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Apparent Density Mapping and 3-D Gravity Inversion of Dharwar Crustal Province

A.P.Singh, D.C.Mishra and G.Laxman
National Geophysical Research Institute, Uppal Road, Hyderabad - 500 007.

Abstract
The Bouguer anomaly over Dharwar crustal province is predominantly negative and at least a part of which seems to be related to the Indian Ocean geoidal low. Zero-free air-based (ZFb) analysis of the geoidal corrected Bouguer gravity values in the Dharwar crustal province suggests that the gravity field may be separated into isostatic regional and residual components. The isostatic regional component, caused by the compensation of the regional topography, was subjected to a gravimetric single density-interface inversion procedure giving a gravimetric Mohorovicic model which is generally in good agreement with the Moho-depths derived by refraction and reflection seismology.

The isostatic residual gravity component correlates well with main surface geological units of the Dharwar crustal province. Apparent density mapping by applying an inverse density deconvolution filter to the isostatic residual gives density values for the upper crust, which corresponds well with the average density values from rock samples.

INTRODUCTION

The Dharwar crustal province is one of the areas of the world, which had preserved the earliest formed crust (Fig.1). It is delimited on the west, south and east by the present day coastline. On the northwest the Deccan volcanic province, the northeastern side the NW-SE trending Gondwana Godavari graben and in the north, the Son-Narmada lineament serves as the tectonic boundary of the province. Though earlier believed to be a singular crustal block, a mosaic of various Precambrian tectonic provinces in age from early Archaean to late Proterozoic is widely accepted.

The crustal thickness in the region has been obtained seismically through Deep Seismic Sounding (DSS) investigation (Kaila et al. 1979; Kaila & Krishna 1992; Sarkar et al. 2001; Reddy et al. 2002), 3-D seismic tomography study (Rai, Srinagesh & Gaur 1993; Srinagesh & Rai 1996) and teleseismic receiver function (Saul, Ravi Kumar & Sarkar 2000; Ravi Kumar et al. 2001; Sarkar et al. 2002). Extensive efforts have also been made to determine the thickness of the crust using Bouguer gravity field in the Dharwar crustal province (Bhattacharji, Sharma & Hemashwari 1984; Subba Rao 2002). These interpretations of the Bouguer gravity filed in the area, however, do not conform well to the seismic observations. The aim of the present investigation is to derive the information from the Bouguer gravity by using the concept of zero free air (ZFa) anomalies (Subba Rao 1996) to isostatic regional-residual separation. The 3D gravity inversion and gravimetric apparent density mapping were then used in interpreting the gravity field in terms of crustal thickening and density variations within the crust. The results for crustal thickening were then compared with seismic results; the calculated lateral density variations for the upper crust were compared to rock sample densities of the main surface geological units of the Dharwar crustal province.

NATURE OF THE BOUGUER ANOMALY

The Bouguer anomaly over the Dharwar crustal province are predominantly negative varying from -130 mGal (L1) east of Mangalore in Karnataka to +30 mGal (H1) over Eastern Ghats mobile belt on the east coast (Fig.2). It apparently follows the structural grains of the province particularly the Dharwar schistose rocks were well demarcated by relatively high gravity values (Qureshy et al. 1967; Kailasam et al. 1983). However, the gravity picture over the schist belts becomes complicated where the schist's are intruded by granites, which because of their comparatively lower density (2.65g/cm^3) yield Bouguer lows (Naqvi 1973). Institutively, the gravity highs encountered in the regions where greenstone belts are absent can reasonably be attributed to high-density intrusive (Krishna & Ramesh 2000) and/or thinning of the crust (Kaila & Bhatia, 1981). On the other hand, gravity lows are normally due to granitic intrusions and/or thickening of the crust (Qureshy, Krishna Brahmam & Aravamadhu 1969; Krishna Brahmam 1993).

The northeastern part of the Bouguer anomaly map of the Dharwar crustal province shows a prominent gradient paralleling the NW-SE trend of the Godavari graben. The small wavelength circular high (H_2) is associated with the high-density garnetiferous granite rocks of Warangal and Karimnagar areas (Kanungo, Murthy & Rama Rao 1976) and the granulite terrane of the Karimnagar (Rajesham, Bhaskara Rao & Murty 1993), respectively. According to Mishra et al. (1987a) the referred

