Chapter 7
Eastern Ghats Mobile Belt

7.1 Introduction: Geological Setting

The Eastern Ghats Mobile Belt (EGMB) derives its name from the mountain of Eastern Ghats in the east coast of India. Apart from reconnaissance survey by individual geologists (C.S. Middlemiss, T.L. Walker, L.L. Fermor, V. Ball), the Geological Survey of India provided a geological map of the EGMB on 1:50,000 scale in later part of the 20th century and also gave periodical reviews in its Reports (see Ramakrishnan and Vaidyanadhan, 2008). Recently, Ramakrishnan et al. (1998) gave a new geological map (1: 1000,000) with a summary of regional geology of the EGMB.

The Eastern Ghats Mobile Belt is a NE-SW trending arcuate Precambrian fold belt of high-grade rocks, extending over a length of ca. 600 km along the east coast of India from north of Cuttack in Orissa to Nellore in Andhra Pradesh (Fig. 7.1). The belt has a maximum width of 100 km in the northern part and less than 20 km in the south where it is concealed under the Phanerozoic cover. The fold belt is in contact with three cratonic blocks, namely the Singhbhum(-Orissa) craton in the north, the Bastar craton in the west, and the Dharwar craton in the south and southwest. To the east of the fold belt is the Bay of Bengal. The boundary between these cratons and the EGMB is termed the *Transition Zone*, having characteristics common to both (see Bhattacharya and Kar, 2002). The contact of western belt of the EGMB against Bastar craton is gradational. Basic granulite, dykes with chilled margins and incipient or arrested charnockite patches are noticed in this marginal zone (cf. Ramakrishnan and Vaidyanadhan, 2008). Around Deobhog, the contact is marked by a Terrane Boundary Shear zone (TBSZ) by Biswal et al. (2004). Shear sense indicators show top-to NW movement. This contact is described as the Eastern Ghats Boundary Shear zone in the map of Ramakrishnan et al. (1998) and is regarded as continuation of Sileru Shear zone. The contact between EGMB and Singhbhum craton is also marked by shear zones, predominantly Sukinda Thrust. The craton-mobile belt boundary is characterized by the occurrence of alkaline rocks in the Bastar and Singhbhum cratons, like those of Prakasan alkaline province in the Transition zone of Dharwar craton to the south of Godavari Graben (Leelanandam, 1990). Alkaline rocks, mainly nepheline syenites are also reported at the contact zone of EGMB-Singhbhum craton in the north as well as in the western

R.S. Sharma, *Cratons and Fold Belts of India*, Lecture Notes in Earth Sciences 127,
DOI 10.1007/978-3-642-01459-8_7,

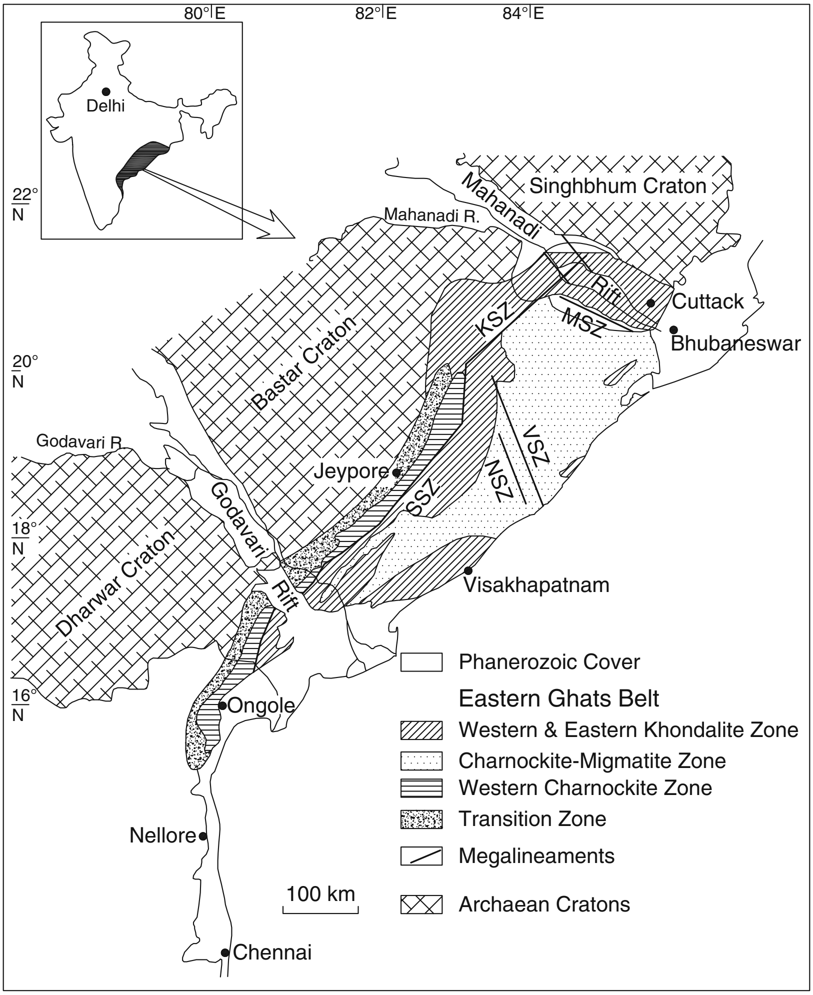

Fig. 7.1 Simplified geological map of the Eastern Ghats Mobile Belt (EGMB) (after Ramakrishnan et al., 1998) with megalineaments after Chetty (1995). MSZ = Mahanadi Shear Zone; NSZ = Nagavalli Shear Zone; SSZ = Sileru Shear Zone; VSZ = Vamsadhara shear Zone. *Inset* shows location of the mobile belt

part of the EGMB, where they are grouped as Khariar Alkaline Complex. These alkaline rocks are deformed and their lenses are seen nearly parallel to the gneissic foliation. The alkaline complex in general has U–Pb and Pb–Pb emplacement ages of 1400–1500 Ma (Upadhya et al., 2006a). The origin of Khariar alkaline complex is attributed to basaltic magma derived from partial melting of enriched lherzolite mantle source within the lithosphere. The basaltic magma fractionated within mantle and gave rise to nepheline syenite (Upadhyay et al., 2006b).

An overview of the EGMB is given by Bhattacharya (1996). The EGMB comprises two major rock groups: one charnockitic and the other khondalitic. The charnockitic group consists of mafic to acidic charnockites, hypersthene-bearing granulites, gneisses and leptynites while the khondalitic group includes garnet-sillimanite gneisses, quartzites and calc-silicates. Based on the dominant lithological assemblages, Ramakrishnan et al. (1998) proposed a 4-fold longitudinal division of the EGMB. These divisions (Fig. 7.1) from W to E are: (1) Western Charnockite Zone (WCZ), dominantly charnockite and enderbite with lenses of mafic-ultramafic rocks and minor metapelites. (2) Western Khondalite Zone (WKZ), dominated by metapelite (khondalite) with intercalated quartzite, calc-silicate rocks, marble and high Mg—Al granulites. The metapelitic granulites are intruded by charnockite/enderbite. Several occurrences of massif-type anorthosites are reported from this zone (Bolangir, Turkel and Jugsaipatna). (3) Central Charnockite-Migmatite Zone (CMZ) has dominantly migmatitic gneisses but also includes high Mg—Al granulites and calc-silicate rocks, all of which are intruded by charnockite-enderbite, pophyritic granitoids and massive-type anorthosite (Chilka Lake region), and (4) Eastern Khondalite zone (EKZ), having lithological similarity with WKZ, but without anorthosite. To distinguish the basement upon which the supracrustals (now seen as metamorphosed metasediments of khondalites, calc-silicates, quartzites etc.) were deposited, as the rocks of the mobile belt, is a very difficult task because of the impress of granulite facies metamorphism on both cover and basement rocks in this region. The recrystallized supracrustals (and their unrecognized basement) and occasionally the charnockite-enderbite rocks have been intruded by post-tectonic alkaline/anorthositic/granitoid rocks. These intrusions are in form of numerous plutons of alkaline rocks, anorthosites and granitoids, and have age range between 1450 and 850 Ma (Subba Rao et al., 1989). According to Ramakrishnan et al. (1998), the stated plutons occur in a linear belt, all along the western margin of the EGMB, between the Western Charnockite Zone (WCZ) and the Western Khondalite Zone (WKZ). But, according to Leelanandam (1997), they occur between the cratonic (non-charnockitic) and charnockitic region (WCZ) of the mobile belt. The presence of several alkaline intrusives in the Transition Zone favours the latter proposition. Several exposures of alkaline complexes have been reported from the high-grade EGMB (Leelanandam, 1998), but structural setting has not been worked out to ascribe them to Rift Valley magmatism or Plume tectonic model. For those alkaline complexes, such as the Koraput complex, which are away from the cryptic suture or the craton-mobile belt contact, rift tectonics cannot be envisaged (cf. Bhattacharya and Kar, 2004; Leelanandam et al., 2006).

The high-grade gneiss-granulite ensemble of the EGMB is surrounded all around by a thrust along which the rocks were thrusted up 10–15 km against the cratonic rocks at the Transition Zone. The thrust is, in fact, a crustal-scale ductile shear zone and defines the western boundary of the EGMB. This shear zone against the contact with Bastar craton is named as Sileru shear zone (SSZ) by Chetty and Murthy (1998), where it is found to be 3.5 km wide. According to Chetty (1995), this shear zone is contemporaneous with the emplacement of extensive alkaline magmatism around Kharia, Koraput and Kunavaram. The northeast termination of the thrust is on the north side of the Mahanadi graben, while the SE margin intersects the coastal plain north of Chennai, thus separating the EGMB from the southern Indian Granulite Terrain (SGT). The thrust is demarcated by low gravity anomaly. To the east of the EGMB there is also a shear zone along Angul-Dhankenal, at which Chilka Lake anorthosites are located (Chetty, 1995).

The EGMB is dissected by two prominent rifts with infillings of the Gondwana (Upper Paleozoic) sediments, which are centred with river-courses of Mahanadi in the north and the Godavari in the south. The Godavari graben also contains Proterozoic sediments (Pakhals) that underlie the Gondwanas. These rifts or grabens trend NW-SE and are thus orthogonal to the general trend of the EGMB (see Fig. 7.1). Merely on the basis of scanty geochronological data and apparently different P-T-paths across the Gondwana graben, Mezger and Cosca (1999) and Sengupta et al. (1990) suggested that the EGMB segments on the N and S of the Godavari rift/graben have different thermal history. If this difference is a geological reality, it must be by reasons other than mantle melting or subcrustal heat variation, because the Godavari graben is devoid of any igneous intrusive material during its formation. The absence of alkaline magmatism in particular also rules out the Godavari graben to be an aulocogen or failed arm (cf. Philpots, 1990). Accordingly, the junction-point of the Godavari graben with the Eastern Ghats Mobile Belt does not represent a triple point (Raman and Murthy, 1997). Hence the suggested difference of thermal history in the north and south of Godavari rift cannot be attributed to mantle plume. We shall examine this aspect later when we discuss the tectono-thermal evolution of the EGMB.

