A detailed gravity picture of Nallamalai Fold Belt–Nellore Schist Belt (NSB) of Eastern Dharwar Craton with marginal Eastern Ghats Mobile Belt in Krishna Region, South India with special reference to Late Archaean NSB evolution

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The Krishna region of south India comprises Eastern Ghats Mobile Belt (EGMB), Nellore Schist Belt (NSB) of Eastern Dharwar Craton (EDC) margin and Nallamalai Fold Belt (NFB) including Cuddapah Basin (CB) from east to west. The gravity surveys are carried out across it, so as to delineate the different litho-tectonic belts and salient structural features. The gravity data is processed to generate regional, residual and derivative maps along with three 2D gravity models. Two major gravity highs over the EGMB and NSB and a wide gravity low across the NFB, along with a linear gravity low representing as Transitional Zone (TZ) between these two highs are delineated. Two curvilinear steep gravity gradients between the NFB-NSB and NSB-EGMB are differentiated as Cuddapah Eastern Margin Thrust and Eastern Ghats Boundary Thrust along with a low angle Malakondasatram Thrust in the central part. The NSB comprises Eastern (EA) and Western (WA) arms of coeval different environmental facies of foreland and back-arc setups. The EA with intense gravity high due to a high-density layer at a depth of ∼10 km is evidenced from 2D gravity model. The thickness of high-density layer (EA) gradually decreases towards westerly and wedges out below the WA suggesting the entire NSB as a single Late Archaean segment. The major linear gravity high of covered eastern part in Kavali–Nellore–Gudur region indicates the southern continuation of EGMB. The occurrence of thin unconformable high-grade schists in two doubly plunging structures and as tectonic lenses, including a major E–W folded erosional remnants in the low-medium grade late Archaean NSB domain are found as eastern continuation of Mesoproterozoic upper Cuddapah extensions at the EGMB front. These erosional remnants are reflected as isolated residual gravity lows in the west and as residual highs in overall EA of NSB in the east. The isolated relative highs and lows within the major low zone of NFB are linked to differential basement configuration due to superposed effects with the N–S non-cylindrical fold.

Keywords. Eastern Dharwar Craton; Nellore Schist Belt; Mesoproterozoic cover sediments/schist; Nallamalai Fold Belt; Eastern Ghats Mobile Belt; gravity low and high zones.

1. Introduction

The Krishna region of south India comprising Late Archaean Nellore Schist Belt (NSB) of Eastern Dharwar Craton (EDC) is bound by Proterozoic Cuddapah sediments in the west and accreted Paleo-Mesoproterozoic Eastern Ghats Mobile Belt (EGMB) towards its east (figure 1). The northern extension of NSB is known as Khammam schist belt, where the Mesoproterozoic Pakhal sequence of Pranhita–Godavari (PG) basin occurs in its northwestern part (Ramakrishna and Vaidyanathan 2008). The eastern Cuddapah (Nagarajarao *et al.* 1987; Saha 2002) and southern Pakhal sequences (Ghosh and Saha 2003; Burhanuddin 2017) are considered to be deformed-metamorphosed as a result of Mesoproterozoic Grenvillian Eastern Ghats orogeny (Mezer and Cosca 1999) due to amalgamation of India–East Antarctica collision during the Rodinia Supercontinental assembly (Dasgupta and Sengupta 2003; Vijaya Kumar and Leelanandam 2008; Mishra and Ravi Kumar 2014). The deformed eastern Cuddapah sequence, popularly known as Nallamalai Fold Belt (NFB) (Nagarajarao *et al.* 1987), is separated from the NSB of eastern part by the Cuddapah Eastern
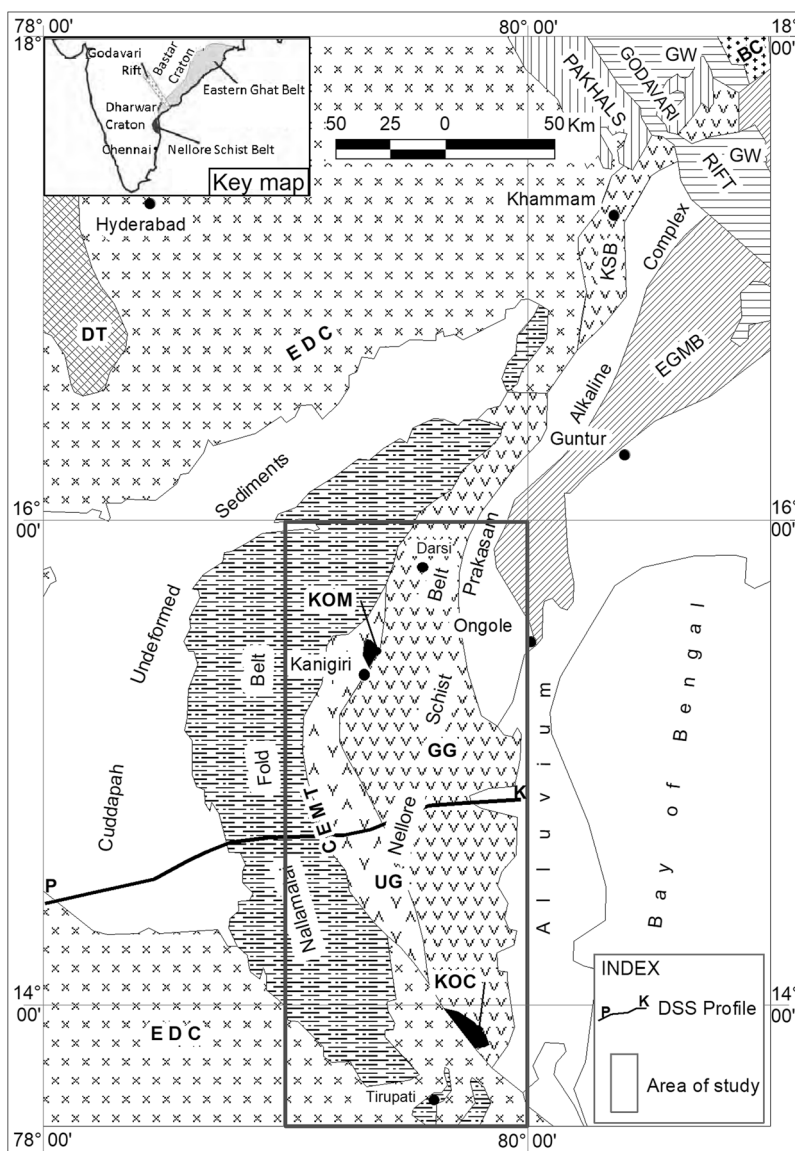
Figure 1. Geological map of the southeastern part of Indian peninsula (source: Saha *et al.* 2015; Kaila *et al.* 1987). (EDC: Eastern Dharwar Craton; BC: Bastar Craton; EGMB: Eastern Ghats Mobile Belt; NSB: Nellore Schist Belt; GG: Guduru Group; UG: Udaigiri Group; KOC: Khandra Ophiolite Complex; KOM: Kanigiri Ophiolite Melange; KSB: Khammam Schist Belt; GW: Gondwana Sediments; DT: Deccan Trap; CEMT: Cuddapah Eastern Margin Thrust).

Marginal Thrust (CEMT). The western contact of NFB is designated as Rudraram line (Kaila *et al.* 1979) and the same is differentiated as superposed Pan-African related Nallamalai thrust (Mathin 2015). A linear Transitional Zone (TZ) between the NSB-EGMB is found associating with rocks of Prakasham Alkaline Province (Leelanandam 1989) and the same is differentiated as Terrane Boundary Shear Zone (TBSZ) (Nagaraju and Chetty 2014). The EGMB is considered as an exhumed belt (Dasgupta and Sengupta 2003; Dobmier and Raith 2003; Mukhopadhyay and Basak 2009; Vijaya Kumar and Leelanandam 2008) due to amalgamation of India and East Antarctica.

The NSB occurring along the eastern margin of EDC is similar to all other Late Archaean schist belts. Still, controversy exists with regard to its age either as Late Archaean/Paleoproterozoic (Dobmeier and Raith 2003) or a part as Archaean and the other as Proterozoic (Srinivasan and Roop Kumar 1995; Saha *et al.* 2015). In recent works, the NSB is, however, differentiated as a single Late Archaean segment (Burhanuddin and Ravi Kumar 2019, 2022; Burhanuddin 2022). Based on the assumption of southern EGMB missing (Yoshida *et al.* 1992), the eastern high-grade Archaean NSB (Srinivasan and Roop Kumar 1995; Saha *et al.* 2015) is, however, classified as Paleoproterozoic Krishna Province (Dobmeier and Raith 2003). In latest works, the unconformable eastern high-grade schists and western clastic sediments are differentiated as erosional remnants of Mesoproterozoic Cuddapah extensions in an otherwise defined NSB domain (Burhanuddin and Ravi Kumar 2019). Further, the southern Khandra Ophiolite Complex (KOC) (Leelanandam 1990) and northern Kanigiri Ophiolite Melange (KOM) (Dharmarao *et al.* 2011) are found as a part of eastern Late Archaean NSB with a characteristic ocean plate stratigraphy (Saha *et al.* 2015; Burhanuddin and Ravi Kumar 2022).