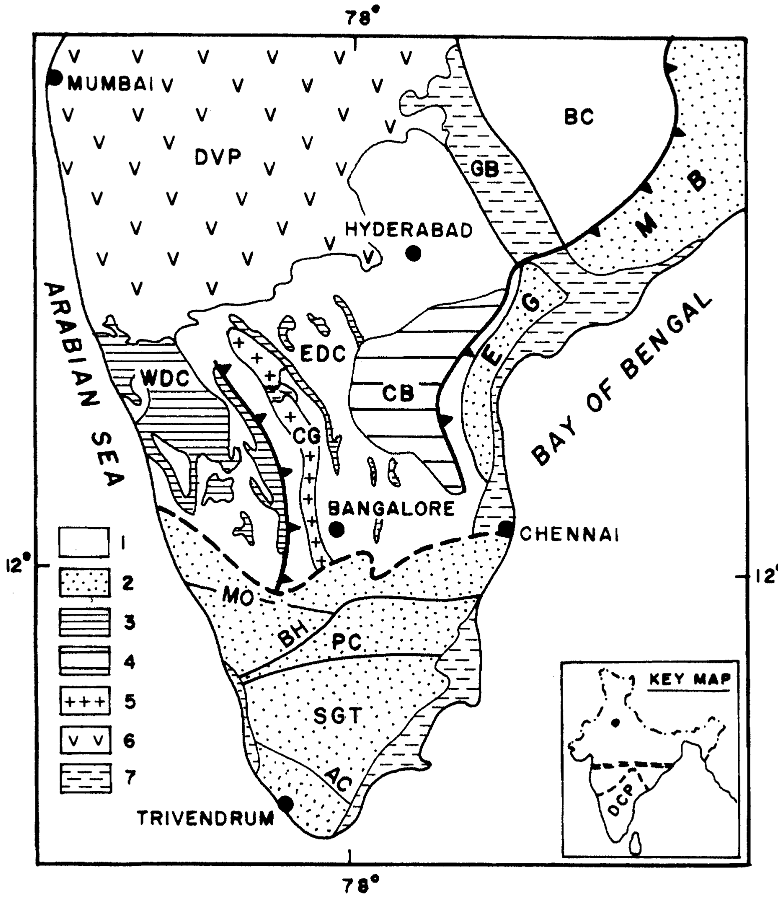

Figure 1. Generalized geological map of the Dharwar crustal province (DCP) representing various crustal blocks (1) Peninsular gneiss complex, (2) Granulite, Charnokite and Khondalite, (3) Schist belts (4) Proterozoic sediments (5) Younger (Closepet) granite, (6) Deccan Traps and (7) Mesozoic to Recent sedimentary sequences. Also shown are BC: Bastar craton, DVP: Deccan Volcanic Province, EGMB: Eastern Ghats mobile belt, EDC: Eastern Dharwar craton, WDC: Western Dharwar craton, SGT: Southern Granulite Terrain, AC: Achankovil shear zone, PC: Palghat-Cauvery shear zone, BH: Bhavani shear zone, MO: Moyar shear zone, CB: Cuddapah Basin, GB: Godavari Basin, and CG: Closepet granite. Dashed line shows the orthopyroxene isograd (Fermor Line).

anomaly is the manifestation of intrusion of mantle material along the shoulder of the Godavari graben and/or the bipolarity in broad regional gravity signature is the manifestation of the continental collision with regional high signifying the upthrusted lower crustal rocks at shallower levels (Mishra, Singh & Gupta 2002).

The -130 mGal gravity low (L1) observed over Hasan towards west coast is the strongest negative anomaly observed in the entire Dharwar crustal province. The extent of the negative anomaly is in fact not limited to any specific geological formation but is spread out well over granites, gneisses and schists as well. However, in all likelihood, the gravity low is probably a result of several granite batholiths exposed in this region and/or the deeper Moho due to isostatic compensation. A pronounced gravity low (L2) of –110 mGal centred above Londa is either a granitic body at depth whose cupolas are exposed around Londa and also at Margao, or thickening of the crust, or a combination of the both (Krishna Brahmam 1993). Another prominent negative anomaly having amplitude of about -30 mGal and indicated by a gravity closure of -110 mGal (L3) has been observed to the south of Bangalore. This anomaly is almost triangular in shape but shows considerable nosing towards north and appears to be the only well-defined negative anomaly associated with the Closepet granite.

The western part of the Proterozoic Cuddapah basin shows gravity high of -60 mGal (H3) with respect to the eastern part. The eastern part of the Cuddapah basin is characterized by a broad gravity low (L4), conforming to its arcuate shape. The gravity high (H3) and low (L4) over the Cuddapah basin has been interpreted in terms of crustal warping (Glennie 1951), or with dense mantle material offset by granitic intrusions underneath the sedimentary columns of the Cuddapah supergroup, respectively (Qureshy et al. 1968). Kaila & Bhatia (1981) explained the high gravity anomaly (H3) to crustal thinning producing a thick lower crust and a thin upper crust. A magmatic lopolith has also been postulated to explain the gravity high (H3; Mishra et al. 1987b, Mishra & Tiwari 1995). They also considered thickening of the crust particularly the upper crustal layers to account for the gravity low (L4) along the eastern part of the Cuddapah basin. Krishna Brahmam (1992) attributed the gravity high (H3) to an igneous body emplaced through meteoritic impact around 1700 Ma. Ram Babu (1993) has attempted to explain the high and low (H3 & L4) through variation in the basement topography, with a minimum depth under the gravity high (H3) and maximum depth under the eastern margin of the basin. South of the Cuddapah basin, is a gravity high (H4) trending almost E-W, which is consonance with the known geological "grain". However, the dyke swarms in that region are aligned E-W and the gravity high may be indicative of Moho upwarp with which the dyke swarms are probably associated (Krishna Brahmam 1993).

