Zero-free air-based gravity anomaly (preliminary) map of South India – A refined and redefined Bouguer map

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Zero-free air-based (ZFb) anomaly map for the southern part of India is prepared by eliminating negative bias from Bouguer map of NGRI using the zero-free air value concept. This map showing regions of positive, negative and zero values brings out the real nature of the gravity field. Positive values are observed over plateaus (Karnataka, Koyna–Sangola and Deccan). Zero values are associated with the Western Ghat mountains and SW part of Cuddapah basin, while their margins and those of mobile belts are characterized by negative values. In light of DSS Moho depths against those expected for regional topography compensated, these positive, zero and negative values reflect thinning, normal thickness and thickening respectively of crust, indicating state of isostasy in this region. Under-compensation causing isostatic instability with plateaus in support of major earthquakes and isostatic equilibrium in the rest of the regions with regional nature of compensation are observed. Karnataka plateau marked with radial river system, major earthquakes in its margin and faulted boundary suggests domal upwarping. Southern granulite terrain is with normal crust, excepting the regions of mobile belts along east and west coast with dense crust.

BOUGUER anomalies are used in continents for interpretation of gravity data. But, these anomalies are observed to have negative values as regional field (negative bias) over which anomalies of our interest (residual) caused by subsurface excess and deficit masses are superposed as highs and lows. To eliminate this negative bias, isostatic correction is made by relating it to compensating mass at depth. But this correction is not effective, since it is based on assumed model for compensating mass. Mathematical techniques used for separation of regional and residual anomalies in Bouguer gravity could not help due to absence of information regarding nature of residual and regional anomaly sources. Subba Rao[1] has introduced the zero-free air value concept to eliminate the negative bias effectively. Using this concept, negative bias is eliminated from Bouguer map of India[2] for its southern part. Its preparation, the nature of gravity field now observed and its correspondence with tectonics are presented in this paper.

In the light of isostatic compensation of topographic masses, the anomalies present in conventional free air gravity are classified by Subba Rao[1] into regional, local and residual. The regional anomaly corresponds to regional topography compensated. The local anomaly relates to local topographic relief and the residual anomaly relates to subsurface anomalous sources of our interest which are in the form of excess and deficit masses.

Due to compensating mass at depth, gravity effect of this regional topography is absent in free air gravity. This is indicated by zero values, termed as regional anomaly. Since bulk of continental topographic mass is more or less compensated, the zero-free air values occur at different elevations representing regional topography. These elevations associated with zero-free air values when used in the computation of Bouguer correction, give rise to negative Bouguer anomalies. Thus the regional anomaly of zero values in free air gravity becomes negative values in Bouguer gravity. These negative anomalies of regional nature exhibit correlation with regional topography[1]. In other words, the Bouguer correction over-corrects the topographic effect, disregarding regional topography. Surface topography variations with respect to this regional topography are the local relief whose gravity effect is present in free air gravity, as it has no compensating mass at depth, unlike the regional topography. Thus, the free air gravity follows local topography, but not regional topography. Gravity effect of this local topography is termed as local anomaly. It is present in free air gravity as positive and negative values, combining with the gravity effect of subsurface excess and deficit masses of our interest, termed as residual anomaly. Since Bouguer correction accounts for local topographic mass and not for subsurface excess and deficit masses, the local anomaly is eliminated and the residual anomaly is retained in Bouguer gravity superposing over the negative bias. Hence by eliminating local anomaly alone from free air gravity (i.e. by correcting for local topographic mass alone) or eliminating the negative bias created in Bouguer gravity due to over-correcting for regional topography, residual anomaly can be obtained. This is illustrated along field gravity profiles (for details, see refs 1 and 3).

