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Unusual lithospheric structure and evolutionary pattern of the cratonic segments of the South Indian shield

P. K. Agrawal and O. P. Pandey

Theoretical Geophysics Group, National Geophysical Research Institute, Uppal Road, Hyderabad 500007, India

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The southern Indian shield, characterised by several prominent geological and geophysical features, can be divided into three distinct tectonic segments: Western Dharwar craton (WDC), Eastern Dharwar craton (EDC) and Southern Granulite terrain (SGT). With the exception of WDC, the entire crust beneath EDC and SGT has been remobilized several times since their formation during the mid- to late Archeans (3.0–2.5 Ga). In order to understand the evolutionary history of these segments, a multiparametric geological and geophysical study has been made which indicates that the south Indian shield, characterized by a reduced heat flow of 23–38 mW/m^2 has a much thinner (88–163 km) lithosphere compared to $\sim$200–450 km found in other global shields. In the EDC-SGT terrain, high velocity upper crust is underlain by considerably low mantle velocity with a thick high conductive/low velocity zone sandwiched at mid crustal level. Our study reveals that the entire EDC region is underlain by granulite facies rocks with a density of about 2.85 to 3.16 g/cm^3 at a shallow depth of about 8 km in the southern part and at even shallower depth of about 1 to 2 km below the Hyderabad granitic region in the north. Cratonic mantle lithosphere beneath EDC may contain a highly conductive, anisotropic and hydrous metasomatic zone between the depth of 90 and 105 km where estimated temperatures are in the range of 850–975°C. It is likely that before the early Proterozoic, the entire south Indian shield was a coherent crustal block which subsequently got segmented due to persistent plume-induced episodic thermal reactivations during the last 2.7 Ga. These reactivations led to self destruction of cratonic roots giving rise to negative buoyancy at deeper levels which may have been responsible for crustal remobilisations, followed by regional uplifting and erosion of once substantially thick greenstone belts. Consequently, the crustal column beneath the EDC has become highly evolved and now corresponds closely to SGT at depth.

Key words: Indian shield, lithosphere, temperature, granulites, Eastern Dharwar craton, velocity structure, tectonothermal events.

1. Introduction

South Indian shield forms one of the most dynamic, sheared and deformed regions among the stable areas of the earth (Pandey and Agrawal, 1999). It is bounded by Godavari graben of Gondwana age in the east and partly covered by Deccan basalts of K-T boundary age in the north. This shield underwent a complex style of evolution and accretion since late Archean times. It is characterized by several geotectonic terrains evolved at different times by different processes. Thermotectonic activity can be traced almost through entire late Archean–Proterozoic era. Even during the last 130 Ma, it has been associated with high order mobility, continental rifting episodes from its western and eastern margins and a major plume interaction (Marion).

As a whole, major part of the southern Indian shield is occupied by mid-Archean–early Proterozoic crystalline rocks evolved during several episodes of magmatism and metamorphism. The remnants of the oldest Archean terrain occur as granite-gneiss-greenstones in the western part (Fig. 1). Broadly, this region can be divided into three individual blocks, exhibiting distinct tectonostratigraphic and geochronologic characters. These are Western Dharwar craton (WDC), Eastern Dharwar craton (EDC) and Southern Granulite terrain (SGT) (Fig. 1). Among them, the SGT situated in the southern part of the peninsula had undergone extensive regional metamorphism during late Archean and Pan African times (550 ± 30 Ma). In view of the above, an attempt has been made here to (i) delineate deep structure of the crust and mantle lithosphere beneath these segmented blocks and (ii) study their evolutionary and deformational pattern by integrating available geological and geophysical data.

2. Geologic and Geotectonic Pattern

Simplified geologic and tectonic setting of the south Indian shield is shown in Figs. 1 and 2. Among the three segments, WDC forms the oldest unit containing mid to late Archean cratonic nuclei, over which lies vast exposures of high grade schists (3.0–3.4 Ga), granite and gneisses (Radhakrishna and Naqvi, 1986; Naqvi and Rogers, 1987). The entire segment is devoid of Proterozoic tectono-thermal events with rock types showing low temperature metamorphism. In contrast, the EDC is characterised by late Archean–early Proterozoic ($\sim$2.5 Ga) cratonic growth with low pressure metamorphism and remoblisation of crustal blocks, containing abundant calc-alkaline to K-rich gran-

