Lithospheric structure of southern Indian shield and adjoining oceans: integrated modelling of topography, gravity, geoid and heat flow data

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SUMMARY
For the present 2-D lithospheric density modelling, we selected three geotransects of more than 1000 km in length each crossing the southern Indian shield, south of 16° N, in N–S and E–W directions. The model is based on the assumption of local isostatic equilibrium and is constrained by the topography, gravity and geoid anomalies, by geothermal data, and where available by seismic data. Our integrated modelling approach reveals a crustal configuration with the Moho depth varying from ∼40 km beneath the Dharwar Craton, and ∼39 km beneath the Southern Granulite Terrane to about 15–20 km beneath the adjoining oceans. The lithospheric thickness varies significantly along the three profiles from ∼70–100 km under the adjoining oceans to ∼130–135 km under the southern block of Southern Granulite Terrane including Sri Lanka and increasing gradually to ∼165–180 km beneath the northern block of Southern Granulite Terrane and the Dharwar Craton. This step-like lithosphere–asthenosphere boundary (LAB) structure indicates a normal lithospheric thickness beneath the adjoining oceans, the northern block of Southern Granulite Terrane and the Dharwar Craton. The thin lithosphere below the southern block of Southern Granulite Terrane including Sri Lanka is, however, atypical considering its age. Our results suggest that the southern Indian shield as a whole cannot be supported isostatically only by thickened crust; a thin and hot lithosphere beneath the southern block of Southern Granulite Terrane including Sri Lanka is required to explain the high topography, gravity, geoid and crustal temperatures. The widespread thermal perturbation during Pan-African (550 Ma) metamorphism and the breakup of Gondwana during late Cretaceous are proposed as twin cause mechanism for the stretching and/or convective removal of the lower part of lithospheric mantle and its replacement by hotter and lighter asthenosphere in the southern block of Southern Granulite Terrane including Sri Lanka. Unusually thinned LAB beneath the region near Bangalore apparently indicates the preserved tectono-compositional effect of late Proterozoic rifted margin of Dharwar Craton.

Key words: Gravity anomalies and Earth structure; Cratons; Tectonics and landscape evolution; Dynamics: gravity and tectonics; Crustal structure.

1 INTRODUCTION
Present-day elevation of relict orogenic belts reflects the buoyancy of the lithosphere supporting the topographic load. The lithospheric buoyancy can be subdivided into contributions from the crust and the mantle through detection of mass distributions both vertically and laterally across a region of interest (Martinec 1994). The capacity to map the density anomalies at lithospheric scales across large regions both on- and offshore provides scopes for establishing the present-day structure of the lithosphere and its links with the observed surface topography. Gravity anomalies may help to determine the state of the lithosphere under the assumption of isostatic equilibrium, which can be interpreted as a result of past processes due to which the lithosphere acquired its actual architecture (Lachenbruch & Morgan 1990). Here, we explore the links between subcrustal mass distribution and surface expression in the topography and geomorphology of the southern Indian shield, south of 16° N, and its extension into the adjoining oceans (Fig. 1). Previous work on the isostatic state of southern Indian shield has speculated that the region is overcompensated, that is, the mean elevation of the region is less than predicted by Airy’s model (Mishra et al. 2004). Solution to this enigma has been put forward by postulating the decrease in the crust–mantle density contrast exerting reduced buoyancy and counteracting the orogen’s isostatic response to
2-D lithospheric density modelling

Figure 1. General geology and tectonic map of the southern Indian shield with the location of the three 2-D profiles P1, P2 and P3 (modified after GSI 1998). Amphibolite facies to granulite facies transition takes place from north to south across the orthopyroxene isograd, popularly known as Fermor line (FL) in southern India. CB, Cuddapah Basin; CSZ, Chitradurga shear zone; EDC, eastern Dharwar Craton; EGMB, Eastern Ghats Mobile Belt; NB, northern block of Southern Granulite Terrane; PCSZ, Palghat–Cauvery shear zone; SB, southern block of Southern Granulite Terrane (referred to as the southern block only in the text); WDC, western Dharwar Craton. [1] Phanerozoic sediments; [2] Deccan Traps; [3] Proterozoic sediments; [4] Granites; [5] Schist belts; [6] Alkaline rocks; [7] Charnockites and khondalites; [8] Granite gneiss. Bangalore dyke swarm (shown by thin black line) is taken from Halls et al. (2007). Pink stars, at the northern end of the profile P1, show the distribution of kimberlitic pipes in the region.

Denudation (Kumar et al. 2011). However, a single cause such as the reduced buoyancy may not be valid for the entire southern Indian shield. Rather, the mechanism of isostatic compensation must involve lateral variations in density in both the crust and upper mantle (Kumar et al. 2011). Lithospheric structure of the southern Indian shield is thus essential for understanding the orogenic processes that mediated crustal evolution and sustained their topography through buoyancy forces.

A large diversity of geological and geophysical methods has been used to study the lithosphere of the southern Indian shield such as the seismic tomography (e.g. Srinagesh & Rai 1996), receiver function analysis (e.g. Kumar et al. 2007; Ramesh et al. 2010), seismology (Mitra et al. 2006), magnetotellurics (e.g. Naganjanyulu & Santosh 2012), geothermics (e.g. Pandey & Agrawal 1999; Agrawal & Pandey 2004), mantle xenoliths (Griffith et al. 2009) and a combination of heat flow, shear wave velocity and mantle xenoliths (e.g. Priestley & McKenzie 2006). Results of these studies are often not complementary owing to large differences in resolution and remain elusive.