This procedure is briefly given below:

1. Identify zero values in conventional free air gravity (after correcting for long wavelength anomaly of satellite-derived gravity data mentioned later).
2. Mark the elevations corresponding to zero-free air values from station elevation map.
3. Join these elevations which represent regional topography compensated.
4. Compute Bouguer correction for the elevations in (2) with density value similar to that used in conventional Bouguer anomaly and subtract this Bouguer correction from the zero-free air value in (1), which gives negative Bouguer values.
5. Join these negative values to represent negative bias.
6. Subtract this negative bias from conventional Bouguer

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anomaly (map corresponding to the above conventional free air gravity) to obtain residual anomaly.

7. Surface topographic variations with respect to the regional topography in (3) are local topographic relief, and Bouguer slab effect of this local topography gives local anomaly.

8. Subtracting this local anomaly from free air gravity in (1) also gives residual anomaly in (6). This method by which residual anomaly can be obtained involves no assumption or bias. But it has limitations[1]: (i) As zero-free air values are also caused by local and residual anomalies of opposite sign, such values are not used. They can be identified as their corresponding elevations given irregular topography deviating from regional topography. (ii) Due to inadequacy of gravity data and presence of large wavelength residual anomalies, enough zero values may not be present to obtain regional topography.

The residual anomaly reflects excess and deficit masses which are caused due to local density changes and due to over, under and regional compensation[1]. As surface topography is the observational plane for gravity data, the above deficit and excess masses include all those present below this surface topography, i.e. within the local topography, within the regional topography and below sea level. In conventional Bouguer anomaly, Bouguer correction is done for the entire topographic mass above sea level, while in this method the correction is made only for local topography, thus redefining the Bouguer anomaly and eliminating its negative bias. To differentiate this anomaly, it is named as zero-free air-based anomaly (ZFb), since it uses the zero-free air value concept.

As continental gravity data are vitiated by influence of long wavelength anomalies like Indian Ocean gravity low, zero-free air values are masked by them[1]. Hence, free air gravity map[2] of the southern part of India (not shown here) is corrected for Indian Ocean gravity low values as taken from satellite-derived gravity map of Marsh[4]. The Indian Ocean gravity low values are shown over Bouguer gravity map in Figure 1. After incorporating this correction, zero values in the free air gravity map are identified. These are shown in Figure 2 by crosses (×). At each zero value, the corresponding elevation is noted from station elevation map (not shown here). These elevations in the form of contour map with 100 m interval are shown in Figure 3. This map is comparable to regional nature of elevation (Figure 4) based on toposheets of Survey of India. Therefore, Figure 3

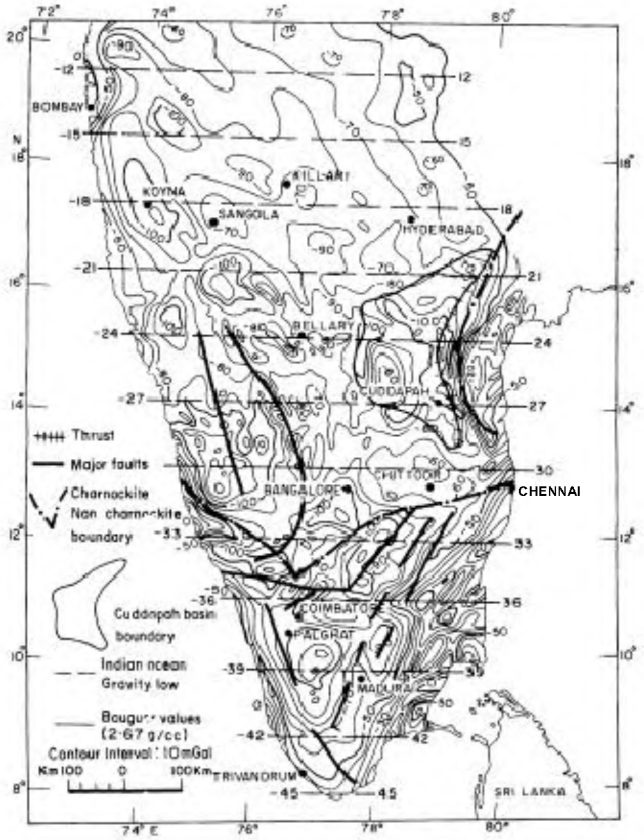

Figure 1. Bouguer gravity map of southern part of India (after ref. 2) superposed with Indian Ocean gravity low value for correction. Major tectonic units, namely greenstone and granulite terrains indicated by charnockite–noncharnockite boundary of Fermor's line[5], major faults (after Grady[14], Katz[15], Drury *et al.*[16] and Drury and Holt[17]) and thrusts (after Narayanaswamy[18]) are shown.