The recent research developments with a considerable increase in knowledge of Late Archaean tectonic settings with regard to NSB evolution further warrant a critical analysis of sub-surface litho-package structures at upper crustal level in Krishna region, along the southeastern margin of EDC-EGMB. Accordingly, the present study is focused on detailed analysis of sub-surface litho-package structures based on the gravity signatures and their integration with regard to Late Archaean NSB evolution and to understand the EDC-EGMB boundary. Detailed gravity data covering the area of Krishna region under the National Geophysical Mapping (NGPM) Programme of Geological Survey of India is used to differentiate sub-surface litho-packages and structures based on the Bouguer anomaly, residual and regional anomaly signatures (figures 4–6). The information pertaining to deep-crustal structures from geological studies (Nagarajarao *et al.* 1987; Babu 2001; Saha 2002; Dobmeier and Raith 2003; Upadhyay 2008; Vijaya Kumar and Leelanandam 2008; Dasgupta *et al.* 2013; Mathin 2015; Saha *et al.* 2015; Hrushikesh *et al.* 2020; Burhanuddin and Ravi Kumar 2022), seismic and gravity studies (Kaila *et al.* 1979, 1987; Kaila and Tewari 1985; Krishna Brahmam 1989; Ram Babu 1993; Singh and Mishra 2002; Singh *et al.* 2004; Mishra and Ravi Kumar 2014; Chandrakala *et al.* 2017) and lineament maps by remote sensing (Venkatakrishnan and Dotiwalla 1987; Nagaraju and Chetty 2014) are judiciously used in the present study for interpretation of shallow crustal structures so as to delineate the major litho-tectonic belts and salient structural features in the Krishna region.

2. Geological background

The Proterozoic eastern Cuddapah and southern Pakhal sediments of CB and PG basins comprising passive margin sequences and show the effects of contractional deformation and metamorphism at the EGMB front (Saha 2002; Ghosh and Saha 2003; Burhanuddin 2017; Burhanuddin and Ravi Kumar 2019) due to Mesoproterozoic collision tectonics. The Paleo-Mesoproterozoic EGMB occurred as an exhumed belt due to the India–East Antarctica collision in response to tectono-thermal effects of 1.0 Ga Grenvillian orogeny (Mezer and Cosca 1999); which led to the Rodinia Supercontinental assembly (Dasgupta and Sengupta 2003; Vijaya Kumar and Leelanandam 2008; Mishra and Ravi Kumar 2014). In continuation of this, the Mesoproterozoic eastern Cuddapah sediments are found deformed-metamorphosed and known as NFB (Nagarajarao *et al.* 1987). Accordingly, these Mesoproterozoic passive margin deformed-metamorphosed sequences of eastern Cuddapah (Nagarajarao *et al.* 1987; Saha 2002; Burhanuddin and Ravi Kumar 2019) and southern PG basins (Burhanuddin 2017; Ghosh and Saha 2003) show the structural parallelism with the EGMB due to the Grenvillian Eastern Ghats orogeny. The major Mesoproterozoic CEMT/Veligonda Thrust
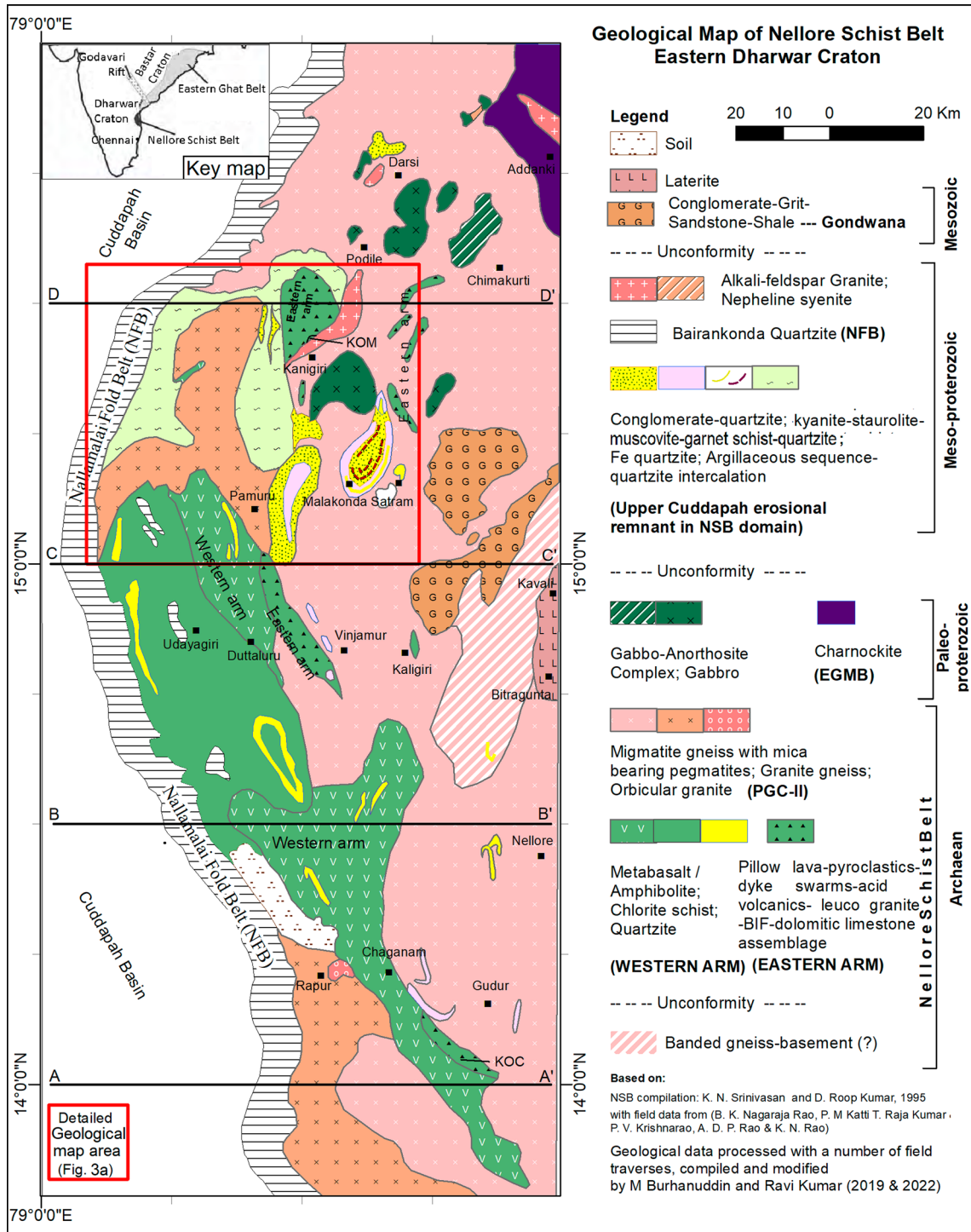
Figure 2. Geological map of Nellore Schist Belt, Eastern Dharwar Craton (source: Burhanuddin and Ravi Kumar 2022). (KOC: Khandra Ophiolite Complex, KOM: Kanigiri Ophiolite Melange).

is believed to separate the Late Archaean NSB in the east and Mesoproterozoic NFB in the west (figure 2; Venkatakrishnan and Dotiwala 1987; Nagarajarao *et al.* 1987; Saha 2002) along with Eastern Ghats Boundary Thrust (EGBT) between the NSB-EGMB (Mishra and Ravi Kumar 2014) in response to the Grenvillian Eastern Ghats orogeny

(Mathin 2015; Burhanuddin and Ravi Kumar 2019, 2022).

2.1 *Nallamalai Fold Belt*

The NFB trends in NW–SE in south, N–S in middle and swerves to NE–SW in north, which

overall parallels with the crescent-shaped CB with eastern bound Mesoproterozoic CEMT/Veligonda thrust (Venkatakrishnan and Dotiwala 1987) and western Rudraram line contacts (Kaila *et al.* 1979). Mathin (2015) has differentiated the Rudraram line as a Paleozoic Pan-African Nallamalai Thrust, where the margins of Neoproterozoic Kurnool in the south and Palnad sediments of northern part are considered to be deformed. In continuation of this, the entire NFB is differentiated as a closed elliptical outcrop of N–S major synclinorium resulting due to a major non-cylindrical fold in response to the Mesoproterozoic Eastern Ghats orogeny coinciding with D2 Grenvillian event (op. cit). A number of zones of culmination and depressions characterize its non-cylindrical character, and the same is reflected by isolated gravity low signatures within the major gravity low zone of CB (Ram Babu 1993; figure 4). A number of alkali-feldspar granite and Lamprophire intrusive plutons (Nagarajarao *et al.* 1987; Chalapathi Rao *et al.* 2016) and domal structures of major granite bodies like Vinukonda and Vellaturu within the NFB (Nagarajarao *et al.* 1987; Saha 2002) show low gravity signatures along the eastern margin of CB (Ram Babu 1993; figure 4).