To image the lithosphere beneath the southern Indian shield, we used an integrated density modelling, based on the combined interpretation of gravity and geoid anomalies and topography and geothermal data (Zeyen & Fernández 1994; Zeyen et al. 2005). Density anomalies can be related to compositional changes in rock materials, as commonly observed between upper and lower crustal rocks and between crustal and mantle rocks, but also due to temperature-dependent parameters that may reflect variations in lithospheric thickness. A combined use of gravity and geoid anomalies can assist in distinguishing mass inhomogeneities occurring within the mantle from those that are confined to the crust because the effect on gravity of a given density variation decays with the square of distance and therefore rapidly with depth. Meanwhile the depth dependence of geoid anomalies is proportional to the inverse of distance, which makes geoid anomalies comparatively more sensitive to deep-seated lithospheric heterogeneities (Turcotte & Schubert 1982).

In this paper, we present 2-D lithospheric models along three profiles (one N–S and two E–W trending) crossing the southern Indian shield and adjoining Indian Ocean. The model is based on the assumption of local isostatic equilibrium and constrained by the topography, heat flow data and by gravity and geoid anomalies. Where available, seismic data on crustal thickness provide further...
constraints. The models so derived along the three profiles are collated with the available lithospheric structures in Section 8 to study its consequences in terms of the geodynamic evolution.

2 GEOLOGICAL SETTING

The southern Indian shield is a collage of cratons and intervening mobile belts assembled between mid-Archaean and Neoproterozoic time (Naqvi & Rogers 1987), and carved into a peninsula by south-tapering passive continental margins (Fig. 1). It has mostly been dominated by the granite–gneiss terrain of Dharwar Craton towards the north, high-grade metamorphic (granulite facies) rocks of Southern Granulite Terrane towards the south and charnockites and khondalites of the Eastern Ghats Mobile Belt towards the northeast. The northwestern margin is overlain by Deccan flood basalts and Phanerozoic sediments cover the continental margins. Based on the lithotectonic differences, the Dharwar Craton is subdivided into the western Dharwar Craton and the eastern Dharwar Craton separated by the Chitradurga shear zone. Similarly, Palghat–Cauvery shear zone divides the Southern Granulite Terrane into the northern and southern blocks of Southern Granulite Terrane (Fig. 1; Ramakrishnan 1993). Hereafter, the southern block of Southern Granulite Terrane is referred to as the southern block only.

Initially, the southern Indian shield was described as a Precambrian exhumed deep crust of the Dharwar Craton. Increase in regional metamorphism from north to south was attributed to northward tilt and effects of differential erosion (Pichamuthu 1960). Recent investigations, however, show that the southern Indian shield is an orogenic domain of amalgamated terrains (e.g. Meert et al. 2010). A sequence of collision tectonics from Pacific to Himalayan type is now a widely accepted proposal for the evolution of the southern Indian shield (e.g. Chadwick et al. 2000; Santosh et al. 2009). More recently, a ‘complete’ orogeny cycle of plate convergence and thickening of the passive continental crust, lower crustal decoupling forced by negative buoyancy, rapid exhumation of high temperature and pressure rocks, and possible tectonic collapse has been proposed for the Southern Granulite Terrane (Singh et al. 2011). Signatures of repeated thermal perturbations (e.g. Ghosh et al. 2004), remobilization of lithospheric mantle (e.g. Pandey & Agrawal 1999), subcrustal metasomatism (Griffin et al. 2009; Mall et al. 2012), and despite long-term denudation the striking geomorphic youthfulness (Radhakrishna 1969) indicate a complex crust–mantle interaction beneath the region. Probably, a combination of tectonic processes shaped the lithospheric root vis-a-vis the surface topography of the southern Indian shield.

3 PREVIOUS GEOPHYSICAL STUDIES

Lithospheric thickness generally decreases with age from >200 km beneath Archaean cratons to intermediate values of 200 ± 50 km in early Proterozoic lithosphere, to about 140 ± 50 km in middle and late Proterozoic cratons (Artemieva & Mooney 2001). Geophysical investigations carried out to delineate the lithospheric evolution of the southern Indian shield reveal comparable thicknesses varying from 80 to 250 km. Lithospheric thicknesses from terrestrial heat flow data beneath the Archaean Dharwar Craton and the early Proterozoic Southern Granulite Terrane are given at 148 and 128 km, respectively (Pandey & Agrawal 1999). Maximum thermal lithospheric thickness of ~186 km (Negi et al. 1986, 1987) to more than 200 km (Gupta et al. 1991) indicates the existence of deep continental lithospheric root beneath the Dharwar Craton. Magnetotelluric studies conducted in the Dharwar Craton show a two-layered lithospheric mantle structure with an upper very resistive layer (>1000 ohm-m) underlain by a relatively low-resistive (<500 ohm-m) layer. Using this typical conductive feature, a lithospheric thickness in the range of ~80–120 km was proposed in the Dharwar Craton (Gokarn et al. 2004; Patro & Sarma 2009). In contrast, a thickness of more than 200 km is identified by a recent magnetotelluric study for the lithosphere beneath the central part of the Dharwar Craton (Naganjaneyulu & Santosh 2012). Based on seismic tomography studies, a lithospheric thickness of ~250 km is estimated for the Dharwar Craton (Srinagakesh et al. 1989). Other surface wave tomography studies gave an average lithospheric thickness of ~100 km in the Dharwar Craton (Polet & Anderson 1995) or ~155 km in the Indian shield (Mitra et al. 2006). Faster arrivals of teleseismic P and S waves made Gupta et al. (2003) propose a lithospheric thickness of 200 km for the eastern Dharwar Craton and ~260 km for the western Dharwar Craton. However, another set of seismic tomography estimates of ~120 km beneath the Southern Granulite Terrane and ~165 km beneath the eastern Dharwar Craton (Jagadeesh & Rai 2008) is comparable to the thermal lithosphere in the region. A shear wave receiver function study of India and adjoining regions reveals that the lithosphere could be 80–100 km in the Dharwar Craton (Kumar et al. 2007). Using joint inversion of P- and S-wave receiver functions, Kiselev et al. (2008) argued that there is no high-velocity lithospheric root at all beneath the Dharwar Craton. In a more recent shear wave receiver function study, the lithospheric thickness in the depth range of 150–210 km was identified in the eastern Dharwar Craton (Ramesh et al. 2010). Geochemical data from kimberlite xenoliths attribute a lithospheric thickness of 160–200 km for Dharwar Craton (Ganguly & Bhattacharya 1987; Griffin et al. 2009). Integrated studies based on temperature data constrained by pressure–temperature estimates from xenoliths lead to a lithospheric thickness of 200–250 km (Artemieva 2006), and 160 km when adding also S-wave velocity data (Priestley & McKenzie 2006). A large variation in estimated lithosphere–asthenosphere boundary (LAB) implies that within the southern Indian shield variations in composition and lithospheric thickness exist, and their determination is not yet conclusive partly due to the use of non-unique single-method data inversion.