7.2 Deformation

The regional geology of the EGMB is less clear, although a general information on structural geology has been given by Sarkar et al. (1981), Halden et al. (1982), Bhattacharya and Gupta (2001), and Chetty (1995). Regional gneissosity generally strikes NE-SW, sub-parallel to the regional trend of the EGMB and dips to the SE. Variations in dip and strike are, however, common. Deformation history of the EGMB has been determined from isolated areas. From the observation that the deformation sequence across the NEGMB is similar, Halden et al. (1982) gave an account of deformational history of the EGMB in the north of the Godavari graben. Structural investigations north of the Godavari rift show four fold phases (D1 to D4) in the EGMB, although the structural elements of different episodes are not uniformly found at different localities of the EGMB. The contact of metapelite and calc-gneiss is taken as the earliest planar structure designated as S0. The first phase, D1, developed reclined and isoclinal folds (F1) with a strong axial-plane foliation (S1) that has become parallel to the compositional layering (S0) in the rocks. Migmatization of rocks of suitable compositions and emplacement of syntectonic granites also occurred during this event. The mineral segregation banding as well as compositional banding in the lithologies including migmatitic quartzo-feldspathic gneisses, metapelites, calc-granulites, mafic granulites and even Opx-bearing granitoids, is taken as S1. The S1 is an axial-plane foliation of rootless and intrafolial folds in the khondalites. In Visakhapatnam area, the pegmatites trend along the foliation or compositional banding of khondalite-charnockite, indicating that these quatzo-feldspathic rocks intruded prior to D2. The D1 was presumably coeval with the granulite facies metamorphism that evidently occurred at great depths of about 25–27 km, considering the estimates of pressure of 8–9 kbar and temperatures of 950 ± 50°C (Paul et al., 1990). The second deformation (D2) also produced isoclinal/reclined folds (F2) which are coaxial with F1, since their axial plane foliation (S2) is parallel to S1. The F2 folds occur on various scales (Bose, 1971; Bhattacharya and Gupta, 2001). Third deformation (D3) produced tight to open folds that are coaxial with F2. The axial plane of F3 folds parallels the shear planes that developed due to westward thrusting of the EGMB against the cratonic nucleus to the west. The shear fabric has either obliterated or transposed earlier foliations in this region. Fourth deformation (D4) produced open, upright folds (F4) transverse to the regional structural grain (Bhattacharya and Gupta, 2001). These folds often show plunges towards SE (cf. Chetty, 1995). The succession of folding indicates that the EGMB underwent a protracted compression, perhaps a thrust-related deformation continuum that can be correlated with the collision with the craton. At places, around Visakhapatnam, one finds NNE kink bands and brittle shears on S1 and S2 foliation, which are considered to be related to D4 that caused retrograde metamorphism (Chetty, 1995). Polyphase deformation is also documented in the southern sector (Sengupta et al., 1999). Here, F1 is a recumbent fold with N-S axial plane, refolded by F2 and F3 (broad warp).

7.3 Geochronology

The isotopic data on the EGMB rocks are scanty and the data also lack proper correlation with tectonic and thermal events. Perraju et al. (1979) recognized a metamorphic event at 3100 Ma, based on Rb–Sr whole rock (granulite) data. Based on U–Pb zircon age, Vinogradov et al. (1964) suggested a metamorphic event at ca. 2600 Ma, which is also supported by some geochronological dates (Rb–Sr whole rock) by Perraju et al. (1979). These ages indicate Archaean ancestory and hence suggestive for the existence of a basement complex (similar to those of the southern high-grade granulite terrain (Chap. 2) on which the Eastern Ghats supracrustals were deposited rather than to suggest protolith ages (> 3.0 Ga old) for the EGMB granulites. Admittedly, supracrustals cannot be laid without a basement. Mezger and Krogstard (1997) dated two distinct zircons from a charnockite gneiss, of which the prismatic zircons gave 3.0 Ga age, interpreted as crystallization/emplacement age of the charnockite, whereas the rounded zircons gave 2.6 Ga (close to lower inrtercept of 3.0 Ga old prismatic zircon) to represent recrystallization or reprecipitation. Recently, Bhattacharya et al. (2001) reported 1.7 Ga old ages for the zircons in the charnockite inclusions which could represent a Pre-F2 granulite facies event or, alternatively, a charnockite magmatism. On the basis of U–Pb method in accessory minerals of the granulites another magmatic/metamorphic event at ca. 900 ± 100 Ma is reported by Grew and Manton (1986), Aftalion et al. (1988) and Paul et al. (1990), which perhaps constrain the last episode of granulite facies metamorphism. A Pan-African thermal event at ~600 Ma has been reported by Aswathanaryan (1964) on the basis of K—Ar biotite age and by Mezger and Cosca (1999) from U—Pb ages in accessory phases in granitoids.

7.4 Petrological Characteristics

Petrologically the EGMB is a gneiss-granulite terrain comprising: (a) metapelitic granulites that include the khondalite (*garnet-sillimanite-perthite-quartz-gneiss),* and Mg—Al granulites *(sapphirine-spinel-cordierite-orthopyroxene-sillimanite-garnet ± quartz).* The khondalites locally contain quartzite bands and the Mg—Al granulites as lenses within metapelites. The Mg—Al granulites also occur as xenoliths in the mafic granulites and at places are generally asociated with garnet leptynites, (b) leptynite (*plagioclase-quartz-perthite ± garnet),* (c) calc-granulites *(wollastonite-scapolite-calcite-plagioclase-garnet-clinopyroxene)* which mostly occur as bands and lenses within or in association with metapelites, (d) charnockite-enderbite (*orthopyroxene-quartz-feldspar ± garnet gneiss*) and mafic granulite (*orthopyroxene-clinopyroxene-plagioclase-garnet*). True charnockites (perthite >> plagioclase) show intrusive relationship with Opx-bearing orthogneisses (mafic granulites and enderbites). Several bodies of alkaline rocks and associated basic rocks are reported to have intruded the granulite complex. Massive-type anorthosites occur in the northern part of the EGMB (Sarkar et al., 1981). A layered igneous complex, comprising anorthosite-gabbro-pyroxenite-chromitite, is reported from the Kondapalle area in the southern part of the EGMB (Leelanandam, 1967, 1997, 1998).

7.5 Tectono-Thermal Evolution

The EGB granulites are shown to be polymetamorphic. The thermal history is reported to be different on either sides of the Godavari graben. Both Northern and Southern segments of the EGMB, abbreviated as NEGMB and SEGMB have experienced ultra high temperature (UHT) metamorphism, as revealed by the presence of sapphirine (Spr)—quartz and spinel (SPL)-quartz and orthopyroxene (Opx)-sillimanite (Sill)-quartz, but the timing of this extreme event is most confusing and least understood, as can be felt from the following description. It is also intriguing to know from the scanty geochronological data that the SEGMB seems to have escaped reworking during Grenville orogeny (~1000 Ma) as well as Pan-African (~550 Ma) orogeny (cf. Mezger and Cosca, 1999; see also Sengupta et al., 1990). The following account deals with the tectono-thermal evolution separately for the Northern and Southern segments of the EGMB and thereafter the evolution of the entire EGMB will be taken, giving different models.

7.6 Northern Segment

In this segment petrological study of the granulites from near coastal region of EGMB, particularly from Paderu (Lal, 1997), Anantagiri (Sengupta et al., 1990), Rajamundry (Dasgupta et al., 1997), Madhuravada and Vizianagaram (Rao et al., 1995) revealed an early ultra high temperature (UHT) metamorphism with thermal peak at 900–1000°C/8–10 kbar. This was followed by high-pressure isobaric cooling (IBC) as documented by the reaction coronas formed from the reactions involving Spr+Spl+Qz (formed at the thermal peak) (Dasgupta and Sengupta, 1995). There is, however, a serious controversy in respect of the retrograde P-T trajectory, which according to Lal (1997), Bhattacharya and Kar (2004), is clock-wise, whereas Dasgupta et al. (1997) and Sengupta et al. (1990) deduced anticlockwise paths for the investigated localities of the NEGMB. The P-T trajectories by different authors (see Fig. 7.2c) reveal that the EGB granulites are polymetamorphic with an impress of two granulite facies metamorphic events. As revealed in the P-T-t paths by different workers, an early M1 event occurred near 8–10 kbar/950 ± 50°C followed by retrograde path or near isobaric cooling to 750–800°C during which corona and symplectitic textures developed, as in Rayagada area (Shaw and Arima, 1996). Dasgupta et al. (1997) further proposed that the isobarically cooled granulites have been uplifted by isothermal decompression (ITD) path to 5 kbar when late cordierite formed from opx + sill involving reactions. Interesting results were drawn from petrologic study of Chilka Lake granulites, about 200 km north of stated localities of the NEGMB. Here, the UHT metamorphism yield a multi-stage P-T-t path (Sen et al., 1995) with a combination of three isothermal decompression (ITD) paths, intervened by two isobaric cooling (IBC) paths from 8–10 kbar/1000°C down to 4.5 kbar/650°C (Fig. 7.2c). According to Sen et al. (1995), the deduced trajectory indicates a discontinuity after the first cooling, implying re-working of the crust in a separate tectonic event. Rickers et al. (2001) also report multi-stage evolution of the Mg–Al granulites from Anakapalle area, similar to that deduced for Chilka Lake granulites by Sen et al. (1995). The Mg–Al granulites to the NW of Visakhapatnam, on the other hand, show a simple isobaric heating-cooling path (Bose et al., 2000). Interestingly, none of the granulites from EGMB preserved the prograde path of metamorphism to enable one to deduce unambiguous sense of movement of the rocks in the P-T space—whether ACW or CW so as to provide important constraints on tectonic history of orogenic belts. However, there appears a broad similarity in the estimated peak P-T conditions with those deduced by Dasgupta et al. (1997). Textural and compositional characteristics of nearly all the Mg–Al granulites from the EGMB bring out a coherent picture of an early phase of UHT metamorphism (∼1000°C) at 8–10 kbar, followed by near isobaric cooling.

Isotopic record on the granulite facies rocks of the NEGMB denotes Greenville thermal event (Mezger and Cosca, 1999), but Archaean, Mid-Proterozoic and Pan-African dates are also reported (Vinogradov et al., 1964; Paul et al., 1990; Shaw et al., 1997; Sarkar et al., 1998; Dobmeier and Simmat, 2002; Krause et al., 2001). Jarick (2000) dated the UHT metamorphism at Anakapalle to be 1100 Ma for the rocks that occur as xenoliths in basic granulites. However, it is not yet clear

