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Gravity Signature, Crustal Architecture and Collision Tectonics of the Eastern Ghats Mobile Belt

Niraj Kumar, A.P. Singh, S.B.Gupta and D.C.Mishra
National Geophysical Research Institute, Uppal Road, Hyderabad – 500 007

ABSTRACT
The Middle-Late Proterozoic Eastern Ghats Mobile Belt (EGMB) exhibits a conspicuous paired gravity anomaly structure with a relative gravity high over the EGMB and low over the adjoining Archaean cratons. 2D gravity modelling across the EGMB, constrained by available seismic information, suggests an eastward dipping crustal column with a thick crust of about 38-40 km under the adjoining older cratons which warped up to 35 km under the younger EGMB. The oblique ridge like structure along with the deep seated intrusive such as anorthosites and carbonatites, and occurrences of ophiolite melange indicate an ancient collision zone along the eastern margin of the adjoining cratons. The westward verging structures together with the exposed charnockite and khondalite rocks along the EGMB may represent lower crustal rock upthrusted from the east to the west. Highly disturbed Middle-Late Proterozoic Purana sedimentary basins abutting the EGMB may represent the peripheral foreland basins over the eastward subducting adjoining Archaean cratons.

INTRODUCTION

The Middle-Late Proterozoic Eastern Ghats Mobile Belt (EGMB), straddling along the east coast, is the most conspicuous curvilinear feature on the geological map of the Indian shield (Fig.1). The 900 km long NE-SW trending EGMB is narrow (~30 km) in the southwestern part and much wider (~300 km) in the northeastern, with a distinct break coinciding with the Godavari rift. On the whole, EGMB is an incomplete mobile belt truncated by the Bay of Bengal and covered by the Phanerozoic continental margin sediments. It is an intensely deformed part of Southwest U.S.–East Antarctic (SWEAT) orogeny with structures having vengeance to the northwest, and metamorphosed under granulite grade (Rao et al. 1995). Bounded by the Archaean Dharwar, Bastar and Singhbhum cratons, the crustal scale terrain boundary shear zone (Biswal et al. 2000) marked by an eastward dipping thrust fault, defines a cryptic suture parallel to the regional NE-SW grain of the EGMB (Chetty & Murty 1994). The tectonic setting for Nellore schist belt was envisaged as a back-arc basin associated with a subduction zone. The Kandra volcanics or Kandra igneous complex (Rao 1992), associated with the Nellore schist belt, are considered by Leelanandam (1990) as possible ophiolites. The gneiss of Khammam schist belt, further north of the Nellore schist belt, exhibits 'arrested charnockitization' features and contains enclaves of charnockite and pyroxene granulite, and these are interpreted to be the lower crustal assemblages of a collision zone (Ramam & Murty 1997). Another significant feature associated with this belt is the large Archaean metamorphosed anorthositic complex, which further vindicates the tectonic setting of oceanic crust (back arc basin) environment (Leelanandam 1987; Ramam & Murty 1997).

Terrains of high-grade metamorphic rocks along ancient sutures have long been suspected to represent exposures of the lower continental crust (Fountain & Salisbury 1981). Evidences of its exposition through continental collision include (1) juxtaposition of dissimilar provinces across a major fault/suture zone, (2) contrasting radiometric ages (3) different metamorphic grades in the mobile belt and the craton adjacent to the belt, (4) different heat flow/heat production regime, (5) dipping sub surface structure, and (6) paired gravity anomaly with steep gradient across the craton-mobile belt boundary (Fountain & Salisbury 1981). In the present paper an endeavour is made to combine geologic, geochronologic, geodynamic/tectonic information and associated seismic and gravity signatures over this area, which have a bearing on its evolutionary history. Emphasis is given to the lower crustal level, which is most significant for geodynamic models and where the crustal configuration is otherwise least resolved. The unified 2-D density model of the EGMB crust/mantle system is then used to elucidate an integrated evolutionary history of the EGMB.