2.2 *Nellore Schist Belt*

The NSB with its western arm (WA) and eastern arm (EA) of two coeval different environmental facies of foreland and back-arc (Chadwick *et al.* 2000)/continental-arc (Vijaya Kumar and Leelanandam 2008) setups in a composite basin (Burhanuddin and Mohakul 2020; Burhanuddin 2022) are found similar to all other greenstone belts of Dharwar Craton (figures 2 and 3a; Burhanuddin and Ravi Kumar 2022). The WA continues from west of Khandra to Chagnam, Rapur–Podalakur section in the south, passes through Udaigiri-west of Pamuru and Pandavu-lagandi in the north (figures 2 and 3a), and tapers towards further north. The occurrence of EA restricting to eastern part at the EGMB front continues from Khandra in the south to Duttaluru–Vinjamuru and Kanigiri–Podili area and beyond into Khammam region in the north (figures 2 and 3a). The WA with amygdular lava-quartzite/arenite-argillite assemblage is found to occur in a foreland basinal setup similar to Bababudan Group of Western Dharwar Craton (Burhanuddin and Ravi Kumar 2019;

Burhanuddin and Mohakul 2020). The EA with its pillow lava, pyroclastics, acid volcanics, thin intercalations of BIF, carbonate lenses, leuco granite, thin dyke swarms, etc., defining the ocean plate stratigraphy (Saha *et al.* 2015; Burhanuddin and Mohakul 2020; Burhanuddin and Ravi Kumar 2022) is believed to be evolved in a back-arc/continental-arc basinal setup (Vijaya Kumar and Leelanandam 2008; Saha *et al.* 2015; Burhanuddin and Mohakul 2020). These WA and EA of different environmental facies are considered to be evolved simultaneously in a composite basin (Burhanuddin and Mohakul 2020; Burhanuddin 2022) with a Late Archaean E–W convergence (Cloos 1982) and subduction-abduction mechanisms (Chadwick *et al.* 2000) in an ophiolitic setting (Krogsted *et al.* 1989; Leelanandam 1990). Due to this process, the subduction of oceanic lithosphere below the continental lithosphere is resulted (Okudaira *et al.* 2000) and the same is witnessed in 2D gravity modelling as discussed in foregoing pages.

The southern and northern extensions of EA are referred to as KOC of late Archaean (Leelanandam 1990) and as KOM (Dharma Rao *et al.* 2011; Saha *et al.* 2015), respectively. The KOC and KOM define ocean plate stratigraphy of EA as already mentioned above (figure 2). The protoliths of NSB (WA – Chagnam sample; figure 2) and (EA – Chundi sample; figure 3a) with ages of 2.7 Ga (Ravikanth 2010) suggests the NSB as a single Late Archaean segment (Burhanuddin and Ravi Kumar 2022). As such, the 1.9 Ga age for NSB is found to belong to intrusive gabbro within the KOC of EA due to Paleoproterozoic Gondwana rifting (Ravikanth 2010), and the same is viewed as an overprint metamorphic effect (Henderson *et al.* 2014) in NSB.

2.3 *Mesoproterozoic upper Cuddapah extension in NSB domain*

A structurally controlled (D1) Mesoproterozoic sequence of major E–W outcrop of Kanigiri–Pamuru area (figure 3a), associating with a number of superposed N–S D2 non-cylindrical folds including two eastern isolated N–S high-grade schists in Mopadu–Malakondasatram doubly plunging synformal structures occurring as erosional remnants within the granite–greenstone terrain of NSB (Burhanuddin and Ravi Kumar
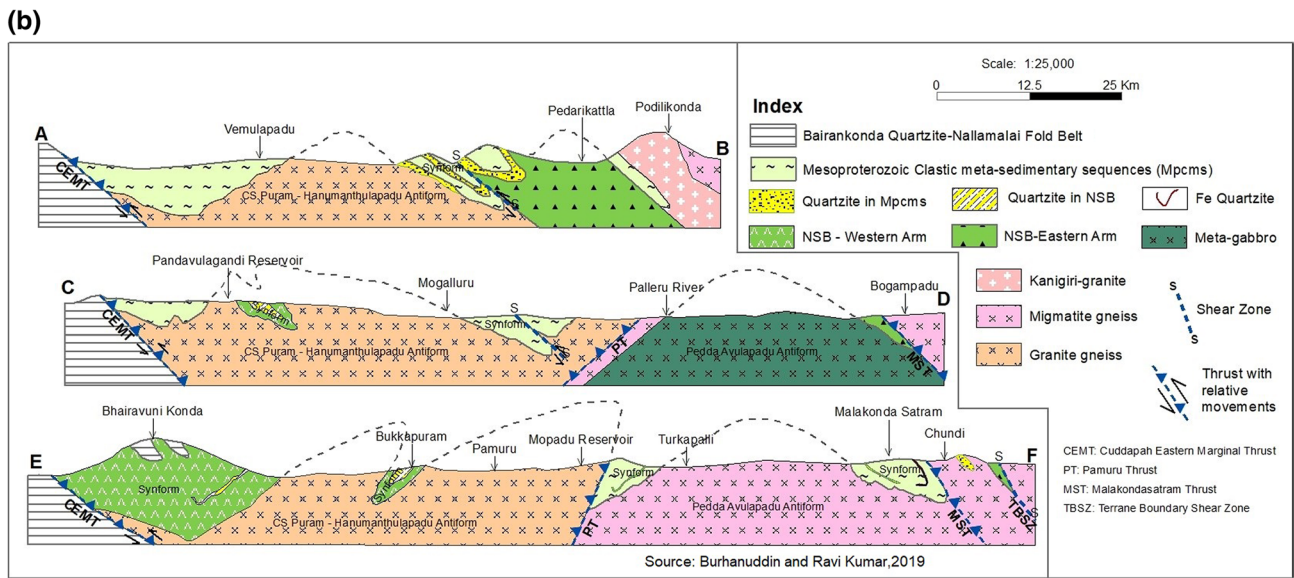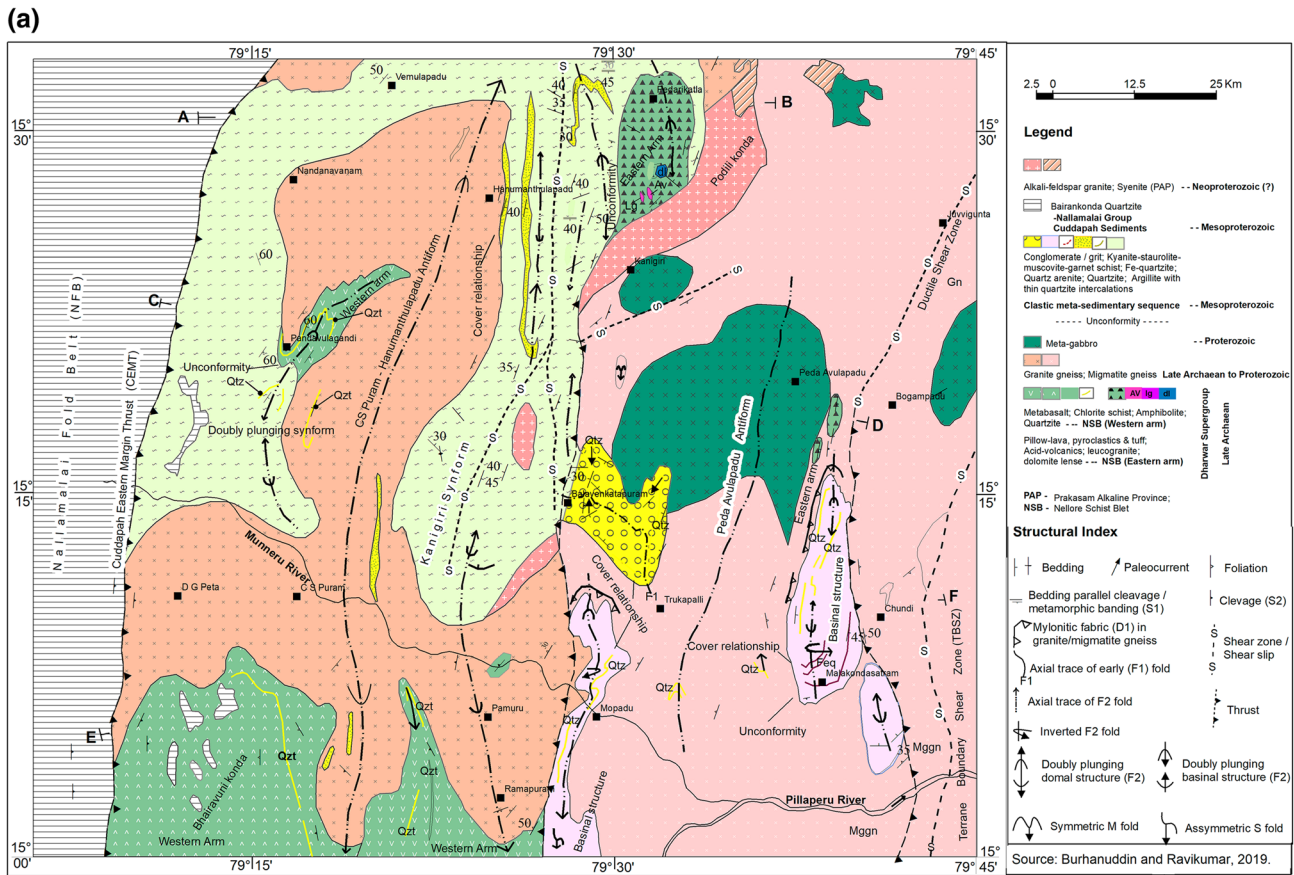
(a)

(b)

Figure 3. **(a)** Detailed geological map in central part of Nellore Schist Belt, Eastern Dharwar Craton (source: Burhanuddin and Ravi Kumar 2019). **(b)** Geological cross-sections in central part of Nellore Schist Belt, Eastern Dharwar Craton (source: Burhanuddin and Ravi Kumar 2019).