4 METHODOLOGY OF INTEGRATED DENSITY MODELLING

To delineate the lithospheric structure of the southern Indian shield, we used the finite element algorithm of Zeyen & Fernández (1994), which determines the 2-D density structure of the lithosphere. The modelling algorithm uses the fact that gravity, geoid and topography (calculated in local isostatic equilibrium) all depend on the density distribution but with different depth dependence (Zeyen et al. 2005) and density, especially in the mantle, depends on temperature. The algorithm is based on a trial-and-error approach. The user defines a model consisting of different crustal layers and the lithospheric mantle with given thermal parameters and densities for each layer. For this model, synthetic observables are calculated (gravity, geoid, topography and surface heat flow) and compared with the measured ones. Then, the model is modified in terms of structure and physical properties to find a better-fitting lithospheric structure until a satisfying fit is found. For a given lithospheric model, the programme solves in a first step the 2-D steady-state heat transport equation assuming no heat loss across the lateral boundaries and fixed temperatures at the top and bottom of the model of 5 and

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1300 °C, respectively. Heat production and thermal conductivities are taken constant in each user-defined body (mainly sediments, upper, middle and lower crust and mantle lithosphere). A similar approach was used, for example, by Fernández et al. (2004) and Jiménez-Munt et al. (2008). Based on the temperature distribution obtained in this way temperature-dependent density of the lithospheric mantle (ρm) is calculated according to

$$\rho_m = \rho_a [1 + \alpha (T_a - T(z))]$$

where ρa is the density of the asthenosphere (taken as 3200 kg m$$^{-3}$$), α is the thermal expansion coefficient (3.5 × 10$$^{-5}$$ K$$^{-1}$$), T(z) is the variation of temperature with depth in the lithosphere and T_a is the reference temperature taken as 1300 °C at the LAB (Zeyen et al. 2005).

The Bouguer gravity anomaly is calculated using Talwani’s 2-D algorithm (Talwani et al. 1959) at each triangular element of the finite element mesh allowing for density variations depending on the pressure, temperature and lithology. The geoid anomaly ΔN is calculated using an algorithm based on the resolution of the gravity potential for a rectangular prism with vertical density gradient, each body being subdivided into vertical columns that extend to infinity in a direction perpendicular to the strike of the lithospheric section (Zeyen et al. 2005).

Topography is calculated under the assumption of local isostatic equilibrium with the compensation depth at the deepest point of the lithosphere within the model space. The assumption of local isostasy is believed to be valid for variations in crustal thickness occurring over horizontal distance larger than ~150 km (Kumar et al. 2011 and references therein). The obtained topography variations are calibrated with respect to average mid-oceanic ridge bathymetry, resulting in the following formula applied to each column of the model (Lachenbruch & Morgan 1990):

$$H = \left[\frac{(\rho_a - \rho_l)}{\rho_a}\right] L + h_0,$$

where H is the topography (in metre), ρa is the asthenospheric density (3200 kg m$$^{-3}$$), ρ_l is the average lithospheric density (kg m$$^{-3}$$), L is the thickness of the lithosphere (in metres) and h_0 is the calibration constant (~2400 m) that allowed us to calculate the absolute topography. If the resulting topography has a negative value, it is supposed that the corresponding basin is filled with sea water, so that the bathymetry is increased as

$$H_{-} = H \left[\frac{\rho_a}{(\rho_a - \rho_{\text{fill}})}\right],$$

where ρ_{fill} is the density of the basin infill, here the one of sea water (1030 kg m$$^{-3}$$).

5 THE DATA

5.1 Topography/bathymetry

The topography (Fig. 2) is taken from the global data set ETOPO1 (ftp://topex.ucsd.edu/pub) with values at 1-min grid spacing (Sandwell & Smith 1997). A considerable part of the continental area is covered with mountains and high plateaus. The most prominent topographic feature of the region is the Western Ghats having high hills. Palghat gap, with an average width of 13 km and an elevation of about 70 m, is the major breach within the Western Ghats that connects the west coast of the peninsular region with the east coast. The high hill ranges of Western Ghats merge with Mysore plateau towards the north and low-level landform of Tamil Nadu plains towards the east. The adjoining Indian Ocean and Arabian

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Figure 2. Topography map (in meters) of the southern Indian shield taken from ETOPO1 (Sandwell & Smith 1997; ftp://topex.ucsd.edu/pub) with the location of our 2-D profiles (P1, P2 and P3), three seismic lines: I—Behera (2011); II—Reddy et al. (2003) and III—Kaila et al. (1979) and Palghat–Cauvery shear zone (PCSZ). PG, Palghat gap; MP, Mysore plateau; TN, Tamil Nadu plain.
Sea are characterized by a broad continental margin and Chagos–Laccadive Ridge: a long linear trail of Reunion plume. In contrast, the eastern continental margin is sharp and includes Sri Lanka as an integral part of the Indian subcontinent.

5.2 Free-air anomaly

The free-air gravity anomaly over the southern Indian shield and adjoining oceanic regions (Fig. 3), taken from ‘1-min’ TOPEX global data sets (ftp://topex.ucsd.edu/pub), shows large variation ranging from less than −50 mGal along the west coast to more than +100 mGal over the high hills. Evidently, a departure from zero free-air value is representative of short-wavelength topography and/or subsurface density distribution. A chain of isolated gravity highs over Chagos–Laccadive Ridge in the Arabian Sea is attributed to subsurface density distribution due to the Reunion plume path. Except a significant characteristic free-air anomaly along the eastern continental margin of India and Sri Lanka the Bay of Bengal otherwise exhibits no prominent gravity anomalies in our study region.

