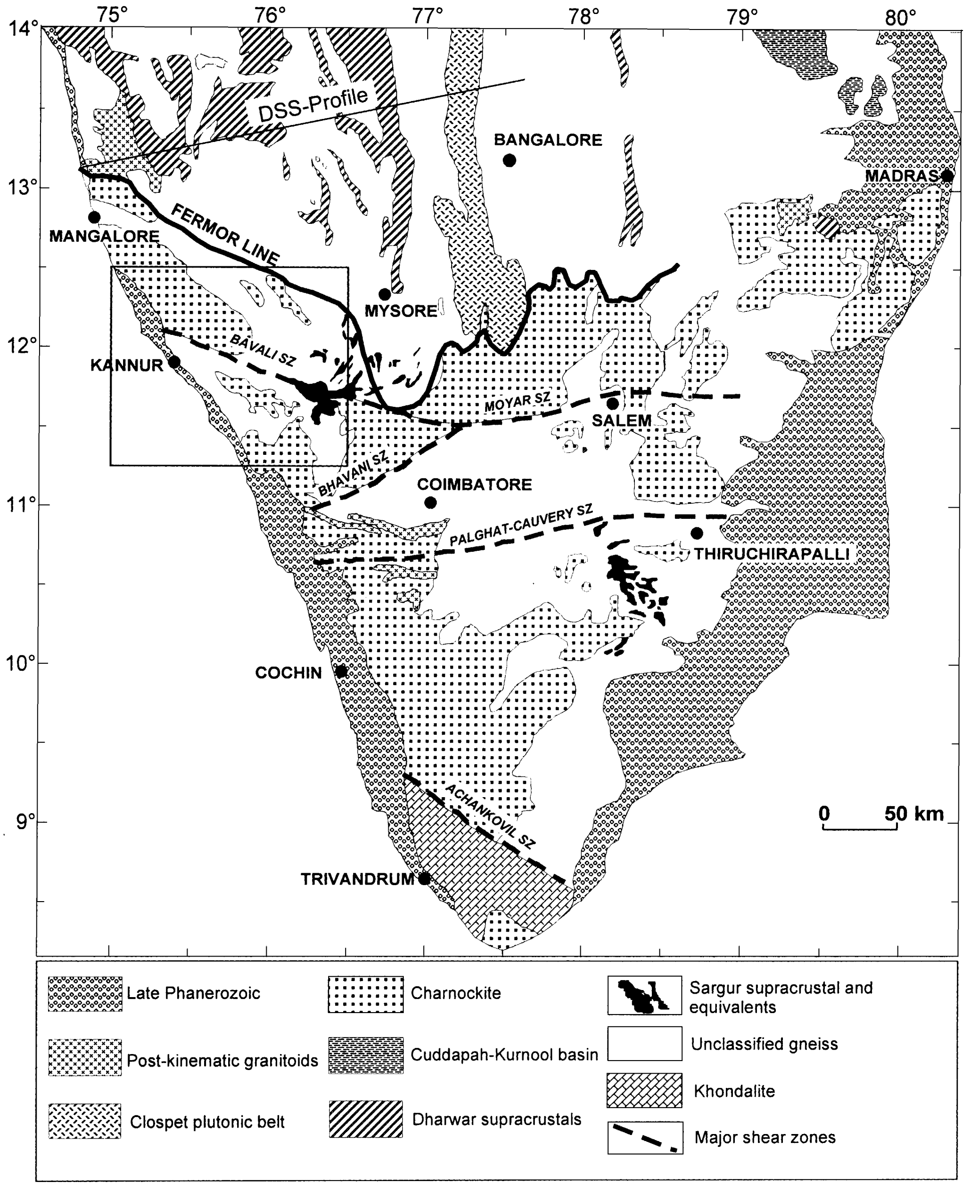


Fig. 1. Simplified geological map of South India (modified after Raith et al., 1983) showing major shear zones (thick dashed lines) and the present study area (marked as rectangle). The line marked as ‘DSS profile’ is the western part of the Kavali–Udipi Deep Seismic Sounding profile (Kaila and Bhatia, 1981).

1990; Plomerova et al., 1993; Ibrahim et al., 1996; Pili et al., 1997).

The Southern Indian shield is regarded as a crustal unit comprised essentially of Archaean continental nuclei and Proterozoic mobile belts, which are represented, respectively, by the granite-greenstone terrain of Karnataka and the high-grade terrain further south (Naqvi and Rogers, 1987). Fermor (1936) first identified a boundary (popularly known as “Fermor line”) to separate charnockitic (granulitic) and non-charnockitic (gneiss-schist) terrains in the shield. It was also recognised that a narrow transition zone exists along which lower grade gneiss granite-greenstone rocks transform to higher grade granulite facies rocks (Pitchamuthu, 1965; Naqvi and Rogers, 1987; Radhakrishna et al., 1990). Various thermotectonic events that operated in the evolution of different units of the shield have left their imprints in terms of the deep crustal structure. The Southern Granulite Terrain (SGT) south of this transition is traversed by a set of prominent faults/shears (Katz, 1978; Drury and Holt, 1980; Drury et al., 1984) which include the Moyar, Bhavani, Palghat-Cauvery and Achankovil shear zones (Fig. 1). The geometry and kinematics along these shears have been studied by Naha and Srinivasan (1996), Sacks et al. (1997) and D’Cruz et al. (2000). Meissner et al. (2002) recently discussed the geochronological evolution of some of these shear zones based on a variety of isotope data. The Bavali shear zone, which appears as the WNW extension of the Moyar shear, forms a major shear system lying very close to the granulite-gneiss transition zone of Southern India. The presence of this structure was first mapped by the Geological Survey of India (GSI) as a fault zone trending WNW-ESE and has been named after the Bavali river of northern Kerala (Nair et al., 1976). The Bavali shear zone and the adjoining Precambrian lower crustal segments provide a unique assemblage of several metamorphic and plutonic rocks and a variety of major structural features. A detailed study of the gravity field over the Bavali shear zone and the associated crustal blocks can, therefore provide significant information on the deep crustal structure of the region. This information may have a bearing on the metamorphic, magmatic and tectonic processes in the SGT, and similar high-grade domains elsewhere.

## 2. Geology of the area

The geological framework of the Bavali shear zone and the adjoining areas has been discussed by Nambiar et al. (1985) based on Landsat data. A revised geological map of the area compiled from Nambiar (1987) and GSI (1995) is given in Fig. 2. As can be seen from the map, the charnockitic rocks and their retrograded products constitute the predominant rock types in the region. The Wynad Schist Belt (WSB) is represented as enclaves of schistose rocks within the gneissic rocks. The geology of the area in many places is obscured by the presence of a thick cover of laterite/soil/vegetation. Based on petrological data, Nambiar et al. (1992) divided the region into different provinces. The area of the present investigation covers parts of three provinces, namely, (1) the WSB which is essentially a gneissic terrain with enclaves of schists and other metasedimentary rocks and a variety of plutons, (2) the northern charnockite/granulite province occurring north of the WSB, and (3) the southern charnockite/granulite province towards the south of the WSB. Some important geological features pertaining to these provinces are presented below.

### 2.1. Wynad Schist Belt (WSB) and associated rocks

The schist-gneiss complex of the Kannur–Mananthavady area (referred to as the WSB) extends for about 150 km in a WNW-ESE direction with an approximate width of 10–20 km. This belt is characterised by the presence of small isolated patches of schists in the gneissic country rock. Nair et al. (1976) interpreted the metapelites and metavolcanics of the belt as correlatives of the Sargurs of the Karnataka area lying northeast of the belt. The most conspicuous feature of this province is the NW-SE trending Bavali shear which strikes over 100 km through the centre of the area (Nair et al., 1976). Several igneous plutons of felsic and mafic composition were emplaced within or close to the gneisses and schists. The gabbro-diorite bodies near Kartikulam and Tolpetti and granite plutons of Peralimala, Ambalavayal and Kalpatta are some of the major plutons in this region (Fig. 3).

A small basin of younger metasediments called the Vengad Group occurs to south of the western end of WSB considered equivalent to Proterozoic Dharwars of Karnataka (Nair et al., 1980; Nair and Nair, 1991).