2019) are delineated as upper Cuddapah extensions. A basement-cover sediment and angular unconformable relationship with both EA and WA of NSB, along with thrust contacts in west and east (figures 2, 3a and b), are established for these sequences. The occurrence of high-grade mineral assemblages in two eastern doubly plunging structures unconformably over the low-medium grade Late Archaean NSB is, however, related to a layer and composition-specific metamorphism in

response to the tectono-thermal Mesoproterozoic Grenvillian Orogenic effects (Moeen 1998; Burhanuddin and Ravi Kumar 2022) at Eastern Ghats front in contrary to the earlier works of which, as high-grade late Archaean (Srinivasan and Roop Kumar 1995) and as Paleoproterozoic Krishna Province (Dobmeir and Raith 2003). In addition to this, the isolated high-grade schist lenses in low-medium grade NSB of eastern part of Vinjamuru–Kavali region too are considered as erosional remnants of Mesoproterozoic upper Cuddapah extensions (Burhanuddin and Ravi Kumar 2019).

2.4 *Eastern Ghats Mobile Belt*

In the evolutionary history of EGMB, two episodes of eastern EDC rifting during 1.9–1.65 Ga and 1.5–1.35 Ga (Vijaya Kumar and Leelanandam 2008), which coincides with the development of Western Charnokite Zone (Ramakrishnan *et al.* 1998) and emplacement of alkaline rocks and carbonatites (ARCs) (Leelanandam 1989; Dasgupta and Sengupta 2003; Upadhyay *et al.* 2006) respectively. The second phase of rifting is followed by 1.0 Ga contractional deformation due to Grenvillian Orogeny (Mazger and Cosca 1999), during which passive margin sequence of Cuddapah and Pakhal sequences (op. cit.) are deformed including the conversion of ARCs as deformed one, i.e., as DARCs (Vijaya Kumar and Leelanandam 2008). The EGMB comprises a western discontinuous charnockite zone along with high-grade quartzo-feldspathic gneiss, which is considered to be derived from the adjoining Peninsular Gneissic Complex-II (PGC-II) of EDC (Hrushikesh *et al.* 2020). This is followed by a thick Khondolite belt in the middle and intrusive high-grade granitoids/migmatites in the east (Ramakrishnan *et al.* 1998). The southern continuation of Addanki–Ongole EGMB domain is found missing (Yoshida *et al.* 1992).

2.5 *Transitional Zone*

The Transitional Zone (TZ) between EDC-EGMB is differentiated as TBSZ (Nagaraju and Chetty 2014), associating with mafic–ultramafic layered complexes of Chimakurthi in the south (Vijaya Kumar and Leelanandam 2008) and Chimalpahad complex in the north (Narsimha Reddy and Leelanandam 2004). In addition to this, a number of gabbro-alkali feldspar granite-syenite plutons are found associating with TZ forming as part of Prakasham Alkaline Province (PAP) and the emplacement of which coincides with the second phase of EDC rifting (Leelanandam 1989; Upadhyay *et al.* 2006; Vijaya Kumar and Leelanandam 2008). The second phase of EDC rifting is followed by contractional deformation at 1.0 Ga of Grenvillian Orogeny (Mezger and Cosca 1999), with which the passive marginal Proterozoic Pakhal (Ghosh and Saha 2003; Burhanuddin 2017) and Cuddapah sequences (Saha 2002; Burhanuddin and Ravi Kumar 2019, 2022) are considered to be deformed-metamorphosed and simultaneously conversion of ARCs as deformed DARCs (Vijaya Kumar and Leelanandam 2008) has resulted.

3. Gravity data and processing

A high-resolution gravity data of 1–2 km station interval covering the eastern part of CB-NSB-western EGMB domains is compiled and processed to generate the Bouguer anomaly map of Krishna region (figure 4), covering an area of $\sim 27,500$ km^2, which bound between latitude: $13°45'$–$16°00'$N and longitude: $79°00'$–$80°00'$E. The gravity data is gridded with 1 km interval by using minimum curvature algorithm in Geosoft software for defining the Bouguer anomalies. The residual Bouguer anomaly representing shallow sources (figure 5) is obtained by subtracting the regional field estimated from the upward continuation. To estimate the appropriate upward continuation height, the Bouguer anomaly is continued upward to a distance of 5, 10 and 15 km (figure 6a–c). In upward continuation of 15 km, most of the shorter wavelength features are removed and is further used in estimating the residual field calculation as mentioned above. These upward continuation maps are further used to image the causative source depth of gravity field based on the semi-empirical relation of upward continuation height (h) and its causative source depth ($h/2$) by Jacobsen (1987). Thus, the Bouguer anomaly continued upward maps to a height of 5, 10 and 15 km, possibly indicate the causative sources buried at and below the depths of 2.5, 5 and 7.5 km, respectively. Further, the Bouguer anomaly horizontal and generalized derivative maps (figure 7a and b) are prepared to delineate the major structural features.
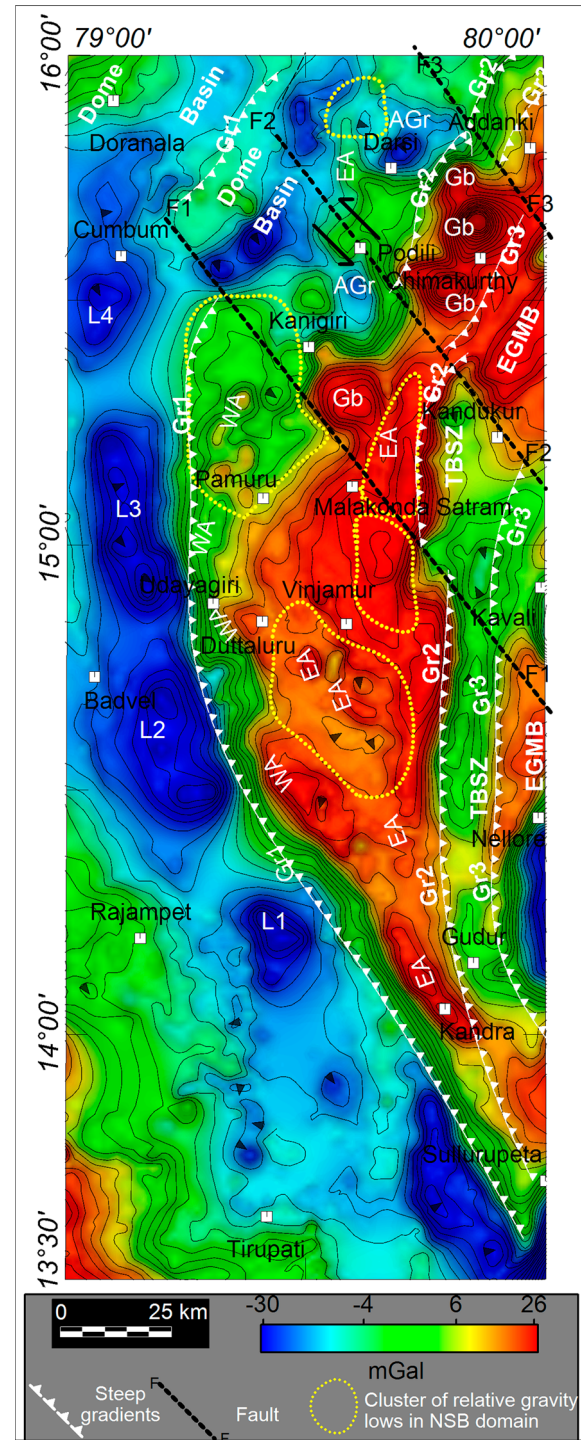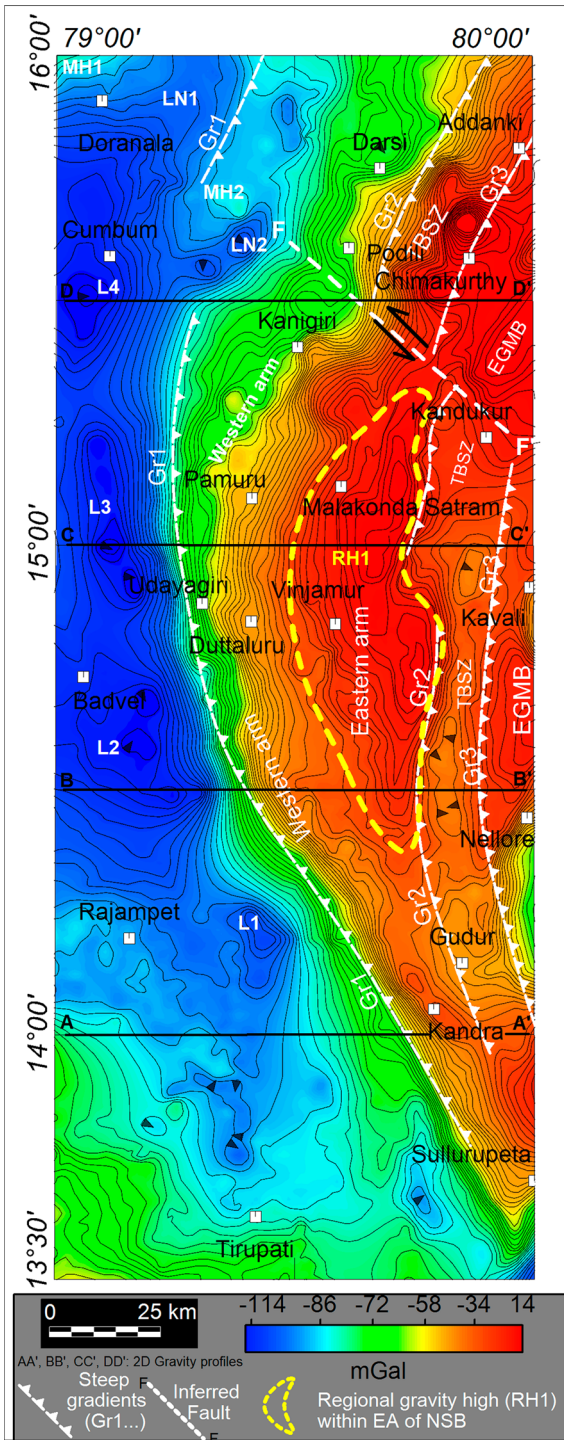
Figure 4. Bouguer anomaly map of Nellore Schist Belt, Eastern Dharwar Craton (source: https://bhukosh.gsi.in/Bhukosh/Public) (L1, L2, L3 and L4: Gravity lows; MH1 and LN1: Relative gravity highs and lows within NFB; RH1: Regional gravity high; Gr1, Gr2 and Gr3: Gravity gradients; TBSZ: Terrane Boundary Shear Zone; F–F′: Fault).