5.3 Complete Bouguer anomaly

Complete Bouguer anomaly map of the southern Indian shield is based on more than 14 000 terrestrial data linked to the International Gravity Standardization Net (IGSN) 71 gravity datum and processed following the Geodetic Reference System (GRS) 80 based international gravity formula (GMSI 2006). The density used for the Bouguer reduction was 2670 kg m⁻³ and terrain correction was achieved by approximating topographic masses with polyhedrons within a radius of 167 km using the Shuttle Radar Topographic Mission (SRTM) 90M Digital Elevation Model. Complete Bouguer anomaly of Sri Lanka, processed on similar lines, is taken from the Gravity Map of Sri Lanka published on 1:1,000,000 scale (GMSL 1975). The composite gravity anomaly map is predominately negative mostly associated with the crustal roots of Western Ghats in peninsular India and Highland area of Sri Lanka (Fig. 4). The relative positive Bouguer anomalies associated with the Palghat gap and Tamil Nadu coastal plains are a consequence of the thinner crustal root and/or lateral density heterogeneity.

5.4 Geoid

The Geoid height of the southern Indian shield, south of 16° N (Fig. 5a), is taken from the EGM2008 global model (http://www. agu.org/pubs/crossref/2012/2011JB008916.shtml) (Pavlis et al. 2012). The values of the geoid anomaly vary from −82 m over Dharwar Craton to −98 m over the Southern Granulite Terrane with a steep gradient between the two domains. A geoid height comparable to Southern Granulite Terrane is located over Sri Lanka and decreases further to −106 m over the adjoining Indian Ocean. To avoid effects of sublithospheric density variations on the geoid, we have removed the geoid signature corresponding to the spherical harmonics developed until degree and order 8 (Bowin 1991; Lemoine et al. 1997). The filtered geoid anomaly (Fig. 5b) shows a relative geoid high over the Dharwar Craton, Sri Lanka and Chagos–Laccadive Ridge, and relative geoid low over the Southern Granulite Terrane and adjoining Bay of Bengal and Indian Ocean.

5.5 Thermal data

The terrestrial heat flow data over the southern Indian shield (Fig. 6) comes from several sources (Gupta et al. 1991; Roy & Rao 2000;
Ray et al. 2003; Roy et al. 2003, 2007, 2008). The offshore data were compiled from the global data source (Pollack et al. 1993). The Archaean Dharwar Craton is characterized by low heat flow values generally ranging from 25 to 50 mW m$^{-2}$. The mean heat flow in the northern block of Southern Granulite Terrane is 36 mW m$^{-2}$, whereas in the southern block it is 47 mW m$^{-2}$ (Ray et al. 2003) with a single higher value of 58 mW m$^{-2}$ in its southwestern corner (Roy et al. 2007). Though the variation in heat flow values in the southern Indian shield can be mostly explained on the basis of radioactive heat production of the crustal rocks; a distinctly higher mantle heat flow in the Southern Granulite Terrane (23–32 mW m$^{-2}$) than in the Dharwar Craton (11–16 mW m$^{-2}$) has been modelled and appears to be a consequence of higher heat production in the subjacent mantle (Ray et al. 2003).

### 6 CONSTRUCTION OF LITHOSPHERIC CROSS-SECTIONS

The structural domains of southern Indian shield were mainly created under the effect of E–W or N–S convergences, most of the structural grains are approximately perpendicular to these directions (Chadwick et al. 2000; Meert et al. 2010). To avoid as much as possible effects of 3-D structures in our 2-D modelling, we chose three profiles criss-crossing the southern Indian shield mostly perpendicular to its structural grains (Fig. 1). The N–S profile (P1) starts at 5°N latitude in the Indian Ocean, follows more or less the N–S trending seismic lines I & II across the Southern Granulite Terrane–Dharwar Craton boundary (Reddy et al. 2003; Behera 2011), and ends at 15°N latitude after crossing the E–W trending seismic line III (Kaila et al. 1979) in the Dharwar Craton (Figs 2–6). One of the two E–W profiles (P2) crosses the Southern Granulite Terrane at about 9.5°N latitude and the other E–W profile (P3) at 13.5°N is close to the seismic line III that crosses the western Dharwar Craton, the eastern Dharwar Craton and the Eastern Ghats Mobile Belt (Kaila et al. 1979). Although our area of interest was the southern Indian shield, we extended the profiles about 300 km into the adjoining oceans to avoid edge effects of deep lithospheric density variations. To avoid interpreting isolated anomaly features on the profile the gravity, and geoid anomaly and elevation data along the three profiles are projected from a 100-km wide strip extending equally on both sides of the profile and calculated the variance within this stripe for 5 km long steps along the profiles shown in Figs 7–10 as uncertainty bars. Since the heat flow data are sparse we take a 200-km wide strip with 100 km on each side of the profile. The modelling approach searches a good fit to gravity, geoid, topography and thermal data along the 1100 km long profiles within the uncertainties defined in this way.

The top and bottom of our lithospheric model correspond to the Earth’s surface and the LAB, respectively. The lithospheric section is divided into a number of bodies with different material properties: density and its pressure and temperature dependency, thermal conductivity and radiogenic heat production. To start with the geometry of different crustal layers of three neighbouring seismic profiles I, II and III (Kaila et al. 1979; Reddy et al. 2003; Behera 2011) together with the results of gravimetry (Singh et al. 2004, 2006; Kumar et al. 2009), was projected on our profiles P1, P2 and P3. Thickness of the thermal lithosphere (Negi et al. 1986, 1987; Gupta et al. 1991; Pandey & Agrawal 1999; Agrawal & Pandey 2004) and seismological lithosphere (Manglik 2002; Kumar et al. 2007; Jagadeesh & Rai 2008), where they exist with linear interpolation in between, was similarly included to construct the geometry of the LAB. Crustal densities have been calculated at some sites along the profiles from the available seismic velocities using the velocity–density relations.
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Figure 5. (a) The geoid height (in metres) of the southern Indian shield, south of 16°N, is taken from the EGM2008 global model (http://www.agu.org/pubs/crossref/2011JB008916.shtml, Pavlis et al. 2012). (b) Geoid undulations with spherical harmonics up to degree and order 8 removed. Also shown are the location of our 2-D profiles (P1, P2 and P3) and three seismic lines: I—Behera (2011); II—Reddy et al. (2003) and III—Kaila et al. (1979).