Interpretations of the gravity anomalies over the Southern Granulite Terrane show that the anomalies exhibit considerable variation over the charnockites themselves. The most pronounced gravity anomaly of the region is the broad gravity low (L5) of -120 mGal centred about 30 km west of the Kodaikanal. The anomaly is roughly oval shaped covering mostly the charnockite outcrops. According to Krishna Brahmam & Kanungo (1976) a major part of this anomaly is again caused by the granitic batholiths at depth and that the scattered outcrops of exposed granitic bodies are but the cupolas of a larger batholith at depth. The contention was contested by Subrahmanyam & Verma (1986) and presence of acid and intermediate charnockites beneath the hill mass is presented as another explanation to the referred anomaly. According to Mishra (1988) and Mishra & Rao (1993) the referred gravity low is caused by crustal thickening. The combined contribution of both the granitic emplacement and crustal thickening to gravity low is more plausible. The long linear gravity low (L6) of approximately –110 mGal coincides with the Krishnagiri granite towards north and Sankari granite towards south and apparently caused by them.

The entire west coast, particularly the area between Mangalore and Cannanore, is dotted with patches of gravity highs. Looking at the short wavelength nature of the inferred coastal anomalies the gravity high is attributed to the emplacement of high-density ultrabasic rocks at comparatively shallow depths (Subrahmanyam & Verma 1986; Krishna Brahmam 1993). Contrary to this view, Mishra & Rao (1993) attributed the coastal gravity highs to deep faults along which Moho upwarped along the coast. A relative gravity high (H6) over Nilgiris hills is in itself an anomalous feature since the high region is expected to have a Bouguer anomaly low due to the compensation of topography. According to Subrahmanyam & Verma (1986) the positive anomaly is the result of the upthrusting of high-density pyroxene granulite. Contrary to this view, Qureshy (1971) based on the regression analysis of the elevation and Bouguer anomaly of the shield region concluded that the upliftment of the Nilgiris block has probably taken place through movement and incorporation of material from the upper mantle into the crust. The adjoining gravity low (L7) has been interpreted by Qureshy et al. (1967) and Krishna Brahmam & Kanungo (1976) in terms of a concealed granitic batholith, which outcrops in a small area near Mananthody. Low anomaly (L8) flanks the eastern margin of the Nilgiris and spreads over a vast gneissic country rock, and it is known that a suite of low-density igneous syenite rocks outcrops in a cluster of small hillocks around Coimbatore (Subrahmanyam & Verma, 1986).

The regional gravity map (NGRI 1978) may not be able to bring out the response of the subtle geological formations, however, it has successfully delineated the broad geological features and structural/tectonic blocks of the Dharwar crustal province. The low density Closepet granite apparently has no gravity expression. However, it is flanked on its west by gravity high. Kaila & Bhatia (1981) believe that the relatively thinner crust overcompensate the effects of low-density granites resulting in no relative gravity anomaly in the region. One plausible explanation could be that by and large there is no appreciable density contrast between the Closepet granite and the surrounding gneisses. Krishna Brahmam (1993), Krishna & Ramesh (2000) feel that the gravity high flanking the western side is caused by emplacement of heavier material probably along a zone of weakness related to the major geo-suture, which demarcates the granite-greenstone terrane into two distinct crustal blocks. In contrast no characteristic gravity signature is observed by Rao & Prasad (2000) to propose a locus of ancient suture between the two Dharwar cratons.

Another striking feature of the Bouguer anomaly map of the Dharwar crustal province is the parallelism between the gravity contours and the structural grains of the Eastern Ghats mobile belt. The gravity field over the Eastern Ghats mobile belt is appreciably positive as compared to that over the Cuddapah basin. This suggests basic differences in the nature of the crust and mantle relationship in the two regions. The anomaly trend in a general NE-SW direction with gravity high of –50 to +30 mGal that starts from near Tiruchchirapalli in the south, trends towards Chennai, follows to the east of the Cuddapah basin in an arcuate fashion and continues northwards along the east coast of India. A steep gradient of Bouguer anomaly in the eastern part of the basin apparently suggests a faulted contact, between the crystalline in the east and the basin on the west (Subrahmanyam & Verma 1986; Verma & Satyanarayana, 1990). According to Singh & Mishra (2002) and Singh et al. (2002a) the bipolar anomaly with steep gradient characterizes a particular crustal configuration that develops at ancient collision zones.