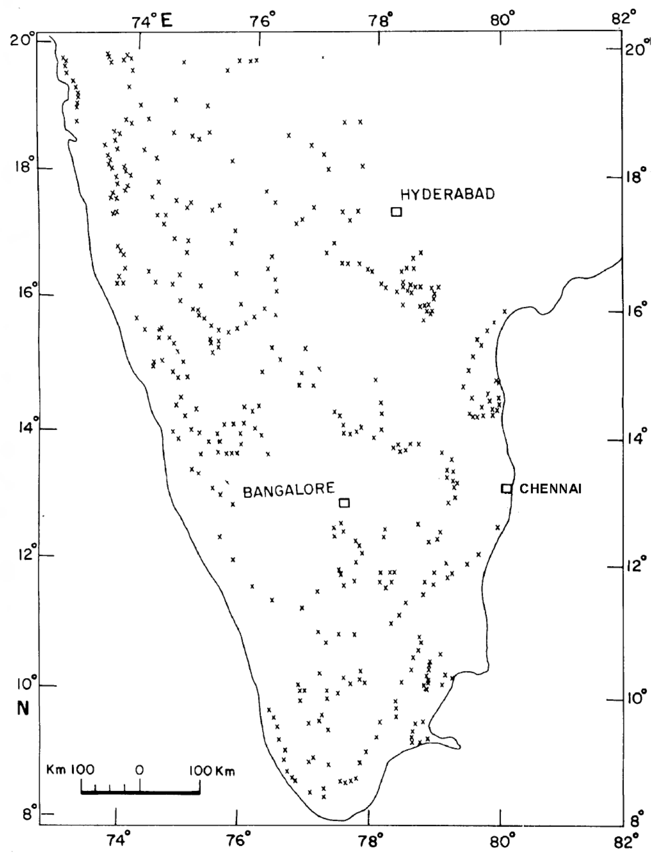

Figure 2. Zero values of free air anomaly map of southern part of India (after ref. 2) incorporating Indian Ocean gravity low correction shown by crossings (×).

represents regional topography in this region as expected, thus proving the validity of this method. It also shows that enough zero values are present to map the regional topography, excepting a major gap at Bangalore (Figure 2). Such gaps are due to large wavelength residual anomalies present. To minimize the error in such areas, interpolation is done considering regional topography of the area as known from station elevation map. It is also observed that unwanted zero values are quite a few (not shown here). These values arise due to local and residual anomalies of opposite sign. Such zero values are omitted in this method as they are not due to compensated regional topography[1]. Their corresponding elevations show irregular topography (deviating from regional topography), thus these values can be identified and are eliminated. At the zero-free air values (Figure 2) and their corresponding elevations (Figure 3), Bouguer values are computed for density 2.67 g/cc (same density used for Bouguer map in Figure 1). This represents the negative bias (not shown here) present in Bouguer gravity map[2] of Figure 1 due to over-correction of regional topography in Figure 3.

The negative bias thus computed above is subtracted from the Bouguer map (Figure 1) after incorporating Indian Ocean gravity low correction to obtain ZFb anomaly, which is shown in Figure 5. It may be seen from Figures 2 and 5 that zero contours of ZFb anomaly are passing through all the points of zero values of free air gravity. This is because in free air gravity, the local and residual anomalies being represented by positive and negative values have zero values as their bounds. In ZFb anomaly, the local anomaly is eliminated by Bouguer correction and the negative values created corresponding to zero-free air values are also eliminated. Thus zero values are same in both free air gravity and ZFb anomaly. Any local anomaly still present with the ZFb anomaly could be due to improper density used in correcting for local topographic mass. In the present study, density used for Bouguer correction is 2.67 g/cc, a value for crystallines, the major rock type in the study area. Hence any local anomaly present is negligible, and it will not distort the residual picture at 10 mGal contour interval in ZFb anomaly map (Figure 5).