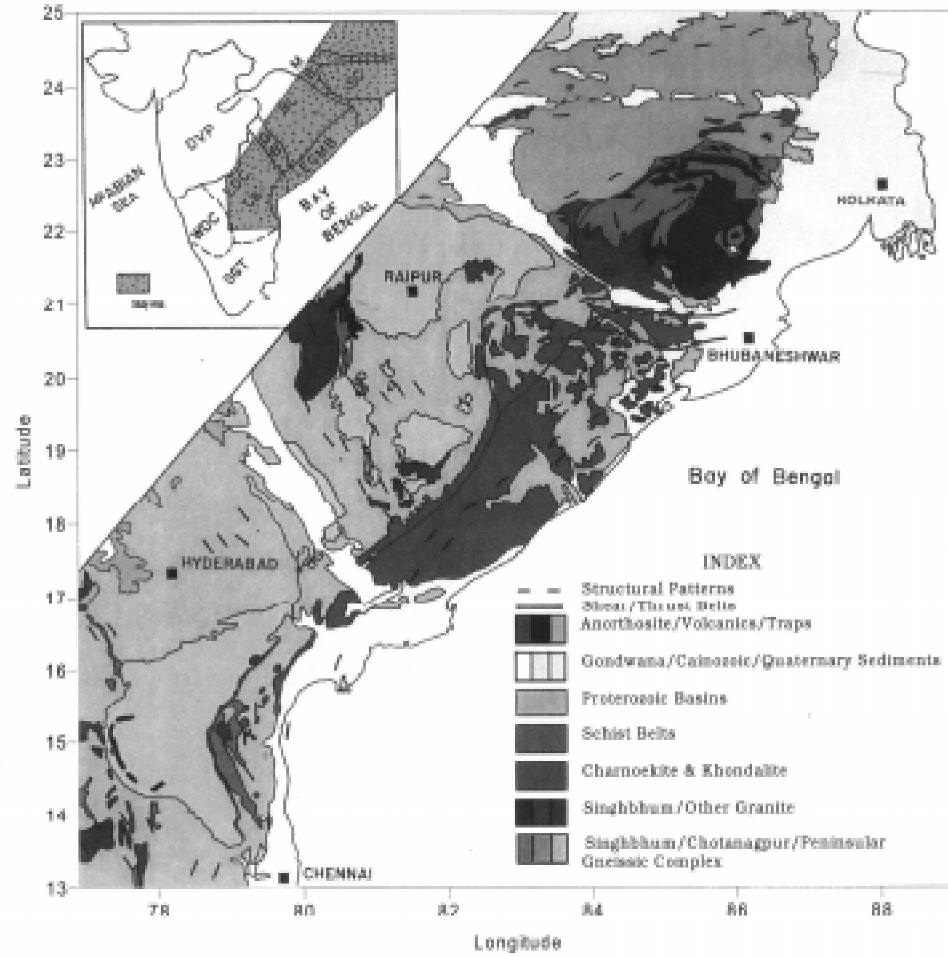

Figure 1. Generalized geological map of Proterozoic Eastern Ghats Mobile Belt and adjoining Archaean cratons showing major shear/suture zones (after Chetty & Murthy 1998), structural patterns and occurrences of anorthosite (after Leelanandam and Reddy, 1998). Abbreviations used as DVP: Deccan volcanic province, EDC: Eastern Dharwar craton, EGMB: Eastern Ghats mobile belt, SGT: Southern Granulite Terrain, WDC: Western Dharwar craton, CB: Cuddapah basin, GB: Godavari basin, MB: Mahanadi basin, and SC: Singhbhum craton.

GEOLOGICAL SIGNATURES OF COLLISION TECTONICS

Juxtaposed dissimilar structural provinces:

The broad structural pattern in the Eastern Dharwar and the Bastar cratons is NW-SE (Fig.1). The Proterozoic Cuddapah, Chattisgarh and Indravati basins have a structural pattern paralleling broadly the orogenic trend of the EGMB. The almost orthogonal structural pattern in the EGMB is contrary to that of the adjoining cratons. The NE-SW trending "Eastern Ghats Trend" is a product of close parallelism of bending, compositional layering and lithological contacts.