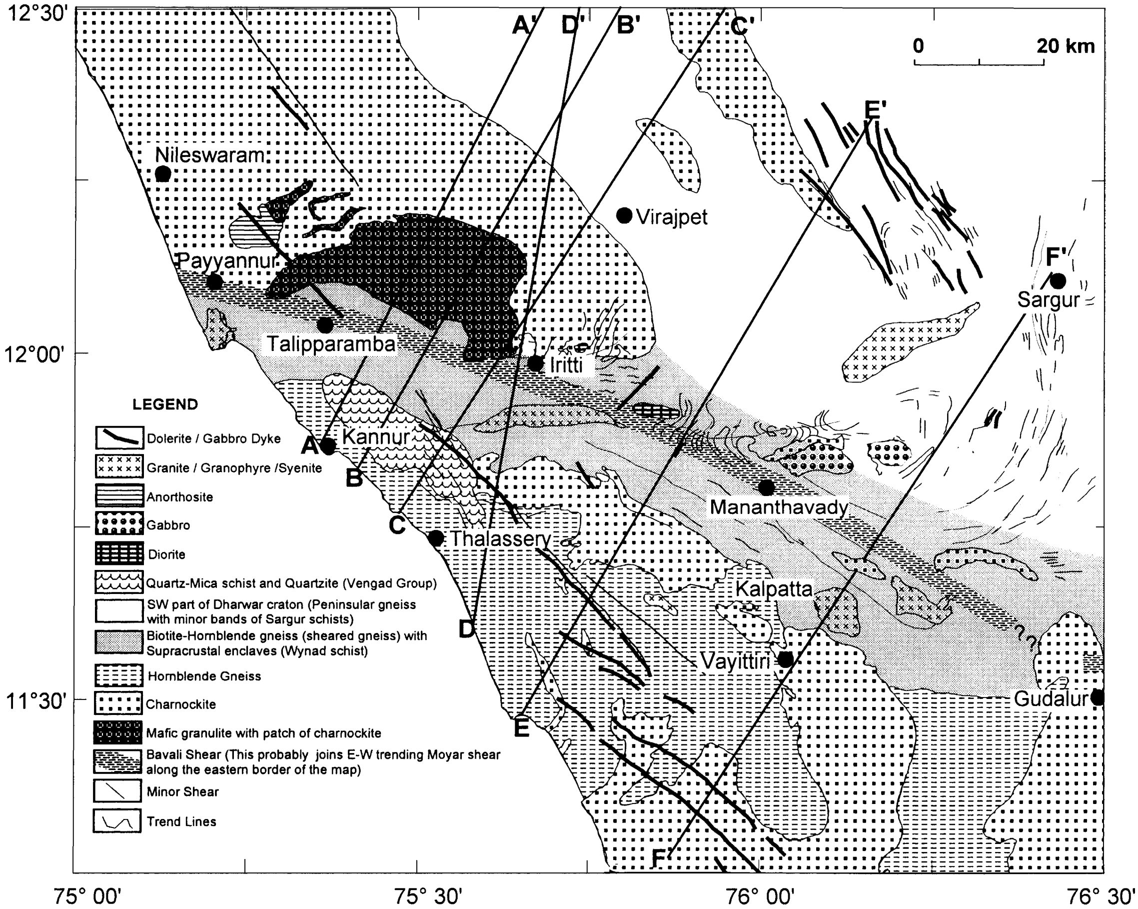


Fig. 2. Geological map of the Bavali shear zone and the adjoining regions (Nambiar, 1987; GSI, 1995). The supracrustals/schist belts in the Dharwar craton and the Wynad Schist Belt are not shown for clarity. The trend lines shown are mainly the trends of these enclaves. Lines AA′ through FF′ indicate the location of six regional gravity profiles considered for modeling the crustal structure below the region.

It consists of schists and quartzites with conglomerates at the base, and unconformably overlies the gneisses and charnockites.

### 2.2. Charnockite/granulite provinces

The charnockite provinces are located in the north as well as south of the WSB. While charnockites in the northern part are coarse-grained and mostly massive and felsic, in the southern part they are medium-grained, banded and of intermediate composition (Nambiar, 1987). Retrogression of charnockites to gneisses with hydrous mineral assemblages is common in both provinces. A massif-type anorthosite body (Perinthatta anorthosite) is situated within the northern charnockite province, 10 km to the north of WSB. The petrological and related aspects of the Perinthatta anorthosite have been documented (Vidyadharan et al., 1977; Nambiar et al., 1997; Kurian et al., 1999).

### 2.3. Dykes

Major dykes running for a few tens of kilometres, somewhat parallel to the coast are prevalent in the area. They are mostly late Phanerozoic in age and include fresh dolerites and subalkalic Fe-rich quartz tholeiites that strike NW-SE, NNW-SSE and NE-SW

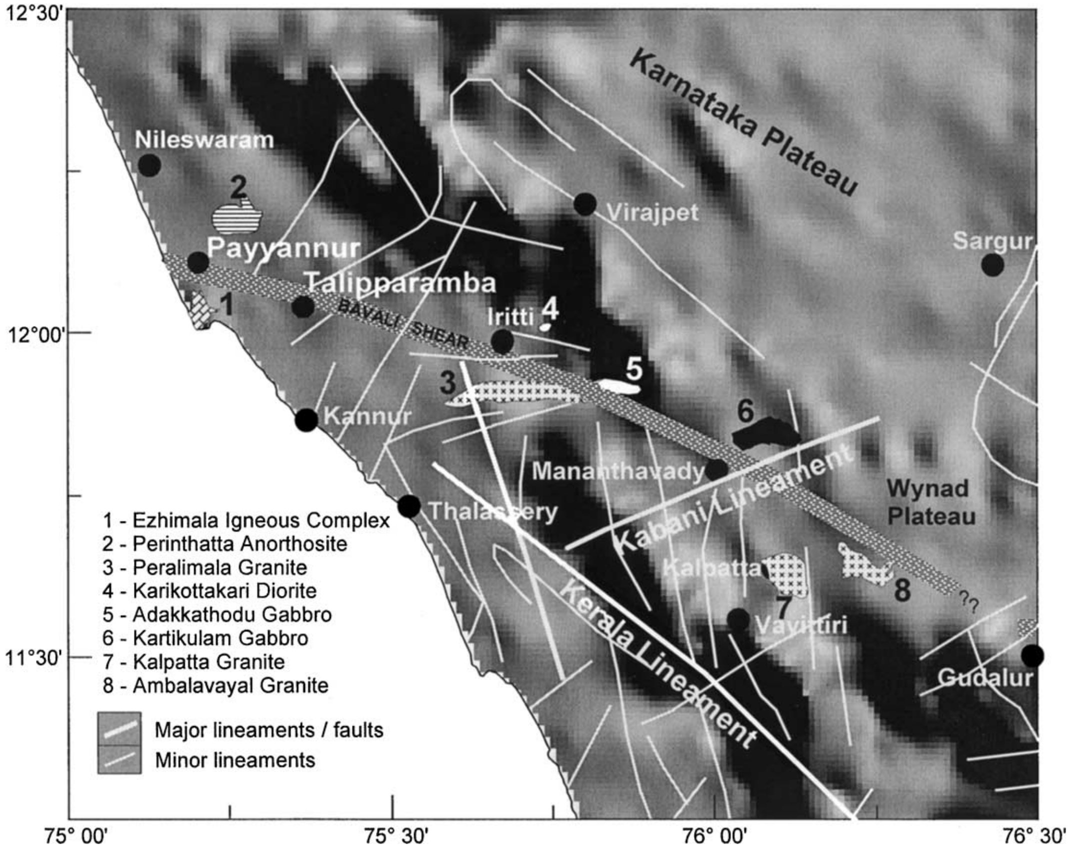


Fig. 3. The shaded relief image of the area prepared from gtopo30 elevation data. The dark shades on the map having elevation mostly ranging 600–1200 m represent the 'Western Ghats', the steep coast-parallel escarpment. The Wynad Plateau has an average elevation of 800 m. The major and minor shears/lineaments in the study area (Varadarajan and Balakrishnan, 1980; Katz, 1978) and plutons (numbered 1–8) along the Bavali shear are also shown.

(Radhakrishna et al., 1986). The K-Ar age data of the NW-SE trending dolerites give a 99–129 Ma range (Radhakrishna and Mathew, 1995). In addition to this, a few dykes of Proterozoic age also occur in the region and have a variety of strike directions (Radhakrishna et al., 1986).