7 LITHOSPHERIC DENSITY STRUCTURE

As already discussed, the relatively abundant available seismic data allowed us to reasonably fix the initial crustal structure and physical properties along the three profiles. Further changes in the crustal thickness and densities were restricted to the minimum possible. Consequently, we changed the depth of lithosphere to fit the measured elevation, and gravity and geoid anomalies. The three (one N–S and two E–W trending) profiles thus modelled provide lithospheric density structure beneath the southern Indian shield, up to 16°N. Since the lateral resolution of our data is of the order of several kilometres small-scale details could not be resolved. Based on multiple tests, we estimate the uncertainty of the Moho and LAB depth to about 10–15 per cent.

7.1 Structure along profile P1

Along profile P1 we deduced a crustal thickness in the Indian Ocean of ∼20 km, which increases to ∼25 km in the continental shelf region and attains a depth of ∼35 km beneath the Kanyakumari at the continent–ocean boundary (Fig. 8). The more or less flat Moho at ∼40 km depth beneath the Southern Granulite Terrane sinks to 42 km along the Palghat–Cauvery shear zone and rises northwards with gentle slope to ∼41 km in the northern block of Southern Granulite Terrane and the Dharwar Craton except an upwarp to a depth of 38 km in a window of about 100 km near Bangalore (between 850 and 950 km on the profile). The 22-km thick oceanic crust is found in the adjoining regions (Sreejith et al. 2008) and is not anomalous if one assumes the Indian Ocean to be isostatically compensated on a local scale (Kumar et al. 2009). Our average crustal model further locates an anomalously dense upper crustal body (No. 7 in Fig. 8) along the Palghat–Cauvery shear zone that divides the southern and the northern blocks of Southern Granulite Terrane.
A step-like variation of the depth of LAB along this profile is the most remarkable feature of our model. On average, it lies at a depth of about 90 km underneath the Indian Ocean, increases gradually to about 135 km under the southern block and subsequently to about 185 km beneath the northern block of Southern Granulite Terraene and the Dharwar Craton. However, it thins abruptly to 145 km near Bangalore (profile km 850–975 in Fig. 8) in the Dharwar Craton, over a region of about 125 km width. Intuitively, LAB at 130 and 145 km in continental regions implies hotter lithospheric mantle beneath the southern block and near Bangalore in the Dharwar Craton, respectively. A thinned lithosphere in the southern block is in agreement with the thermal lithosphere inferred by the heat flow (Pandey & Agrawal 1999) and seismic lithosphere delineated by the tomography studies (Jagadeesh & Rai 2008).

7.2 Structure along profile P2

Along profile P2 the ocean–continental boundaries are dominated by the so-called ‘edge effect’ anomaly though weak in nature along the west coast (Fig. 9). Following the modelling results, this anomaly appears to be related to the transitional crust varying from 18 to 24 km in the Arabian Sea. Seismic studies in the offshore regions show that the Moho lies at a depth of 18–19 km, which is deeper than for normal oceanic crust (Naini & Talwani 1982). A thicker oceanic crust beneath the Chagos–Laccadive Ridge indicates the possible presence of quasi-continental and/or underplated material at the base of the crust (Arora et al. 2012). The asthenosphere below the Arabian Sea is placed at a depth of ~70 km, commensurate with the age of the seafloor in this area. Gravity as well as shear velocity structure delineated LAB, in general, varying from 70–120 km along the western continental margin of India (Manglik 2002; Radhakrishna et al. 2002; Arora et al. 2012) indicating a quasi-continental lithosphere for this region. On the continent, the profile crosses the southern block, where ~38 km thick crust is associated with an asthenospheric shallowing to a depth of ~130 km. The crossover point of profiles P1 and P2 provides evidence of relatively thin lithosphere in the southern block. Extension of ~30 km thick continental crust and ~130 km thick lithosphere towards the east signifies a considerably stretched lithospheric structure beneath Sri Lanka. Along the eastern continental margin of Sri Lanka, the Moho depth changes from ~22 km of transitional crust to ~14 km of normal oceanic crust in the Bay of Bengal where lithosphere lies at a depth of ~85 km. Our crustal and lithospheric depths conform well to recent surface wave dispersion estimates of 17 and 85 km, respectively, in this region (Mitra et al. 2011).