Changing metamorphic grade:

Archaean granite and gneisses form the basement in the Eastern Dharwar craton, the Bastar craton and the Singhbhum craton (Fig.1). They host a series of linear and irregular Schist belts with mainly volcanic rocks. The voluminous plutonic intrusion of K-granites reveals the juvenile crustal accretion of the region (Naqvi & Rogers 1987; Jayananda et al. 2000). The Cuddapah, Chhattisgrah and Indravati basins display the development of lower argillo-arenaceous sediments of Proterozoic age. In contrast the EGMB, is mostly made up of high-grade metamorphic (granulite facies) rocks, such as charnockite, mafic granulite, khondalite and leptynite (Dasgupta 1998). Granite, gneiss and

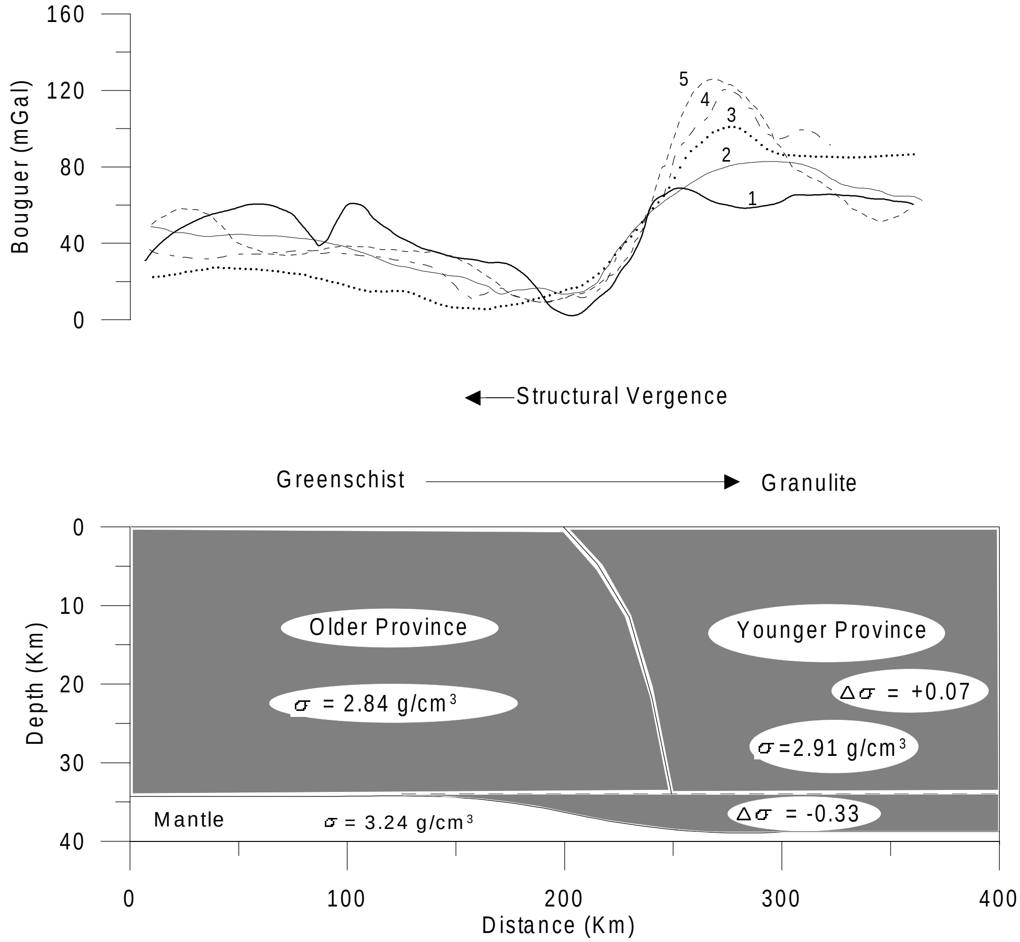

Figure 2. Four gravity profiles across boundaries of various Precambrian structural provinces or terrain's and one profile across Appalachian Orogen. Profile 1 crosses eastern margin of West African Craton (»600 Ma). Profile 2 is mean curve for five profiles crossing boundaries of Canadian Shield that juxtapose variously »2560 Ma and »1000 Ma, and »1800 Ma and »1000 Ma terrains. Profile 3 is mean curve for nine profiles crossing Appalachian Orogen and may reflect » 450 Ma collision. Profile 4 crosses from Archaean Dharwar Craton into Proterozoic Eastern Ghats Mobile belt (1600-1300Ma) of Indian Shield. Profile 5, in Australia, crosses from >2300 Ma Yilgran Block into the Fraser Orogenic domain affected by a series of Proterozoic orogenic events commencing with high-grade metamorphism 1950-1800 Ma. A typical model based on mean Canadian Shield profile is also illustrated. Major geological features of suture zones are indicated (after Thomas 1992).

limited occurrences of carbonatite, syenite and anorthosite form the next most important lithologic unit in the EGMB (Leelanandam 1990; 1993).