### 2.4. Structure

The Bavali shear zone is a major deformational zone with a contrast in lithology, structure and metamorphism across it (Nair et al., 1976). The zone forms the western part of the regional Proterozoic high-strain zone recognised by Drury and Holt (1980) that encompasses the Moyar and Bhavani shear zones. This structure has a very good geomorphic expression as it offsets the Western Ghat trend (Fig. 3). The extensive Pan-African magmatism of northern Kerala has been linked by several workers to this linear structure (Nair et al., 1976; Nair and Vidyadharan, 1982; Santosh and Nair, 1986; Nair and Santosh, 1984). The major rock types along the shear zone are sheared biotite gneiss with enclaves or tectonic slices of schists of the WSB. Pseudotachylytes and mylonites are seen at several places along the Bavali valley (Sinha-Roy and Ravindrakumar, 1985; Soney, 2000). Recent structural analysis along the Bavali shear zone by Soney (2000) indicated three generations of regional folding, with the main shearing occurring between the second and third generations of folding. He further noticed that the shear zone has a minimum width of 5 km and is dipping steeply (∼70°) towards the SSW. The kinematic indicators along it are suggestive of dextral as well as dip-slip movements.

### 2.5. Metamorphism

The dominant rocks of the area are amphibolite to granulite facies metamorphic rocks. The P-T estimates on the rocks of the WSB and the two charnockite provinces (Krishnaraj et al., 1994; Ravindrakumar and Chacko, 1994; Ravindrakumar and Srikantappa, 1987; Nambiar et al., 1992; Soney, 2000) on either side of it indicate that the region is a deeply exhumed high-grade terrain. A critical evaluation of the granulites on either side of the Bavali shear zone by Soney (2000) showed that the rocks on the north of the shear register 10–12 kb pressures, while those on the south of the shear indicate 6–8 kb. The exhumation levels based on the pressures corresponding to the core compositions of coexisting phases where 35 km for the northern province and 23 km for the southern province implying differential uplift of the two blocks separated by the Bavali shear zone (Soney, 2000).

### 2.6. Geochronology

For many of the acidic and alkaline intrusives, which lie within or close to the shear zone (Fig. 3), isotope age data are available which range in age from 595 to 765 Ma. For the Ezhimala pluton, a Rb-Sr isochron age of 678 Ma is reported by Nair and Vidyadharan (1982). For the Kalpatta granite, a U-Pb zircon age of 765 Ma was obtained by Odom (1982). For the Peralimala and Ambalavayal granites, Rb-Sr method yielded ages of 750 and 595 Ma, respectively (Santosh et al., 1989). No geochronological data are available for the gneisses and charnockites of the area. However, similar rocks from the other parts of the SGT indicate an age of nearly 2.6 Ga for the main granulite formation (Crawford, 1969; Spooner and Fairbairn, 1970; Venkatasubramanian, 1975; Odom, 1982) and a localised high-grade metamorphism during Pan-African time (Choudhary et al., 1992). A recent geochronological work by Meissner et al. (2002) along Moyar-Bhavani and Palghat shear zones reveals a series of crustal generation/modification events ranging in age from 3.0 Ga to 488 Ma.

## 3. Gravity data

A number of agencies and workers have been involved in the collection and analysis of the gravity data in the South Indian shield region. These include the Survey of India (SOI), Oil and Natural Gas Corporation (ONGC), Hawaii Institute of Geophysics, National Geophysical Research Institute (NGRI), and the Centre for Earth Science Studies (CESS). Though some parts of the Kerala state were covered during these surveys, the data collected were not sufficient to make any meaningful geological interpretation. Under the program of generating new gravity data in the northern Kerala region, we collected gravity data from nearly 850 locations by utilising 36 permanent gravity base stations established by Radhakrishna et al. (1998) in the region. The observations were made at an average station interval of 1 or 2 km along all accessible roads. An American Paulin altimeter was simultaneously employed to collect the station elevations during the survey. The maximum error involved in elevation measurements is around 10–15 ft. Fig. 4 shows the distribution of gravity data collected by us and also by other agencies in the study region. The normal correction was made based on the 1930 International Gravity Formula and the combined elevation correction was made using the density of surface rocks as 2.67 g/cc.

## 4. Gravity anomaly map

Based on nearly 850 gravity observations collected in the present study and data from nearly 150 gravity stations generated by other organisations, the Bouguer anomaly map was prepared at 5 mGal contour interval (Fig. 5). It reveals some major features of the geology of the area:

- An E-W trending gravity gradient zone extending from Payyannur to Iritti characterised by a sharp gradient of 3.0 mGal/km, which falls along the shear zone to a certain extent. This zone extends further east of Iritti but has a wider and gentler gradient of 0.4 mGal/km.
- A broad gravity low with a relief of 20 mGal in the Wynad plateau east of Kalpatta and Mananthavady towards SE of the shear zone referred to as Wynad Plateau Gravity Low (WPGL).

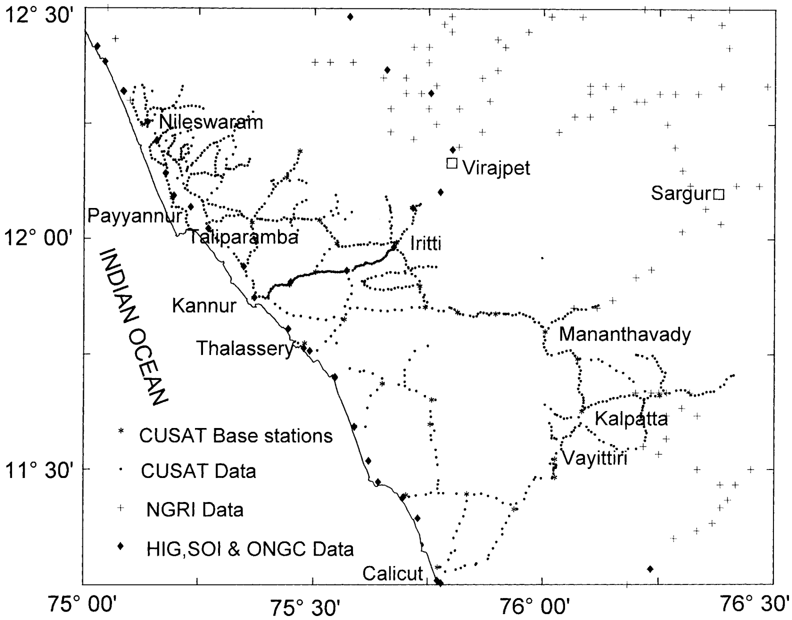


Fig. 4. Distribution of gravity data in the area. CUSAT data are those collected in the present study. NGRI data taken from Qureshy et al. (1981) and the HIG, SOI and ONGC data taken from Woollard et al. (1969).

- A broad gravity high increasing from −70 to −40 mGal in the north-west portion of the map can be correlated with the main charnockite body north of the shear zone and is referred to as the Northern Charnockite Gravity High (NCGH). This high increases further up to +20 mGal towards the coast near Nileswaram.
- A series of gravity lows characterised by the −105 mGal contour starting from east of Kannur region and extending to south of Vayittiri.
- Gravity field increases from –90 mGal to –60 mGal towards the coast between Calicut and Thalassery.
- Two small positive closures and a negative closure in between (all with relief around 15 mGal) are seen 15 km NE of Payyannur in the northern charnockite province.

Some important inferences regarding the subsurface mass distribution can be made by correlating the Bouguer anomaly map with surface geology and rock density data. Densities of all major rock types in the area have been considered from an earlier publication (Kurian et al., 1999) as well as additional data collected subsequently and are summarised in Table 1.