7.3 Structure along profile P3

Our 2-D integrated modelling along profile P3 reveals ~20 km thick crust across the Arabian Sea, which sinks from 21 to 34 km in continent–ocean transition zone, west of the Dharwar Craton (Fig. 10). As expected, the reduced ‘edge effect’ anomaly and associated thicker than normal crust along the west coast signifies a transitional crustal thickness of 38–42 km under the western Dharwar Craton, reducing to 36–38 km beneath the eastern Dharwar Craton (Kaila et al. 1979). Lithospheric thickness along the profile is 155–170 km beneath the Dharwar Craton that thins towards the oceans to less than 70 km in the Arabian Sea and 100 km in the Bay of...
Figure 7. Initial lithospheric model and observed and calculated response along south to north profile P1 at 77.5° E. In Figs 7(a–d), continuous lines correspond to calculated response of the initial model and dots with uncertainty bars correspond to measured data. Discrepancy between the observed data and calculated response indicates departure of our assumed lithospheric model from the most optimum model. In Fig. 7(b), blue line and symbols corresponds to free-air gravity anomalies, green ones to Bouguer anomalies. The lithospheric model is presented in Fig. 7(e) with available thermal lithosphere: * with error bar (Negi et al. 1986, 1987; Pandey & Agrawal 1999; Agrawal & Pandey 2004), seismological lithosphere: blue dashed line (Manglik 2002), green dashed line (Jagadeesh & Rai 2008), red dashed line (Kumar et al. 2007) and initially assumed LAB: black dashed line. Crustal bodies are shaded in grey. In the mantle, temperature distribution is plotted at every 200 °C with 1300 °C isotherm corresponding to the LAB. Fig. 7(f) shows a blow-up of the crustal structure of our initial model with Roman numbers and related dashed lines showing the available Moho depths from different seismic models: I—Behera (2011), II—Reddy et al. (2003) and III—Kaila et al. (1979). The numbering of the bodies corresponds to the numbers in Table 1. Extent of NB: northern block and SB: southern block of the Southern Granulite Terrane are given on the top of the graphic. Crossing points with other profiles (P2 and P3) and PCSZ: Palghat–Cauvery shear zone are indicated with straight vertical dashed and solid lines, respectively. For abbreviations see Fig. 1.

Bengal. Recent surface wave dispersion study of Bay of Bengal delineated similar crustal and lithospheric depths of 20 km and over 100 km, respectively (Mitra et al. 2011). Our lithospheric model in Dharwar Craton is also quite close to seismological and chemical tomography results where a lithosphere of 155–210 km was suggested (Ganguly & Bhattacharya 1987; Gupta et al. 2003; Griffin et al. 2009; Ramesh et al. 2010). Similar to the N–S profile (P1), the most significant feature of this profile is a 250-km wide lithospheric upwarp to a depth of ~140 km necessary to account for the gravity, geoid and topography near Bangalore (between km 550 and 800 on the profile). It is located quite accurately in a region of dyke swarms (Fig. 1), suggesting that the modelling procedure is robust to independent data.

8 DISCUSSION

In our models, the base of the lithosphere lies at a depth of about 70 km in the Arabian Sea, about 90 km underneath the Indian Ocean and 85–100 km in the Bay of Bengal. It increases gradually to ~130–135 km under the southern block including Sri Lanka and subsequently to ~170–180 km beneath the northern block of Southern Granulite Terrane and Dharwar Craton (Figs 8–10). This step-like LAB structure indicates a near normal lithospheric thickness beneath the adjoining oceans, the northern block of Southern Granulite Terrane and the Dharwar Craton. Considering the age, an unusually thin lithosphere beneath the southern block including Sri Lanka is, however, atypical.

8.1 Oceanic regions

The LAB in the Arabian Sea (profiles P2 and P3) varies from a depth of ~70 km in the west beneath oceanic crust to ~130 km at the continent–ocean boundary. Under the Chagos–Laccadive Ridge, the depth to the LAB is similar to the depth below the oceanic region (~65 km). It is to be noted that the free-air low over the Chagos–Laccadive Ridge could also be explained by a combination of a gentler rise of the LAB along with a local decrease in density. We keep to the former alternative, as we have no constraints to define this possible low-density zone. In the transitional zone, the LAB depth increases sharply over the continental margin along profile P3 whereas along profile P2, this depth change occurs near 200 km offshore indicating a wide quasi-continental lithosphere for this region. The LAB in the Indian Ocean (profile P1) also increases gently from 90 km in the oceanic region to 130 km at the continent–ocean boundary. This considerable stretching of the southwestern continental margin of India resulted perhaps due to the separation of
Figure 8. Modelling results of south to north profile P1 along 77.5°E derived by modifying the initial lithospheric model (Fig. 7e) little by little keeping our model as near as possible to the constraints used and minimizes the discrepancies. The derived lithospheric model is presented in Fig. 8(e). For further explanations, see Fig. 7. Solid circles at crossover points show the position of equivalent body boundaries on the intersecting sections.

Figure 9. Modelling results of west to east profile P2 along 9.5°N. Extent of CLR: Chagos–Laccadive Ridge and SGT: Southern Granulite Terrane are given on the top of the graphic. For further explanations, see Fig. 7. Solid circles at crossover points show the position of equivalent body boundaries on the intersecting sections.
Figure 10. Modelling results of west to east profile P3 along 13.5°E. Extent of CLR: Chagos–Laccadive Ridge; EDC: eastern Dharwar Craton and WDC: western Dharwar Craton are given on the top of the graphic. For further explanations, see Fig. 7. Solid circles at crossover points show the position of equivalent body boundaries on the intersecting sections.

Table 1. Physical parameters of the different bodies used in the modelling.

<table>
<thead>
<tr>
<th>No.</th>
<th>Description</th>
<th>HP (μW m⁻³)</th>
<th>TC (W m⁻¹ K⁻¹)</th>
<th>Density (kg m⁻³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Sediment</td>
<td>1.0</td>
<td>2.0</td>
<td>2300</td>
</tr>
<tr>
<td>2</td>
<td>Upper crust of Dharwar Craton</td>
<td>0.5</td>
<td>3.3</td>
<td>2720</td>
</tr>
<tr>
<td>3</td>
<td>Upper crust of Southern Granulite Terrane</td>
<td>0.5</td>
<td>2.5</td>
<td>2730</td>
</tr>
<tr>
<td>4</td>
<td>Oceanic upper crust</td>
<td>0.5</td>
<td>2.5</td>
<td>2740</td>
</tr>
<tr>
<td>5</td>
<td>Middle crust of Dharwar Craton</td>
<td>0.25</td>
<td>2.5</td>
<td>2780</td>
</tr>
<tr>
<td>6</td>
<td>Middle crust of Southern Granulite Terrane</td>
<td>0.20</td>
<td>2.5</td>
<td>2800</td>
</tr>
<tr>
<td>7</td>
<td>Intrusive</td>
<td>0.5</td>
<td>2.5</td>
<td>2870</td>
</tr>
<tr>
<td>8</td>
<td>Intrusive</td>
<td>0.5</td>
<td>2.5</td>
<td>2890</td>
</tr>
<tr>
<td>9</td>
<td>Lower continental crust of Dharwar Craton</td>
<td>0.16</td>
<td>2.0</td>
<td>2930</td>
</tr>
<tr>
<td>10</td>
<td>Lower continental crust of Southern Granulite Terrane</td>
<td>0.16</td>
<td>2.0</td>
<td>2930</td>
</tr>
<tr>
<td>11</td>
<td>Oceanic lower crust</td>
<td>0.2</td>
<td>2.0</td>
<td>2940</td>
</tr>
</tbody>
</table>