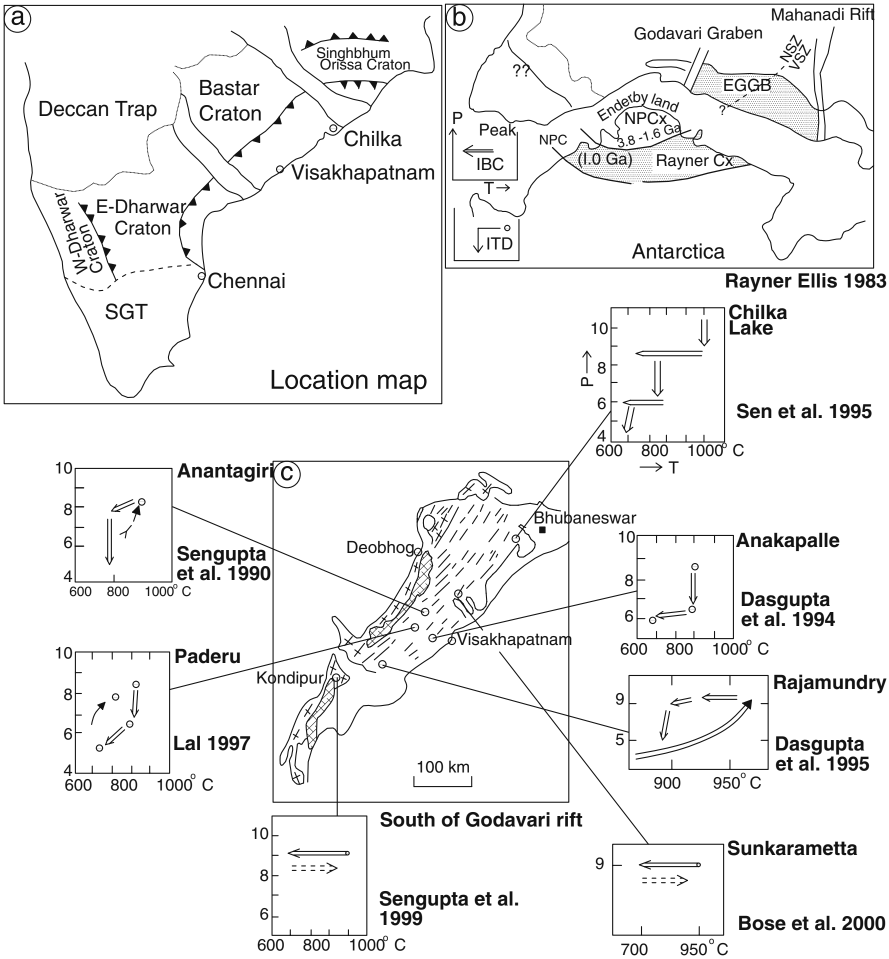

Fig. 7.2 Location map (**a**); the attempted correlation of EGMB with Napier Complex (NPCx) and Rayner Complex (Rayner Cx) of the Enderbyland, Antarctica (**b**); (**c**) shows a synoptic history of P-T paths (see text) in different domains of the Eastern Ghats Mobile Belt. Note that the UHT metamorphism with high pressure IBC and IBC heating-cooling paths are attributed to an earlier event of ∼1.6 Ga, whereas ITD path to a later, ∼1.0 Ga event (Dasgupta et al., 1994; Mezger and Cosca, 1999; Sengupta et al., 1999; Rickers et al., 2001; and others). The difference in metamorphic evolution in North and South EGMB may not be real (see text)

whether this age is truly representative of the regional UHT metamorphism in the EGMB. The scattered isotopic evidence (Paul et al. 1990; Shaw et al. 1997) suggests a distinct Late Archaean age (2.6–2.8 Ga) for basic magmatism. If the basic magma is the source for high temperature heating of the deeper crustal rocks, the metamorphism would be Late Archaean. However, interpretation of these isotopic data in relation to deformation and petrologic processes has not yet been critically attempted. In the Central Khondalite zone a NE-SW trending megacrystic, syn-D3 granitoid intrudes the khondalites and associated gneisses and granulites (including sapphirine-granulites). Geological setting unambiguously suggests that the granitoid is older than 1400 Ma anorthosite and alkaline intrusions (Sarkar et al., 1981; Ramakrishnan et al., 1998). The granitoid whole-rock Rb—Sr yielded 1890 and 1215 Ma ages as emplacement and overprint ages, respectively (Bhattacharya et al., 2001). This implies that granulite facies metamorphism was between 1890 and 1215 Ma. Again, at Chilka Lake the garnet leptynite, related to axial-plane foliation of F2 in pelitic granulite contains patchy charnockite. The leptynite whole-rock Rb—Sr age is 1913 ± 82 Ma while the zircons in the patchy charnockite gave 1.7 Ga age (Bhattacharya et al., 2001). This zircon age could be taken to represent a Pre-F2 granulite metamorphism (older event), or alternatively a charnockite magmatism. Here, it must be stated that according to the study of Kar (2001), the source rocks of the low Rb—Sr leptynites and high Rb—Sr charnockites must be different. The patchy charnockite in the host leptynite gneisses, considered by Bhattacharya et al. (1994) as relict structure, is interpreted by Dobmeier and Raith (2003) as arrested charnockites (in-situ charnockite). But as stated earlier, Kar (2001) considers them as caught up xenoliths within letynite the foliation (S1) of which is not found in the leptynite having only S2 foliation.

Dasgupta and Sengupta (2003) attribute the UHT metamorphism with high-pressure IBC and IBC heating-cooling path of UHT granulites to an earlier event of about 1.6 Ga and the ITD path to a later event of 1.0 Ga event (see also Rickers et al., 2001; Mezger and Cosca, 1999). It means that there was a granulite event at 1.6 Ga when rocks of NEGMB resided at lower crustal levels. After 600 Ma, i.e. at ∼1000 Ma, these granulites were then exhumed by ITD path (superposed on high-P IBC path) to mid- to lower-crustal levels. Partial re-setting during a late overprint at 550∼Ma (Pan-African) has also been suggested by Mezger and Cosca (1999).

7.6.1 Southern Segment

The EGMB rocks to south of the Godavari rift i.e. in the Southern Segment, have only limited information in regard to their thermo-tectonic evolution. In Ongole (Dasgupta et al., 1997) as well as in Kondapalle (Sengupta et al., 1999), where the metapelitic granulites are intruded by layered noritic gabbro-pyroxenite-anorthosite, the granulites also bear the imprint of UHT granulite facies metamorphism, with P-T conditions similar to that documented in the granulites of Northern segment (NEGMB). Also the isobaric cooling trajectory on the retrograde path is comparable with that recorded in the granulites of NEGMB. However, there is no record of any isothermal decompression event, and it is a matter of enquiry as to how these granulites were excavated from deeper levels, about 25 km, where they suffered ultra high temperature (UHT) followed by isobaric cooling (IBC).

Available U—Pb cooling ages of minerals suggest that the areas of Ongole and Kondapalle had UHT metamorphism (granulite facies metamorphism) at 1300 and 1600 Ma, respectively, after which time they presumably did not experience any other granulite facies event.. However, the $^{40}Ar/^{39}Ar$ in amphibole from near shear zones gave ~1000 Ma (Grenvillian age) which is simply taken to indicate resetting of the radioclock (Crowe et al., 2001).

Resetting of isotope systems is also reported in rocks of the northern segment during M2 event at ~1000 Ma. According to most workers, the UHT metamorphism represents an earlier event of ca. 1600 Ma. The second granulite facies event is understood to have occurred at temperatures around 850°C, which the rocks of NEGMB attained during IBC from UHT event (M1). The source of heat for the UHT metamorphism was obviously the basic/mafic magma that underplated the overlying crustal rocks. The second granulite facies (M2) event in SEGMB is also the result of the isobaric cooling that occurred at around 850°C. Again, the metapelitic granulites south of the Godavari rift show UHT P-T path with isobaric heating and cooling (Sengupta et al., 1999), which is similar to the isobaric heating-cooling path reported from NW of Visakhapatnam in the north of the Godavari rift (Bose et al., 2000). These similarities in two distant areas located in the northern and southern segments are as striking as are the dissimilarities in the P-T-t paths in nearby localities of the northern EGMB, as stated already. Notwithstanding, the isobarically cooled rocks of NEGMB are documented to have been subsequently brought to shallower levels by isothermal decompression (ITD) during an orogney (Pan African) (cf. Sengupta et al., 1999; Dasgupta and Sengupta, 2003). The Southern Segment of the EGMB is considered to have escaped this orogenic event as the rocks retain older ages and do not show isothermal decompression. But it remains to explain as to how the granulites of SEGMB were excavated from lower crustal levels (corresponding to 8 kbar) to be juxtaposed with the granulites of the NEGMB, observing that no later "decompressive" orogeny affected this area (cf. Bhattacharya and Gupta, 2001).

It seems to this author that the entire charnockitic rocks of the EGMB have been exhumed by upthrusting along a ductile shear zone, a suggestion that finds support from the presence of the shear zone around this Proterozoic fold belt (stated earlier). To show the temporal equivalence of the retrograde path of the Northern and Southern segments of the EGMB, one has to accept that the peak of M1 granulite facies metamorphism at 950°C was Mid-Proterozoic (ca. 1600 Ma) in the belt as a whole while the later Grenville event (M2, 1000 Ma) would be at lower temperatures (750–850°C). This implies that following M1, the granulites remained stationary in an isostatically compensated lower crust for about 600 Ma with no uplift. Such a situation, however, appears remote. The multi-stage IBC-ITD paths of the Chilka Lake granulites indicate that they were affected by two or more geological events (Sen et al., 1995). It is almost certain that if the rocks were subjected to high-pressure heating and isobaric cooling they ought to have undergone isothermal decompression to be able to be exposed near the surface. After isobaric cooling if the rocks remained buried in great depths they need an orogeny to be excavated. In the case of the residence for 600 Ma, the 1600 Ma old granulites must have been involved in the Grenville orogeny, failing which their excavation must have been during the Pan-African orogeny. But more geochronological work is required to have a satisfactory answer to this problem.

7.7 Is Godavari Graben a Major Terrain Boundary?

The shear (thrust) zone that surrounds the EGMB all around is also responsible to upthrust the granulites of the mobile belt. It is cut across by the Godavari graben to suggest that crustal extension giving rise to the Godavari rift must be younger than the third deformation (D3) recognized in the region (Bhattacharya and Gupta, 2001). The graben is devoid of any igneous material, but contains sediments of Pakhal Group (Mid-Proterozoic) and Gondwanas (Upper Palaeozoic to Mesozoic). K–Ar date on glauconites from the Pakhals gave 1300 ± 53 to 1188 Ma age (see Raman and Murthy, 1997). These dates indicate that the graben is younger than the UHT metamorphism in the granulites of SEGMB but older than the Grenvillian thermal event in NEGMB. Despite it being younger than the surrounding thrust, the Godavari graben is erroneously regarded as a terrain boundary between the two domains lying on its either side, merely on the basis of scant isotopic data on accessory minerals (Mezger and Cosca, 1999) and partial P-T- paths (Sengupta et al., 1990). If the granitic rocks are missing from the graben and the sediments directly rest upon the granulite basement, as disclosed geophysically by Pande and Rao (2006), there does not seem to be a thermal activity during and after the formation of the Godavari graben. The following points should help the reader on the validity of this proposition.

(1) The retrograde P-T path from the UHT metamorphism (M1 at ca. 950°C) in Southern sector of the EGMB (abbreviated SEGMB) is similar to that deduced for the granulites of NEGMB, although their temporal equivalence is not yet ascertained. Accepting that these two sectors are correlatable, the peak of M1 granulite event at 950°C in NEGMB would also be Mid-Proterozoic (1600–1300 Ma). If so, the second granulite event (M2) would be Grenvillian age (~1000 Ma) at lower temperature of 750–850°C. In this context, the Ar–Ar age of ~1000 Ma of amphibole from SEGMB can be interpreted to indicate Grenvillian age in the Southern segment. Under the situation, a mechanism very similar to ITD would have to be conceived also for the SEGMB granulites.
(2) If the granulites (charnockites-enderbites) from the Western Charnockite Zone (WCZ) to the north of the Godavari graben are 1.6 Ga old, as suggested by Mezger and Cosca (1999), and hence comparable to the granulites south of Godavari graben, it rejects the proposition that Godavari rift is a N-S divide within the EGMB; The WCZ extends unobstructed to the south of the Godavari graben.
(3) The difference in metamorphic evolution in NEGMB and SEGMB may not be real if an analogy were not drawn with the Enderby Land, East Antarctica. Dasgupta and Sengupta (2003) suggested similarities of P-T paths such that the North sector of the EGMB is correlatable with Rayner complex while Southern sector of the EGMB is correlatable with the Napier complex (Fig. 7.2b).
(4) The UHT event followed by retrograde P-T trajectory for the granulites of SEGMB is similar to that for the granulites of Northern sector of the EGMB, although time equivalence is not yet demonstrated.