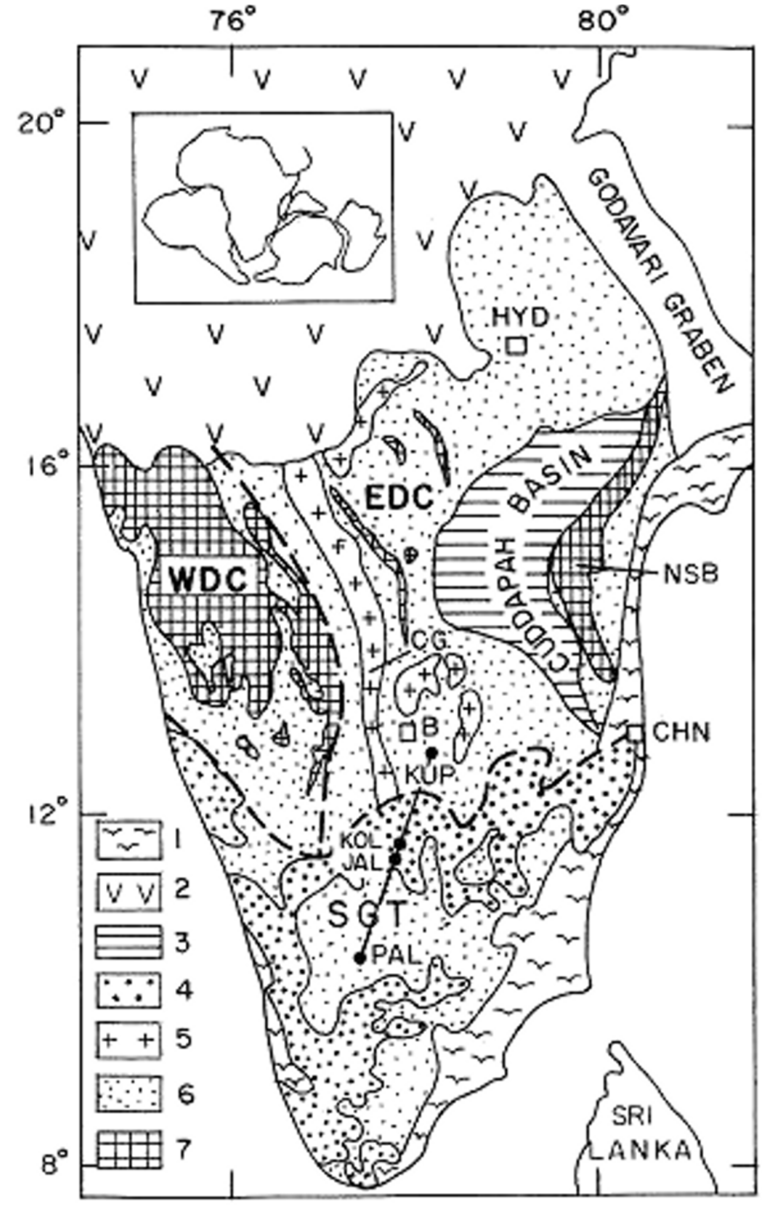

Fig. 1. Generalized geological map of south Indian shield (GSI, 1993). WDC: Western Dharwar Craton; EDC: Eastern Dharwar Craton; SGT: Southern Granulite Terrain; KUP: Kuppam; PAL: Palani; KOL: Kolattur; JAL: Jalakandapuram; HYD: Hyderabad; B: Bangalore; CHN: Chennai; CG: Closepet granite; NSB: Nellore schist belt; 1: Alluvium; 2: Deccan volcanics; 3: Mid-proterozoic sedimentary basin; 4: Charnockites; 5: Granites; 6: Granite, gneiss, migmatites; 7: Greenstone belt (Dharwar). Inset shows assembly of Gondwana continental blocks including India.

itoids along with thin elongated greenstone belt (Harish Kumar *et al.*, 2003). This region evolved during various episodes from 2.7 Ga to 1.1 Ga, the last one being a major kimberlitic event (Anil Kumar *et al.*, 1993). This terrain is extensively intruded by mafic dyke swarms and is unconformably overlain by mid-Proterozoic Cuddapah super group sedimentary sequence. Most of the granites and gneisses of EDC have elevated initial $^{87}Sr/^{86}Sr$ ratios (Pandey *et al.*, 1995). EDC is separated from WDC by a steep mylonitic zone along the Chitradurga fault zone (CDF in Fig. 2) which runs through the middle of the Dharwar craton. A thrust zone possibly exists around the eastern margin of EDC (Drury *et al.*, 1984). It also contains a number of hot springs (Fig. 2).

South of WDC and EDC lies the SGT terrain below latitude 12.5°N. This zone can be divided into two distinct terrains situated either side of Palghat—Cauvery Shear Zone. (PC in Fig. 2). The northern block is made up of late Archean–early Proterozoic (?) granulites consisting mainly of charnockites and retrograde gneisses while the southern block is of Pan-Africann age (550 ± 30 Ma) and is composed of charnockites, khondalites, granites and gneisses. Some sections of SGT are even pressently tectonically active showing large uplift like Nilgiri (Fig. 2). Deepest part of the granulitic crust is exposed in many areas.

3. Heat Flow Distribution, Temperature Regime and Geoelectric Signatures

Heat flow in the Dharwar craton (Fig. 3) shows a wide range from 27 to 75 mW/m^2 with an average of 31 ± 4 and 40 ± 11 mW/m^2 for WDC and EDC respectively. Heat flow variation in SGT is large with an average of 36 ± 4 mW/m^2 for the northern block and 47 ± 8 mW/m^2 for the southern

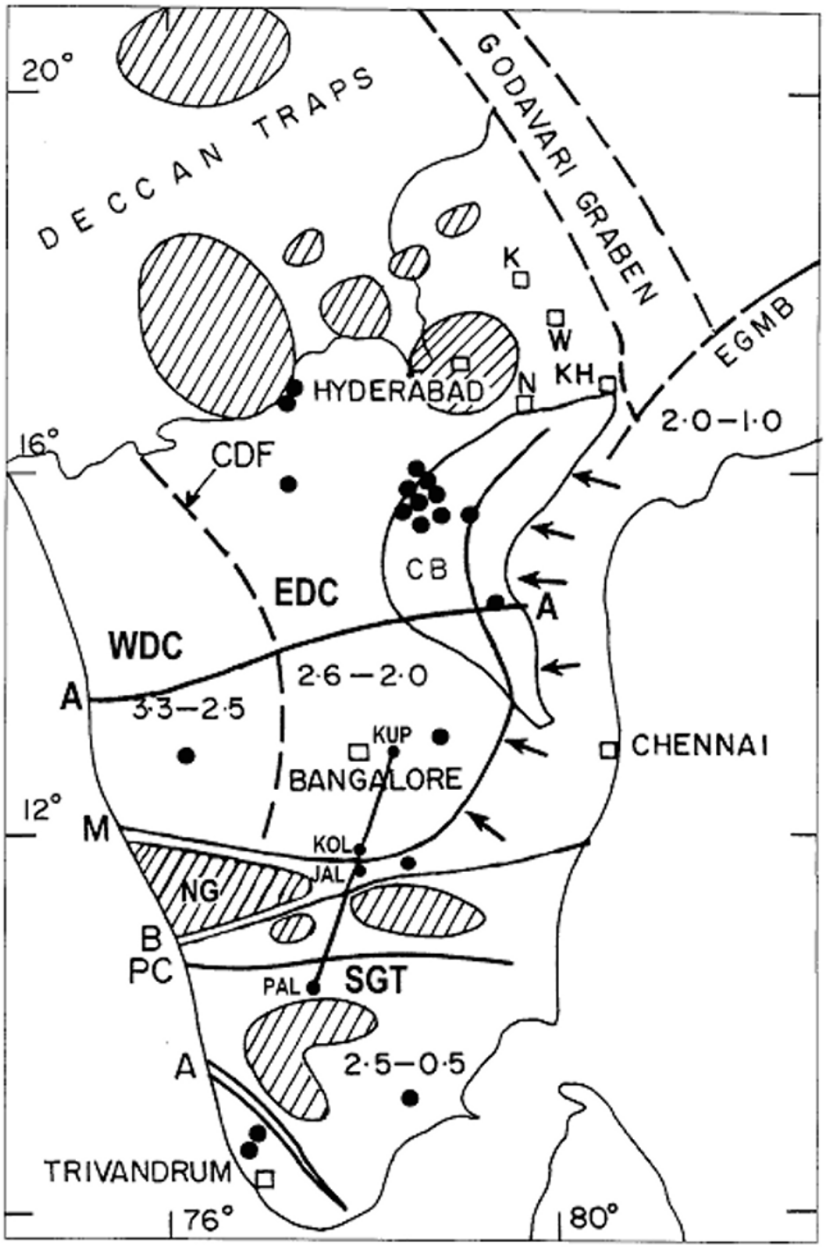

Fig. 2. Simplified geotectonic map of South Indian shield. M: Moyar shear zone; B: Bhavani shear zone; A: Achankovil shear zone; PC: Palghat-Cauvery shear zone; EGMB: Eastern Ghat mobile belt; CB: Cuddapah basin; CDF: Chitradurga Fault zone; K: Karimnagar; W: Warangal; KH: Khammam; N: Nalgonda; NG: Nilgiri. Ages are in Ga. Arrows indicate direction of thrusting. Solid dots indicate location of hot springs. Uplifted regions (Krishna Brahmam and Negi, 1973; Thakur and Nagarajan, 1992; Rantsman *et al.*, 1995 etc.) are shown by slanted lines. AA indicates location of CSS profile across WDC and EDC along which velocity-depth distribution has been shown in Fig. 5. Location of seismic profiles from Kuppam (KUP)–Jalkandapuram (JAL) and Kolattur (KOL)–Palani (PAL) as shown in Fig. 6 is also given.

block.