Nos. 1–11—number of the body in Figs 7–10; HP, heat production (μW m⁻³); TC, thermal conductivity (W m⁻¹ K⁻¹); T(z), temperature as function of depth (°C); z, depth (km). Weight average value of HP and TC are basically taken from Roy & Rao (2000), Ray et al. (2003, 2008), Kumar & Reddy (2004), Afonso et al. (2005) and Vilà et al. (2010).

India, Africa and Antarctica during the breakup of Gondwana. The sharp boundary of the eastern continental margin of India along profile P3 shows the presence of relatively low-angle normal faults which bear similarities with the conjugate East Antarctica margin and possibly could have evolved as a sheared or transform margin (Krishna et al. 2009). Regarding profile P2, the spreading history in conjugate oceanic regions of Sri Lanka and Antarctica, is still not very clear. Chari et al. (1995) have found that the region between India and Sri Lanka had experienced limited extension, which provides some evidence for the eastern continental margin of Sri Lanka to consider it as transform nature of the margin (Krishna et al. 2009).

8.2 Dharwar Craton

The lithospheric thickness of 155–185 km obtained under the Dharwar Craton is apparently lower than other Archaean cratons like Kaapvaal and Siberia but conforms well with the earlier geological and geophysical studies indicating a 160–200-km thick lithosphere (Negi et al. 1986, 1987; Srinagesh et al. 1989; Gupta...
et al. 1991, 2003; Agrawal & Pandey 2004; Artemieva 2006; Mitra et al. 2006; Kiselev et al. 2008; Ramesh et al. 2010; Naganjaneyulu & Santosh 2012). Our estimates are also consistent with the palaeolithospheric sections, which yield a 160–200-km thick lithospheric mantle inside the Dharwar Craton (Ganguly & Bhattacharya 1987; Griffin et al. 2009). According to Kiselev et al. (2008), the high S-velocity (around 4.7 km s$^{-1}$) mantle keel of the craton is present only at shallow depths (less than about 150 km), but at larger depths it is replaced by a low-velocity layer (S velocity around 4.3 km s$^{-1}$), perhaps related to a hot mantle plume. The bottom part of the keel might be lost during this thermal perturbation. Alternative explanation for the low velocity was given as anomalous composition. ‘Refertilization’ by metasomatization (Griffin et al. 2009; Mall et al. 2012) around the time of rising of the plume, iron enrichment and increase in the proportion of modal clinopyroxene and garnet on a larger scale might reduce the velocities in the uppermost mantle, beneath the Dharwar Craton. Alternatively, the uppermost mantle of the Dharwar Craton has never been depleted (Kiselev et al. 2008). LAB modelled at ~100 km in the Dharwar Craton by Kumar et al. (2007) is not seen in our model. Recently, Oreshin et al. (2011) also demonstrated that there is neither the LAB at a depth of 100 km nor the Low-Velocity Zone. The shallower receiver function LAB in the cratonic part would be, in fact, a new and thus far unknown discontinuity in the interior of the mantle lithosphere caused by sudden changes of anisotropy or other parameters (Abt et al. 2010; Yuan & Romanowicz 2010). The anomalous seismic properties of the Dharwar Craton upper mantle are otherwise indicative of a metasomatic alteration or of an elevated temperature or both (Agrawal & Pandey 2004; Oreshin et al. 2011). Simple reduction of shear velocity at ~100 km in Dharwar Craton is apparently the Hales discontinuity resolved by azimuth-dependent S velocity (Jagadeesh & Rai 2008; Kiselev et al. 2008). Similarly, variation of electrical resistivity at around 120 km (Gokarn et al. 2004; Patro & Sarma 2009) may be attributed to the compositional variation (upper mantle characterized by spinel peridotites underlain by garnet peridotites, Jagadeesh & Rai 2008). The hypothesis of lithospheric thinning to ~100 km in Dharwar Craton during the breakup of Gondwana therefore seems untenable.

The anomalously thinned lithosphere of about 145 km delineated near Bangalore in Dharwar Craton is rather exceptional but found associated with (i) 2.3-Ga-old subalkaline tholeiites dyke swarms near Bangalore (Kumar et al. 2012), (ii) volcanic lava flows and sills as old as 1.9 Ga (Anand et al. 2003) and (iii) widespread 1.1-Ga-old diamondiferous kimberlitic intrusions (Kumar et al. 1993) in an area of about 500 km$^2$. In the given situation, it might be an imprint of either a long-lived large mantle upwelling under the eastern Dharwar Craton lasting since the late Archaean (Jayananda et al. 2000) or a small Neoproterozoic asthenospheric plume similar to those observed beneath the southwestern Cuddapah Basin (Mall et al. 2008), the initial thermal input of which promoted gentle doming possibly accompanied by thinning of the subcontinent lithosphere. Assuming that there was such a temperature perturbation, it would have had plenty of time to diffuse away and it should have vanished today. Recently, Leelanandam et al. (2006) associated the occurrence of alkaline rocks and carbonatites in the nearby regions with intracontinental rifts that deformed when involved in collisions between continents. Their ages mainly fall in a range between 750 and 800 Ma, although older ages in the range from 1920 to 2000 Ma have also been reported (Kumar & Gopalan 1991; Natarajan et al. 1994). The anomalously thinned lithospheric region near Bangalore may also be inferred to indicate the location of preserved rifted margin of Dharwar Craton that deformed during the late Proterozoic. If all these geological and geophysical interpretations are correct, then our delineated LAB signifies that the Archaean to Proterozoic lithospheric root beneath the Dharwar Craton at 1.1 Ga does exist today except in an area of ~30 000 km$^2$ near Bangalore where it may have been removed during its late Proterozoic history and/or has suffered tectonocompositional effects of a rifted margin and a suture. A similar idea has been put forward by Artemieva (2003) concerning the east European platform in Russia.