Table 1
Densities of common rock types of the area

| S. no. | Rock type | No. of samples | Mean (g/cc) | S.D. | Range (g/cc) |
|---|---|---|---|---|---|
| 1 | Granite | 63 | 2.67 | 0.0385 | 2.57–2.78 |
| 2 | Gabbro | 18 | 2.99 | 0.140 | 2.64–3.14 |
| 3 | Diorite | 7 | 2.75 | 0.0811 | 2.68–2.92 |
| 4 | Anorthosite | 13 | 2.77 | 0.0940 | 2.67–3.01 |
| 5 | Dolerite | 6 | 3.02 | 0.1231 | 2.87–3.21 |
| 6 | Mafic granulite and associated charnockites | 25 | 2.88 | 0.2116 | 2.57–3.27 |
| 7 | Charnockite | 27 | 2.76 | 0.1139 | 2.60–3.00 |
| 8 | Hornblende gneiss | 17 | 2.73 | 0.1292 | 2.57–3.16 |
| 9 | Biotite gneiss | 11 | 2.71 | 0.0745 | 2.64–2.89 |

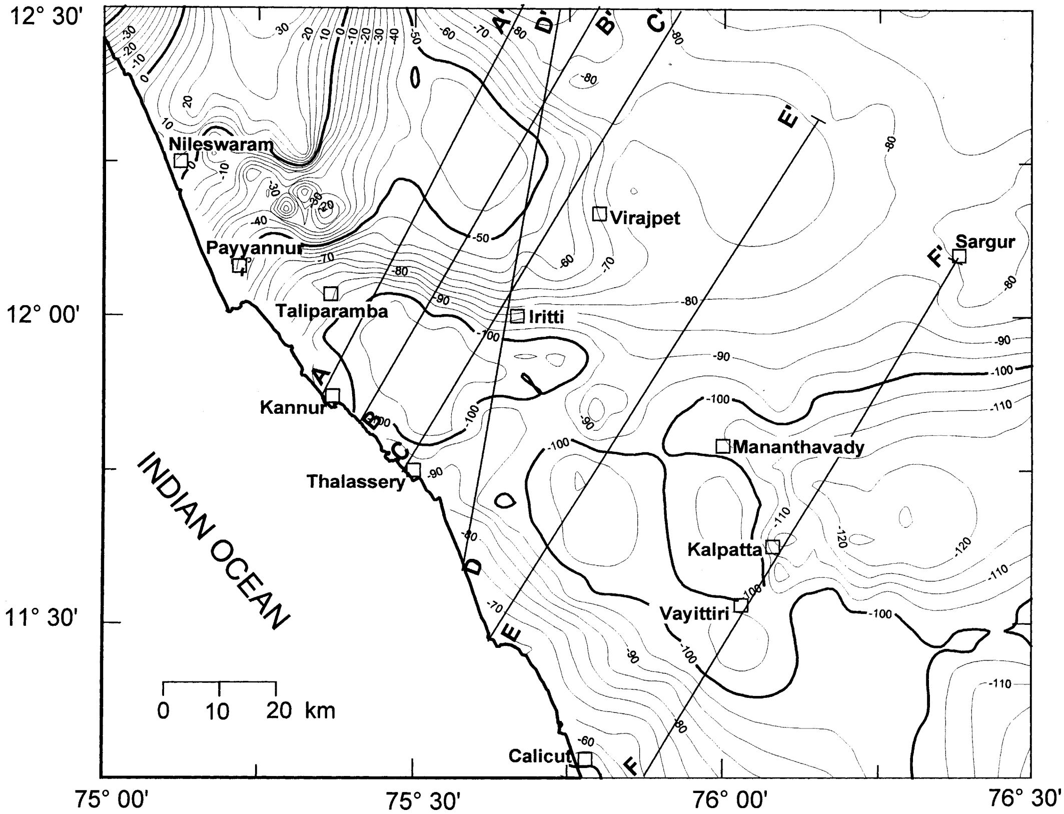


Fig. 5. Bouguer anomaly map of the Bavali shear zone and adjoining regions. Contour interval 5 mGal. Lines AA′ through FF′ represent profiles selected for two-dimensional gravity modeling.

The E-W gradient zone seen on the Bouguer anomaly map coincides with the Bavali shear as well as the gneiss-charnockite boundary west of Iritti, where the gravity values sharply increase northward across the boundary. However, east of Iritti, this gradient zone falls within the gneiss-schist province and becomes gentler within the Wynad plateau region. Further, the steep gradient north of Iritti marks the charnockite in the NW part of the region which causes broad Bouguer anomaly high. The northern charnockite province is also associated with an isostatic anomaly high in the published NGRI map (NGRI, 1978).

Though the density of charnockites (2.76 g/cc) is higher than the surrounding biotite gneiss (2.71 g/cc), this density contrast alone would not be sufficient to explain the observed gravity high over the charnockite region. The E-W gravity gradient, as well as the broad gravity high encircling the charnockite terrain, may indicate (i) a regional rise in the crust–mantle boundary; (ii) the presence of high-density gabbroic mass in the lower crust; (iii) the variations in the thickness of upper crust; or (iv) a combination of some of these features.

The localised anomalies near Payyannur, which are in proximity to the Perinthatta anorthosite and the Ezhimala gabbro-granophyre plutons may be interpreted as due to small intrusives at shallow depths or under soil cover.

The region south of the schist-gneiss province is characterised by a series of Bouguer anomaly lows. East of Kannur, this gravity low coincides with the Vengad basin in which quartz–mica schists and quartzites occur. The low densities (2.65 g/cc) of these formations may partly or wholly account for the gravity low. However, further south, near Vayittiri, the gravity lows coincide with the steep southeast slopes of the Wynad plateau. These gravity lows are coincident with the wide retrogressed granulite (hornblende gneiss) belt in the region.

The coastward positive gradient observed between Calicut and Thalassery was also noticed at many places along the west coast of India by several workers and has been explained in terms of crustal upwarp or localised thinning of the crust (Qureshy et al., 1981; Chandrasekharam, 1985; Mishra, 1989). North of Thalassery, the gravity data indicate that such thinning in the region is either absent or is masked by anomalies due to upper crustal inhomogeneties. The broad gravity low east of Kalpatta and Mananthavady in the Wynad plateau region indicates lighter crust beneath the area. While interpreting the regional gravity

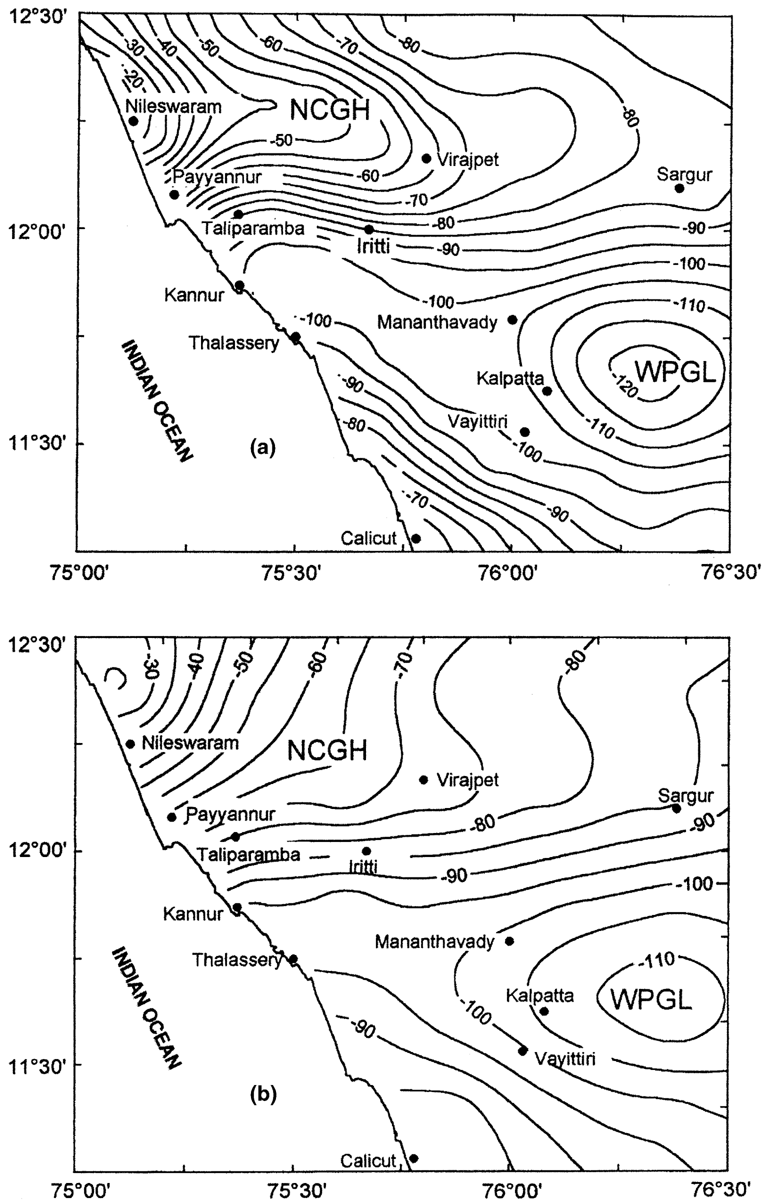


Fig. 6. Maps showing spatially filtered Bouguer anomalies for (a) 1/8° × 1/8° grid averaged values, (b) 1/4° × 1/4° grid averaged values. WPGL: Wynad Plateau Gravity Low; NCGH: Northern Charnockite Gravity High.

anomalies of South India, Krishna Brahmam and Kanungo (1976) inferred that the widespread gravity low in between Mananthavady and Gudalur further south could be due to a buried granite intrusion. Although the region contains the Kalpatta and Ambalavayal granite bodies, they are not of sufficient volume to account for the observed gravity low. This observation suggests that there may be large granite bodies at depth. Alternatively, this gravity low indicates thickening of the crust below the Wynad plateau.