In order to estimate deep seated temperatures, we assume an exponential decrease of heat production with depth and calculate the temperature T at a depth z using the following relationship (Lachenbruch, 1968):

$$T(z) = T_o + \frac{q_r}{K} z + \frac{D^2}{K} A_o [1 - \exp(-z/D)]$$

where T_o is surface temperature, K is thermal conductivity, A_o is heat production, q_r reduced heat flow and D is exponential decay scaling parameter (or characteristic depth). In these calculations, To is taken as 25°C, thermal conductivity is taken uniformly as 3.0 W/m°C (except for NSGT 2.44 and SSGT 2.30; Ray *et al.*, 2000) and characteristic depth 10 km as obtained from heat flow—heat generation relationship for the Indian shield (Pandey, 2003). Temperature-depth calculations depend heavily on the heat production value assigned to the upper crust. Thus, for WDC and EDC, we use the detailed compilation of Gupta *et al.* (1991) for the Dharwar craton. In case of EDC, we have not considered anomalous heat generation value of Hyderabad granitic terrain and for WDC, we restrict only to the values belonging to the Chitradurga supracrustal belt and its surrounding areas. Our recent detailed study (Pandey *et al.*, 2002) suggests that highly radioactive granitic layer at Hyderabad does not extend beyond a kilometer or so at depth. For SGT, heat generation

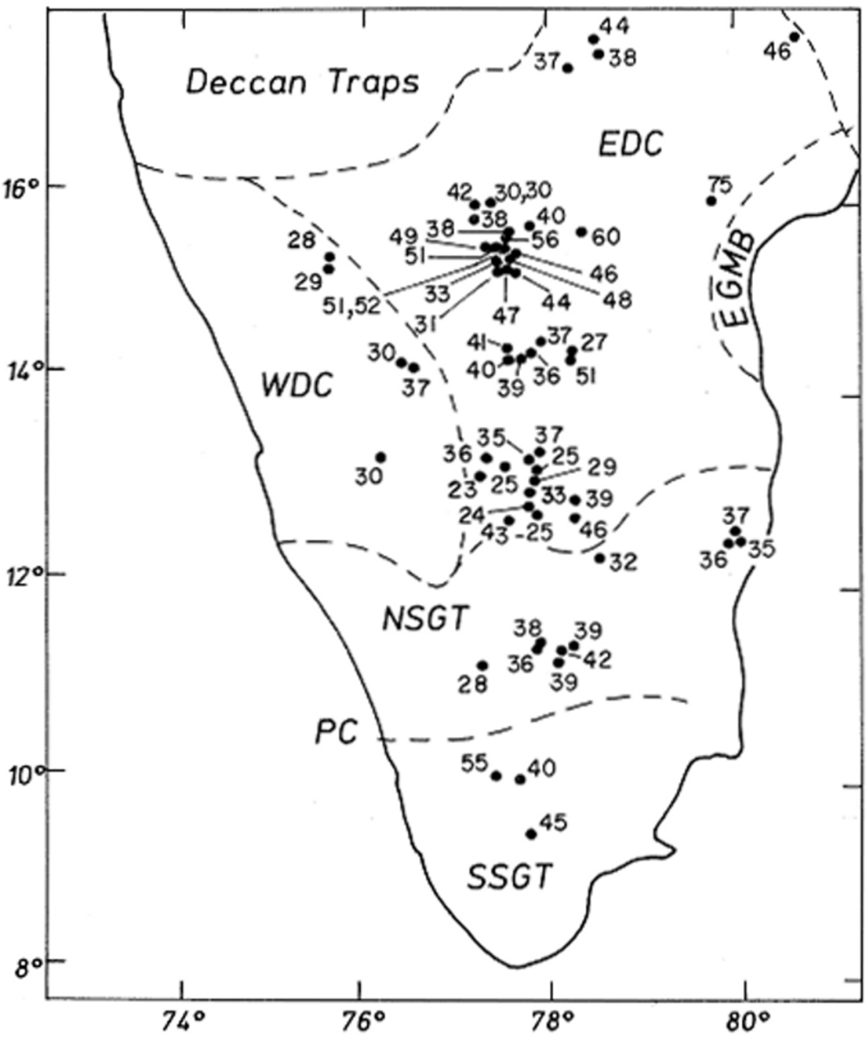

Fig. 3. Heat flow (in mW/m^2) distribution in the south Indian shield. Data is taken from Gupta and Rao (1970), Gupta *et al.* (1987, 1991), Roy and Rao (2000) and Rao *et al.* (1976, 2001). NSGT and SSGT denote Northern and Southern block of SGT. EGMB: Eastern Ghat mobile belt.

data is taken from a very detailed work of Ray *et al.* (2000) covering hundreds of measurements. The reduced heat flow (i.e. heat flow coming out from the lower crust and upper mantle) is then estimated by removing the effect of a 10 km thick crustal radioactive column from the observed mean surface value, which varies from 23 to 38 mW/m^2 among the segments.

Calculated temperature-depth distribution for WDC, EDC and SGT is shown in Fig. 4 from which the base of lithosphere is determined as being the mantle solidus, i.e. intersection of the geotherm with the peridotite incipient melting point curve. This provides lithospheric base at 88 to 163 km depth which is considerably low compared to 200–300 km found in other stable areas of the earth (Chapman and Pollack, 1977). It implies that lithosphere beneath these segments besides being unusually shallow, is also quite warm. Such an inference is supported by seismic evidence that suggest even shallower cratonic root depths ($\sim$100 km only) beneath the Indian shield compared to about 250–450 km found elsewhere (Polet and Anderson, 1995). The cratonic mantle lithosphere appears to contain a highly conductive, hydrous and seismically anisotropic metasomatic zone between the depth of 90 and 105 km (Saul *et al.*, 2000; Sastry *et al.*, 1990) where the estimated temperature could be 850–975°C. This zone is found at much deeper level of $\sim$150 km or more in other global stable areas. All the thermal parameters of WDC, EDC and SGT are summarised in Table 1.