8.3 Southern Granulite Terrane

The ~180 km deep LAB in the northern block of early Proterozoic Southern Granulite Terrane is quite comparable to the Archean Dharwar Craton. Its observation at a depth of ~130–135 km in the southern block including Sri Lanka considering its comparable age seems atypical and calls for a plausible explanation. Under the influence of certain tectonic environments, cratons can be destroyed and the lithospheric keels become thinner but the specific mechanism by which the deep lithospheric root of the southern block was destroyed is still under debate. Intuitively, it could be interpreted as a stretched lithosphere due to the separation of India, Africa and Antarctica during the breakup of Gondwana. However, the lithosphere is still very thick (more than 180 km) below the cratons of South Africa, Australia and Antarctica (Kumar et al. 2007). Even along the E–W profile (P3) over Dharwar Craton, a normal lithospheric thickness along the west coast of India is not favourable for this possibility. Kumar et al. (2007) infer that the plume that partitioned Gondwana may have melted the lower half of the Indian lithosphere. Although localized reworking of the lithosphere through mantle plume related magmatism might be a distant possibility; absence of an anomalously warm or thin lithosphere beneath the Deccan volcanic province (Kumar & Mohan 2005) precludes their role in thinning the lithosphere on a regional scale.

LAB beneath the southern block could also be modelled with a normal lithosphere having relatively low-density material. Such a model would however be incompatible with the surface heat flow of this area. A thermal lithospheric thickness of about 88–128 km suggests that the lithosphere is thin (Pandey & Agrawal 1999; Agrawal & Pandey 2004). Another indication for the lithosphere being very warm is the existence of shallow melting depths (Roy & Rao 2000). Besides, low pressure-temperature and high temperature charnockites and granulites are explained through some process of post-orogenic lithospheric thinning, bringing the asthenosphere into close proximity with the lower crust (Harley 1998; Kröner & Brown 2005). If so, the granulites of the southern block are the imprint of thermal perturbation due to a lithospheric remobilization which might have been the part of the pervasive 550 Ma Pan-African signatures (Bartlett et al. 1995). Its further removal in the southern block by subsequent thermal perturbations (possibly plume related that partitioned the Gondwana; Kumar et al. 2007) cannot be ruled out completely. Although, the area affected by the two events in Africa still has more than 150 km thick lithosphere (Artemieva 2009), asymmetrical rifting during the dismantling of Gondwana may have caused stronger lithospheric thinning of the Indian than the African side. Losing the bottom part of the lithosphere during the rapid drift of the Indian Plate in the Mesozoic may be another distinct possibility (Negi et al. 1986). We thus believe that the southern block including Sri Lanka has undergone multiple deformation at the lithospheric mantle level; and a combination of factors seems to have played a role: (1) massive remobilization of the southern block at 550 Ma, (2) its further removal from below by thermal perturbations comparatively younger in ages and (3) additional lithospheric stretching.
of the southwestern continental margin of India and the southern block including Sri Lanka due to the separation of India, Africa and Antarctica. Higher values of present-day mantle heat flow are produced due to an enriched mantle (Ray et al. 2003) and/or the perceived thermal perturbations that also produced the currently observed peak-and-ridge topography that is lacking in the Dharwar Craton (Radhakrishna 1969).

Our lithospheric thickness, though it ignores possible flexural effects, agrees with the pattern of the elastic thickness of the lithosphere (Te) obtained from observed topography and gravity anomaly data (Stephen et al. 2003; Tiwari & Mishra 2008). Considering that for temperatures higher than ~800 °C the strength of the lithosphere is practically zero, we can compare the thickness of the mechanical lithosphere with the depth of this isotherm. From our modelling, we find that the deepest regions of the 800 °C isotherm underneath the Dharwar Craton and the Southern Granulite Terrane are at about 90 and 60 km depth, respectively (Fig. 8). This corresponds to a Te of 35 and 13 km in the Dharwar Craton and the Southern Granulite Terrane, respectively (Tiwari & Mishra 2008). Besides, we found that the average temperature of the lithospheric mantle beneath the Dharwar Craton is less than under the southern block. A reduced Te value for a 40-km thick Proterozoic crust and sufficiently hot at Moho depth (present-day mantle heat flow is 23–32 mWm−2) further signifies a mechanically deformable lithosphere beneath the southern block (Kumar et al. 2011).

9 CONCLUSIONS

Integrated 2-D modelling of gravity and geoid anomaly and topography data, using geological, seismic and thermal information establishes a new model of the lithospheric structure of the southern Indian shield and adjoining oceanic regions. Our analysis confirms that the Archaean Dharwar Craton and the northern block of Southern Granulite Terrane preserve a thick (165–180 km) lithospheric root though it is thinner than the other undisturbed Archaean cratons like Kaapvaal and Siberia. The extensive ‘erosion’ of the LAB (~130 km deep) inferred beneath the southern block and Sri Lanka is correlated to remobilization of Mesoproterozoic Pan-African event at 550 Ma and late Cretaceous thermal perturbation that separated the India, Africa and Antarctica. A considerable lithospheric stretching of the southwestern continental margin of India including Sri Lanka resulted perhaps during this breakup of the Gondwana. Unusually thinned LAB beneath the region near Bangalore probably indicates the preserved tectono-compositional effects of late Proterozoic rifted margin of Dharwar Craton.
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