Regional Pattern of Isotopic Age

The basic rock types of the Eastern Dharwar craton range in age from 2700 to 2500 Ma (Naqvi & Rogers 1987). However, the evolution of the Purana sedimentary basins abutting the EGMB is around 1600 to 1800 Ma (Craford & Compston 1973). The Singhbhum craton is even an older nucleous of the Indian shield (Naqvi & Rogers 1987). Though the number and ages of metamorphic events in the EGMB are debatable, up to four metamorphic episodes are proposed. The age of the most widespread episode when most of the granulites in the belt are formed is around 1,000 Ma (Grew & Manton 1986; Paul et al. 1990; Sarkar & Paul 1998). The granites that are deformed and regarded as syntectonic were emplaced about 1,600 Ma ago (Gupta et al. 1984). Similarly, a mafic/anorthositic body was emplaced syntectonically about 1,400 Ma ago (Sarkar et al. 1981). Alkaline plutons are post-tectonic one and have an age of about 1,300 Ma (Clark & Subba Rao 1971; Subba Rao et al. 1989).

A faulted contact:

Fermor (1936) suggested that the granulite terrain as a whole has been block uplifted and thrust over the adjoining parts of the non-charnockite terrain along a deep-seated fault. Banerjee (1990) considers the central EGMB, north of Godavari Rift, as a horst bound on all sides by faults. The NE-SW trending Sileru shear zone is regarded as a major shear/thrust zone between the Archaean granite-greenstone terrain in the west and the EGMB in the east (Subrahmanyam 1983; Chetty & Murthy 1994). The Angul-Dhenkanal shear zone is the eastward extension of the Sileru Shear zone and represents a collisional boundary associated with transpressive tectonics of dextral nature (Chetty & Murthy 1994). The Cuddapah eastern margin thrust defines the western contact of the EGMB with the Dharwar craton in the sector south of the Godavari River (Radhakrishna & Naqvi 1986; Naqvi & Rogers 1987; Singh & Mishra 2002).

GRAVITY SIGNATURE OF COLLISION TECTONICS

Paired (positive and negative) gravity anomaly encountered across such juxtaposed crustal provinces worldwide (Fig.2) characterizes a particular crustal configuration that is commonly developed at collision zones namely, Greenville-Superior-Churchill provinces in Canada, the Limpopo belt-Kaapvall craton in South Africa, the Fraser block-Yilgarm shield in Western Australia, and the Ivrea zone of Italy (Gibb & Thomas 1976; Wellman 1978; Coward & Fairhead 1980; Fountain & Salisbury 1981; Gibb et al. 1983; Reeves 1985; Thomas & Gibb 1985; Thomas 1992;). The gravity anomaly decreases by about 40 to 50 mGal over a distance of about 210 km as we come from the older province towards the younger one and then rises sharply with a steep gradient by about 80 to 100 mGal within about 80 km of contact of the two provinces. The gravity field over the younger province is about 24 mGal higher than the regional background over the older province. In order to explain this anomaly a down flexuring of the crust of normal density underlying the older province was envisaged to account for the negative anomaly and a thicker as well as a denser crust underlying the younger province was envisaged to account for the positive gravity field (Gibb & Thomas 1976; Gibb et al. 1983).