4. Crustal Velocity Structure

Controlled source seismics (CSS) derived velocity-depth function along an E-W profile across WDC and EDC (AA in Fig. 2) is shown in Fig. 5. In WDC, crustal P-wave velocity increases from 6.0 km/s at surface to 6.2 km/s at 22–24 km depth and then 6.8 km/s to 7.0 km/s above Moho, identified at an average depth of 40 km with a high Pn velocity of 8.4 km/s (Reddy *et al.*, 2000; Sarkar *et al.*, 2001), while in EDC, seismic velocity increases from 5.9 km/s at surface to 6.2 km/s at the depth of 5–8 km and then 6.7 to 7.0 km/s at depth of 20–37 km. Here, Moho depth and Pn velocity are 37 km and 7.8 kms respectively (Reddy *et al.*, 2000). As regards SGT, a coincident deep seismic reflection and refraction study has recently been conducted across the Dharwar craton in the north-south direction from Kuppam KUP) to Palani (PAL) (Figs. 1, 2). This profile runs through the entire breadth of the northern block of SGT In this region, crust has been interpreted as consisting of four

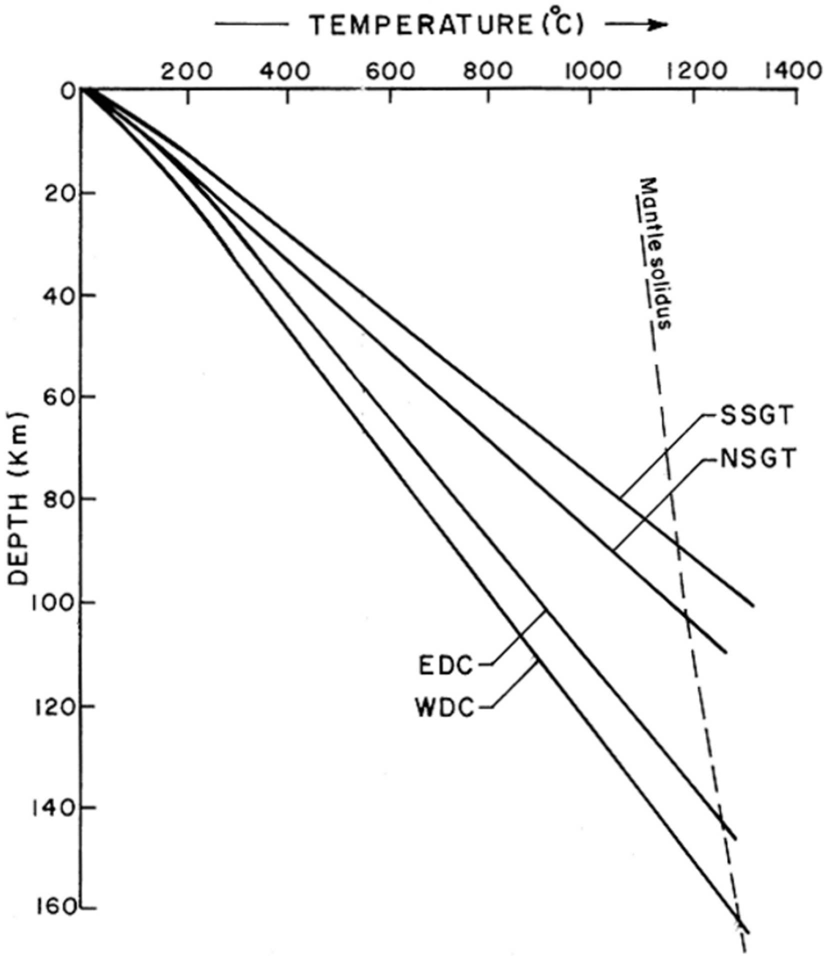

Fig. 4. Temperature-depth distribution in WDC, EDC, NSGT and SSGT.

Table 1. Geothermal parameters of the cratonic segments of south Indian shield.

	WDC	EDC	NSGT	SSGT
Number of q data	5	43	10	3
Heat flow range (mW/m^2)	28–37	23–75	28–42	40–55
Mean heat flow (mW/m^2)	31 ± 4	40 ± 11	36 ± 4	47 ± 8
Heat generation (μW/m^3)	0.81	1.48	0.21	0.90
Reduced heat flow (mW/m^2)	23	25	34	38
Estimated temperature at 40 km (°C)	358	407	485	561
Estimated depth to Asthenosphere (km)	163	142	103	88

Data Source: Gupta *et al*. (1987, 1991); Roy and Rao (2000); Gupta and Rao (1970); Rao *et al*. (1976, 2001); Ray *et al*. (2000).

layers corresponding to upper, middle, low velocity layer and the lower crust (Reddy *et al*., 2003). P-wave velocities for these layers are 6.1–6.3, 6.5–6.55, 5.90–6.05 and 7.1 km/s respectively (Fig. 6). Moho is identified at a depth of around 40–45 km.

Recent analysis of teleseismic receiver function (Gupta *et al*., 2003; Sarkar *et al*., 2003) also suggests a considerable shallowing of Moho in EDC (average ~35 km) compared to an average of ~44 km in WDC and ~46 km in SGT. If we take into account an erosion of 15–25 km from SGT, then almost a doubling of crust is envisaged there, consequent to a possible subduction of WDC underneath SGT during Archean times (Pandey and Manglik, 2003). In that case, the low velocity layer found beneath SGT would correspond to a sandwitched granitic crust.

5. Subcrustal Tomographic Study

Srinagesh and Rai (1996) carried out a three-dimensional P-wave velocity tomographic study using teleseismic rays from a variety of azimuths to find velocity structure of the

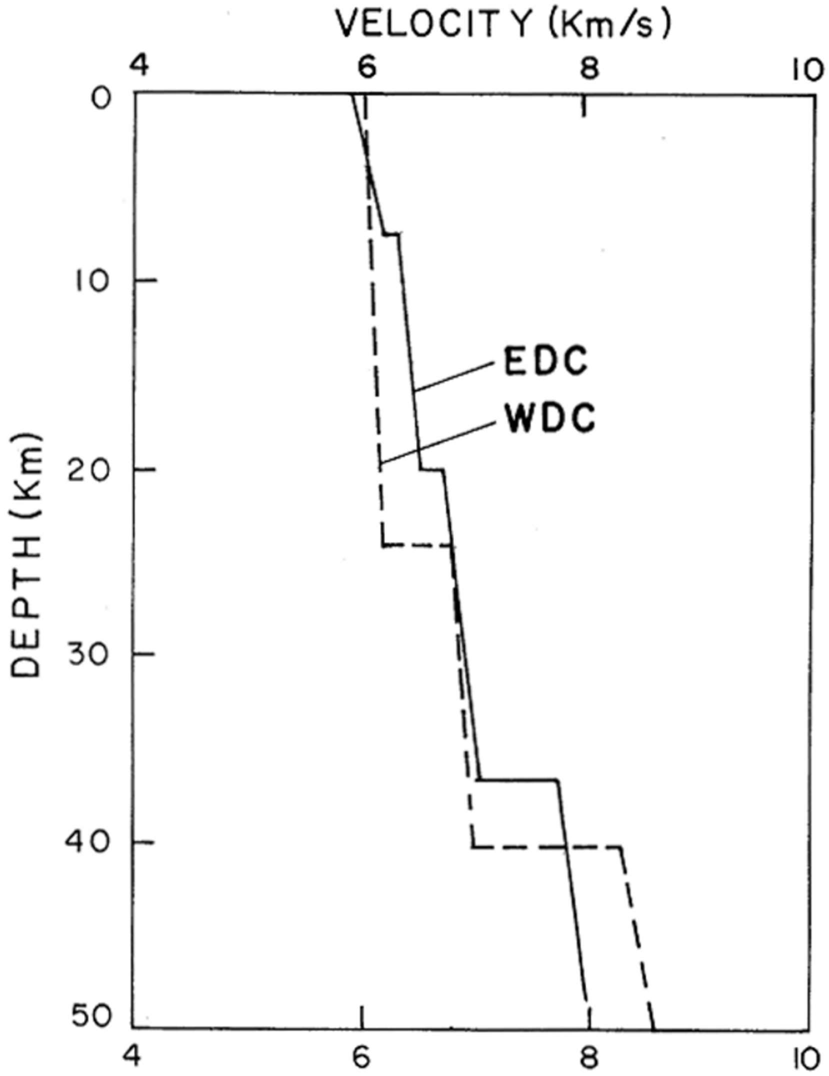

Fig. 5. Crustal P-wave velocity-depth distribution for WDC and EDC (after Reddy *et al.*, 2000).