In order to ascertain the depth and extent of various subsurface masses causing the gravity anomalies, spatially filtered maps ($1/8^\circ \times 1/8^\circ$ and $1/4^\circ \times 1/4^\circ$ grid averaged) have been prepared using method given by Woollard (1969) and are shown in Fig. 6. It is seen that, the WPGL has been defined as a broad low of upto 15–20 mGal in both the maps. However, the NCGH which was well expressed in the $1/8^\circ \times 1/8^\circ$ grid averaged map, is partially smoothed out in $1/4^\circ \times 1/4^\circ$ map. This anomaly smoothing of NCGH may be because it is essentially a mid-to-lower crustal feature.

Another significant aspect that can be more clearly observed from these maps is that the Bavali shear zone along most of its length separates two distinct gravity fields marked by a gradient. This gradient coincides with the surface expression of the shear zone between Payyannur and Mananthavady. But beyond Mananthavady the gradient occurs NE of shear zone. Considering the anomalies with wavelengths greater than 56 km are reflected in the $1/4^\circ \times 1/4^\circ$ grid averaged map, the observed gradient represents mass anomalies extending to much deeper levels. Another significant aspect is that the E-W trending gravity gradient seen on the Bouguer anomaly map persists in both the averaged maps reflecting that it represents mass anomalies extending up to subcrustal levels.

## 5. Gravity modelling

In the present study, gravity field variation along six profiles AA′ through FF′ (see Figs. 2 and 5 for their locations) crossing the Bavali shear zone and the adjoining areas has been interpreted in terms of two-dimensional crustal models. The free-air and Bouguer anomalies in relation to the elevation and the surface geology for these profiles are shown in Fig. 7. The profiles selected have a near NE-SW alignment running from the coast to the interior, across the shear zone and major geological formations. Four profiles (AA′ through DD′) traverse the northern charnockite province and intersect the shear along its western portion, one profile (EE′) occurs in the central part of the shear zone and another profile (FF′) traverses the southern part of the shear zone as it passes through the Wynad plateau. It may be noted that the profile EE′ has poor data control along its northeastern part. While the Bavali shear is located along the coastal plains in profiles AA′–DD′, in profiles EE′ and FF′ it occurs over the higher topography of the Wynad plateau.

### 5.1. Density of crustal layers

The SGT contains granulite facies rocks that represent an exhumed lower to middle crustal section with exhumation levels of 20–35 km (Harris et al., 1982; Raith et al., 1983; Radhakrishna et al., 1990; Mahadevan, 1994). The study area is dominated by granulite facies rocks and their retrogressed products with overall higher densities (dominantly above 2.73 g/cc with values not lower than 2.65 g/cc). These density values are typical of a highly exhumed crustal section. During exhumation of the lower crust, changes such as shearing/retrogression/volume-expansion, may lower the densities of rocks. However, such changes may not be to the extent of eliminating the lower crustal density signatures in them. For the South Indian shield, Kaila and Bhatia (1981) have generated a density model along the Kavali–Udipi Deep Seismic Sounding (DSS) profile across the Dharwar craton, where the upper and lower crustal transitions are well defined. A two-layer crustal model is adopted by considering: (1) the average densities for the surface rocks; (2) the mid-to-lower crustal exhumation in this region; and (3) the density model inferred from DSS data.

The upper of the two layers is heterogeneous with a variety of rocks at the surface having varying densities and depth of extents. The density values for major rock types of the area are 2.76 g/cc (charnockite), 2.73 g/cc (hornblende gneiss), 2.71 g/cc (biotite gneiss), 2.67 g/cc (granite) as given in Table 1. For the supracrustals of Vengad sedimentary rocks, a value of 2.65 g/cc has been used. Based on the seismically constrained density model of Kaila and Bhatia (1981), the lower layer of the crust has been assigned a density

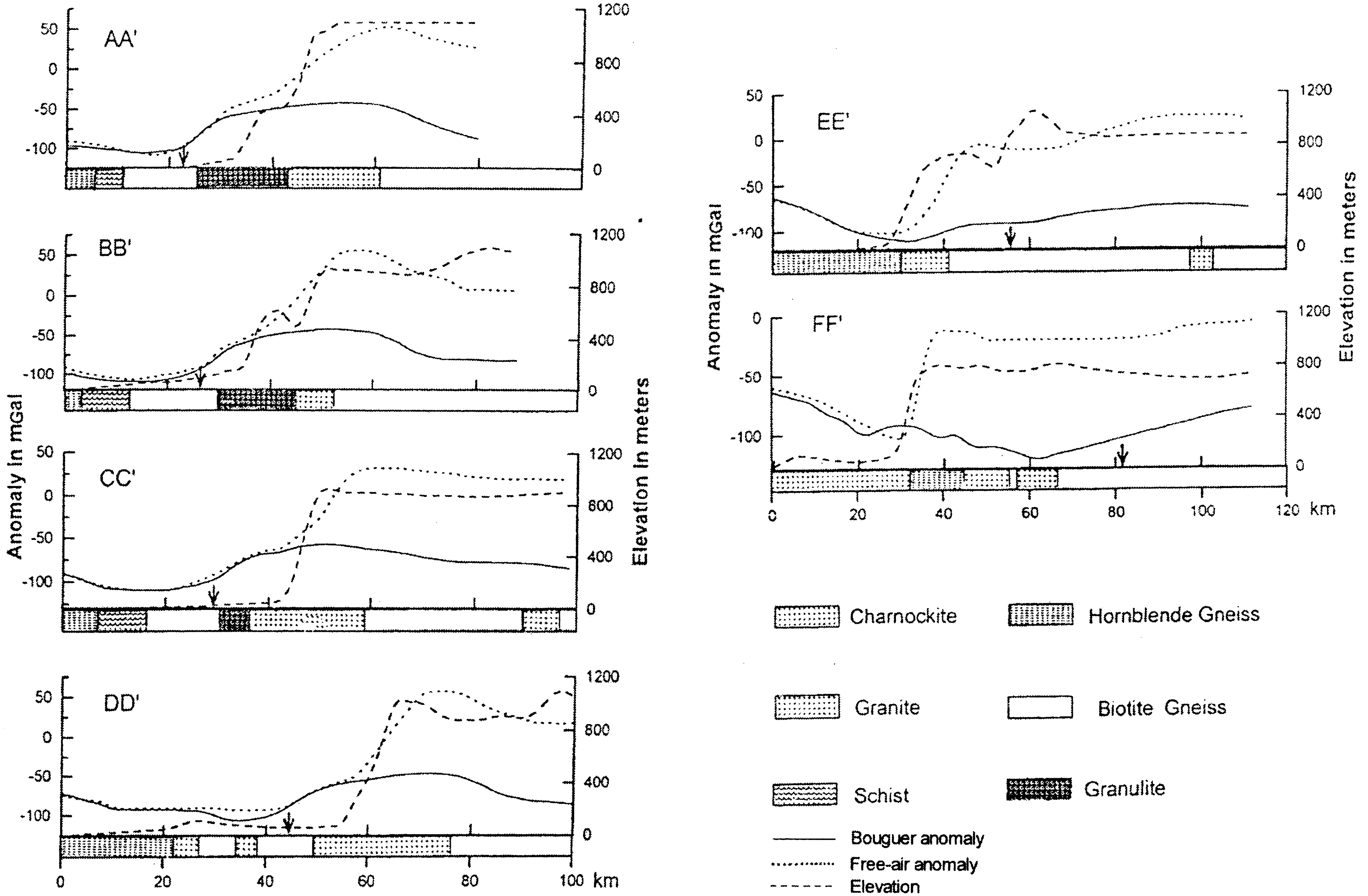


Fig. 7. Variation of the gravity field, elevation and the surface geology along six profiles (AA′ through FF′) across the Bavali shear zone. The location of the shear zone is indicated with an arrow on each profile. Details are discussed in the text.

of 2.85 g/cc and the mantle beneath it with 3.3 g/cc. This two-layer density model for the crust is consistent with the simplified two-layer crustal model based on velocity–density relations of the major rock types (Ramachandran, 1992).