NATURE OF THE BOUGUER ANOMALY ACROSS THE EGMB

The Bouguer anomaly map of the EGMB and adjoining Archaean cratons is shown in Fig.3 (NGRI 1978). Though the gravity field of each province distinguishes itself from others but the overall pattern shows the characteristic pattern observed world over. The Bouguer anomaly map of the EGMB shows a distinctive linear gravity high following the structural trends within the belt with a conspicuous break in the Godavari valley graben. This gravity high is flanked to the west by a series of gravity lows with a steep gradient. The most prominent gravity low aligned parallel to the eastern margin of the Cuddapah basin where it juxtaposes with EGMB. Similarly, in the vicinity of the Bastar-EGMB boundary, a belt of gravity lows over the eastern margin of the Bastar craton is followed to the east by a rise in the gravity field over the EGMB. That the Fermor's (1936) boundary, towards the north, takes an abrupt eastward turn, running parallel to the southern margins of the Mahanadi basin, extends right up to the east coast north of Bhubaneshwar, the gravity contours (Fig. 3) follow the same course taking an abrupt E-W trend over the Mahanadi basin. The EGMB, along this Mahanadi basin, is juxtaposed against the Singhbhum craton over which the gravity contours show a relative low. Thus, from the southern tip of the Cuddapah basin, up to the Singhbhum craton, the parallelism between the gravity contours and the structural grain of the EGMB with crowding of gravity contours along the EGMB boundary suggests a faulted contact bringing in close juxtaposition of crustal blocks of contrasting character (Subrahmanyam 1978, 1983). Similar to characteristic gravity signature observed across the juxtaposed crustal provinces worldwide, the average gravity anomaly decreases as we come from the adjoining Archaean cratons towards the younger EGMB and then rises sharply with a steep gradient across the contact of the two provinces (Fig. 2). The gravity field over the EGMB is higher than the regional background over the Archaean cratons. Following the arguments discussed above the steep gravity gradient across the boundary of the Archaean cratons/EGMB was explained in terms of two crustal domains with a density difference of 0.07 to 0.1 g/cm^3 (Subrahmanyam & Verma 1986; Verma & Satyanarayana 1990) ignoring the layered crustal configuration of the region (Kaila et al. 1979, 1987).

UNIFIED SUBSURFACE CRUSTAL STRUCTURE

Quantitative gravity modelling is inherently nonunique, particularly on a crustal scale where our knowledge is inadequate. Its integration with deep seismic depth sections provides an excellent tool to model the crustal architecture. The two available depth-migrated seismic sections across Cuddapah