The ZFb anomalies are resolved into positive, negative and zero values demarcating regions of excess mass, deficit mass and absence of such masses respectively. The study region is considered as two broad tectonic units, namely granulite and greenstone terrains. Fermor's line[5] (charnockite and non-charnockite boundary) demarcating

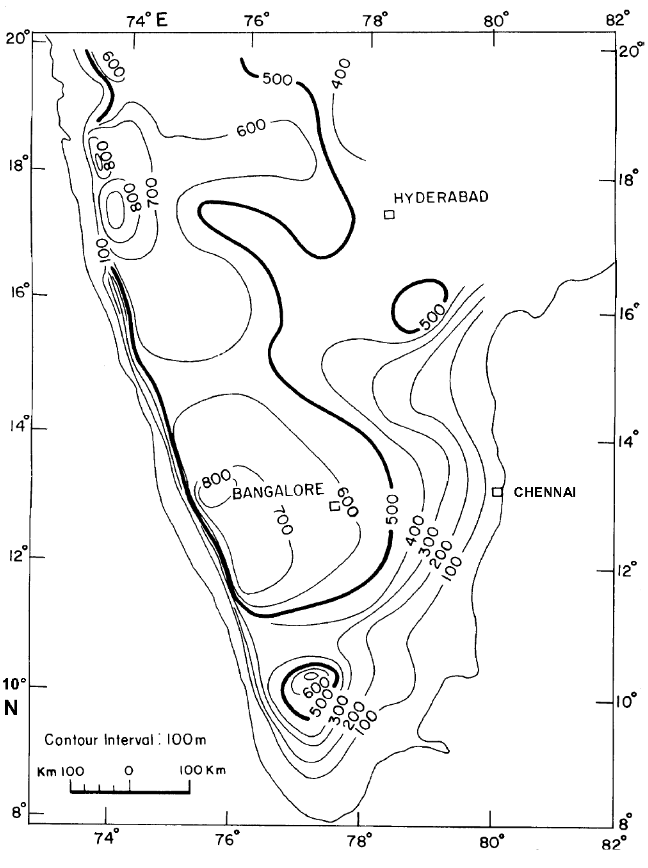

Figure 3. Elevations corresponding to zero value crossings shown in Figure 2 bringing regional topography shown here need no Bouguer correction.