(5) If the ITD path, associated with the presumed orogney (Pan-African?) brought the granulites of NEGMB to shallower depths to be exposed by erosion, how were the granulites from Southern sector excavated from the same depth (≡ 8 kbar) to be juxtaposed with the granulites of Northern sector unless the exhumation was similar in place and time.

In summary, the EGMB granulites are found to be polymetamorphic, and the thermal history for the granulites on either side of the Godavari graben begins with the UHT metamorphism (M1) with 900–1000°C and 8–10 kbar, followed by isobaric cooling (M2) at 750–800°C. However, the retrograde path in the granulites north of Godavari is also characterized by the ITD related to a supposed later metamorphic event, not documented in the granulites of the Southern sector. Temperatures in excess of 900°C, retrieved from thermometry on minerals formed after post-F3, suggest that granulite facies conditions continued from M1 to M2 and even M3. Since the mineralogy of M1 event is different from that of M2 or M3, it is debatable whether the granulite facies metamorphism is a continuous one. Sengupta et al. (1999) contended that the ITD event in NEGMB is essentially a re-working of older UHT granulites and hence this event represents a separate event (? Pan-African), not affecting the region south of the Godavari rift. If the ITD path associated with an orogeny brought the granulites of the NEGMB to shallower depth, how the granulites of SEGMB would then be excavated from same depth unless exhumed in a similar way. This and other points stated already do not support the proposition that the Godavari rift represents a major crustal boundary. If the later event related to the uplift of the high-grade terrain could simply be in the form of a passive (i.e. with no associated structures or fabric) thermal pulse then it had only reset the isotopic systems during the Grenvillian orogeny (cf. Bhattacharya and Gupta, 2001). A more precise definition of structures and fabrics is necessary to distinguish it from the earlier event. As stated earlier, the M2 event (ca. 1000 Ma) is inferred from U—Pb cooling ages of zircon, allanite, monazite, sphene etc. (Grew and Manton, 1986). Partial resetting during a late Pan-African thermal overprint at ~550 Ma has also been suggested (Mezger and Cosca, 1999; Mezger et al., 1996).

7.8 Agreed Observations and Facts

In order to have a comprehensive picture and to conceive a more plausible evolutionary model, we should have an inventory of the agreed geological data and facts on the rocks of the EGMB. These are enumerated below:

1. The Eastern Ghats Mobile Belt (EGMB) is a gneiss-granulite tract of intensely deformed granulite facies rocks.
2. The EGMB has dominantly two types of rocks: charnockitic-enderbitic in the western part while khondalites and other orthopyroxene-free rocks occur to the east.

3. The rocks trend in NE-SW to NNE-SSW direction and are parallel to the orographic trend.
4. Anorthosites, mafic intrusions and alkaline bodies, including carbonatites clearly post-date all tectonic events and are restricted in the western part of the EGMB.
5. Anorthosites and mafic intrusives are younger than most other rocks in the EGMB Rb–Sr whole rock age of anorthosites and alkaline rocks ranges from 1400 to 1300 Ma (Sarkar et al., 1981; Subba Rao et al., 1989).
6. The EGMB has a peripheral thrust zone (ductile shear zone) which dips towards SE.
7. Extensional shears in EGMB are late and post-date all penetrative structures related to F1 and F2 (Bhattacharya and Gupta, 2001).
8. EGMB has a gravity high and the thrust shows a gravity low
9. The Godavari rift intersects the EGMB and disrupts its gravity profile.
10. The EGMB granulites are polymetamorphic with an early UHT (of uncertain age) with ~950°C, followed by isobaric cooling at temperatures of ~800 ± 50°C (granulite metamorphism M2.
11. South of the Godavari graben the EGMB granulites have no record of either Grenvillian (1000 Ma) or Pan-African (600 Ma) reworking; its rocks retain older ages and do not show isothermal decompression.
12. It is unclear whether the EGMB rocks had an early Archaean or early Proterozoic metamorphic history.
13. U–Pb cooling ages of accessory minerals in the granulites from north of Godavari graben indicate last granulite facies metamorphism to be Grenvillian age (~1000 Ma) (Grew and Manton, 1986; Mezger and Cosca, 1999), but partial re-setting during 550 Ma (Pan-African) is also suggested (Mezger and Cosca, 1999).
14. U–Pb cooling ages of minerals in the granulites from south of Godavari graben indicate granulite facies metamorphism during Mesoproterozoic (1600 and 1300 Ma). Grenvillian age is indicated by Ar–Ar dates of amphibole, which could be interpreted differently.
15. The folding events are a thrust-related deformation continuum correlatable with collision with the cratons during Mesoproterozoic.
16. The EGMB is supposed to have been juxtaposed against the East Antarctica in all Proterozoic reconstructions.

7.9 Evolutionary Models and Discussion

As stated already, the EGMB is a NE-SW trending gneiss-granulite tract, comprising charno-enderbite and mafic granulite of magmatic origin and khondalite with minor calc-gneisses and quartzites as recrystallized metasediments (supracrustals) under granulite-facies conditions. These magmatic and metasedimentary rocks appear in alternate bands each of which is designated by a name (Ramakrishnan et al., 1998), depending on the dominance of the rock type. The western part dominated by the charnockitic rocks is designated the Western Charnockite Zone (WCZ) while the central part of the fold belt dominated by the charnockitic-migmatitic rocks is designated Central Charnockite-Migmatite Zone (CMZ). The khondalite dominated zone in the west, between the two charnockite zones, is designated Western Khondalite Zone (WKZ), while khondalites dominantly occurring in the eastern part of the fold belt are designated Eastern Khondalite Zone (EKZ). It is interesting to note that a given zone also contain rocks from other zone, though in minor amount. The contact between the charnockites and khondalites is obscured. The contact of the EGMB with the cratonic rocks, in particular of Bastar craton, is also a wide zone which has characteristics of both the terrains (i.e. Craton and mobile belt) and hence is called the Transition Zone. The zone occurs along a significant length of the western margin. Geological information on rocks of the Transition zone is not sufficiently known, except from isolated regions (cf. Bhadra et al., 2003).

Field studies have not been able to recognize the basement upon which the precursor of the metasedimentary granulites were deposited, perhaps because both cover and basement have been deformed and thoroughly recrystallized under granulite facies conditions during the Eastern Ghats orogeny. But geochronological data suggest that protoliths between 3.2 and 2.6 Ga are present in the EGMB (Vinogradov et al., 1964; Perraju et al., 1979). The charnockites of the EGMB, yielding a whole-rock Rb–Sr age of 2800–2600 Ma (Perraju et al., 1979) compare well with the charnockites from Madras and Nilgiri Hills, having Rb–Sr isochron age of 2580 ± 80 Ma (Crawford, 1969), as also with the Kabbaldurga charnockites of 2500 Ma age.

The possible basement may have been the Precambrian gneiss laid upon by a supracrustal sequence of shale-silt-sandstone and impure carbonates, as a precursor of metapelite/khondalite, quartzite, and calc-gneisses. Models have been proposed for the evolution of the EGMB and are discussed below.

Model 1 (Ramakrishnan and Vaidyanadhan, 2008)

This model is based on nature and composition of the possible basement and the geochronology of the cover rocks constituting the EGMB. The Proterozoic age supracrustals of khondalite (garnet-sillimanite-graphite gneiss), calc-silicates, quartzites with or without garnet/sillimanite, and the migmatites must have an Archaean basement. The supracrustals and the charnockites of the EGMB occur in parallel bands or longitudinal zones. Gradual contact is often found between the cratons and the EGMB, implying that Archaean gneisses and granites (converted now into charnockite and enderbite of the EGMB) were the possible basement for supracrustal rocks of the EGMB. Geochronological data of the enderbite yielded U–Pb zircon ages of 1700–1720 Ma with ΣNd (T_{DM}) model ages (protolith) of 2.3–2.5 Ga to ssuggest that the basement was mainly a gneiss-granite association. Nd model ages of granitoids of the Eastern Dharwar craton also indicate a provenance age of 2.6–2.8 Ga which correspond to the ages of granitoids of Eastern Dharwar craton and also with the rocks of the Napier Complex in East Antarctica (Yoshida, 2007). From this it is assumed that the basement rocks for the EGMB supracrustals were Late Archaean gneiss-granitoid association.

To understand the geodynamic evolution of the EGMB, we must know that India was in contact with East Antarctica and that the EGMB formed a part of the SWEAT (SouthWest United States and East Antarctica) orogen during Rodinia (1.3–1.0 Ga) supercontinent. Prior to the Rodinia assembly, the Archaean continental crust of the united India and East Antarctica rifted with initiation of alkaline magmatism followed by sedimentation of the Khondalite Group. It is also suggested by the authors that the minor Mg—Al rich sediments have been produced from weathering of mafic volcanics of the rift basin. There was also a likelihood for the occurrence of basic sills and flows that were intercalated with the sedimentary pile. In addition, felsic volcanics and volcani-clastics were also deposited but all are not identifiable within deformed and metamorphosed rocks of the EGMB. The cover rocks and the basement were then deformed (superposedly) and metamorphosed (granulite facies grade) by magmatic underplating, as a result of crustal delamination, producing ultra-high temperature (UHT) rocks. The movment path of these UHT rocks in the P-T space was found to be anticlock-wise with isothermal (ITD) decompression and also isobaric cooling (IBC) in some instances. The mobile belt witnessed intrusion of massive anorthosites and late-tectonic granitoids and charniockites. This is a geo-history of the Granulite belt, which is not interpreted in terms of Phanerozoic-type plate tectonics which so elegantly explains the evolution of most fold belts in various continents of the world.

Model 2 (Upadhyay, 2008)

The geodynamic evolution of the EGMB has been discussed in reference to the origin of the alkaline complex occurring at the contact of the EGMB and the Archaean cratons. According to Upadhyay (2008), there was a rifting during Mesoproterozoic period when Columbia Supercontinent fragmented, resulting into the opening of ocean between eastern India and East Antarctica. Following the rifting, metasedimentary sequence of EGMB was deposited during 1.4–1.2 Ga. The rifted basin closed during the Grenville time (1.0 Ga) due to collision of eastern India and East Antarctica when Rodinia began to assemble. The collision is considered to result into the development of the Grenvillian Eastern Ghats—Rayner Complex orogen whose constituent rocks were metamorphosed to granulite facies conditions, by underplating due to crustal delamination. The EGMB accreted to the cratons and subsequently thermally overprinted during Pan-African (0.5–0.6 Ga) orogeny when the EGMB granulite belt was thrust westward over the cratonic foreland. The author (Upadhyay, loc. cit.) suggests that the present crustal geometry exposed only the eroded Pan-African thrust contact between the Craton and the EGMB, and not the original Grenvillian suture which may be underlying the granulite thrust sheet.