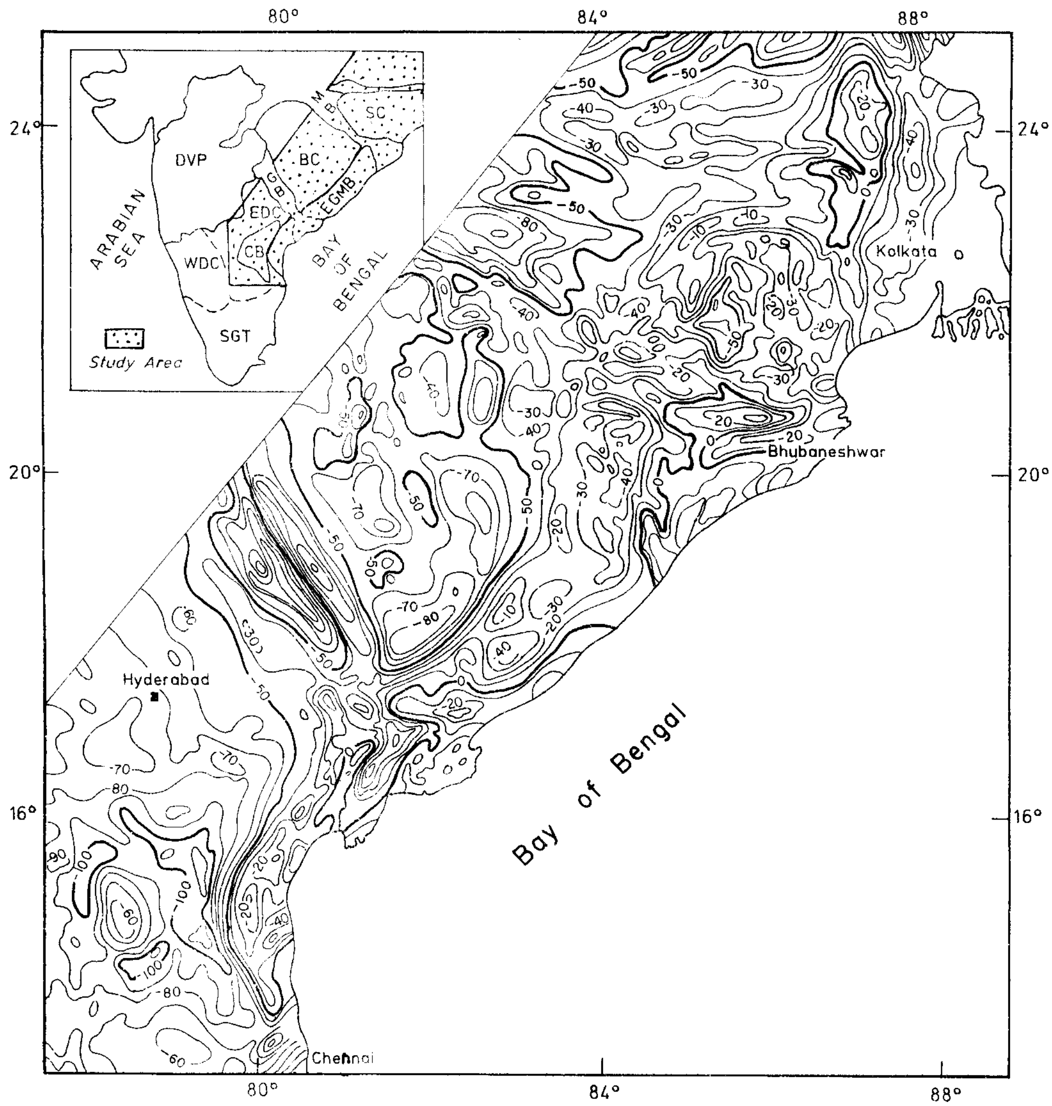

Figure 3. Nature of the Bougure anomaly (in mGal) over the study region (after NGRI, 1978) showing strong gradient along the contact zone.

basin-EGMB junction, clearly shows a three layer crustal configuration beneath the region (Kaila et al. 1979, 1987). All the reflectors from shallow depths to the Moho boundary show a consistent down dip towards east as if the entire crustal column has buckled down in the eastern part of the Cuddapah basin. The EGMB situated on the eastern margin of the Cuddapah basin, has moved upwards and overridden the basin causing an over thrusting of the Nallamalai formations (Kaila et al. 1979, 1987).

The observed Bouguer anomaly along the available two DSS profiles was modelled by Singh and Mishra (2002). Following that analogy, the averaged profile after Subrahmanyam and Verma (1986), is modelled again constraining from the available seismic information discussed above (Fig. 4). The gravity profile is characterized by a broad relative gravity low over the adjoining Archaean cratons and a broad gravity high over the EGMB. The gravity low over the older provinces is modelled with the eastward dipping crustal columns i.e., the upper and the lower crusts and the Moho as suggested by the seismic section (Kaila et al. 1979, 1987). Corroborating the gravity gradient, the entire crustal column including the Moho was warped up beneath the EGMB. The broad gravity high over the EGMB is thus accounted for by a high-density oblique ridge like body, constrained from the high-