crust and uppermost mantle beneath south Indian craton. According to them, the tomographic images of various geotectonic blocks show a definite correlation with surface geology and velocity images in the upper mantle to a depth of about 177 km. Averaged P-wave velocity variations beneath these regions at the depth range of 40 to 177 km (corresponding to the lithospheric mantle) reveals large differences in the velocity features (Fig. 7). For example, higher velocities of about 1 to 2% is observed beneath WDC compared to much lower velocities of -0.3% to -1.6% beneath SGT and -0.4% to -1.8% beneath EDC. It may be of interest to note that between WDC and SGT there is a velocity contrast of almost 2% to 3% at the lithospheric mantle level. Higher upper mantle velocity beneath WDC can be attributed to relatively cold nature of the lithosphere relative to EDC and SGT.

6. Gravity Anomaly Pattern

Gravity field has been gainfully utilized to understand the subsurface mass/density distributions and also the extension of concealed geologic features. Depending upon the wavelength the Bouguer gravity anomaly may be caused due to sources lying in the crust or beyond. The contours of a carefully prepared gravity map can be a useful guide in understanding the trend of the extension of a geological formation. The regional gravity map of a part of the south Indian shield (Fig. 8) (NGRI, 1975) depicts contour patterns over WDC, EDC and SGT. An examination of the anomaly map shows that the trend of the gravity contours in the EDC and WDC is NW-SE while over SGT it is dominantly NE-SW. Observed gravity patterns in SGT appear to continue into EDC as shown by the solid dotted line. It may be pertinent to mention here that a high order negative gravity bias (around -120 mgal) noticed over WDC compared to EDC and SGT, may be attributed to the fact that WDC has remained altogether unaffected by the past tectonothermal events indicating relatively cold and thicker lithosphere associated with higher uppermost mantle velocity (Fig. 7).

7. Upliftment and Erosion of Greenstone Belt in EDC

Except cratonic areas of WDC, almost the entire southern shield has been episodically uplifting which seems to be continuing even today. (Radhakrishna, 1993) (Fig. 2). Its surrounding region, like the Western Ghats bordering Deccan

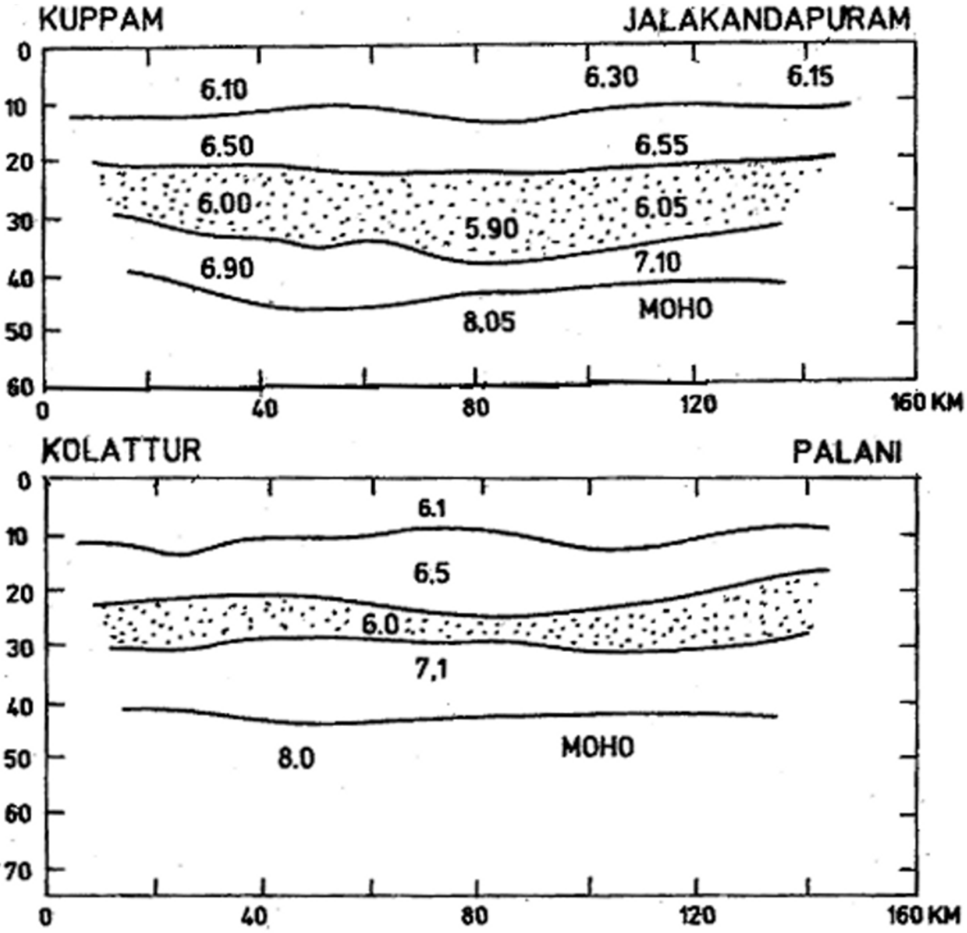

Fig. 6. 2-D velocity structure along Kuppam—Jalakandapuram and Kolattur—Palani traverses the location of which is shown in Figs. 1, 2 (Reddy *et al.*, 2003). Dots refer to low velocity zone.