Subrahmanyam (1978) feels that the relationship of the Dharwar craton to the charnockite terrane south of it has not yet been well defined, but the two provinces appear to be related by a continual progression in metamorphic grade of a single crustal block. Contrary to this view Mishra (1988) suggested that the Palghat-Tiruchi line, although probably not a suture

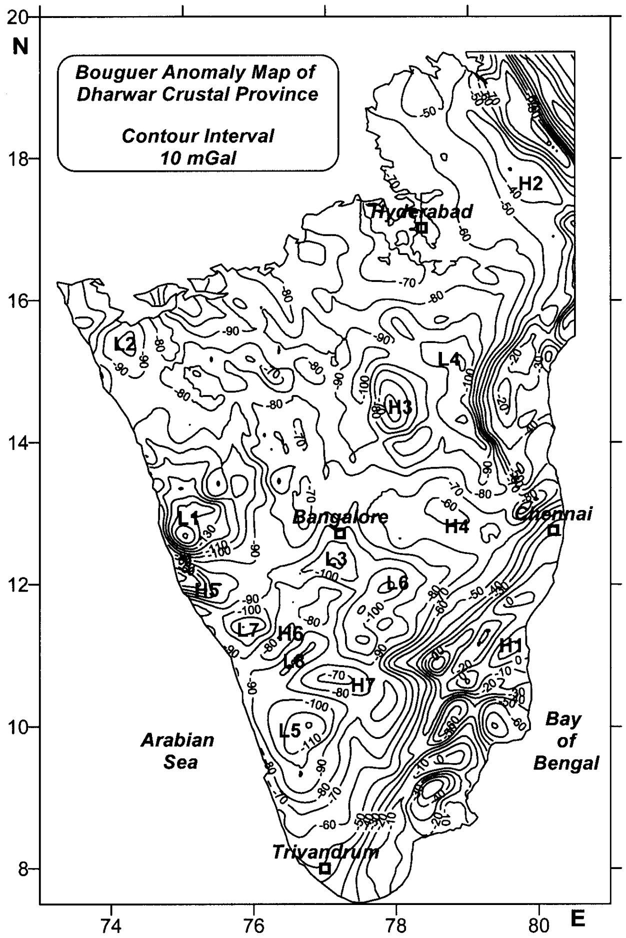

Figure 2. Bouguer anomaly map (in mGal) of the Dharwar crustal province showing gravity gradients (G_s), and various relative gravity highs (H_s) and lows (L_s).

zone, is significant, representing probably the junction of two crustal blocks during the Precambrian which might have overridden each other forming a thick crust towards the south from which even if the upper part is eroded away the remaining part is still thicker than a normal crust. The gravity high located between the Coimbatore and the Namakkal is partly over charnockites and partly over the Cauvery basin. There is no immediate explanation for this gravity high in terms of surface geology as it spread over a vast gneissic-migmatite countary. However, the gravity high is explained in terms of a gabbro-anorthosite mass underlying the gnessic rocks at shallow depths, whose surface expression are the basic complexes exposed in the area (Singh et al. 2002b). According to Krishna Brahmam (1993) the paired gravity anomaly (Ootacamund-Kollegal gravity high flanked by Coimbatore-Dharmapuri gravity low) is a signature of ancient plate tectonics.

REGIONAL-RESIDUAL SEPARATION

Interpretation of the gravity data normally begins with the decomposition of the gravity anomalies into its various source components (regional-residual anomalies), estimation of source parameters (position, size and shape) and finally translation of these mass distributions into the geological models. Regional and residual separation of gravity fields is a vital subject in gravity interpretation. One established procedure is to separate regional and residual fields through convolution. Another common procedure is the manual operation of smoothing. These two approaches are complementary in the sense that "filtering" can be based on a few general assumptions, whereas "smoothing" is more akin to local modelling and interpretation in which more external information is integrated into the process. A generalization of standard separation filters, denoted as