Figure 5. Residual Bouguer anomaly map of Nellore Schist Belt, Eastern Dharwar Craton (L1, L2, L3 and L4: Gravity lows within NFB; MH1 and LN1: Relative gravity highs and lows within NFB; Gr1, Gr2 and Gr3: Gravity gradients; WA: Western Arm of NSB; EA: Eastern Arm of NSB; AGr: Alkali granite; Gb: Gabbro; TBSZ: Terrane Boundary Shear Zone).

The Bouguer gravity 2D models (figure 8) are generated along four E–W gravity profiles at latitude: 14°00′N; 14°30′N; 15°00′N and 15°30′N for quantitative analysis across the NFB-NSB-EGMB

domains. In 2D gravity modelling, the density values for sub-surface litho-units are obtained from the physical property measurements of representative collected rock samples (table 1) in
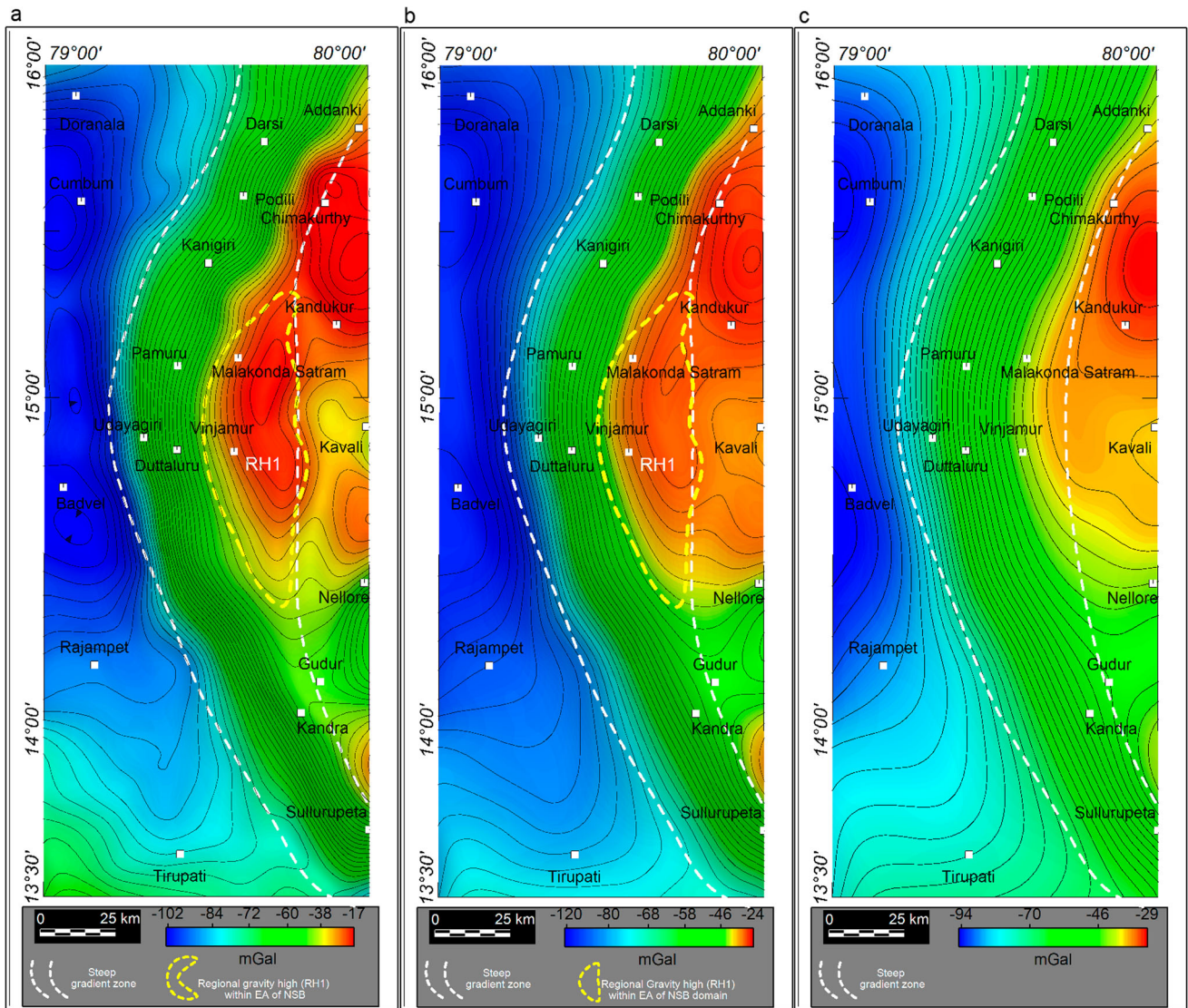
Figure 6. Bouguer anomaly upward continuation maps of Nellore Schist Belt, Eastern Dharwar Craton. Upward continuation to a height of **(a)** 5 km, **(b)** 10 km, and **(c)** 15 km.

CB-NSB-EGMB domains. The representative rock samples, including meta-sediments, meta-volcanics and high-grade schists of Proterozoic to Archaean age, show a wide range of density values (table 1). The metasedimentary units like quartzite, limestone, phyllite, etc., with low-density values, vary from 2540 to 2630 kg/m^3, and the meta-volcanics and amphibolite samples of NSB domain show high-density values in the range of 2700–2960 kg/m^3. The gabbroic and ultramafic samples of PAP have registered the highest density value of 3030 kg/m^3. Further, the crustal layer densities (upper crust: 2670 kg/m^3, middle crust: 2760 kg/m^3 and lower crust: 2900 kg/m^3) are obtained from the existing gravity models (Singh and Mishra 2002; Singh *et al.* 2004) and seismic sections (Kaila *et al.* 1979; Chandrakala *et al.* 2017).

3.1 *Bouguer anomaly character of NSB and its adjoining region*

In Bouguer anomaly map (figure 4), the gravity values with a range of –114 to +14 mGal, increasing from west to east indicate the presence of various litho-tectonic domains, namely, NFB, NSB, TZ and EGMB along the southeastern margin of EDC. The overall NW–SE to NNE–SSW gravity contour pattern from south to north parallels with the crescent shaped CB. A detailed description of the Bouguer anomaly signatures in major litho-tectonic domains is discussed below.

NFB domain: In the western part of Krishna region, the overall major gravity low zone of –111 to –90 mGal defines the NFB with cumulative effect of thick Proterozoic cover sediments over the
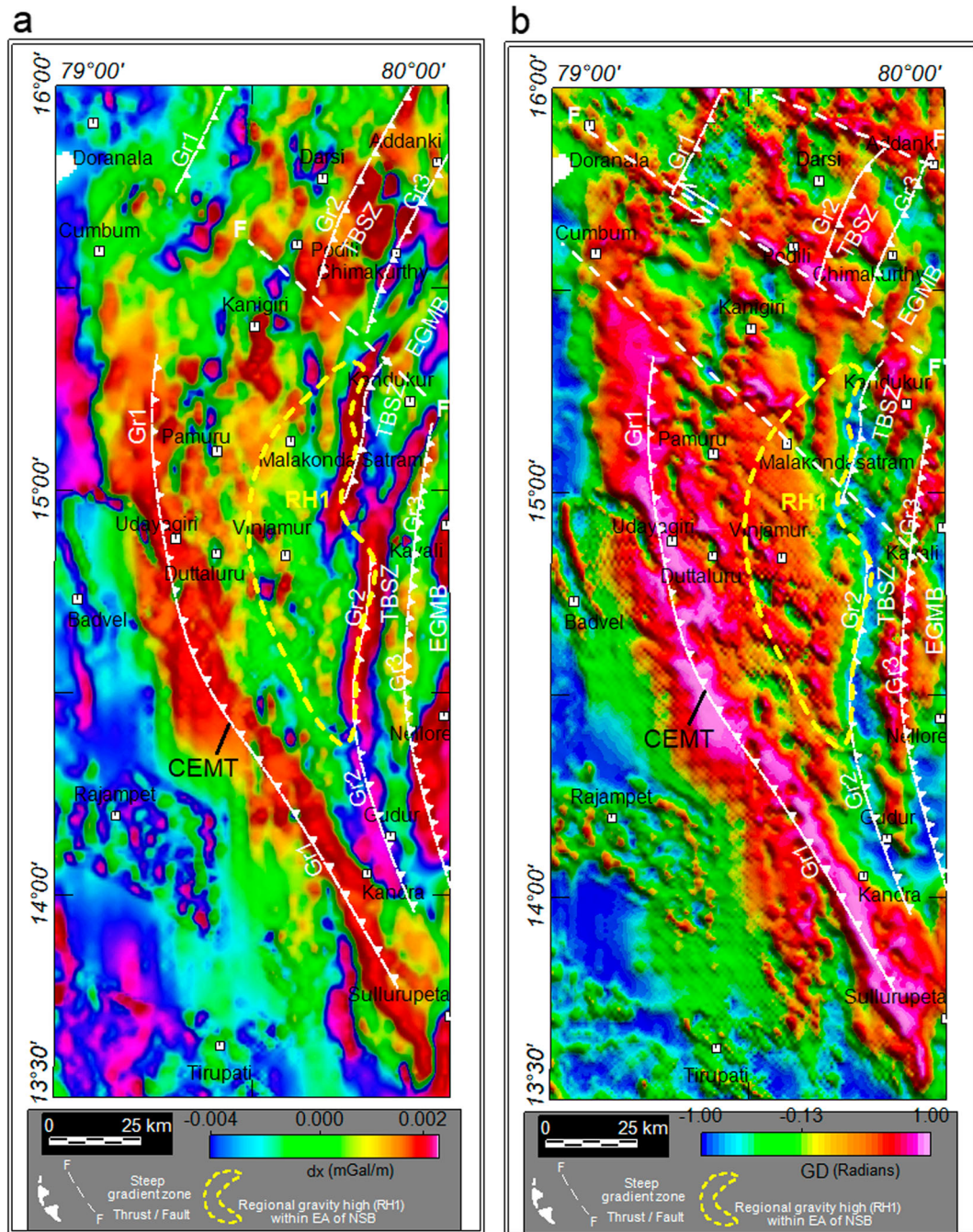
Figure 7. Bouguer anomaly derivative maps of Nellore Schist Belt, Eastern Dharwar Craton. **(a)** Bouguer anomaly horizontal derivative map. **(b)** Bouguer anomaly generalized derivative map.