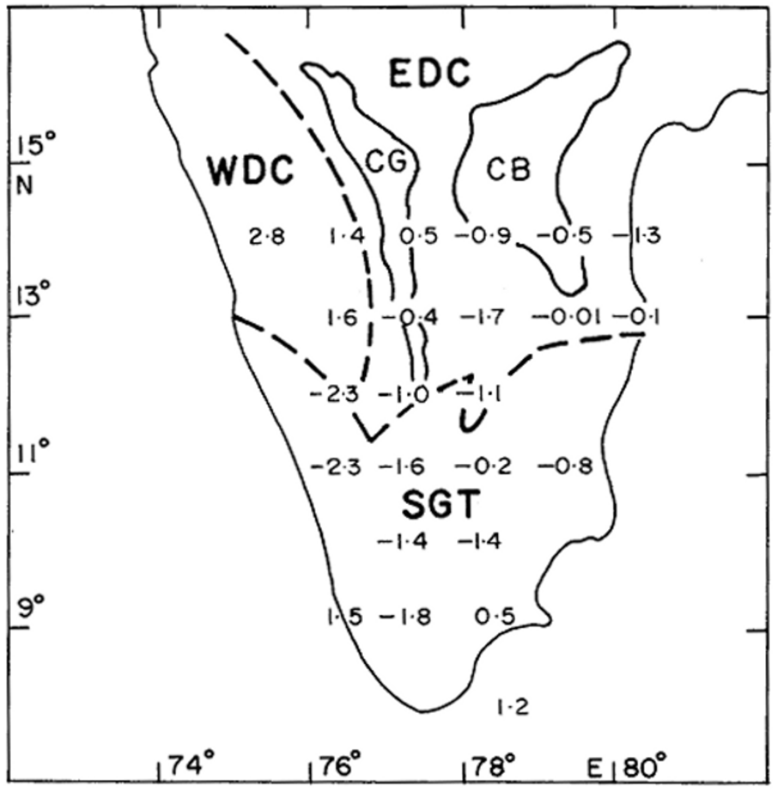

Fig. 7. Averaged P-wave velocity variations (%) at the depth level of 40–177 km in the Southern Indian shield (after Srinagesh and Rai, 1996). CG: Closepet granite; CB: Cuddapah basin.

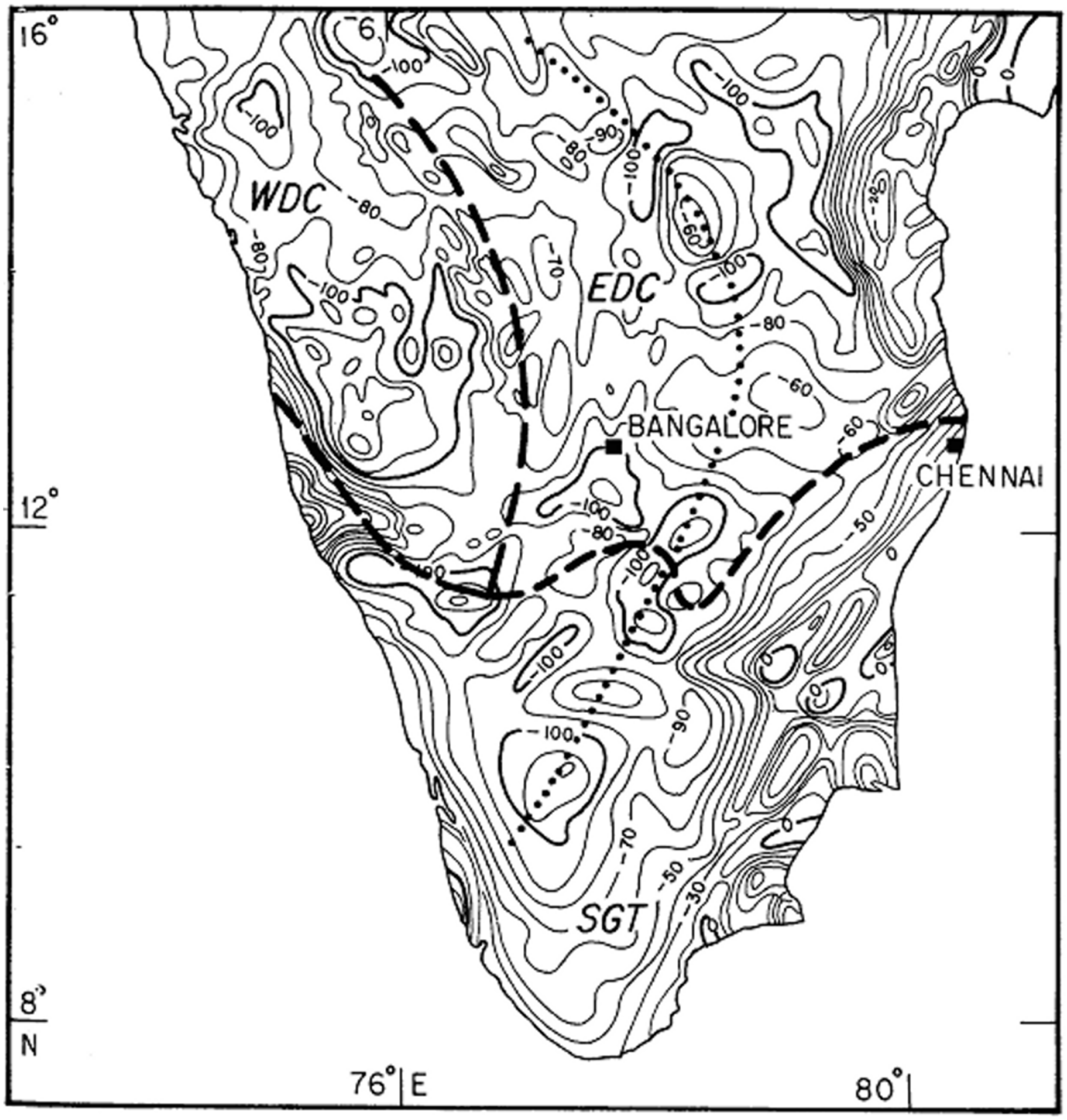

Fig. 8. Bouguer gravity anomaly map of India (Scale 1:5000,000) (NGRI, 1975). Possible extension of gravity trends from SGT to EDC is shown by solid dotted line.

Traps on the west coast and the Eastern Ghat physiographic province (EGMB) (Fig. 2) has also been uplifting (Ramkrishnan *et al.*, 1994; Babu, 1998). Due to uplift and denudation, once quite thick (5 km or even more) exposed greenstone belts which earlier covered the entire southern shield till the close of the Dharwar age, appears to have been removed away from the surface (Babu, 1998). As a result, we now only see the underlying granite-gneiss rocks exposed at the surface. Only a few narrow strips of the greenstone schist belt now remains between Closepet granite (CG) and Nellore schist belt (NSB). The latter is still about 22 km wide and 0.8 to 1.5 km thick and shows marked resemblance with the Holenarsipur schist belt (>3.0 Ga) of WDC.

8. Discussion of Results and Conclusions

Presently the south Indian shield appears to form a mosaic of several blocks, evolved at various times by different geotectonic processes. Numerous tectonothermal events, encompassing almost entire Proterozoic period appears to have affected the greater part of this region, particularly EDC and SGT. For example, a close look at Figs. 5 and 6 would reveal that P wave velocity in upper crust is much lower (6.0 to 6.2 km/s) in WDC than EDC and SGT. Similarly Pn wave velocity of 8.4 km/s below WDC is much higher than 7.8 km/s recorded below EDC. Similar is the case for the mantle lithosphere (40–177 km) where seismic tomographic modelling indicates the presence of 1% to 2% higher velocities beneath WDC, compared to much lower velocities beneath EDC and SGT (Fig. 7). The lithospheric thermal picture reveals similar pattern (Table 1). Lithosphere is colder and much thicker beneath WDC compared to other tectonic segments. Apart from this, there is a presence of mid-crustal high conductivity layer in EDC (Gokarn *et al.*, 1998; Sastry *et al.*, 1990) and low velocity layer (~6.0 km/s) in SGT. No such high conductivity/low velocity layer is reported from WDC.