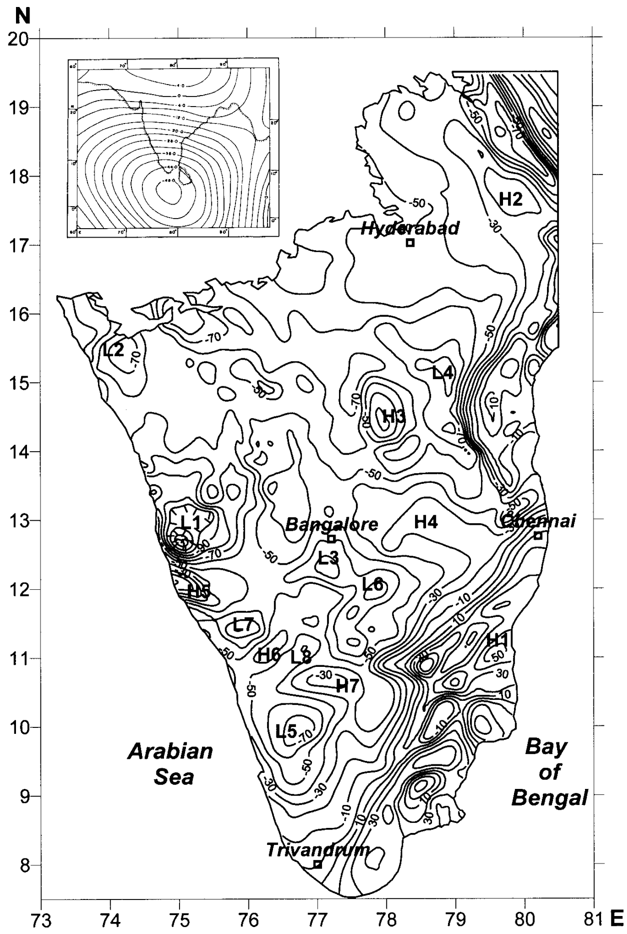

Figure 3. Geoidal corrected Bouguer anomaly (GCBA) map (in mGal) of the Dharwar crustal province. Prominent gravity highs and lows are same as in Fig.2. Effect of the Indian Ocean Geoidal Low on gravity field (after Marsh 1979) is also shown as inset.

uniformly sub-optimum filters, quantitatively supports the statement that a wide span of separation problems may be solved adequately using some convenient, small standard filter family. However, no unequivocal standard sub-optimum separation filter for the potential filed maps has been given using elementary function in both space and wave-number domains that is numerically stable and is also physically comprehensible when applied to real, non-random anomalies. Simple band-pass filtering, though mathematically comprehensible and well defined, is not readily comprehensible in physical terms. Subsequent local modelling based on the processed data requires that the separator be mathematically and numerically explicit, a condition which goes against using manual smoothing of contours to obtain the regional field (Jacobsen 1987). In the given situation decomposition and separation of at least the known components of the regional seems to be more appropriate. Data filtered in this way is even suitable for direct quantitative modelling and interpretation.

Geoidal Correction:

Given that the Bouguer anomaly is the ensemble of all subsurface source horizons, at least a part of the predominant negative bias, in the large wavelength Bouguer anomaly over the Dharwar crustal province, seems to be related to the composition of the upper mantle (Verma & Satyanarayana 1990). In fact satellite derived gravity map (inset in Fig.3) shows a long wavelength anomaly centred over the Indian Ocean geoidal low whose effect varies from near zero over the 25^{0}N to –48 mGal at the southern tip of the India (Marsh 1979). For quantitative modelling of the crustal component of the Bouguer anomaly, the part related to this geoid's variation, which is caused by subcrustal source horizon, should be removed from the observed gravity field (Qureshy & Midha 1986). The geoidal corrected Bouguer anomalies are shown in Figures 3 and referred hereafter as geoidal corrected Bouguer anomaly (GCBA). As is apparent from the Figures 2 and 3 that the major gravity anomalies remain the same in the geoidal corrected field but their amplitudes are reduced/enhanced depending upon their nature whether they are gravity highs or lows.

Isostatic Regional anomaly and Moho configuration:

The regional component still in the geoidal corrected Bouguer anomaly is the long wavelength isostatic response of the regional topography. These anomalies are observed to have negative values as regional field. To separate this negative bias, isostatic correction is made by relating it to compensating mass at depth. Mathematical relations used for such separations are not effective as they are based on assumed model for isostatic compensation. Subba Rao (1996) has recently introduced the zero free air values concept to eliminate this negative bias effectively. Based on the zero free air anomalies concept the isostatic component of the regional topography in the observed Bouguer anomaly of south Indian shield is obtained. The free air anomaly would average to zero when the gravitational effect of topographic mass is balanced by an equal and opposite mass at the depth (Woollard 1959). The regional elevations corresponding to the zero free air anomalies are the elevation involved in the isostatic compensation. Since the zero free air values can also arise due to resultant effect of local mass distribution such zero values are not used for computation of the regional in the Bouguer gravity field.

For the present investigation the GCBA was subjected to this process of regional-residual separation and the values in the GCBA corresponding to the zero in the Geoidal Corrected Free Air anomaly expected due to compensation of the regional topography was taken as the isostatic regional (Fig.4). As is apparent from the Figure 4 the west coast, where the average elevation is near the mean sea level, a negative gravity anomaly in the isostatic regional reflects mass deficiency. In fact the negative Airy isostatic anomaly over the Western Ghats spreading over the low-lying coastal plains indicates a regional overcompensation through undissipated crustal root in the mantle (NGRI 1978).