### 5.2. Moho configuration

The Kavali–Udipi DSS profile located just north of the study region (see Fig. 1 for location) suggests that the crust is 38–39 km thick below the Karnataka Plateau and thins down to 35 km under the west coast. In the absence of any such DSS data for the SGT, the $1/4^{\circ} \times 1/4^{\circ}$ average Bouguer anomaly values have been used to compute the crustal thickness using the formula, $T = 31.6 - 0.078\,\Delta g$ suggested by Qureshy et al. (1967) for Peninsular India. The crustal thickness in general is estimated to be 36–41 km. These crustal thickness values were contoured at an interval of 1 km and the Moho variations along the six selected profiles were plotted as shown in Fig. 8. It is interesting to note that the NE block of the Bavali shear zone is underlain by a Moho rise of 2–3 km and in a few profiles this rise coincides with the downward extension of the shear.

### 5.3. Gravity models

Based on crustal densities and the Moho configuration discussed above, two-dimensional gravity modelling was carried out along the profiles using the SAKI program of the USGS (Webring, 1985). The models are presented in Figs. 9–11.

The models show that the thickness of the upper crustal layer (dominated by gneisses and charnockites) is different on either side of the Bavali shear zone. (However, the plane separating this contrasting density structure does not coincide exactly with the downward projection of the shear zone especially in SE portion of the shear.) In the southwestern part of the shear, the thickness of the upper crust is mostly between 15 and 25 km, while in the northeast part, the overall thickness of the upper crust is 5 and 15 km. The charnockite (2.76 g/cc) of the northern province extend upto 5–10 km (as seen in profiles AA′ to DD′) and is underlain by a denser (2.85 g/cc) crustal layer. The mafic granulite (2.88 g/cc) within the charnockite of the province appears to be more or less a lensoid body with shallow extension. The gneiss occurring to the NE of the charnockite province also extends down to shallow depths of less than 10 km in profile AA′ to CC′, but in DD′ it extends down to 20 km. The surface that separates the gneiss from the charnockite may represent part of the regional amphibolite–granulite facies transition close to the Fermor line of the southern Indian Precambrian shield. In most of the profiles, this surface dips towards the gneiss and structurally it might represent a contact along which there is a change in the grade of metamorphism or a detachment fault, for which no surface expression has been mapped so far along the Fermor line. In profiles which are extending into Karnataka craton (EE′ and FF′ which cross the Fermor line) the thickness of the biotite gneiss layer increases towards the craton interior upto 30 km.

The most prominent feature in the mid-to-lower crustal level in all the profiles (except FF′) is the high-density body (2.98 g/cc) which contributes significantly to the gravity high over the northern charnockite province. This has larger dimensions in profiles AA′ and BB′ and diminishes progressively to the southeast and practically disappears in profile FF′ below the Wynad plateau. Alternatively, we have modelled the observed high as due solely to a Moho rise without invoking a high-density body at depth. A sharp rise in the Moho of as much as 20–25 km is required to account for the gravity high. Such a rise in the Moho in any region would imply large scale rifting and the consequent tectonics (e.g. graben formation and crustal thinning) for which the area shows no evidence. Further, the crustal thickness values estimated from the spatially averaged Bouguer anomalies preclude such extreme localised thinning of the crust in the region, though minor undulations of 2–3 km in the Moho are inferred. However, an independent test of an elevated Moho or the presence of a high-density body can be resolved only by seismic methods.

The EE′ profile cuts across the gneisses bounded by charnockite west of Mananthavady and has some distinctive features. The charnockite mass itself has a shallow extension to less than 5 km and appears to be a floating body or a small band of incipient charnockite surrounded by gneiss. The Bavali shear zone is traceable by a steep but prominent line of separation of crustal units with different densities extending down to a depth of around 20 km in profile AA′ to DD′. However, such an expression for the shear is not clear in the southeastern part (profiles EE′ and FF′).

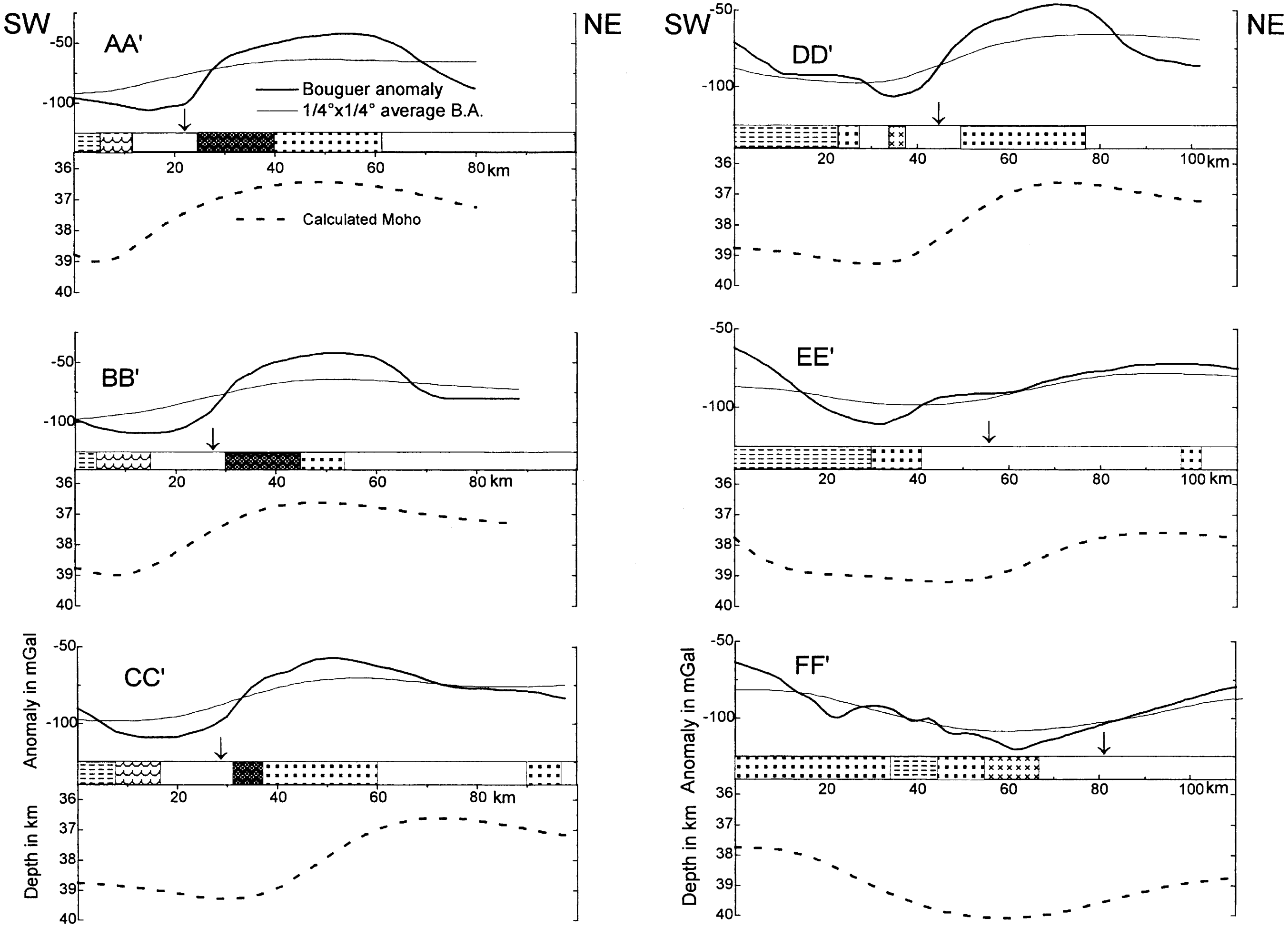


Fig. 8. Moho configuration along six gravity profiles estimated from 1/4° × 1/4° average Bouguer anomalies. Details of geology are adopted from Fig. 2. The arrow shown on each profile indicates the location of Bavali shear. Moho configuration shown here is vertically exaggerated for the purpose of correlation with surface features.