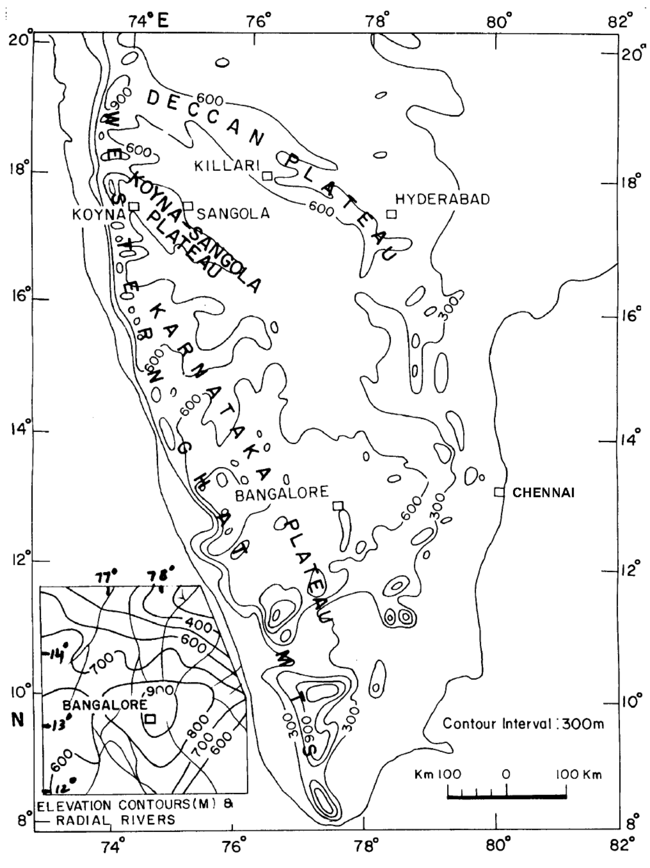

Figure 4. Regional topography map as presented at larger contour interval of 300 m based on Survey of India toposheets. Plateaus and the Western Ghats mountains are indicated. *Inset*, Radial river system and associated elevations of Karnataka plateau.

these two units is shown in Figures 1 and 5. In granulite terrain (south and east of Fermor's line), ZFb anomaly map shows positive values (reaching 20 to 60 mGal) over mobile belts, namely Kerala, Madurai and the Eastern Ghats (Figure 5), while negative values (reaching – 30 to – 60 mGal) are observed along margins of these mobile belts marked by thrust and major faults. In the greenstone belt (to the north and west of Fermor's line), positive values are observed confined to plateau regions. For example, Karnataka plateau, Koyna–Songola plateau and Deccan plateau show anomalies of the order of 40 mGal, 10 mGal and 5 mGal (see Figures 4 and 5). Zero gravity field (Figure 5) is observed over the Western Ghats mountain belt, including its extension into the southern granulite terrain, and negative values reaching – 50 to – 60 mGal are observed along the western margin of this mountain belt (Figure 4). Negative gravity values (– 10 to – 40 mGal) are observed in the region of low topographic relief where Proterozoic basins, namely Kaladgi and Bhima basins (not shown here) and Cuddapah basin are distributed. According to Radhakrishna and Naqvi[6], this is another tectonic unit where Proterozoic basins are developed along margins of craton and mobile

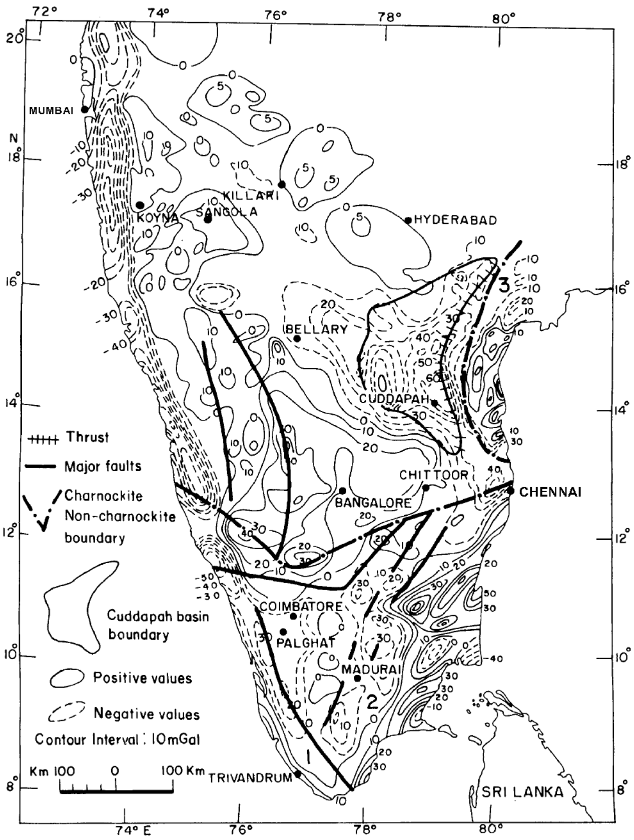

Figure 5. Zero-free air-based anomaly obtained on subtracting negative bias from Bouguer anomaly map after Indian Ocean gravity low correction. The major tectonic units, faults, thrusts are as in Figure 1. 1, 2 and 3 are Kerala, Madurai and the Eastern Ghats mobile belts respectively.

belts. Over southwestern part of Cuddapah basin, the gravity field becomes zero. Thus the various tectonic units, namely the Western Ghats, plateaus and distributed region of Proterozoic basins and mobile belts are brought out with distinct gravity signatures.