It is generally believed that the isostatic compensation is achieved at the level of Moho, which bears an inverse relationship to topographic elevations (Bhattacharji, Sharma & Hemashwari 1984). Indeed a general correlation between topographic elevation and Moho is found over continental areas. The isostatic regional of the GCBA was therefore subjected to the single layer inversion, assuming density contrast $\Delta\rho$ = -0.4 g/cm^3 between crust (ρ = 2.9 g/cm^3) and mantle (ρ = 3.3 g/cm^3) and a depth of 38 km for the mean level of the Mohorovicic discontinuity in the Dharwar crustal province. The Moho undulations (Fig.5), evidently due to the deep seated compensation of the regional topography (Subba Rao 2002), is found to vary between 35 km beneath the Eastern Ghats mobile belt to 42 km maximum beneath the western Dharwar craton and generally agrees well with other published Moho depths beneath the region (Bhattacharji, Sharma & Hemashwari 1984). On comparing seismic and seismological findings in the region, the results are found to be in fair agreement in the western and eastern Dharwar cratons (Kaila et al. 1979; Kaila & Krishna, 1992; Saul, Ravi Kumar & Sarkar 2000; Ravi Kumar et al. 2001; Sarkar et al. 2001, 2002) except for an upward vertical shift accompanied by a lateral shift along the gradient towards the south of the Palghat gap (Reddy et al. 2002).

Residual Anomaly and Apparent Density distribution:

The residual gravity field (Fig.6) generated by subtracting the isostatic regional field (Fig.4) from the GCBA (Fig.3) represents the gravity field not involved in the compensation. The residual gravity field correlates well with the major surface geological units in this region. The map shows most pronounced positive values (reaching 50 mGal) over Eastern Ghats mobile belt. The conspicuous positive values (+30 mGal) are also observed over

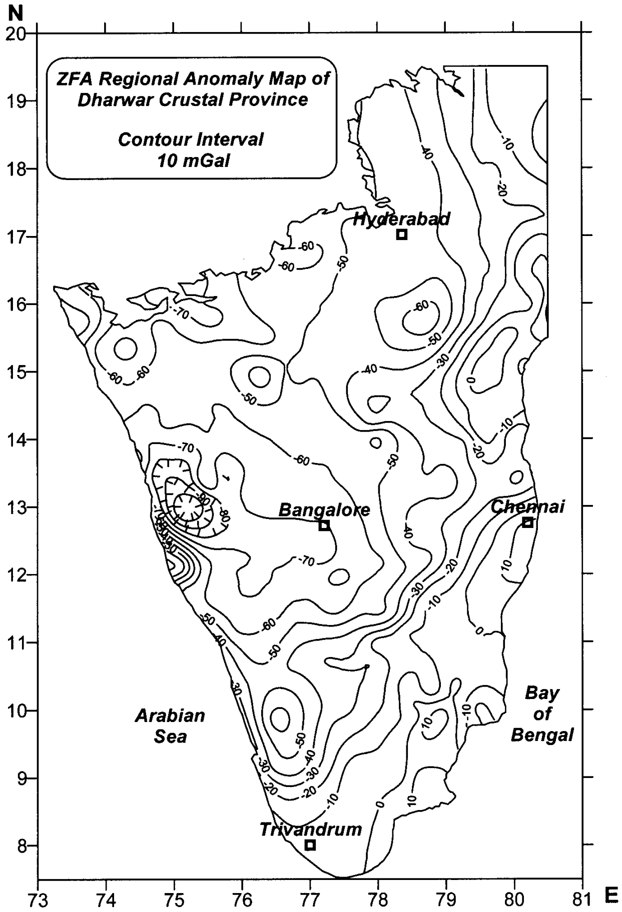

Figure 4. Isostatic regional anomaly map (in mGal) of the Dharwar crustal province. The geoidal corrected Bouguer anomaly map (Fig.3) is used to separate the isostatic regional based on the Zero Free Air (ZFA) anomaly of the region (Subba Rao 1996). Regional highs (H_s) and lows (L_s) generally indicate the undulation at Moho level.

the Karnataka plateau encompassing the Bangalore region. The negative isostatic residual values (reaching -40 to -50 mGal) are observed along the west coast and over the eastern part of the Cuddapah basin, respectively. The Godavari graben is marked by the maximum negative (-60 mGal) residual anomaly due to sedimentary deposits.