granitic floor (Nagarajarao *et al.* 1987). A series of gravity low closures (L1, L2, L3 and L4; figure 4) within the NFB are found as alternating zones of culmination and depressions as a result of secondary domal and basinal structures due to a doubly plunging major N–S non-cylindrical fold in the central part of NFB (Mathin 2015). In the northwestern part of NFB (Dornala–Darsi area; figure 4), these secondary domal structures are corroborated with the relative gravity highs (MH1 and MH2) in eastern part of a major Ishwarkuppam dome (figure 4). The intervening linear gravity lows (LN1 and LN2) are corroborated with the secondary basinal structures due to relatively thick cover sediments. Thus, an overall undulating basement configuration is resulted in NFB due to secondary dome and basinal structures along the above-said non-cylindrical fold in response to the Mesoproterozoic Grenvillian event (op. cit).
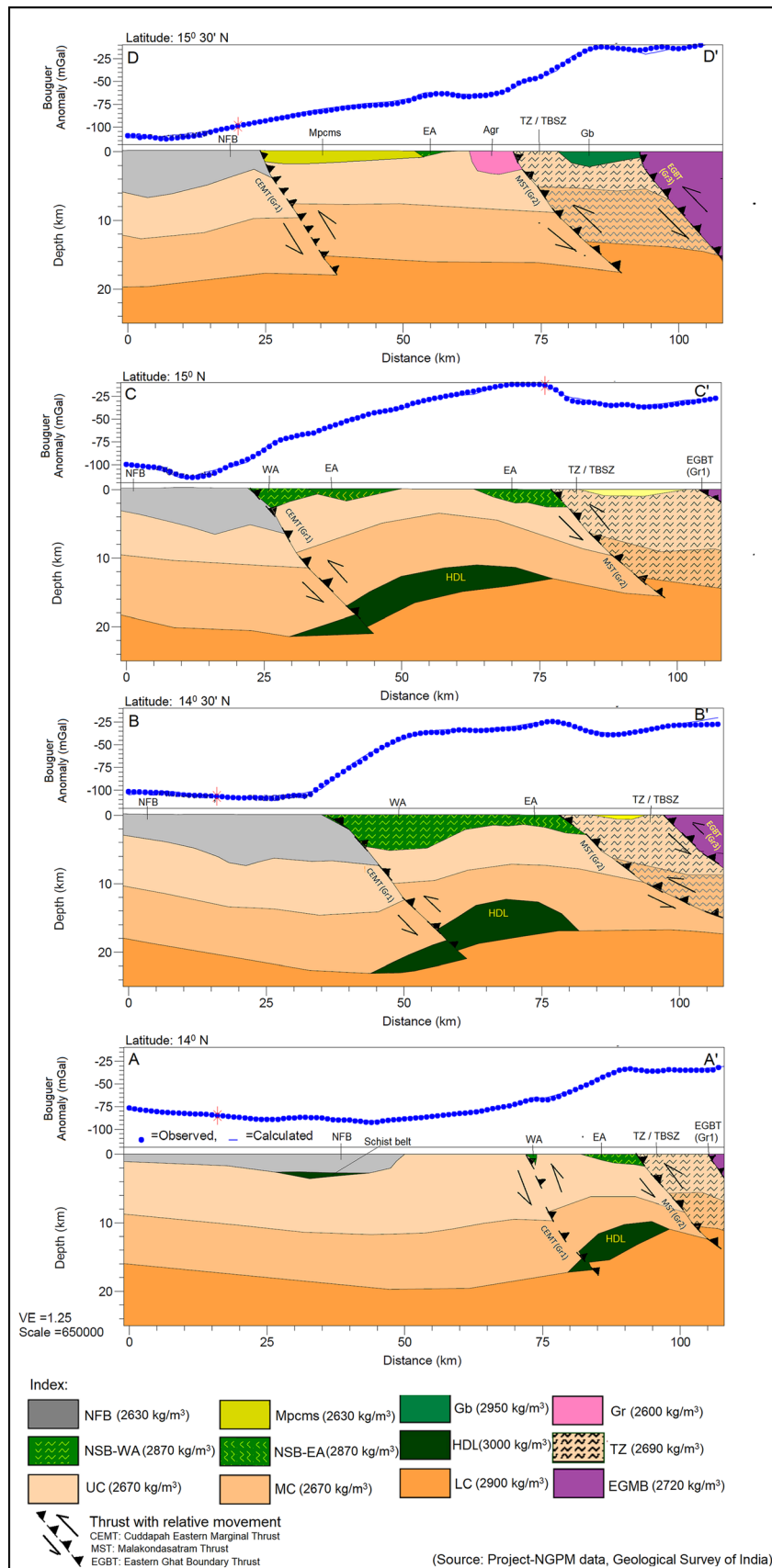
Figure 8. 2D-gravity models (AA′, BB′, CC′ and DD′) along the Latitude: 14°00′N, 14°30′N; 15°00′N and 15°30′N (NFB: Nallamalai Fold Belt; Mpcms: Mesoproterozoic clastic metasedimentary sequence; Gb: Gabbro; Gn: Younger granite; EGMB: Eastern Ghats Mobile Belt; NSB-WA: Western Arm of NSB; NSB-EA: Eastern Arm of NSB; HDL: High Density Layer below the NSB-EA; TBSZ: Terrane Boundary Shear Zone; UC: Upper Crust; MC: Middle Crust; LC: Lower Crust).

Table 1. *Physical property of representative rock samples.*

Sl. no.	Rock type	No. of samples	Density (kg/m^3)		
			Low	High	Average
1	Quartzite	11	2600	2650	2630
2	Pegmatite	01	2630		2630
3	Gabbro	02	3050	3060	3060
4	Granite/granite gneiss	21	2540	2740	2640
5	Phyllite	07	2600	2750	2690
6	Granodiorite	01	2610		2610
7	BIF	01	3380		3380
8	Chlorite schist	05	2680	2880	2780
9	Schist	04	2660	2880	2770
10	Mica-Schist	09	2540	2870	2710
11	Migmatite	05	2600	2750	2650
12	Amphibolite	08	2820	3050	2980
13	Metabasalt	08	2690	2960	2820
14	Ultramafic/mafic	03	3030	3050	3040
15	Dolerite	07	2650	2980	2870
16	Dolomite	02	2570	3020	2790
17	Quartz	04	2620	2660	2640

The eastern margin of NFB is marked as a curvilinear gravity gradient (Gr1) of –90 to –55 mGal indicating a wide tectonic zone, namely, CEMT (Venkatakrishnan and Dotiwala 1987; Saha 2002). In this zone, the Bouguer contours depict as NW–SE to NE–SW with steep gradients (figure 4) from south to north, respectively, where the rocks of NSB in the hanging wall of CEMT rides over the NFB of western part. The Gr1 is characterized by steep gradient in contour pattern both in northern and southern parts, except in the central part with a gentle gradient in Kanigiri–Pamuru area. This characteristic gravity gradient pattern along CEMT may indicate the differential up-throw movements along the hanging wall of NSB.

NSB domain: The gravity-high zone of –55 to –15 mGal in the eastern part of NFB is defined as Late Archaean NSB, along the eastern margin of EDC (figure 4). This gravity-high zone associated with an intense elliptical high (RH1) in eastern part of NSB is marked as EA of back-arc setup with ocean plate stratigraphy (Saha *et al.* 2015; Burhanuddin and Ravi Kumar 2022). The intensity of gravity high (RH1) gradually decreases towards westerly over the discontinuous WA of foreland setup, which is considered to be evolved on the granitic floor (figure 2; Burhanuddin 2022). The intense gravity high (RH1) of EA is corroborated with the DSS studies (Kaila *et al.* 1979) referring to

occurrence of high-density layer at 12–20 km depth (Mishra *et al.* 1987; Singh and Mishra 2002; Singh *et al.* 2004). Further, the EA of NSB is considered as evolved on the oceanic floor (Burhanuddin and Mohakul 2020), where the amphibolites of eastern (EA) and western (WA) are found deriving from two different mantle sources (Krogsted *et al.* 1989).