The ZFb anomalies as mentioned earlier reflect excess and deficit masses caused by under, over and regional compensation and by local density changes. As Bouguer gravity map is based on station interval of 8 to 10 km, short wavelength anomalies are not observed; thus effects of local density changes are less evident. Hence, ZFb anomaly reflects essentially the excess and deficit masses caused by under, over and regional compensation. In the study area, the regional topographic mass and large density changes present within the crust are involved in compensation, and hence they can cause above excess and deficit masses. For regional topography, assuming Airy's theory of isostasy its compensating mass is represented by crustal root and it can be computed by equating with the regional topographic mass, i.e. $\Delta R \times \Delta\sigma = lc \times h$, where $\Delta\sigma$ is density (g/cc) contrast between crust and mantle, lc is density (g/cc) of regional topographic mass above sea level, h is height (km) of the regional topography and ΔR is thickness (km) of crustal root. For zero elevation (sea level) and normal density, the crustal column has a thickness (say T_o) referred as the standard crustal column. Adding the above crustal root (ΔR) for regional topography fully compensated to T_o, crustal thickness (say T) is obtained, i.e. $T = T_o + \Delta R$, referred to as the normal crustal thickness. Crustal thickness T for the regional topography fully compensated is shown in Figure 6 assuming T_o as 33 km and $\Delta\sigma$ as 0.4 g/cc, and lc as 2.90 g/cc in Deccan trap region and 2.70 g/cc for crystalline terrain in the rest of the region. Depth of Moho in this region is known by three Deep Seismic Sounding (DSS)[7–9] profiles which are also shown in Figure 6. Since the crustal thickness T, which is estimated for regional topography fully compensated is referred to as normal crustal thickness, the DSS Moho depths equal, lower or higher than T suggest normal, subnormal and abnormal crustal thickness respectively; these values indicate state isostasy in the region. Normal crustal thickness indicates iso-static equilibrium, whereas subnormal values suggest under-compensation. Abnormal values indicate over-compensation or regional nature of compensation. Abnormal crustal thickness creates deficit mass. Subnormal crustal thickness creates excess mass and normal thickness creates no excess and deficit masses. These deficit or excess masses and the absence of such masses are reflected by negative, positive and zero gravity values respectively in ZFb anomaly map (Figure 5).

Kavali–Udipi DSS profile[7] cuts across South India from the west coast to the east coast. It indicates crustal thickness as 38 km in the western margin of the Western Ghats, as 37 km in south-western part of Cuddapah basin and as 40 km in the eastern margin of Cuddapah basin, where the normal crustal thickness T values are 34, 35 and 34 km respectively. This shows abnormal crustal thickness in these regions and as expected negative ZFb values are observed. In the Western Ghats mountain belt, DSS profile indicates a normal crustal thickness of 38 km, and thus the ZFb gravity field is zero in this region. In the Karnataka plateau, crustal thickness is 34 km from DSS profile where T value is 37 km, thus indicating subnormal crustal thickness and positive ZFb gravity values as expected. In the Koyna region also, similar observations are made from two DSS profiles[8,9] showing abnormal crustal thickness reflected by negative ZFb values in the western margin of the Western Ghats, normal crustal thickness reflected by ZFb values in the Western Ghats mountains and subnormal crustal thickness reflected by positive ZFb values in the plateau region of Koyna. In these regions, DSS Moho depths are 39–40 km in the western margin of the Western Ghats, 39 km in the Western Ghats and 38 km in the plateau region against T values of 34, 39 and 38.5 km respectively.