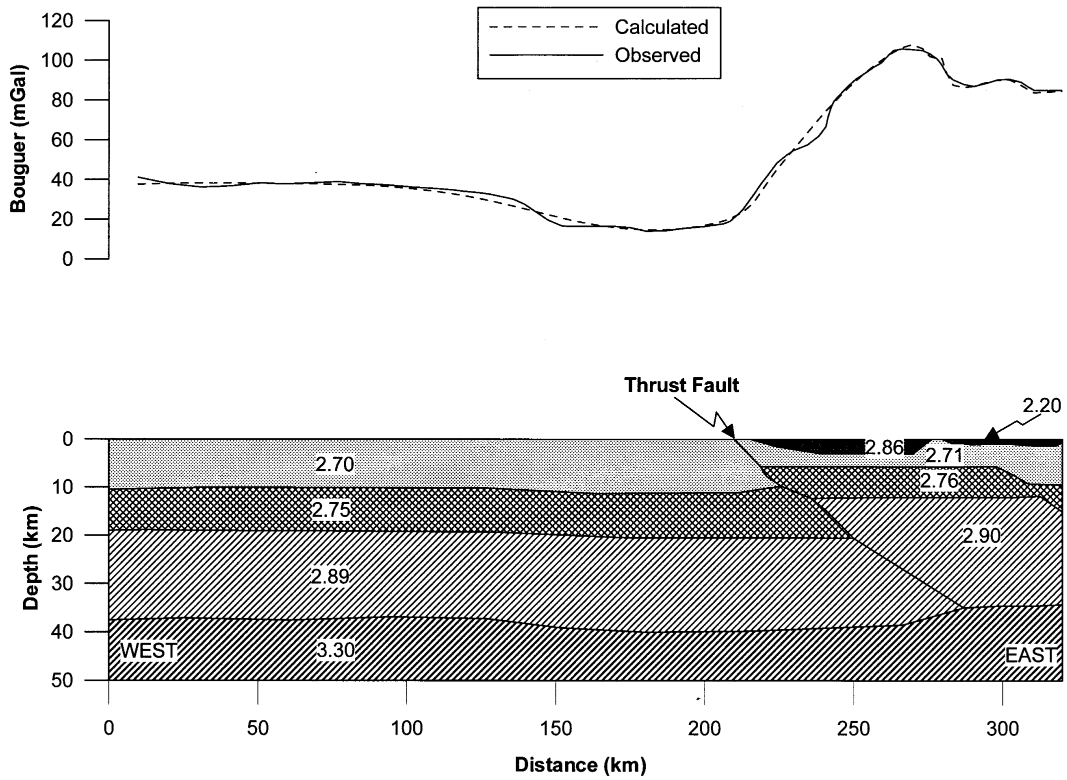

Figure 4. 2-D crustal configuration along the same profile (No. 4 in Fig.2) showing an overall thicker crust beneath the adjoining older (Archaean) cratons and a thinner crust beneath the younger (Proterozoic) EGMB. Their contact zone signifies the welding of two distinct crustal domains through continental collisions. Densities are in g/cm^3.

seismic velocity (V_p=7.2 km/s), sitting over the Moho warped up to a depth of 35 km beneath the coastal region. Small wavelength high spreads over the outcrop of the charnockite; schist belts and gabbroic rocks in the surrounding areas may have caused the same. The coastal gravity low spreads over the alluvial covered area of the coastal regions of the EGMB and therefore adjusted by known Quaternary sediments (ρ=2.10 g/cm^3) exposed at the surface (Singh & Mishra, 2002).

DISCUSSION

Deep Crustal Architecture:

An early work based on the Bouguer anomaly and elevation data (Narain 1973) shows the depth to the Moho near Eastern Indian craton around 40 km. Subrahmanyam and Verma (1986) and Verma and Satyanarayana (1990) also envisaged a normal crust with Moho at a depth of 38 km beneath the adjoining Archaean cratons. In their gravity model the EGMB crust is denser and thicker than that of the Dharwar and Bastar cratons. In contrast Kaila and Bhatia (1981) assumed a modified crust over the EGMB with the presence of a layer with density of 3.05 g/cm^3 above the Moho. The oblique ridge like high-density body together with the shallower than normal crustal thickness beneath the EGMB was suggested as the cause for the referred gravity gradient. The inferred oblique ridge like structure originating right from the base of the up warped crust all along the EGMB therefore assumes a special significance in the realm of present day structure and Proterozoic geodynamic evolution of the EGMB (Singh & Mishra 2002).

Geodynamic Link:

Terrains of high-grade metamorphic rocks (granulites) along ancient sutures have long been suspected to present exposures of the lower continental crust. In view of exposed charnockite and khondalite rocks, the oblique ridge like crustal configuration (Fig. 4) appears to represent the lower crustal rocks thrust upwards from the east to the west. The existence at the surface at the present day of rocks of such deep-seated metamorphism implies uplift and profound erosion. The belt can be regarded as a "vestigial facet", i.e. an exhumed basal part of an orogenic belt, planed off by erosion.

Their metamorphic pressure-temperature-time history provides vital information about the tectonic settings and evolutionary processes operative within the region. Earlier the high temperature-pressure regime required for the regional high-grade metamorphism was explained by the addition of mantle-derived magma at the base of the crust (magmatic underplating). The subsequent vertical upliftment and deep erosion was held responsible for its exposition on the earth's surface. With the advent of plate tectonics, an alternative mechanism was proposed for producing such exposures. One of the most attractive of these mechanisms is the obduction of lower crustal layer through continental collision. The upward movement and subsequent erosion would then expose the lower crust along the suture (Fountain & Salisbury 1981). Although these two end member models are equivocally proposed for the evolution of the EGMB, the latest observations seems to converge around a continental-continental collision model (Subrahmanyam & Verma 1986; Chetty & Murthy 1994; Singh & Mishra 2002). Being deeply eroded part of the SWEAT orogenic belt located along the juxtaposed margins of the India and Antarctica and in view of the correlation of the Dharwar craton and the EGMB with the Napier complex and Rayner complex, respectively, presumed collision is believed to be between the cratons on the India and Antarctica during Middle-Late Proterozoic times. The geometry of the folded and shear belts within the EGMB may be even better explained, with an oblique collision instead of a straight collision (Chetty & Murthy 1994).