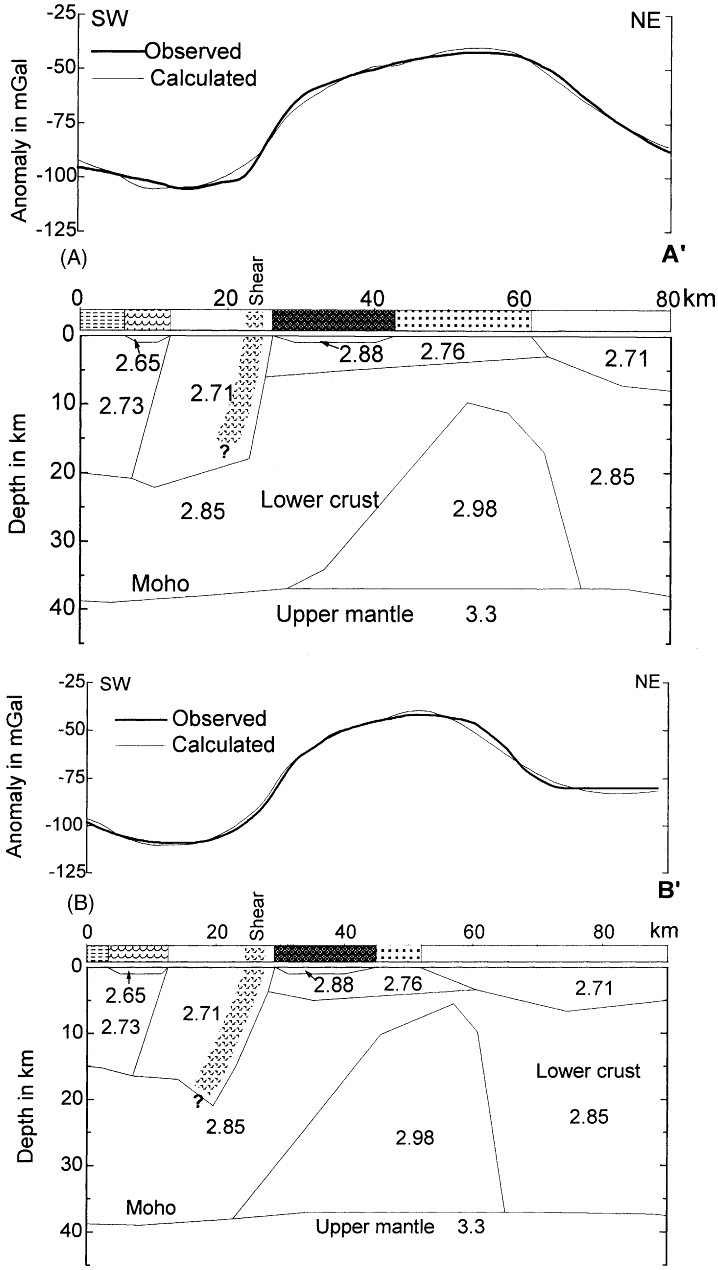


Fig. 9. Interpreted crustal models along profiles AA′ and BB′. The surface geology and location of the shear are considered from Fig. 2. The surface geology is indicated as horizontal bar above the crustal model.

The biotite gneiss south of the northern charnockite province (which marks the WSB) appears as a long tabular unit of around 15 km width and around 25 km depth with a southwesterly dip as seen in profiles AA′ to DD′.

Along the southwestern part of the WSB, the surface rocks (charnockite and hornblende gneiss) extend down to 15–25 km. Except in profiles EE′ and FF′, modelling the observed gravity anomalies requires only minor changes in the thickness of the crustal

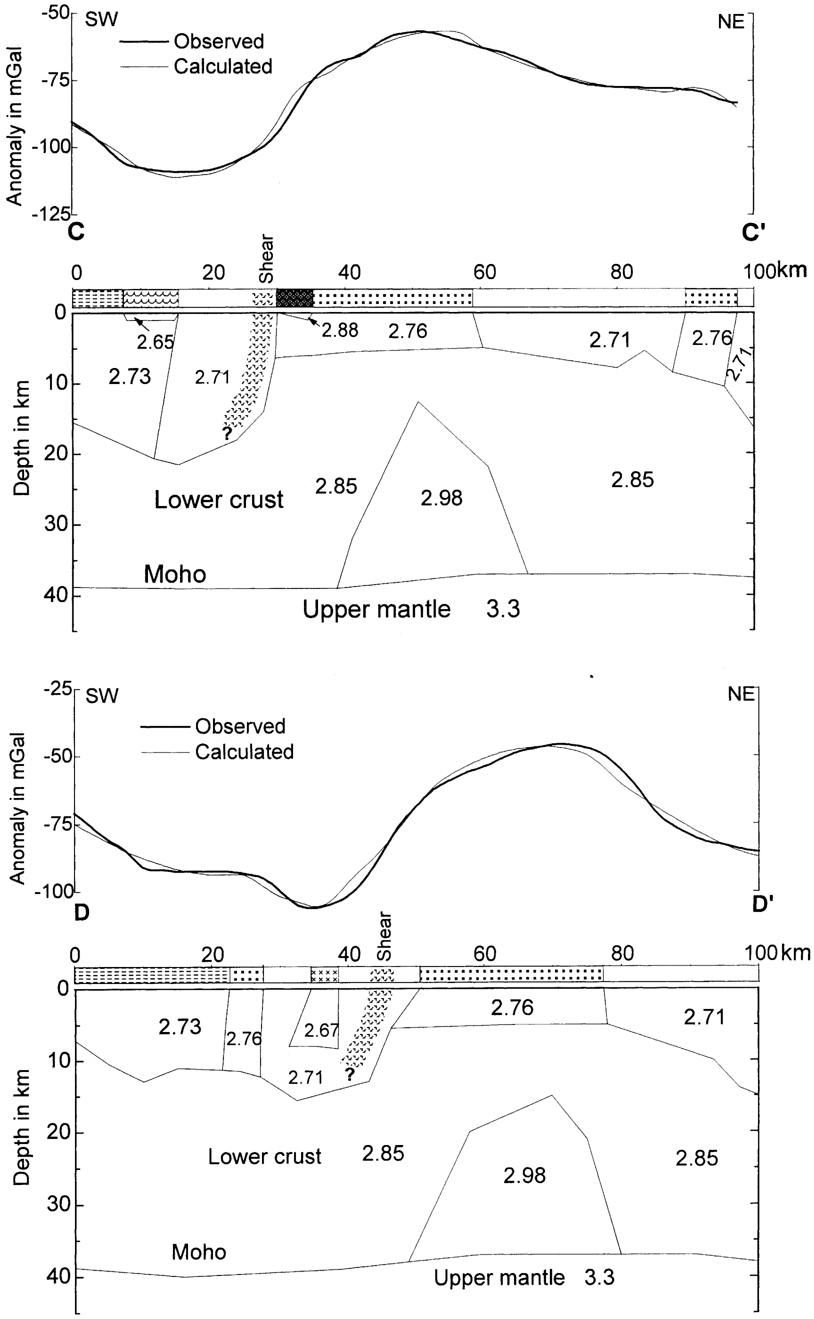


Fig. 10. Interpreted crustal models along profiles CC′ and DD′.