Subnormal crustal thickness indicated above suggests

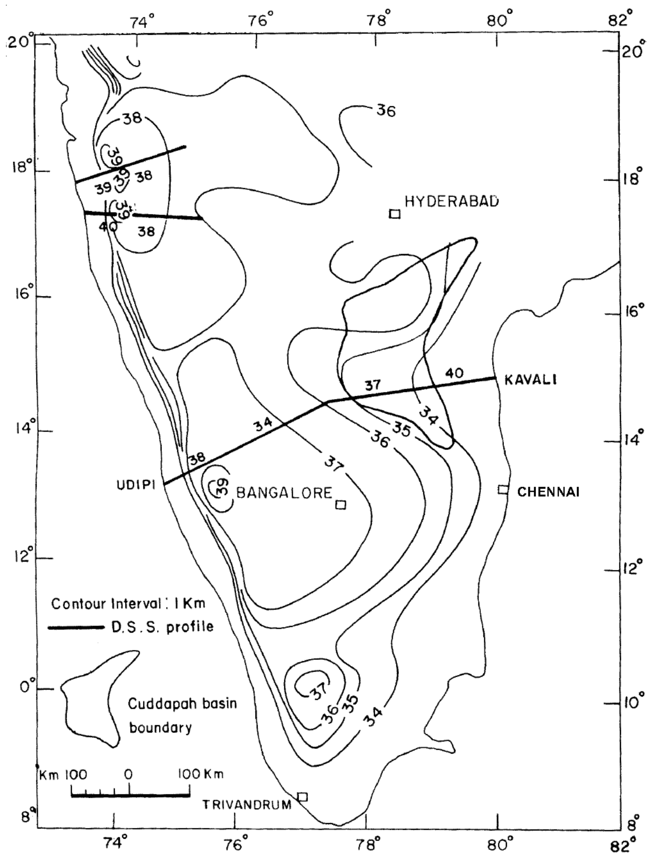

Figure 6. Crustal thickness (T) contour map (km) for fully compensated regional topography assuming 33 km as standard crustal column thickness (T_0) at sea level, 0.40 g/cc as density contrast of crust with mantle, and density of regional topographic mass as 2.9 g/cc in Deccan trap region and as 2.7 g/cc in region of crystallines. Moho depths along three Deep Seismic Sounding profiles are given as known from DSS data (after Kaila *et al.*[7–9]). Contour interval is 1.0 km.

under-compensation and this leads to isostatic instability in these areas. Incidentally, Koyna, Killari, Bellary and Coimbatore shown in Figure 5 had witnessed major earthquakes with magnitude 5.5 and above[10,11] and are with these plateau regions. Radial river system (inset Figure 4) with Karnataka plateau indicates domal upwarping of crust and along its margins are the Bellary and Coimbatore earthquakes, while a major fault (Bhavani–Mayor) marks its southern boundary. The crustal upwarp may cause plateau uplift to which the seismicity may be related. However, repeated observations of gravity and elevations, and detailed seismic station network are necessary to verify this plateau uplift and to understand better the seismotectonics of these regions.

Normal crustal thickness beneath the Western Ghats mountains suggests isostatic equilibrium. Abnormal crustal thickness beneath its western margin is due to crustal downwarp extending beyond limits of the topographic load of the mountain belt. Sudden rise of mountains in this western margin causes such downwarp due to elastic behaviour of the crust; thus the compensation is of regional nature, instead of local.