Transitional zone: The N–S linear gravity low between EDC-EGMB (figure 4) is differentiated as Transitional Zone (TZ) forming eastern margin EDC. The TZ comprises a narrow zone of granite mylonite with negligible NSB enclaves (figure 2). The northern part of TZ is associated with a series of elliptical gravity highs and lows (figure 4), corroborating with the intrusive gabbro and alkalifeldspar granite-syenite plutons of PAP (Leelanandam 1989). In addition to this, such intrusive gabbro and alkali feldspar granite-syenite plutons (figure 3a) are also common even within the NSB domain. The TZ is found to comprise Chimakurthi and Pasupugallu mafic–ultramafic complexes, which are also characterized by the high-intensity gravity high closures in northern part of area (figure 4). The emplacement of these mafic–ultramafic complexes coincides with the initial phase of Paleoproterozoic EDC rifting (Vijaya Kumar and Leelanandam 2008; Ravikanth 2010). Thus, the entire TZ associated with PAP is considered as a cryptic suture (Leelanandam 1989). The two TZ

bound steep gravity gradients (Gr2 and Gr3; figure 4) are referred to as MST in the west (figure 3a and b; Burhanuddin and Ravi Kumar 2019) and EGBT towards its east (Mishra and Ravi Kumar 2014). The MST (Gr2) and EGBT (Gr3) with low and moderate angles define the overall limit of TBSZ between the EDC-EGMB.

EGMB domain: In the covered eastern part, the gravity high in N–S to NE–SW is marked as EGMB at Kavali–Nellore–Gudur region in southern continuation of Addanki–Ongole domain (Dobmeier and Raith 2003). Thus, the hitherto unidentified southern extension of EGMB is delineated as gravity high in eastern laterite covered part (figure 4) in concurrence with the latest magneto-telluric studies (Chandrasekhar *et al.* 2018). Further, the earlier structural features of eastern part show the dislocation in Addanki, Chimakurthi–Kandukur and Malakondasatram–Kavali areas by NW–SE faults due to the superposed effects of later tensional events (figure 4).

3.2 *Residual Bouguer anomaly signatures*

The residual Bouguer anomaly of Krishna region shows the shallow sub-surface litho package and salient structural features reflected as residual gravity highs and lows along with the gravity gradients (figure 5). Towards west of CEMT (Gr1), a number of relative elliptical gravity lows (L1, L2, L3 and L4) with intervening relative high zones in an overall major low of NFB domain are corroborated with the uneven basement configuration resulting due to secondary basin and domal structures along a major N–S non-cylindrical fold (Mathin 2015) as already mentioned above. In granite–greenstone terrain NSB of central part, an isolated E–W Mesoproterozoic erosional remnant in Kanigiri–Pamuru area is evidenced by a cluster of residual gravity lows (yellow dotted polygon in figure 5); which rides over the Bairankonda Quartzite of NFB in the west (figure 3a). Towards further east, the Mesoproterozoic high-grade erosional cover sequence (kyanite–staurolite–muscovite–garnet schist) occurring in two isolated N–S doubly plunging structures of Mopadu and Malakondasatram are, however, evidenced as linear N–S gravity highs (figures 3a and 5) due to underlying high-density character of EA. These high-grade schist occurrences are in tectonic contact with the westerly dipping Pamuru (PT) and easterly dipping Malakondasatram (MST) thrusts

in the west and east (figure 3a and b), respectively, where the latter is reflected as a steep gravity gradient (Gr2; figure 5). The gravity signatures over the PT are feeble with gentle N–S to NE–SW linear gravity contours in Duttalurur–Pamuru–Kanigiri area (figure 5) and the same is delineated based on geological observations (figure 3a). The PT and MST show the overriding effect of basement rocks, with which deep burial of high-grade Mopadu–Malakondasatram occurrences resulted (figure 3b). A continuous residual gravity high over the eastern part of NSB is marked as EA with ocean plate stratigraphy of back-arc setup, while the discontinuous patches of WA depict as residual linear gravity highs in the western part (figure 5).

A N–S linear gravity low zone between the two highs of EDC-EGMB characterizes the TBSZ occupied by the intrusive PGC-II with granite–mylonite association. The MST and EGBT are reflected as two steep gradients (Gr2 and Gr3; figure 5) as mentioned above. In northern strike continuation of TBSZ, the occurrence of Chimakurthi and Pasupugallu mafic–ultramafic complexes and alkali feldspar granite-syenite plutons of PAP are reflected as elliptical gravity highs (Gb: Gabbro) and lows (AGr: Alkaline Granite). In addition to this, the similar elliptical gravity highs and lows within the EDC too are referred to as mafic and acidic intrusives within the NSB domain. In extreme eastern part, the elliptical gravity highs in covered laterite region of Kavali–Nellore–Gudur indicates the southern continuation of Addanki–Ongole EGMB domain as already described above.

3.3 *Regional Bouguer anomaly signatures*

The regional Bouguer anomaly maps prepared based on the upward continuation to the height of 5, 10 and 15 km (figure 6a–c) show intense gravity low extending from shallow to deeper levels in the western part of Krishna region. This low zone is reflected as a closed outcrop pattern of large synclinorium in the central part of NFB (Mathin 2015), where a thick column of sediments ∼10 km is envisaged by seismic studies (Kaila *et al.* 1979) towards the south of Ishwarkuppam dome (Nagarajarao *et al.* 1987). In addition to this, the relative gravity lows with intervening highs within the low gravity zone at Badvel and Cumbum areas (figure 6a and b) signifies secondary basinal and domal structures, along the axial trace major

non-cylindrical folds relating to Mesoproterozoic Grenvillian orogenic movements (Mathin 2015).

In western part of NSB domain, a number of discontinuous residual highs (figures 4 and 5) relating to WA of NSB are absent in the regional gravity maps (figure 6a–c) due to its limited depth extension and underlying intrusive PGC-II at depth. The presence of regional gravity high (RH-1) relating to the high-density layer of EA of NSB has confirmed its depth extension, which even continues from shallow to mid-crustal levels (figures 6a and b) based on the fact of its evolvement on the oceanic floor (Burhanuddin 2022). The missing of same in deeper depths (figure 6c) is due to intrusive PGC-II similar to the WA as mentioned above. The tracing of southern continuation of Addanki–Ongole EGMB domain in covered part of Kavali–Nellore–Gudur region in present work, negates the earlier views of its missing (Yoshida *et al.* 1992). In this zone, the regional gravity high (figure 6c) pertaining to EGMB indicates its continuity even into the deeper parts.

The easterly dipping CEMT (Gr1) and MST (Gr2) within the EDC (figure 4) represent possible Mesoproterozoic imbricate thrusts originating from EGBT (Gr3) sole thrust along the contact of EDC-EGMB. These imbricate thrusts are likely to merge with the sole thrust at deeper depth in different structural levels, with which the respective thrust-bound litho-tectonic belts (NFB, NSB and TZ) along eastern margin of EDC are progressively wedged out. Thus, in figure 6(c) of deeper level, the wide gravity gradients could not be explained similar to the shallow level interpretations in NSB (figure 5), which is also due to the combined effect of underlying Late Archaean intrusive PGC-II (Ramakrishnan and Vaidyanathan 2008). The overall NSB domain occurring in hanging wall is found as an overriding block (Kaila *et al.* 1979; Mishra *et al.* 1987) along the Mesoproterozoic CEMT (figures 2 and 3a).

3.4 *Bouguer anomaly derivative maps*

The Bouguer anomaly horizontal and generalized derivative maps demarcate two major gravity gradients with regard to CEMT and TBSZ between the NFB-NSB and NSB-EGMB belts (figure 7a and b). The curvilinear CEMT shows intense and feeble gradients in southern and central (Pamuru–Kanigiri area) parts (figure 7a), which indicates the differential thrust movements along the hanging wall of NSB. The restricted occurrence of isolated Mesoproterozoic upper Cuddapah erosional remnants with underlying NSB in Kanigiri–Pamuru area (figure 3a) is related to feeble gradients, where the preservence of these sediments is resulted due to comparative less upthrow movement along the NSB's hanging wall (figure 7a). Thus, the Mesoproterozoic upper Cuddapah extensions in NSB domain are subjected to erosion in both southern and northern parts due to maximum upthrow movements along the hanging wall of CEMT. It is interesting to note that, unlike the northern and southern parts, the Bairankonda quartzite of basal NFB is in direct contact with the upper Cuddapah extensions in the central part (Burhanuddin and Ravi Kumar 2019; figure 3a and b) due to this mechanism. Thus, the occurrence of erosional remnants of upper Cuddapah extensions unconformably over the NSB is overall related to post-deformational history either as erosion or preservence due to differential upthrow movements along the hanging wall of Mesoproterozoic CEMT.

In the eastern part, a major N–S liner gradient (figure 7a and b) represents the overall disposition of TBSZ, including MST and EGBT, towards its west and east, respectively. In its northern strike continuity, a cluster elliptical high zone with a general NE–SW trend signifies the intensely deformed region associating with layered mafic–ultramafic complexes, gabbroic and alkaline plutons of PAP (figures 2, 7a and b). The TBSZ is dissected by a number of NW–SE faults due to superposed later tensional events from south to north (figure 7b).