A correlation between the main tectonic units and the average bulk density of the formations was investigated by applying the technique of apparent density mapping. The approach is based on the assumption that the residual gravity anomaly is caused by a laterally varying density contrast within an infinite horizontal slab. The density can then be calculated by deconvolution of the residual gravity data. In the present application, a thickness of 10 km for the horizontal layer representing the upper crust was chosen as a compromise suggested by the seismic investigation (Kaila et al. 1979). Based on the densities of 1294 Precambrian rocks, Subrahmanyam & Verma (1981) obtained an average density of 2.75 g/cm^3 for sample rocks from southern Indian shield. Later Ramachandran & Bose (1991) reported 2.76 g/cm^3 as an appropriate choice for the mean density of the crystalline crust in Southern granulite terrain. Hence the resulting apparent density map (Fig.7) is forced to a mean of 2.75 g/cm^3 to be compatible with the actual rock formation densities of the Dharwar crustal province.

Though the results consistently explain the observed gravity field in the Dharwar crustal province, when interpreted in terms of the geology of the region, two major sources of error have to be kept in mind. These are the oversimplification and the ambiguity of the gravity method. Obviously, the assumption that the upper crust can be described by a 10 km thick horizontal

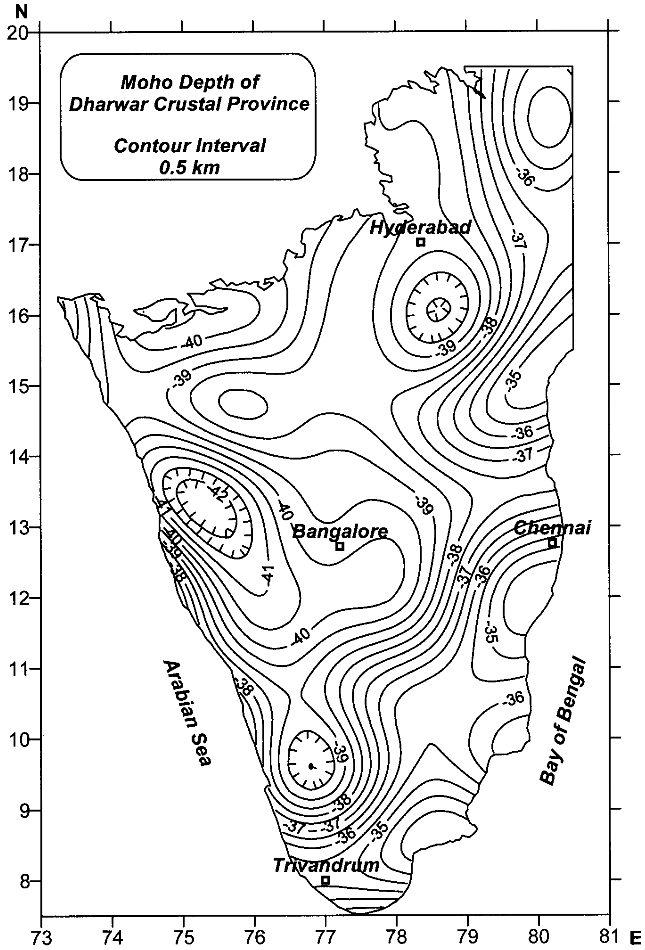

Figure 5. The Moho relief (in km) of the Dharwar crustal province calculated by gravimetric inversion of the Isostatic regional field using the density contrast of –0.4 g/cm^3.

plate with laterally varying density is an over-simplification of the true geology. For example, the sedimentary basins like the Cuddapah basin (more than 10 km thick) is reflected in the unrealistically low-density values (about 2.64 g/cm^3) for the Proterozoic sediments of the basin. Similarly the Dharwar supracrustal is known to be less than 10 km thick. This discrepancy is reflected in the unrealistically low-density value (2.8 g/cm^3) for the schist belt. Within the given limitations, the apparent density values otherwise arguers well with the main units of the Dharwar crustal province.

Apart from the over-simplification of the geological model, the gravity model suffers from ambiguity. Attribution of high frequency features to shallow depth, i.e., upper crust, is strictly valid it is not necessarily valid to attribute low frequency features to deep-seated structures, i.e., the Moho discontinuity. It is possible that some low frequency features of the Bouguer gravity map are not associated with the Moho relief but are in fact caused by broad, shallower features within the upper or the lower crust. This may be true in southern granulite terrain where the calculated crustal thickness shows shallower undulations than are supported by seismically derived values (Reddy et al. 2002). Though the 0.4 g/cm^3 is a reasonable assumption for the density contrast between the lower crust and upper mantle, the present model does not consider any density contrast within the lower crust or below the Moho discontinuity. However, judging from the good correlation between the isostatic residual and the subsurface geological features, and the Moho-depths derived by gravimetric inversion compared to seismic results, there is little evidence for major horizontal density variations in the lower crust or the upper mantle.