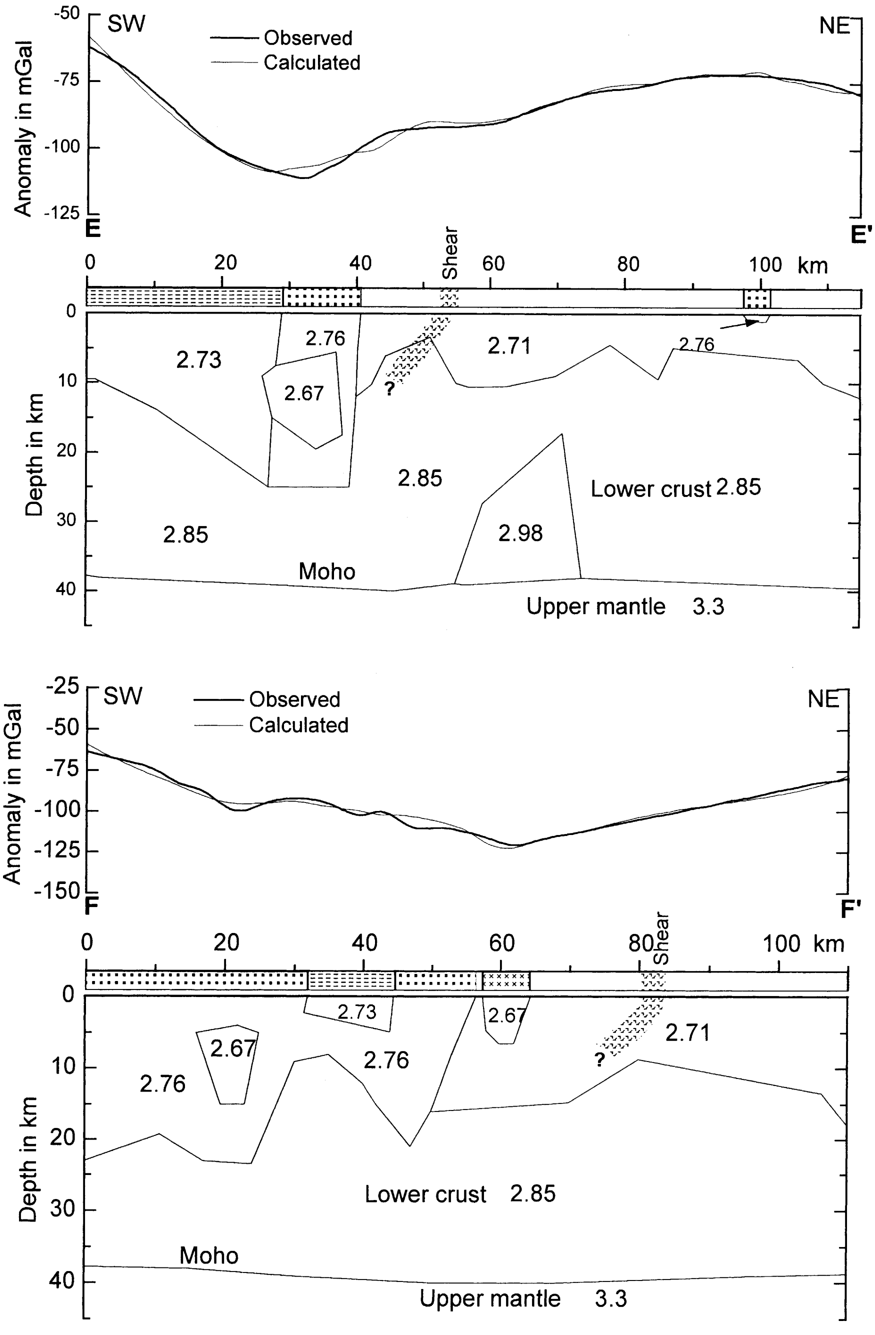


Fig. 11. Interpreted crustal models along profiles EE′ and FF′.

layer. In EE′ and FF′, the presence of two gravity lows necessitates the induction of concealed granitoid bodies to model them. The concealed granitoids in both the profiles have an approximate cross-sectional area of 100 km$^2$. In the case of EE′ profile, a small granite body occurs on the surface (Fig. 2) close to the gravity low, which is in support of the model.

## 6. Discussion

The major shear zones within the SGT of Peninsular India have often been linked to crustal evolution and exhumation processes. Drury et al. (1984) proposed a late Archaean crustal shortening and thickening in South India prior to the development of major transcurrent shears. This model was supported by Chetty (1996) who provided structural evidence such as westward verging imbricate thrust zones along the Cauvery and Salem–Attur shear zones. Mahadevan (1998) believed that several of the ductile shear zones in the SGT result from differential uplift of the high-grade domains.

The gravity models presented here provide insights into the deeper crustal structure of a part of the SGT. The crustal models arrived at, especially in the AA′ to EE′ profiles, point to the presence of a thick crust (∼38 km) with a high-density mass (2.98 g/cc) at its base that thins towards Wynad region in the east. The Bavali shear zone is manifested in the gravity profiles by a steep gravity gradient especially along the northwest part. The gravity models exhibit a plane separating two contrasting crustal densities close to the Bavali shear zone. It has been possible to model the downward extent of the structure to a depth of 32 km. However, in the models along profiles AA′, BB′ and DD′ this downward extension meets a slight rise in Moho indicating that this could be a crustal-scale fault. The aeromagnetic maps analysed for the Southern Peninsular India also exhibit varying magnetic trends and crustal properties across this shear (Ramachandran, 1985; Harikumar et al., 2000). The Bavali shear zone within the Wynad region appears less prominent which may be a reflection of the differences in the geometry of the fault in the Wynad region compared to the NW region.

The high-density material of 2.98 g/cc in the lower part of the crust modelled along the profiles AA′ to EE′ below the northern charnockite province may imply that this material is an intrinsic part of the crustal structure below the province. The presence of such a high-density mass would correspond to a seismic velocity of nearly 7.2 km/s and is consistent with the existence of such velocities in many Proterozoic crustal segments of major Precambrian craton elsewhere in the world (Christensen and Mooney, 1995). A number of hypotheses on the genesis of this high-density mass are:

- It may have evolved along with the protolith of the charnockitic rocks, which were metamorphosed around 2500 Ma (Radhakrishna et al., 1990). Considering exhumation levels of ∼35 km for charnockites in the region and the crustal thickness of 38–40 km estimated by gravity, it is possible that the crustal thickness during the late Archaean in the region may have been ∼70 km (cf. Harris et al., 1982).
- It may have originated along with the intrusives of gabbro or anorthosites exposed in and around the northern charnockite province and have been localised in deeper portions by virtue of the higher density of the magmas from which they were evolved. According to the Ashwal (1993) model of anorthosite genesis, the denser residual fraction, after separation of anorthosite, sinks into the lower crust. The high-density material of 2.98 g/cc inferred in the lower crust may have resulted from this process. In an independent analysis of the gravity field of Perinthatta anorthosite of northern charnockite province, Kurian et al. (1999) ruled out the presence of such large high-density masses in the upper portion of the crust (<10 km), but has not ruled out its presence at depth.
- It may be possible that the high-density body was emplaced during the Pan-African anorogenic event, synchronous with the alkaline and other granitoids in the region. However, some of these granitoids as Kalpatta and Ambalavayal occur in the region of homogeneous crust, where no high-density material is present at depth.
- It represents a Phanerozoic underplating.

Apart from the large massive bodies of charnockites north of the shear zone and west of Virajpet (Fig. 2) there are some enclaves or bands of charnockitic rocks of much smaller outcrop dimensions associated with hornblende gneisses and biotite-hornblende gneisses (migmatite). In the gravity field these charnockitic rocks, being relatively more dry, may be expected to show up as distinct masses of higher density compared to the associated gneissic rocks, which have a lower density. This density contrast has been utilised in modelling the charnockitic bodies. In the profiles CC′ to EE′ these bodies show up as bands extending down to a maximum depth of 10 km. Charnockitic bodies of this nature has been characterised as relics of the transformation of charnockites to gneisses and also as charnockites being formed from hornblende gneisses. Such distinction in origin has to be necessarily based on petrological studies.

## 7. Conclusions

Interpretation of the gravity anomalies along the Bavali shear zone and adjacent areas has led to the following major conclusions which offer valuable constraints on the various probable models of evolution of the granulite terrain and emphasises the role of shears in them.

- Crustal thickness estimates based on regional gravity anomalies, on assumptions of isostatic equilibrium, range between 36 and 41 km in the region of Bavali shear zone of the Southern Granulite Terrain of Peninsular India.
- The region consists of different blocks with distinct gravity anomalies. The gravity high observed over the northern charnockite province is modelled as a thick high-density body of 2.98 g/cc occupying lower part of the crust which represents either a Precambrian mafic crust, Pan-African magmatic emplacement, or Phanerozoic underplating.
- The WSB appears as a long tabular unit of around 15 km width and 25 km depth with a southwesterly dip.
- The Bavali shear is manifested by a steep gravity gradient in its western part for a length of nearly 60 km. The derived crustal models in this region exhibit a plane separating two contrasting crustal densities close to the Bavali shear zone. The shear zone is seen to extend down to a depth of 30 km and in some profiles the downward extension meets with a slight Moho rise suggesting that this could be a crustal-scale structure. However, in the eastern part, the shear zone becomes less prominent.

## Acknowledgements

Financial support provided by the DST (Project Nos. ESS/CA/A9-31/93 and ES/5(12)/WB/Project/96) is gratefully acknowledged. The authors have been greatly benefited by many useful discussions with T.M. Mahadevan and C. Subrahmanyam. Critical and very useful comments offered by R. Blewett, M. Pilkington and B. Bell who reviewed the paper are also acknowledged.

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