Moreover, there are several regions in EDC and SGT which are neotectonically uplifting (Fig. 2) and have remained active since late Archean with large scale episodic crustal remobilisation, kimberlitic, granitic and basic dyke intrusions. Kimberlitic intrusions occuring in the proxim-

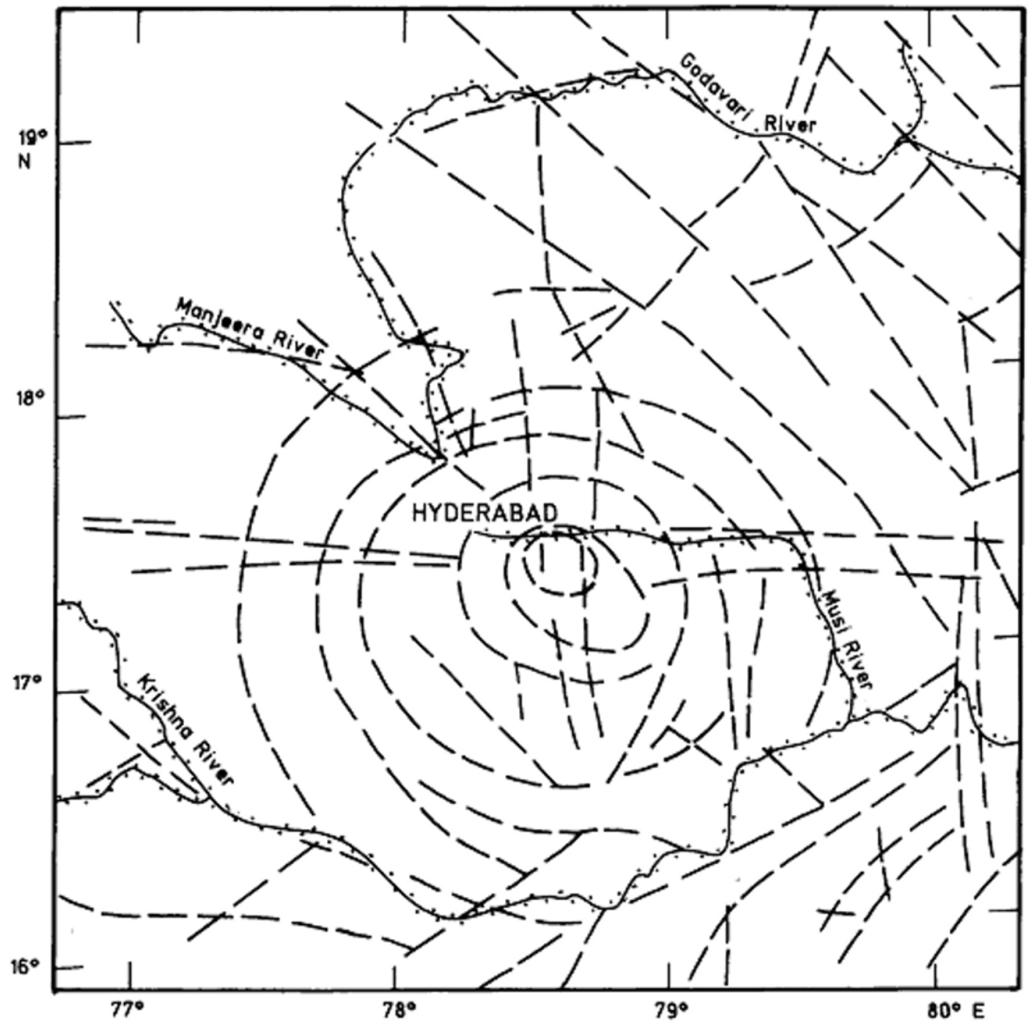

Fig. 9. Morpho-structural pattern around Hyderabad segment of EDC (revised after Rantsman *et al.*, 1995).

ity of the intersection of major structural lineaments in EDC (Chetty, 2000) are absent in WDC. Geophysically too, the lithosphere beneath EDC and SGT differs from that of WDC, although they may appear to be similar to each other. P-wave velocity of 6.3–6.5 km/s obtained between the depth of 8 and 20 km beneath EDC compares favourably with that of 6.5 km/s between 10 and 20 km depth in SGT (Figs. 5, 6). Similarly lower crustal velocity between 30 km and Moho is almost identical (6.9 to 7.1 km/s) for both the segments.

Since upper crustal granulites in SGT are associated with velocities of 6.1–6.3 km/s (Fig. 6), the velocities of 6.3–6.5 km/s obtained below 8 km in EDC would definitely correspond to granulite facies rocks. This inference would be strengthened further, if we convert this velocity into density following Barton (1986), Sarma (1994) and Birch's equation (Anderson, 1972). The conversion results in a range from 2.85–3.16 g/cm^3. These order of densities would correspond to Amphibolites in low grade terrain to granulitic facies gneisses, migmatites, Khondalites and Basic—ultrabasic charnockites in high grade terrain (Subrahmanyam and Verma, 1981). Therefore, we infer that below a depth of $\sim$8 km onwards, EDC crust corresponds more closely to SGT which are well supported by geophysical observations (Figs. 3–8). Interestingly enough, average S-velocity and Poisson's ratio are also almost similar (3.7–3.8 km/s and 0.24–0.27 respectively) beneath EDC and SGT (Saul *et al.*, 2000; Ravi Kumar *et al.*, 2001; Gupta *et al.*, 2003).