Model 3

The depositional basin was obviously a rift (extensional regime), formed due to ductile stretching and thinning of the crust by subcrustal convection currents. Consequently, the supracrustal rocks were heated by under- and intra-plated mafic/ultramafic melt whose parental magma was possibly derived (by decompression melting) from depleted mantle in Palaeoproterozoic time. The crustal rocks were thereby subjected to deep-seated UHT metamorphism (granulite facies conditions) as if there was a regional scale thermal metamorphism at lower crustal depth. This conclusion, however, depends on the age of UHT metamorphism and that of the emplacement of the magmatic rocks. Fractionation in dry conditions of the parental magma gave rise to gabbro, norite, enderbite and charnockite at lower crustal levels (20–25 km) at which depths these magmatic rocks intruded the basement complex (incl. metasediments). It is perhaps this way that the khondalitic rocks are seen intruded by charnockitic-enderbitic rocks in the EGMB, although other mechanisms may also be considered for charnockite-metapelite association in the EGMB). In this proposed model, the charnockitic rocks appear as products of deep-seated (granulite) metamorphism of quartzo-feldspathic rocks many of which were initially igneous. The ultra high temperature metamorphism (UHT) by magma underplating of the crust not only caused granulite facies metamorphism but also resulted in partial melting of biotite-bearing protoliths, which gave rise to migmatization, formation of Mg—Al granulites (sapphirine-bearing) and emplacement of syntectonic granite. There are no geochronological data on the timing of UHT metamorphism, but Jarick (cited in Dasgupta and Sengupta, 2003), on the basis of U—Pb TIMS study of zircon and a Pb isotopic study of leached feldspar, suggests that the M1 (UHT) metamorphism took place at about 1400 Ma. On the other hand, Dobmeier and Raith (2003), from synthesis of available geochronological data, concluded that M1 event occurred at about 1100 Ma. This discrepancy could be due to partial resetting of mineral ages during cooling and due to overprinting by a later high-grade M2 event. Parallelism of melt fraction with gneissic layering and occurrence of F2 and F3 folds in them imply that the F1 leucosomes were solid throughout the later deformation (Gupta et al., 2000). From the given evidence, it may be suggested that both charnockitic-khondalitic zones exhibit a similar deformation history in which D1 produced reclined to isoclinal folds as well as gneissic layering in the rocks, refolded coaxially by D2 and then superposed by open upright D3 folds plunging eastwards. The main phase of migmatization was syn-F1, but melts are documented to have generated continuously during the granulite facies conditions but their amount decreased successively. It is possible that F1, F2 and F3 could be continuum or they are temporally separated phases, but peak of M1 is reported to be pre- to syn-F1.

The anticlock-wise path (ACW) deduced for the granulites from different areas of the EGMB is consistent with the heating by magma underplating (England and Thompson, 1984). Most of the information of UHT was obtained from sapphirine-spinel- bearing high Mg—Al granulites and calc-silicate granulites (see Dasgupta and Sengupta, 2003). The P-T trajectory, deduced by different authors, reveals that the EGMB granulites are polymetamorphic with an impress of two granulite events. An early M1 occurred near 8–10 kbar/$\sim$950 $\pm$ 50°C., followed by retrograde path or near isobaric cooling to 750–800°C during which coronas and symplectite textures developed. According to Dasgupta et al. (1997) the isobarically cooled granulites have been re-worked by M2 at $P = 8$–8.5 kbar and 850°C which is characterized by near ITD to 5 kbar when late cordierite formed from Opx + Sill involving reaction. The age of M2 is given as 950–1000 Ma (see Grew and Manton, 1986; Mezger and Cosca, 1999).

The three deformation/fold phases have caused sufficient shortening of the crust which finally yielded to shearing and helped excavate the high-pressure granulites to shallower depth to be emplaced on the cratonic rock.

The intrusion of anorthosites and alkaline rocks (~1400–800 Ma) occurring only along the western margin (the Transition Zone) of the EGMB suggests that there was a collision tectonics (Chetty, 1995; Chetty and Murthy, 1998). The prevailing NE-SW trend of the fold belt suggests a dominant E-W compression during the Eastern Ghats Orogeny. The compression is attributed to the collision between the continents of India (eastern part) and the Antarctica, giving rise to this Eastern Ghats fold belt. The Grenvillian isotope signature is taken as the time of collision and amalgamation of Rodinia (Hoffman, 1991; Boger et al., 2001; Fitzsimons, 2000; Kelly et al., 2000). The supercontinent Rodinia is conceived to have assembled due to suturing at the end of Mesoproterozoic (1100–900 Ma). According to SWEAT model (SW US-East Antarctica Model), the EGMB is the site of suturing that linked East India and the Antarctica (see Gopalkrishnan, 1998). According to Powell et al. (1994), the Rodinia fragmented between 830 and 750 Ma and re-assembled into Gondwanaland at ca. 500–550 Ma due to Pan-African orogeny (Rogers, 1996). Owing to the similar thermo-tectonic evolution of EGMB-Antarctica, these continents do not seem to have separated during the fragmentation of Rodinia.

It is commonly believed that the Eastern Ghats orogeny gave rise to large-scale isoclinal folding superposed by another fold phase that occurs all over the EGMB. While the litho-units of EGMB were subjected to UHT metamorphism at lower crustal levels, intrusions of alkaline rocks and anorthosites occurred, mostly in the western margin of the EGMB. The intrusive rocks form an integral part of the high-grade belt of the EGMB. These rocks are frequently located within the Western Charnockite Zone to appear as if they are confined between the cratonic (non-charnockitic) and mobile belt, or as if confined between WCZ and Western Khondalite Zone (WKZ) (cf. Ramakrishnan et al., 1998; Leelanandam, 1998). From their nearly undeformed nature but mildly sheared fabric near shear zones, it is suggested that these rocks were definitely post-D2, but pre- or syn-D3, although they have not been studied for their structural setting. Nor are these alkaline and anorthosites isotopically dated, although a range from 1400 to 800 Ma is given by Subba Rao et al. (1989). Like Adirondack mountains and Stillwater complex, layered anorthosite-gabbro-pyroxenite are found at several places in the EGMB, particularly in Kondapalle area south of the Godavari graben and in Bolangir and Chilka lake in the north of the graben. In these localities, the predominance of orthopyroxene (rather than olivine) as an early cumulate phase in the ultramafic zones indicate high-pressure crystallization of a tholeiitic magma. This parental magma is considered to have been intruded at depth just after the peak of M1 and cooled slowly together with the enclosing charnockites and granulites (cf. Leelanandam, 1998). It may be conceived that consequent upon the magmatic underplating near the crust/mantle interface, the plagioclase concentration as a crystal-laden mush separated from the parental magma, perhaps by filter pressing. The next event that followed culminated into shearing along which the EGMB was upthrusted against the cratons in the west. This shear boundary (Sileru shear zone of Chetty, 1995) is most conspicuous, particularly between the EGMB and the Bastar craton (Gupta et al., 2000; Bhattacharya et al., 2001). The thrusting of the EGMB over the Bastar craton is regarded Pan-African in age. The development of mylonite foliation and its superposed folding are the features of this event. The last episode of deformation is marked by open folds (F4) the axial plane of which is nearly parallel to the shear plane. The overprinting of the weak amphibolite facies metamorphism (M3), suggested by Mezger and Cosca (1999, and references therein) is related to this event recognized as Pan-African (cf. Gupta et al., 2000) during which the granulite-khondalite rock-suite of the EGMB was excavated along a shear zone.

The contrasting P-T-t paths in neighbouring localities of the EGMB of the northern segment to the north of Godavari graben and similarity of P-T-t paths in localities of the belt on either side of the graben should be accepted as an incomplete P-T trajectory deduced from silica-deficient Mg—Al granulites. Therefore these deduced paths may not be able to give a clear picture of the thermo-tectonic evolution of the two segments of the EGMB. From the interpretation of isotopic data and from the age and lithological composition of the Godavari graben, it is doubted that the geohistory of the regions on either side of the graben is different, as discussed earlier. The shear zone bordering the EGMB all around the fold belt does not support the excavation of the North and South segments of the EGMB in different times. This is also evident from the coincidence of the shear plane with the axial planes of the F3 fold that predate the peak of granulite metamorphism (because 900–950°C was obtained on minerals annealed in post-F3). Excavation along the thrust would account for the existing structural and mineralogical data on the EGMB. The development of the mylonitic foliation is related to the upthrusting movement of the EGMB rocks along the shear zone.

7.10 Newer Divisions of the Eastern Ghats Mobile Belt

We know that the shear-bound Eastern Ghats Mobile Belt (EGMB) is entirely made of granulite facies rocks, and attempts have been made to propose its divisions from different point of view. The GSI made the first attempt to prepare a geological map (1: 1 million scale) of the EGMB with four-fold longitudinal sub-divisions, based on the dominant lithological assemblage (Ramakrishnan et al., 1998). To recall, these divisions from west to east are called Western Charnockite Zone (WCZ), Western Khondalite Zone (WKZ), Central Charnockite-Migmatite Zone (CMZ) and Eastern Khondalite Zone (EKZ). These zones are alternately dominated by charnockitic and khondalite rocks as if the pelitic granulite (khondalite) and charnockites were folded. Ramakrishnan et al. (1998) also proposed a Transition Zone (TZ) along the western margin of the EGMB. This Zone contains a mixture of high-grade rocks (similar to those occurring in the east EGMB) and lower grade rocks of the craton and alkaline intrusions. The TZ of Ramakrishnan and others has been now shifted further west by Gupta et al. (2000). The thermo-tectonic evolution of granulites from all the four zones is similar with UHT metamorphism followed by retrograde path of isobaric cooling (IBC) or isothermal decompression (ITD), although prograde path has not been established along this anticlock-wise trajectory suggested by most workers in the EGMB (Dasgupta and Sengupta, 2003).

With limited geological information available on rocks from south of Godavari graben, Mezger and Cosca (1999) suggested on the basis of scant isotopic data that these rocks of EGMB had a different tectono-thermal history as compared to those occurring to the north of the Godavari graben. This author has already given reasons that do not support this division, significant among them is the southern continuation of 1.6 Ga old granulites of the West charnockite Zone across the Godavari graben into Kondapalle-Ongole areas. Again, if the ITD path associated with an orogeny brought the Northern region of the EGMB to shallower depth, it is difficult to understand as to how were the granulites south of the Godavari rift excavated from similar depths to be juxtaposed with the granulites north of the rift, unless they were uplifted together. Also, the suggested difference in metamorphic evolution in these two sectors is not real, because of incomplete P-T-t paths. These and other arguments invalidate the two-fold division of the EGMB across the Godavari graben. The correlatibility of northern EGB with the Rayner complex and of southern EGMB with the Napier complex of the Enderby Land is also questionable because of the similarity in metamorphic evolution of the North and South regions of the EGMB (cf. Dasgupta and Sengupta, 2003). Unless an intensive geochronolgical data is available, these two divisions of the EGMB, even if tentative, cannot be taken seriously. An isotopic age must ensure that it is event specific and is not indicative of a mixed age or even re-setting age.

A different scheme of subdivision of the EGMB has been adopted by Chetty (1995) and Chetty and Murthy (1998) who gave a two-fold division of the EGMB on the basis of interpretation of landsat imagery. According to these authors, the EGMB is divisible into two blocks on either side of the Negavalli-Vamosdhara shear zone (NVSZ) recognized as Negavalli shear zone (NSZ) and Vamasdhara shear zone (VSZ) in the centre of the EGMB (Fig. 7.1). These blocks are called the Archaean Araku Block in the south and the Proterozoic Chilka Block in the north. Although the NVSZ is far from the Godavari graben, the shear zone itself is considered to be an extension of the Napier-Rayner boundary in the East Antarctica (Chetty, 1995). It appears that neither the Godavari graben nor the NVSZ be regarded as a terrain boundary because of inconsistent isotopic data on the granulitic rocks of the EGMB. The age-data are too few to uphold these divisions of the EGMB, either by the NV-shear zone or the Godavari graben. A division based on structural criteria is useful only to separate homogenous/ inhomogeneous domains and surely not for delimiting the antiquity of rocks that were all subjected to granulite facies metamorphism over a vast region.