Origin of Anorthosites:

The EGMB forms a belt of terrain that is host to majority of the known massive-type anorthosites in India, except that of Bengal (Fig.1; De 1969). The origin of these rocks remains a controversial and problematic issue, so much so in fact that Philpotts (1981) considered that "origin of large Precambrian anorthosite massifs remains one of the major unsolved problems of petrology". One controversy concerns the "granitic" components of the anoprthositic suite that are often found intimately associated with anorthositic and mafic elements. On one hand, these have been explained as a fractional differentiation product of the parent magma that produced the anorthositic components (Morse 1969), while on the other hand it has been argued that "granite" and anorthosite are not comagmatic (Emsile 1987). De (1969) states that all the EGMB anorthosites are intruded into catazonal metasedimentary rocks, which are thought to have formed, near the base of the crust (Isachsen 1969). The pattern of distribution of the Indian anorthosites may therefore trace the axis of an orogenic belt, the line connecting the outcrops having once been rectilinear or simply arcuate.

Though, no Indian anorthosites have been dated Sarkar et al. (1981) and Sarkar and Paul (1998) have argued, that their ages fall within the range 1300-1520 Ma. Most of the massive anorthosites of EGMB occur in the western and northern margins of the belt, but for the concentration in Chilka Lake. The occurrences of intrusive and grabbroic anorthosites over the EGMB was taken as the surface manifestation of the high-velocity/high-density subsurface oblique ridge like body (Kaila & Bhatia 1981). Their origin was in turn genetically linked to possible magmatic/plutonic igneous emplacement at the crust/mantle boundary. According to Bhattacharya & Shalivahan (2002) these massive anorthosites are probably shallow pretectonic intrusives formed during the onset of the rifting of the continental margin, as evidenced by the Chilka lake anorthosites where a cluster of bodies, situated in the eastern part of the EGMB, has perhaps been formed by mantle plume activity. While anorthosites are spread over the EGMB, the alkaline and co-spatial subalkaline plutons are localized closed to the western margin of the EGMB. With widely differing ages, their intrusion through pre-existing weak zones is not compatible with the passage of continent over "plumes" rising from fixed "hot spots" in the deep mantle. Further no direct evidence is available for basaltic underplating at least beneath the southwestern part of the EGMB (Leelanandam 1993). Besides the anorthositic complex of Kanigiri is much older than the Chilka Lake plume activity. According to Ramam & Murty (1997) association of the Nellore greenstone belts and the Kannigiri anorthosite complex vindicates the tectonic setting of Proterozoic continental collision.

CONCLUSIONS

The present synthesis suggests the following evolutionary scenario for the evolution of EGMB. The post-Archaean cratonic stabilization of peninsular shield was marked among others by the evolution of foreland Purana basins around the Dharwar and Bastar cratons about 1600 Ma ago. The EGMB probably developed through obduction along the passive continental margin of the amalgamated cratons by 1500 Ma ago. Alkaline magmatism and anorthositic plutonism became prominent in the continental collision by 1400-1300 Ma. The onset of a compressional regime with forces directed towards northwest resulted in tight to isoclinal folding and development of NE-SW structural grain, parallel to which crustal scale shear zones developed. Concomitant with this deformation, granulite facies metamorphism and migmatisation occurred along the axial zone 1000 Ma ago. The foreland zone of the orogen was marked by the Eastern Ghats front between the sheared eastern margin of the Purana basins and chranockite massifs of the EGMB. Siluru shear zone marks the majority of the boundary of the supracrustal belt with the cratonic basement, which was interpreted as the suture by Chetty & Murthy (1994). The Sukinda thrust likewise marks the northern part of the boundary of the EGMB in juxtaposition with the Singhbhum craton.

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