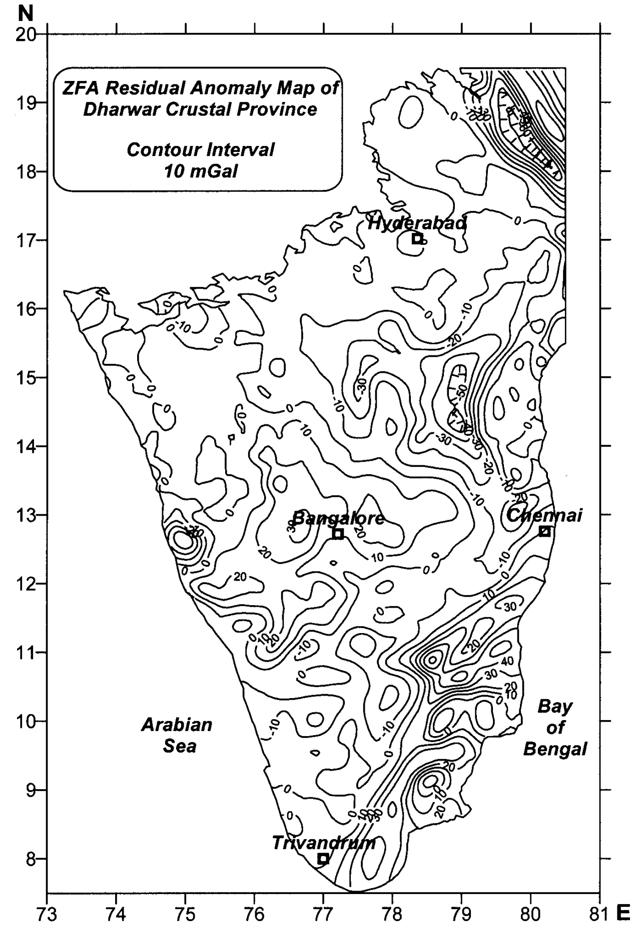

Figure 6. Isostatic residual anomaly map (in mGal) of the Dharwar crustal province. The residual field is obtained by subtracting the isostatic regional field (Fig.4) from the geoidal corrected Bouguer anomaly map (Fig.3). Residual highs (H_s) and lows (L_s) generally show the contribution from the shallow sources.

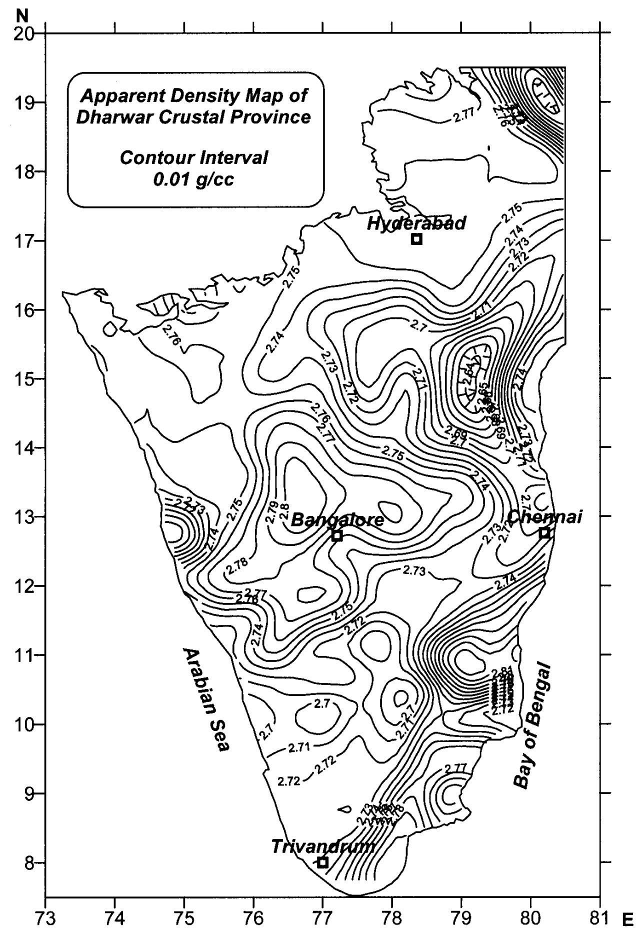

Figure 7. Apparent density map based on the deconvolution of the residual gravity field (Fig.6) to a mean of 2.75 g/cm^3.

CONCLUSIONS

Geoidal corrected Bouguer anomaly map of the Dharwar crustal province is prepared by eliminating negative bias from Bouguer map of NGRI (1978). The Zero-free air based regional-residual separation provides a more realistic approximation of the Moho configuration and apparent density distribution, respectively. The thickest Moho of 42 km beneath the western Dharwar craton and thinnest of 35 km beneath the Eastern Ghats mobile belt conform well to the seismic observations. Despite limitations of the method the apparent density mapping of the region is in agreement with the surface geology of the Dharwar crustal province.

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