It is not known if the shear zone (NVSZ) in the central part of the EGMB is coeval with the encircling thrust zone of the EGMB along which the granulites of the Eastern Ghats were thrust upon the craton on the west. This boundary shear zone has received different names, sector-wise. The NW- trending sector is named Sileru shear zone and the E-W trending sector in the north is named Mahanadi shear zone. This Terrain boundary shear zone or thrust defines the border between the Archaean rocks (schist/gneiss) of the eastern margin of the Craton and Proterozoic granulites on the western margin of the Mobile belt. The seismic profile along Alampur-Koniki revealed a major eastern dipping thrust (Kaila et al., 1987). The greater crustal thickness westward underneath near Cuddapah basin, compared to the eastern margin, is the consequence of this upthrusting (Kaila et al., loc. cit). The central shear zone of Nagavalli-Vamosdhara (see Fig. 7.1) is in fact a combination of two NNW-SSE trending shear zones that are considered to coalesce at both ends (Chetty et al. 2003). The coalesced shear zone is thought to be an extension of the Napier-Rayner boundary in the East Antarctica, but palaeomagnetic data are inconsistent with the correlation of the EGMB with the East Antarctica (Torsvik et al., 2001).

Within the southern Indian shield, the nature and extension of the EGMB towards south is also enigmatic. Based on gravity data it is considered that the EGMB continues southwards along the east coast up to Cape Comorin and then swerves to west and north (Subramanyan, 1978). In this way the EGMB crosses the coast between Ongole and Kavali and re-emerges again near Chennai. According to this setting the EGMB is linked to the whole part of the Southern Granulite Terrain (SGT) through Bay of Bengal. However, such a link does not seem possible as the SGT is devoid of Mesoproterozoic event, unlike the EGMB (Braun and Kriegsman, 2002). In contrast to the SGT, the EGMB shows (a) close intermingling of charnockitic rocks and khondalites, (b) greater abundance of khondalite, (c) intense deformation of the belt before UHT metamorphism, and (d) abundance of Mn-formation as pointed out by Naqvi and Rogers (1987, p. 113).

In view of its significance for the continental assembly and break-up of Rodinia and East Gondwanaland, the EGMB has been receiving international attention. Based on Nd model ages and supported by Rb–Sr and Pb isotope data, Rickers et al. (2001) have identified 4 crustal domains in the EGMB (Fig. 7.3). Their Domain-I nearly coincides with the Western Charnockite Zone (WCZ) of Ramakrishnan et al. (1998). But the Domain south of the Godavari Rift (Domain IA of Rickers et al., 2001) is a distinct crustal block formed from juvenile material between 2300 and 1700 Ma. However, Sengupta et al. (1999) report mid-Archaean Nd modal ages for the mafic granulites of the Kondapalle area, which is considered a heat source for the UHT metamorphism over a vast region of the EGMB. Notwithstanding, Rickers et al. (2001) observed a notable difference between the WCZ rocks occurring on either side of the Godavari Rift. They noticed Archaean isotopic signatures in the north as compared to Proterozoic signatures in the south, supporting the earlier notion (Mezger et al., 1996; Sengupta et al., 1999) that the Godavari Rift is a terrain boundary (crustal boundary).

The remaining 3 Domains are in the north of the Godavari graben. The Domain II and III are correlatable with the N and S structural divisions suggested by Chetty and Murthy (1998). Rickers et al. (2001) placed the boundary between Domains II and III along the Nagavalli-Vamosdhara lineament (Chetty and Murthy, ibid) in the central part of the EGMB. The metasediments of Domain II have model ages of 2100–2500 Ma while those of Domain III have Nd model ages between 1800 and 2200 Ma (Fig. 7.3). In Domain II, the Nd model ages for orthogneisses show a gradual variation from areas near the Godavari Rift (3200 Ma) and decreases (1800 Ma) towards NE in beginning of Domain III. The Domain IV of Rickers et al. contains

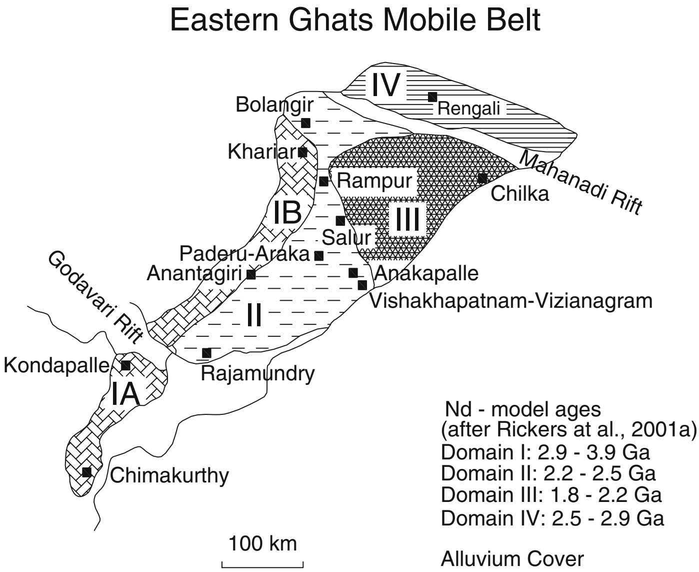

Fig. 7.3 Age domains in the Eastern Ghats Mobile Belt (after Rickers et al., 2001) (see text for details)

metasediments with Nd model ages of 2500–2900 Ma, although Domains II and IV are lithologically similar.

The similar U—Pb mineral ages from orthogneisses at Phulbani (Domain III) and at Angul (Domain IV) suggest Grenvillian thermal event. It is intriguing that the strong Grenvillian impress in Phulbani is not recorded at Chilka Lake in the same Domain. It is also not clear from the subdivisions of Rickers et al. (2001) as to which domain should the anorthosites of Bolangir and Turkel belong, although their geological setting is similar to that in Angul and Dhenkanal in Domain IV.

These divisions after Rickers et al. (2001) are confusing in that the isotopic data overlap and the divisions are at high angles to the regional trend. These divisions based on Nd model ages are, therefore, ambiguous. This author would like to make here a note of caution, particularly for field geologists, on the application and use of Nd model ages on crustal rocks. We infer growth curve of a rock with time from a measured $\sum$Nd and known ^{147}Sm/^{144}Nd ratios. However, if the rock sample was derived from CHUR (Chondrite Uniform Reservoir) the separation event can be fixed by the intersection of this growth curve with the horizontal curve of CHUR. But if the source of the rock sample was DM (Depleted Mantle), the separation time can be obtained as the intersection point of DM and growth curve. However, if the rock sample was derived from a crustal source that had separated from DM at a certain time, then the age will be very much younger than previous cases and difference could be as high as 500 Ma (see Sharma and Pandit, 2003). Moreover, if the Sm/Nd ratios are high, model ages need to be calculated using a two-step evolution. Also, if the orthogneisses are highly evolved, their Sm/Nd ratios would be changed by fractional crystallization. So it is really a question as to how reliable are these model ages on the granulitic rocks that have been metamorphosed at great depth and subjected to melting and fluid activity, thereby disturbing their protolith composition and even isotopic systems. In brief, the model ages cannot be a superior criteria over the one based on lithological assemblage for dividing the granulite facies rocks of the EGMB (cf. Ramakrishnan et al., 1998).

Recently, a new scheme of subdivision of the EGMB has been proposed by Dobmeier and Raith (2003) on mere assumption that the entire granulite terrain of EGMB consists of several crustal segments with distinct geological history. Their evaluation of the existing geological and isotopic data led them to suggest that the EGMB also includes the Nellore-Khammam Schist Belt as well as the lower grade rock-units at the southern margin of the Singhbhum craton. Their four subdivisions of this Eastern Ghats region are called Provinces and are named as follows (Fig. 7.4)

1. Rengali province
2. Jeypore province
3. Krishna province
4. Eastern Ghats province.

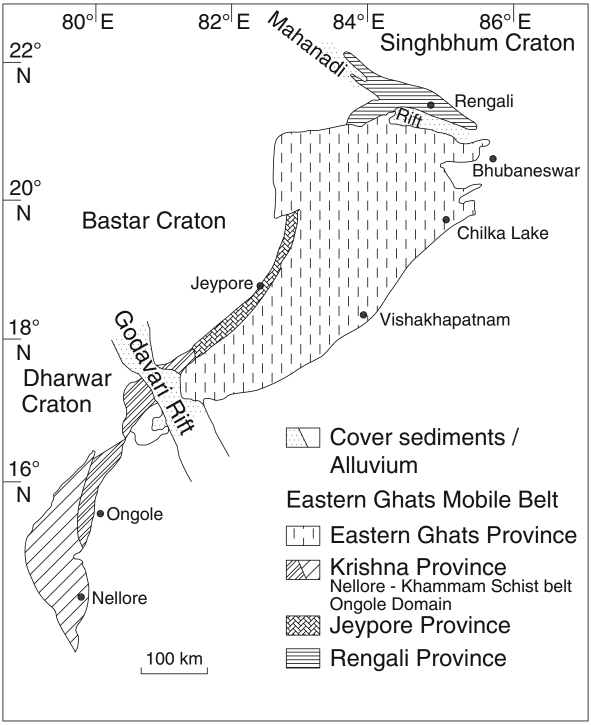

Fig. 7.4 Newer division of Eastern Ghats Mobile Belt into crustal provinces (after Dobmeier and Raith, 2003). See text for details

Two of these four Provinces are further divided into Domains separated by mega lineaments and shear zones, following the works of Nash et al. (1996) and Crowe et al. (2001), but ignoring the lineaments recognized in the central part of the EGMB by Chetty and Murthy (1998).

7.10.1 Rengali Province

The Rengali Province is the area with SW-NE trend located between the Bastar/Bhandara and Singhbhum cratons and hence beyond the north of Eastern Ghats Boundary Thrust Zone. This Province is mainly a low- to medium-grade volcano-sedimentary sequence which is similar to the Iron Ore Group and on which basis it was earlier assigned to the Singhbhum craton by Mahalik (1994). On the contrary, Nash et al. (1996) regarded them as a cover sequence to the south-dipping charnockitic-migmatitic gneisses of Angole within EGMB. The Rengali Province is dissected by faults and exposes a block of granulite facies gneisses and mafic granulites—the Badarma Complex, which is also included by Dobmeier and Raith in the Rengali Province. It must be noted that their metamorphic grade and geological history are quite contrasting. The very basis of recognizing Provinces is thus challenged. Moreover, the age and P-T evolution of Rengali Province are poorly constrained.

7.10.2 Jeypore Province

The Jeypore Province represents the northern portion of Western Charnockite Zone of Ramakrishnan et al. (1998), hence dominantly composed of charnockitic-enderbitic rocks. Because of dominance of intermediate rocks with calc-alkaline affinity Dobmeier and Raith (2003) think that these rocks are related to magmatism in an Andean-type active continental margin setting. But it is uncertain what part of the terrain was subducted and why do these granulites give so high pressures coinciding with the pelitic granulites with which they are associated in the EGMB.