Geologically, in addition, there are several studies to support the occurrence of granulite facies rocks in several parts of EDC. For example, charnockite assemblage minerals and in particular pyroxene bearing granodiorites and granites are known to occur in the Hyderabad granitic region situated in the northern part of EDC (Sarma, 1954; Sitaramayya, 1971). They evolved at considerable depth from an anatectic melt formed at high temperature ($\sim$800°C) and under 5 to 10 kb water vapour pressure (Sitaramayya, 1971). Our recent geological and geophysical studies of the uplifting Hyderabad granitic region (Pandey *et al.*, 2002) suggests the presence of acid to intermediate grade granulite facies rocks at a shallow depth of about one kilometer or so only, as at least 8–10 km thick high radioactive surface granitic layer has been eroded from this region due to regional upliftment which has controlled the morphotectonics and also severely disrupted the river courses and drainage pattern (Fig. 9). Charnockitisation has also been reported in the banded gneissic granites and alaskites at Nalgonda town of EDC situated about 90 km SE of Hyderabad (Fig. 2) and its surroundings (Somayajulu and Veeraiah, 1981). Besides this, a large zone of exposed

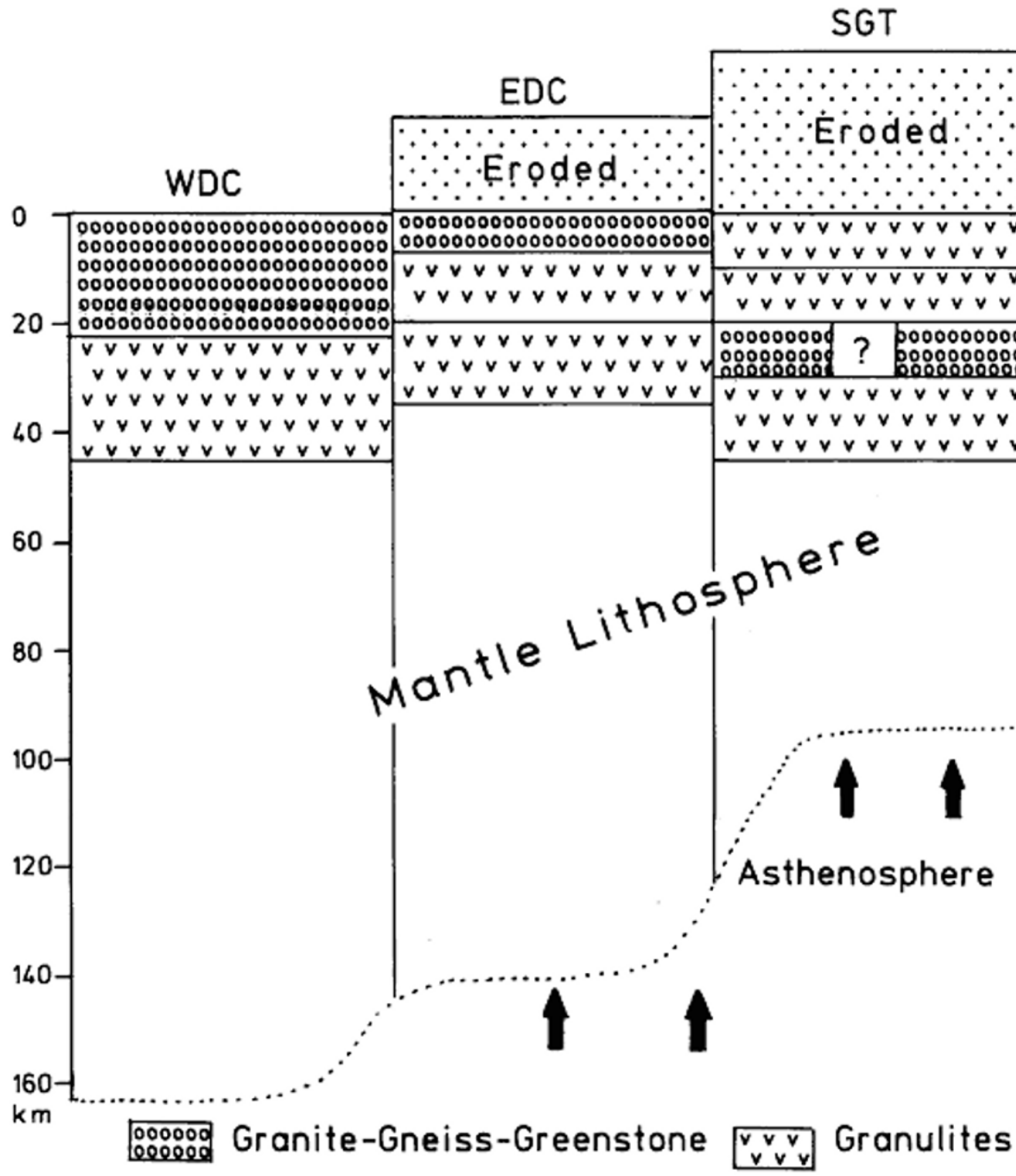

Fig. 10. A possible crustal cross section beneath WDC, EDC and SGT, as inferred from available geological and geophysical informations.

granulite terrain has been discovered paralleling the southern flank of Godavari graben (Rajesham *et al.*, 1993) covering the districts of Kraimnagar, Warangal and Khammam (Fig. 2).

Presence of granulitic facies rocks at a shallow depth beneath EDC is hardly surprising, considering its past geologic history when it experienced extensive tectonothermal magmatic activities at around 2.7–2.2 Ga, 1.9–1.8 Ga, 1.2–1.1 Ga, and 0.85–0.5 Ga (Naqvi and Rogers, 1987; Rogers and Callahan, 1987; Acharya, 1997; Anil Kumar *et al.*, 1993; Radhakrishna and Naqvi, 1986 etc.). The earliest activity (2.7–2.5 Ga) was caused by a rising mantle plume beneath a matured ancient crust which induced low degree melting of upper mantle resulting in generation and accretion of large quantity of calc-alkaline magmas observed in EDC (Jayananda *et al.*, 2000; Harish Kumar *et al.*, 2003). In fact, all other Proterozoic thermal events might have some associations with the rising mantle plume in some way or the other. For example, the presence of large number of exposed Proterozoic kimberlites ($\sim$1.1 Ga) and lamproites are nothing but plume generated. The plume origin conforms well with the models of the crystallisation of diamonds in the subcontinental lithosphere (Haggerty, 2000). Besides, this region has also been affected by a major plume activity as late as 110–88 Ma (Curray and Munasinghe, 1991; Storey, 1995) which is well reflected in various geophysical fields (Reddy *et al.*, 1993). The heat and fluids associated with these plume-generated magmatic activities seem to have caused crustal reworking, differentiation, dehydration and high temperature–low pressure metamorphism, besides large scale regional uplifting and consequent erosion. This is the reason why a thick column of greenstone sequences from EDC has disappeared leaving behind only a few of its remnants and exposures at the surface. In fact, almost 15–20 km of the upper crust or even more is reported to have been eroded away from the Archean low- to high-grade transition zone lying around 12–13°N (Condie *et al.*, 1982) In some parts of the SGT, even the deepest part of the granulitic crust is now exposed.

We believe that the southern Indian shield, comprising now of WDC, EDC and SGT segments were a coherent crustal block till about late Archean which became geologically and geophysically different during course of time lending credence to the observations of Rogers (1986). These blocks became unrelated as they evolved, differentiated and metamorphosed consequent to episodic lithosphere-plume interaction. Lithospheric mantle beneath these regions were not strong enough to resist the forces of these events which ultimately resulted in destroying the deeper roots, thereby causing negative buoyancy. Moho beneath EDC is now at least 8–10 km less than WDC and SGT and its characters are more close to SGT than WDC. A plausible crustal cross section, based on currently available geoscientific data over WDC, EDC and SGT is shown in Fig. 10.

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P. K. Agrawal (e-mail: pramod_matin@yahoo.co.in) and O. P. Pandey