Kavali–Udipi DSS profile[12] indicates high crustal velocity beneath the Eastern Ghats mobile belt, suggesting dense crust. This is excess load within the crust and thus needs compensation similar to the regional topography. The compensating mass can be in the form of crustal root formation. This dense crust is a sharp change similar to sudden rise on the western margin of the Western Ghats mountains. Thereby regional compensation can be expected with this mobile belt as well, causing crustal downwarp to extend beyond its limit as in case of the Western Ghats mountains. Thus abnormal crustal thickness is present as mentioned earlier, and is reflected by negative gravity values[13] whose axes follow the margin of the mobile belt demarcated by thrust along the eastern margin of the Cuddapah basin (Figure 5). In the southern granulite region also, along the east and west coasts, axes of negative gravity values coincide with major faults which demarcate boundary of mobile belts of Madurai and Kerala, suggesting crustal structure with these mobile belts similar to that of the Eastern Ghats mobile belt discussed above (Figure 5). Whether the positive gravity values observed over these mobile belts (Kerala, Madurai and the Eastern Ghats) indicate under-compensation or locally denser basement due to igneous complex, is not clear. Crustal thickness of 40 km is reported with the Eastern Ghats mobile belt from DSS profile, where the value of T for regional topography compensated is 33.5 km. This crustal thickness difference of 6.5 km (40 – 33.5) represents the compensating mass for the dense crust of mobile belt. Considering this compensating mass in isostatic equilibrium state, an increase of 0.08 g/cc in crustal density (lc) can be expected as computed based on Airy's theory of isostasy for crustal root mentioned earlier. Here, ΔR is 6.5 km and $\Delta\sigma$

as 0.4 g/cc and h as 33 km for standard crustal column thickness at sea level are taken as assumed earlier. Considering 2.84 g/cc as normal density of the crust, the dense crust has 2.92 g/cc as its density.

Zero gravity field (Figure 5) over SW part of Cuddapah basin suggests isostatic equilibrium probably for dense sediments. In this region, the crustal thickness is 37 km as shown by the DSS profile and a value of 34.5 km only for T is expected for regional topography compensated here. This crustal thickness difference of 2.5 km can be equated with a positive density contrast of 0.1 g/cc for 10 km thickness sediments based on Airy's theory. Here ΔR is 2.5 km, $\Delta\sigma$ is 0.4 g/cc assumed earlier, lc is density contrast of sediments and h, its thickness is 10 km. Considering a density of 2.7 g/cc for crystallines, the density of sediments is 2.8 g/cc. This estimated density of 2.8 g/cc as well as 10 km thickness for sediments are well within geological estimates. This high-density sediment causes regional compensation similar to the dense crust with the mobile belt as explained earlier, by which downwarp of the crust extends beyond limits of this basin. This is reflected by negative gravity values observed along margins of the southwestern part of the basin (Figure 5).

Thus ZFb anomaly map reflects essentially the state of isostasy with different tectonic units in the study area with Airy's theory of isostasy operative and that the standard crustal column thickness and densities assumed for the crustal model are reasonable.

Using the zero-free air value concept of Subba Rao[1], ZFb anomaly map prepared for the southern part of India has brought out the real nature of gravity field over this region, which is otherwise not evident from Bouguer gravity map due to negative bias. The ZFb anomaly map has helped to understand better the tectonics of the region by indicating isostatic equilibrium with the Western Ghat mountains and isostatic instability with plateaus, the region of major earthquakes. In granulite terrain, the regions of mobile belts (Kerala, Madurai and the Eastern Ghats) along the east and west coasts are with anomalous crust, while the rest of the region is with normal crust. The regional topography and negative bias maps obtained now for the southern part of India can be utilized for any local and regional data sets to obtain ZFb anomaly map.

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Basement structure of the southwestern part of the Cuddapah Basin from aeromagnetic anomalies

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The basement configuration of the southwestern part of the Cuddapah Basin was derived from aeromagnetic data by transforming it into pseudo-gravity anomalies with a low-pass filter. The inferred picture shows a general depression of the basement elongated in a NW-SE direction and reaching a maximum depth of about 10 km near Muddanuru. The steep dip of the basement in the southern and southwestern part suggests that the sediments were derived from the southern and southwestern sides of the basin.

THE Cuddapah Basin (Figure 1) is one of the well-studied Proterozoic basins of India. The basin, filled with Precambrian rocks of the Cuddapah and Kurnool super groups, comprises mainly shales, limestones and quartzites, with basic sills in the southwestern part. The Archean granites, gneisses and schists surrounding the basin might constitute the basement[1–4]. In the last three decades, extensive geophysical studies over the Cuddapah Basin have been carried out to understand its structure and evolution. These include detailed studies

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