7.10.3 Krishna Province

The Krishna Province of Dobmeier and Raith (2003) lies to the south of the Godavari graben. This Province comprises granulites of Ongole (equivalent to southern part of the WCZ of Ramakrishnan et al. (1998) and low- to medium-grade Nellore-Khammam Schist belt which is located between Cuddapah Boundary Shear Zone (CBSZ) and marginal zone of the EGMB. Dobmeier and Raith justify the grouping of these crustal terrains by geochronological data. Following Raman and Murthy (1997), the Nellore-Khammam belt is recognized as the Nellore Schist Belt (NSB) in the south and the Khammam Schist Belt (KSB) in the north. The western upper part of the NSB, consisting of low-grade metasediments, has been named

Udayagiri Domain and the eastern lower unit of medium-grade meta-volcano sedimentary sequence named as Vinajamuru Domain (VD) by Dobmeier and Raith (2003, p. 153). At Chamalpahar in the northern end of VD there are layered mafic complexes that synkinematically intruded migmatitic gneisses and amphibolites (Leelanandam and Narashima Reddy, 1998). Dobmeier and Raith assigned the amphibolites to back-arc setting, following Mukhopadhyay et al. (1994). But Hari Prasad et al. (2000) argued that the protoliths formed in two different tectonic settings, comparable to recent ocean island arc and continental marginal arcs. The boundary between the VD and Ongole Domain (South of Godavari graben) is blurred or uncertain (cf. Dobmeier and Raith, 2003, p. 156). From the Nd model ages of 2.6–2.8 Ga and zircon/monazite ages near 1.6 Ga for UHT metamorphism, Kovach et al. (2001) suggested a separate Ongole Domain that possibly thrusted on Domain 1A of Rickers et al. (2001).

7.10.4 Eastern Ghats Province

On the consideration that the results of Nd isotope mapping by Rickers et al. (2001) do not support the subdivisions of the khondalite lithologies earlier proposed by GSI (see Ramakrishnan et al., 1998), Dobmeier and Raith (2003) carved out the largest Province called the Eastern Ghats Province. This Province includes the Eastern Khondalite Zone (EKZ), the Central Charnockite-Migmatite Zone (CMZ) and a part of the Western Khondalite Zone (WKZ) of Ramakrishnan et al. (1998). The Eastern Ghats Province contains all granulite facies rocks and the sapphirine-bearing assemblages. Lastly, if the metamorphic history of the proposed domains is different, it is a matter of serious enquiry as to when and how the collage of the different domains/blocks had occurred. The models of Rickers et al. (2001) as well as of Dobmeier and Raith (2003) fail to answer this and other questions put forth in the preceding sections.

The different schemes of classification have been compiled by the writer in a comparative way and shown in Table 7.1.

The Eastern Ghats Province is extended by Dobmeier and Raith (2003) to south of Godavari graben, which was earlier recognized as a crustal-scale boundary of the EGMB. The ranges of Nd model ages given by Rickers et al. (2001) were also used for further subdivision of this Province into Domains. However, these divisions reflect regional scale compositional heterogeneity for the EG-Province.

From U–Pb ages of detrital zircons Dobmeier and Raith infer that deposition of sediments (precursor of khondalitic gneisses etc.) did not cease before 1.35 Ga, while an early episode of felsic magmatism (obtained from Sm–Nd whole-rock isochron) at 1.45 Ga (Shaw et al., 1997) was found to be almost coeval with an alkaline complex near Khariar (Sarkar and Paul, 1998; Aftalion et al., 2000). But it is not definitely known whether the alkaline complex intruded the Bastar craton or the Eastern Ghats Province. A second pulse of felsic plutonism is inferred at about 1.2 Ga, on the basis of discordant U–Pb zircon data (Crowe, 2003). Dobmeier and Raith have tried to constrain the early UHT metamorphism (8 kbar/950°C) at

Table 7.1 Newer divisions of the Eastern Ghats Mobile Belt with respect to those given by GSI (1998)

Basis	Divisions					References
Lithological assemblage	Transition zone	Western charnockite zone	Western khondalite zone	Central charnockite-migmatite zone	Eastern khondalite zone	Rama-krishnan et al. (1998) GSI view
	(TZ) between cratons and EGMB and has characteristics of both	(WCZ) mainly charnockite-enderbite with lenses of mafic/ultra-mafics and minor metapelites	(WKZ) mainly metapelites intercalated with Qtzites, calcsilicates, marbles and Mg–Al granulites. Contain an-orthothosite	(CMZ) mainly migmatite incl. Qz-diatextite, Mg–Al granu-lites, intrusions of charnockite. CMZ missing S of Godavari rift	(EKZ) similar to WKZ but devoid of anorthosites	
Nd Model age (assumed depleted mantle as source of nearly all EGMB rocks)	← *Domain-I*, 2.9–3.9 Ga →		← *Domain-II*, 2.2–2.5 Ga → (south of Nagavalli-Vamsadhara (NV) SZ)			Rickers et al. (2001)
	Domain-IV 2.5–2.9 Ga between Mahanadi SZ and SB-craton in the North			← *Domain-III* → 1.8–2.2 Ga bounded on three sides by lineaments; NVSz on SW Mahanadi Sz on N and Koraput-Sonapur Sz on W		

Table 7.1 (continued)

Basis	Divisions			References
Distinct Geol. history; limits of mega-lineaments; also geochronology for further subdivisions into domains	← *Rengali province* → (N of Mahanadi graben)	← *Jeypore province* → (Confined only to N of Mahanadi graben) ← *Krishna province* → (confined mainly to S of Godavari; consists of igneous complexes (anorthosite incl.) Includes Nellore and Khammam Schist Belts on W)	← *Eastern Ghats province* → (recognized on both sides of Godavari but missing to the N of Mahanadi)	Dobmeier and Raith (2003)

1100 Ma from dating with common Pb method and ^{207}Pb—^{206}Pb SHRIMP ages for euhedral zircons from leucogranite. This is a very significant conclusion along with the longitudinal extent of the Eastern Ghats Province across the Godavari graben. The second granulite facies metamorphism is dated at about 1000 Ma from U—Pb monazite ages from metasedimentary and metaigneous rocks (Aftalion et al., 1988; Mezger and Cosca, 1999) and from Pb—Pb single zircon evaporation ages from high Mg—Al granulites (Jarick, 2000) and EPMA monazite dates (Simmat, 2003). U—Pb age-data of sphene from calc-silicate rocks of the Eastern Ghats Province gave cooling age at about 570–530 Ma, pointing to a Pan-African thermal overprinting of the Khariar Domain. But it should be noted that the Khariar Domain of the Eastern Ghats Province is located near the mega-lineament, called Sileru Shear Zone (Chetty, 1995), or Lecher-Kunavaram-Koraput shear zone (Chetty and Murthy, 1998), or Lakhna thrust (Biswal, 2000), and this Pan-African age could be due to reactivation of this shear zone. The Angul Domain north of Mahanadi graben, however, gave different cooling ages at 930 ± 30 Ma, which led Dobmeier and Raith to suggest that this Domain was tectonically and thermally decoupled from the Eastern Ghats Province prior to Pan-African thermal event. The authors have given a comparative picture of isotopic data and thermo-tectonic events (Dobmeier and Raith, 2003, Fig. 5, p. 154) for their proposed crustal provinces of the Eastern Ghats fold belt, which are likely to be modified by more intense geological and geochronological work on this mobile belt.

References

Aftalion, M., Bowes, D.R., Dash, B. and Dempster, T.J. (1988). Late Proterozoic charnockites in Orissa, India: U—Pb and Rb—Sr isotopic study. J. Geol., vol. 96, pp. 663–676.

Aftalion, M., Bowes, D.R., Dash, B. and Fallick, A.E. (2000). Late Pan-African thermal history in the Eastern Ghats terrane, India from U—Pb and K—Ar isotopic study of the Mid-Proterozoic Khariar alkali syenite, Orissa. Geol. Surv. India Spl. Publ., vol. 57, pp. 26–33.

Aswathanaryan, U. (1964). Isotopic ages from the Eastern Ghats and Cuddapahs of India. J. Geophys. Res., vol. **69**, pp. 3479–3486.

Bhadra, S., Banerjee, M. and Bhattacharya, A. (2003). Tectonic restoration of polychronous mobile belt-craton assembly: constraints from corridor study across the western margin of the Eastern Ghats Belt, India. Mem. Geol. Soc. India, vol. **52**, pp. 109–130.

Bhattacharya, S. (1996). Eastern Ghats granulite terrain of India: an overview. J. Southeast Asian Earth Sci., vol. **14**, pp. 165–174.

Bhattacharya, A. and Gupta, S. (2001). A reappraisal of polymetamorphism in the Eastern Ghats Belt—a view from north of the Godavari rift. Proc. Indian Acad. Sci. (Earth Planet. Sci.), vol. **110**(4), pp. 369–383.

Bhattacharya, S. and Kar, R. (2002). High temperature dehydration melting and decompressive P-T path in a granulite complex from the Eastern Ghats, India. Contrib Mineral Petrol, vol. **143**, pp. 175–191.

Bhattacharya, S. and Kar, R. (2004). Alkaline intrusion in a granulite ensemble in the Eastern Ghats Belt, India: shear zone pathways and pull-apart structure. Proc. Indian Acad. Sci. (Earth Planet Sci.), vol. **113**(1), pp. 37–48.

Bhattacharya, S., Kar, R., Misra, S. and Teixeira, W. (2001). Early Archaean continental crust in the Eastern Ghats Belt, India: isotopic evidence from the charnockite suite. Geol. Mag., vol. **138**, pp. 609–618.

Bhattacharya, S., Sen, S.K. and Acharyya, A. (1994). Structural setting of the Chilka Lake granulite-migmatite-anorthosite suite with emphasis on the time relation of charnockites. Precambrian Res., vol. **66**, pp. 393–409.

Biswal, T.K. (2000). Fold-thrust geometry of the Eastern Ghats Mobile Belt, a structural study from its western margin, Orissa, India. J. African Earth Sci., vol. **31**, pp. 25–33.

Biswal, T.K., Ahuja, H. and Sahu, H.S. (2004). Emplacement kinematics of nepheline syenites from the Terrane Boundary shear zone of the Eastern Ghats Mobile Belt, west Khariar, NW Orissa: Evidence from Meso- and micro-structures. Proc. Indian Acad. Sci. (EPS), vol. **113**, pp. 785–793.

Boger, S.D., Wilson, C.J.L. and Fanning, C.M. (2001). Early Palaeozoic tectonism within the East Antarctica craton: the final suture between east and west Gondwana? Geology, vol. **29**, pp. 463–466.

Bose, M.K. (1971). Petrology of the alkaline suite of Sivamalai, Coimbatore, Tamil Nadu. J. Geol. Soc. India, vol. **12**, pp. 241–261.

Bose, S., Fukuoka, M., Sengupta, S. and Dasgupta, S. (2000). Evolution of high Mg−Al granulites from Sunkarametta, Eastern Ghats, India: evidence for a lower crustal heating-cooling trajectory. J. Metam. Geol., vol. **18**, pp. 223–240.

Braun, I. and Kriegsman, L.M. (2002). Proterozoic crustal evolution of southernmost India and Sri Lanka. In: Yoshida, M., Windley, B.F. and Dasgupta, S. (eds.), Proterozoic East Gondwana: Supercontinent Assembly and Breakup. Geol. Soc. Lond. Spl. Publ., vol. **206**, London.

Chetty, T.R.K. (1995). A correlation of Proterozoic shear zones between Eastern Ghats Belt, India and Enderby Land, East Antarctica, based on LANDSAT imagery. Mem. Geol. Soc. India, vol. **34**, pp. 205–220.