3.5 *2D gravity models*

The 2D gravity depth models are generated along the four E–W profiles (figure 4; AA′, BB′, CC′ and DD′ covering latitude: 14°00′N; 14°30′N; 15°00′N and 15°30′N, respectively) for quantitative interpretation across the NFB-NSB-EGMB domains (figure 8). Along the axial trace of N–S non-cylindrical fold of NFB; the 2D models show a total sediment thickness of ∼7 km in central part (BB′ and CC′ profiles; figure 8); and the ∼4 km thickness in its northern and southern parts (AA′ and DD′ profiles, figure 8) is interpreted. The profile DD′ 2D gravity section (figure 8) also shows a thin layer (∼2 km) of Mesoproterozoic Cuddapah extensions (Mpcms) in NSB domain that are in

thrust contact (CEMT) with the Bairankonda quartzite of NFB in the west. In all 2D gravity sections, the major structural features like CEMT and EGBT show moderate angle except in middle MST of gentle, which corroborated with the sub-horizontal foliation in mylonitic-gneiss (TBSZ) (Burhanuddin and Ravi Kumar 2019) of eastern hanging wall (figure 3a and b). These structural features with easterly dip show overriding mechanism of hanging wall in response to the Mesoproterozoic Grenvillian Eastern Ghats orogeny (Mathin 2015; Burhanuddin and Ravi Kumar 2019, 2022).

A thick high density layer (HDL) at a depth of ~ 10 km below the EA of NSB extends towards westerly and gradually becomes thin and wedges out below the WA (BB′ and CC′, figure 8) indicating a clear-cut subduction mechanism of EA. As per the established works (Cloos 1982; Krogsted *et al.* 1989; Leelanandam 1990; Chadwick *et al.* 2000; Okudaira *et al.* 2000), the subduction of oceanic lithosphere relating to back-arc setup of EA (Burhanuddin and Mohakul 2020; Burhanuddin and Ravi Kumar 2022; Burhanuddin 2022) is considered to be subducted below the continental lithosphere of foreland (WA), and the same is reflected in 2D gravity modelling with the occurrence of EA below the WA (figure 8). As such, the inversal of WA and EA (figure 3a and b) is, however, related to the superposed Proterozoic inversal mechanism due to easterly dipping thrusts. Similarly, the postdated Mesoproterozoic inversion mechanism (CEMT) is clearly evidenced in these profiles (figure 8). Based on the fact of WA's restricted occurrences in Rapur–Udaigiri–Pandavulagandi area (figures 2, 3a and 5), its presence in AA′, BB′ and CC′ profiles of southern part and total absence in DD′ profile of northern part can be seen (figure 8). As mentioned above, a similar overriding effect of Mesoproterozoic upper Cuddapah erosional remnants with basal Bairankonda quartzite of NFB can also be seen in 2D profile of DD′ (figures 3a, b and 8).

4. Discussion

The litho-tectonic divisions of Precambrian terrain of Krishna region are corroborated with two gravity highs belonging to EGMB in eastern and the NSB of central part with a very wide gravity low across the CB (Ram Babu 1993) including the Mesoproterozoic NFB of west (figure 4). These two gravity highs are separated by a long linear gravity low with granite-mylonite representing as TBSZ (figures 4 and 5; Burhanuddin and Ravi Kumar 2019, 2022), where the mafic–acidic intrusive plutons of PAP (Leelanandam 1989; Vijaya Kumar and Leelanandam 2008) are differentiated (figures 4 and 5). In the present work, the missing southern EGMB (Yoshida *et al.* 1992) is traced in Kavali–Nellore–Guduru region (figures 4–6) in concurrence with the latest works (Chandrasekhar *et al.* 2018).

The overall gravity high of central part (figure 4) represents as late Archaean granite-greenstone terrain of NSB with its two parallel arms of WA and EA of different coeval environmental facies (Burhanuddin and Ravi Kumar 2019, 2022) in a foreland and back-arc basinal setups of late Archaean composite basin (Burhanuddin and Mohakul 2020; Burhanuddin 2022). Based on the fact of EA with intense gravity high (RH1 in figure 4) due to high-density layer (HDL) (figure 8; Kaila *et al.* 1979; Dobmeier and Raith 2003) is considered to be evolved on the oceanic floor of back-arc setup based on the presence of oceanic crust imbricates (Leelanandam 1990; Saha *et al.* 2015). The coeval WA of foreland setup with detrital cross-bedded quartzite-subaerial volcanic eruptions (Chadwick *et al.* 2000; Burhanuddin and Mohakul 2020; Burhanuddin and Ravi Kumar 2022) in a composite basin (Burhanuddin 2022) on a granitic basement is considered for NSB evolution. During this process, a Late Archaean E–W convergence (Cloos 1982) with a subduction–abduction mechanism (Chadwick *et al.* 2000) in an ophiolitic setting (Krogsted *et al.* 1989; Leelanandam 1990) with which, the subduction of oceanic lithosphere below the continental lithosphere is resulted (Okudaira *et al.* 2000). Thus, the HDL of EA (Kaila *et al.* 1987; Dobmier and Raith 2003) gradually decreases westerly and wedged out below the WA (figures 4 and 7), in response to the above said late Archaean mechanisms as inferred in 2D gravity modelling (BB′ and CC′ in figure 8).

In NSB domain, the overall structurally controlled isolated E–W Mesoproterozoic sedimentary erosional remnants of Kanigiri–Pamuru including small outliers at Darsi in northern part (figures 2 and 3a), occurring unconformably over the both EA and WA of NSB are differentiated as eastern continuation of upper Cuddapah (figure 3a; Burhanuddin and Ravi Kumar 2019, 2022) sequences. In this E–W erosional remnant occurrence, a cluster of isolated residual gravity lows

(figure 5) are found relating to unconformable Mesoproterozoic upper Cuddapah sequence with underlying vast granitic terrain of NSB. A linear NE–SW Pandavulagandi WA outcrop represents as an isolated residual gravity high within the Kanigir–Pamuru Mesoproterozoic erosional remnant occurrence (figure 5). In the eastern part of NSB, the two isolated high-grade Mopadu–Malakondasatram occurrences (figure 3a) are considered belonging to eastern continuation of Mesoproterozoic upper Cuddapah extensions (Burhanuddin and Ravi Kumar 2019). The occurrence of these high-grade schists in an otherwise defined low-medium grade NSB is the result of layer-composition specific metamorphism at the EGMB front in response to tectono-thermal effects of Mesoproterozoic Eastern Ghats Grenvillian orogeny (Moeen 1998). These high-grade occurrences are underlying the high-density EA of NSB, which results in residual gravity high signatures in Mopadu–Malakondasatram areas (figure 5).

The CEMT (Venkatakrishnan and Dotiwala 1987), MST (Burhanuddin and Ravi Kumar 2019) and EGBT (Mishra and Ravi Kumar 2014) structural features within the EDC (figures 3a, b and 4) are resulted in response to the Mesoproterozoic Grenvillian Easternghats orogeny as imbricate thrusts (figures 6c, 7a and 8) originating from EDC-EGMB boundary sole thrust (EGBT). These imbricate thrusts are likely to merge with the main EGBT at different structural levels at depth, which causes wedging out of thrust-bound litho-tectonic units in the NSB domain. Based on this mechanism and coupled with the underlying continuous intrusive granitic layer (PGC-2) (Ramakrishnan and Vaidyanathan 2008), the gravity high of NSB could not be explained at the deeper levels (figure 8), similar to the interpretations of which at shallow depth (figures 4 and 5). Further, the high-density material of EA continuing westerly and wedging out below the foreland of WA (figure 8) is related to the Late Archaean subduction-ophiolitic mechanisms, as mentioned above. The decrease in intensity of gravity high is due to both underlying granitic basement (Chadwick *et al.* 2000; Burhanuddin and Mohakul 2020) and intrusive PGC-II (Ramakrishnan and Vaidyanathan 2008) below the WA as mentioned in the preceding paragraphs. These overall observations suggest the entire NSB as a single continuous segment of late Archaean, contrary to the existing classifications (Srinivasan and Roop Kumar 1995; Dobmeier and Raith 2003; Saha *et al.* 2015).

5. Conclusions

- In Krishna region, two gravity highs of eastern and central parts are defined as Eastern Ghats Mobile Belt (EGMB) and Nellore Schist Belt (NSB) with intervening linear gravity low of Transitional Zone and a wide gravity low of Nallamalai Fold Belt (NFB) in the west.
- In the eastern part of NSB, the high-density material of back-arc setup continues westerly and wedges out below the western foreland setup as envisaged from 2D gravity model, suggesting a Late Archaean subduction mechanism in an ophiolitic setting.
- The eastern gravity high in laterite covered part of Kavali–Nellore–Gudur region establishes the southern continuation of EGMB.
- A series of gravity highs and lows relating to secondary dome and basinal structures along the non-cylindrical fold of NFB is corroborated with the uneven basement configuration.
- The differential gravity gradients with regard to Cuddapah Eastern Marginal Thrust indicate differential up-throw movements along the NSB's hanging wall, which resulted in the preservation of unconformable upper Cuddapah erosional remnants in Kanigir–Pamuru area of central part.
- The western and eastern contacts of NSB with steep gravity gradients are interpreted as imbricate thrusts generating from Eastern Ghats Boundary Thrust in response to the Mesoproterozoic Grenvillian Eastern Ghats orogeny.

Author statement

B Ravi Kumar: Geophysical data generation, compilation and reprocessing and interpretation by incorporating the deep-crustal inferences derived from deep seismic and regional gravity data. M Burhanuddin: Conceptualizing the research work by integration of geological and geophysical data. G Udaya Laxmi: Interpretation of gravity data.

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