Chetty, T.R.K. and Murthy, D.S.N. (1998). Eluchuru-Kunavaram-Koraput (EKK) shear zone, Eastern Ghats Granulite Terrane, India: a possible Precambrian suture zone. Gondwana Res. Group Mem., vol. **4**, pp. 37–48.

Chetty, T.R.K., Vijay, P., Narayana, B.L. and Girdhar, G.V. (2003). Structure of the Nagavali shear zone, Eastern Ghats Mobile Belt, India: correlation in the East Gondwana reconstruction. Gondwna Res., vol. **6**(2), pp. 215–219.

Crawford, A.R. (1969). Reconnaissance Rb−Sr dating of Precambrian rocks of southern peninsular India. J. Geol. Soc. India, vol. **10**, pp. 117–166.

Crowe, W.A. (2003). Age constraints for magmatism and deformation in the northern Eastern Ghats Belt, India: implications for the development of East Gondwanaland. Precambrian Res., vol. **110**, pp. 1–8.

Crowe, W.A., Cosca, M.A. and Harris, L.B. (2001). $^{40}Ar/^{39}Ar$ geochronology and Neoproterozoic tectonics along the northern margin of the Eastern Ghats Belt, in north Orissa, India. Precambrian Res., vol. **108**, pp. 237–266.

Dasgupta, S., Ehl, J., Raith, M.M. and Sengupta, P. (1997). Mid-crustal contact metamorphism around the Chimakurthy mafic-ultramafic complex, Eastern Ghats Belt, India. Contrib Mineral Petrol, vol. **129**, pp. 182–197.

Dasgupta, S., Sanyal, S., Sengupta, P. and Fukuoka, M. (1994). Petrology of the granulites from Anakapalle—evidence for Proterozoic decompression in the Eastern Ghats, India. J. Petrol., vol. **35**, pp. 433–459.

Dasgupta, S. and Sengupta, P. (1995). Ultrametamorphism in Precambrian granulite terrains—evidence from Mg-Al granulites and calc-granulites of the Eastern Ghats, India. Geol. J., vol. **30**, pp. 307–318.

Dasgupta, S. and Sengupta, P. (2003). Indo-Antarctic correlation: a perspective from the Eastern Ghats granulite belt, India. In: Yoshida, M., Windley, B.F. and Dasgupta, S. (eds.), Proterozoic East Gondwana: Supercontinent Assembly and Breakup. Geol. Soc. Lond. Spl. Publ., vol. **206**, London, pp. 131–143.

Dasgupta, S. and Sengupta, P., Ehl, J., Raith, M. and Bardhan, S. (1995). Reaction textures in a suite of spinel granulites from the Eastern Ghats Belt, India: evidence for polymetamorphism, a partial petrogenetic grid in the system KFMASH and roles of ZnO and Fe_2O_3. J. Petrol., vol. **36**, pp. 435–461.

Dobmeier, C. and Raith, M.M. (2003). Crustal architecture and evolution of the Eastern Ghats Belt and adjacent regions of India. In: Yoshida, M., Windley, B.F. and Dasgupta, S. (eds.), *Proterozoic East Gondwana: Supercontinent Assembly and Breakup*. Geol. Soc. Lond. Spl. Publ., vol. **206**, London, pp. 145–168.

Dobmeier, C and Simmat, R. (2002). Post-Grenvillian transpression in the Chilka Lake area, Eastern Ghats Belt—implications for the geological evolution of peninsular India. Precambrian Res., vol. **113**, pp. 243–268.

England, P.C. and Thompson, A.B. (1984). Pressure-temperature-time paths of regional metamorphism. I. Heat transfer during the evolution of regions of overthickened continental crust. J. Petrol., vol. **25**, pp. 894–928.

Fitzsimons, I.C.W. (2000). Grenville-age basement provinces in East Antarctica: evidence for three separate collisional orogens. Geology, vol. **28**, pp. 879–882.

Gopalkrishnan, K. (1998). Extensions of Eastern Ghats Mobile Belt, India—a geological enigma. Geol. Surv. India Spl. Publ., vol. **44**, pp. 22–38.

Grew, E.S. and Manton, W.I. (1986). A new correlation of sapphirine granulites in the Indo-Antarctic metamorphic terrain: Late Proterozoic dates from the Eastern Ghats Province of India. Precambrian Res., vol. **33**, pp. 123–137.

GSI (1998). Geological and Mineral Map of Tamil Nadu and Pondicherry. Scale 1 : 500,000 with Explanatory Brochure, 38 p. GSI Publ. Kolkata.

Gupta, S., Bhattacharya, A., Raith, M. and Nanda, J.K. (2000). Contrasting pressure–temperature–deformational history across a vestigial craton-mobile belt assembly: the western margin of the Eastern Ghats Belt at Deobogh, India. J. Metam. Geol., vol. **18**, pp. 683–697.

Halden, N.M., Bowes, D.R. and Dash, B. (1982). Structural evolution of migmatites in granulite facies terrane: Precambrian crystalline complex of Angul, Orissa, India. Trans. R. Soc. Edinburgh: Earth Sciences, vol. **73**, pp. 109–118.

Hari Prasad, B., Okudaira, T., Hayasaka, Y., Yoshida, M, and Divi, R.S. (2000). Petrology and geochemistry of amphibolites from the Nellore-Khammam Schist Belt, SE India. J. Geol. Soc. India, vol. **56**, pp. 67–78.

Hoffman, P.F. (1991). Did the breakup of Laurentia turn Gondwanaland inside-out? Science, vol. **42**, pp. 1409–1412.

Jarick, J. (2000). Die thermotecktonometamorphe Entwicklung des Eastern Ghats Belt, Indien—ein Test der SWEAT Hypothese. Ph.D. thesis, J.W. Goethe Universitaet, Frankfurt.

Kaila, K.L., Tewari, H.C., Roy Chowdhury, K., Rao, V.K., Sridhar, A.R. and Mall, D.M. (1987). Crustal structure of the northern part of the Proterozoic Cuddapah basin of India from deep seismic soundings and gravity data. Tectonophysics, vol. **140**, pp. 1–12.

Kar, R. (2001). Patchy charnockites from Jenapore, Eastern Ghats granulite belt, India: structural and petrochemical evidences attesting to their relict nature. Proc. Indian Acad. Sci. (Earth Planet. Sci.), vol. **110**, pp. 337–350.

Kelly, N.M., Clark, G.L., Carson, C.J. and White, R.W. (2000). Thrusting in the lower crust: evidence from the Oygarden Islands, Kemp Land, East Antarctica. Geol. Mag., vol. **137**, pp. 219–234.

Kovach, V.P., Simmat, R., Rickers, K., Berezhnaya, N.G., Salnikova, E.B., Dobmeier, C., Raith, M.M., Yakovleva, S.Z. and Kotov, A.B. (2001). The Western charnockite zone of the Eastern Ghats Belt, India: An independent crustal province of Late Archaean (2.8 Ga) and Paleoproterozoic (1.7–1.6 Ga) terrains. Gondwana Res., vol. **4**, pp. 666–667.

Krause, O., Dobmeier, C., Raith, M.M. and Mezger, K. (2001). Age of emplacement of massif-type anorthosites in the Eastern Ghats Belt, India: constraints from U-Pb zircon dating and structural studies. Precambrian Res., vol. **109**, pp. 25–38.

Lal, R.K. (1997). Internally consistent calibrations for geothermobarometry of high-grade Mg−Al rich rocks in the system $MgO-Al_2O_3-SiO_2$ and their application to sapphirine-spinel granulites of Eastern Ghats, India and Enderby Land, Antarctica. Proc. Indian Acad. Sci. (Earth Planet Sci.), vol. **103**, pp. 91–113.

Leelanandam, C. (1967). Occurrence of anorthosites from the charnockitic area of Kondapalle, Andhra Pradesh. Bull. Geol. Soc. India, vol. **4**, pp. 5–7.

Leelanandam, C. (1990). The anorthosite complexes and Proterozoic mobile belt of peninsular India: a review. In: Naqvi, S.M. (ed.), Precambrian Continental Crust and Its Mineral Resources. Dev. Precambrian Geol., vol. **8**. Elsevier, Amsterdam, pp. 409–435.

Leelanandam, C. (1997). The Kondapalle layered complex, Andhra Pradesh, India: a synoptic overview. Gondwana Res., vol. **1**, pp. 95–114.

Leelanandam, C. (1998). Alkaline magmatism in the Eastern Ghats Belt—a critique. Geol. Surv. India Spl. Publ., vol. **44**, pp. 170–179.

Leelanandam, C., Burke, K., Ashwal, L.D. and Webb, S.J. (2006). Proterozoic mountain building in peninsular India: an analysis based primarily on alkaline rocks distribution. Geol. Mag., vol. **43**, pp. 195–212.

Leelanandam, C. and Narashima Reddy, M. (1998). Precambrian anorthosites from peninsular India—problems and perspectives. Geol. Surv. India Spl. Publ., vol. **44**, pp. 152–169.

Mahalik, N.K. (1994). Geology of the contact between the Eastern Ghats Belt and the north Orissa craton, India. J. Geol. Soc. India, vol. **44**, pp. 41–51.

Mezger, K. and Cosca, M.A. (1999). The thermal history of the Eastern Ghats Belt (India), as revealed by U–Pb and $^{40}Ar/^{39}Ar$ dating of metamorphic and magmatic minerals: implications for the SWEAT correlation. Precambrian Res., vol. **94**, pp. 251–271.

Mezger, K., Cosca, M.A. and Raith, M.M. (1996). Thermal history of the Eastern Ghats Belt (India) deduced from U–Pb and $^{40}Ar/^{39}Ar$ dating of metamorphic minerals. (Abstract) V.M. Goldschmidt Conference, 1, p. 401.

Mezger, K. and Krogstard, E.J. (1997). Interpretation of discordant U–Pb zircon ages: An evaluation. J. Metam. Geol., vol. **15**, pp. 127–140.

Mukhopadhyay, I., Ray, J. and Guha, S.B. (1994). Amphibolitic rocks around Kotturu, Khammam district, Andhra Pradesh: structural and petrological aspects. Indian J. Geochem., vol. **9**, pp. 39–53.

Naqvi, S.M. and Rogers, J.J.W. (1987). Precambrian Geology of India. Oxford University Press, New York, 223p.

Nash, C.R., Rankun, L.R., Leeming, P.M. and Harris, L.B. (1996). Delineation of lithostructural domains in northern Orissa (India) from landsat thematic mapper imagery. Tectonophysics, vol. **260**, pp. 245–257.

Pande, O.P. and Rao, V.K. (2006). Missing granitic crust (?) in the Godavari graben of southeastern India. J. Geol. Soc. India, vol. **67**(3), pp. 307–319.

Paul, D.K., Ray Barman, T., McNaughton, N.J., Fletscher, I.R., Potts, P.J., Ramakrishnan, M. and Augustine, P.F. (1990). Archaean-Proterozoic evolution of Indian charnockites: isotopic and geochemical evidence from granulites of the Eastern Ghats Belt. J. Geol., vol. **98**, pp. 253–263.

Perraju, P., Kovach, A. and Svingor, E. (1979). Rubidium-strontium ages of some rocks from parts of the Eastern Ghats in Orissa and Andhra Pradesh, India. J. Geol. Soc. India, vol. **20**, pp. 290–296.

Philpots, A. (1990). Principles of Igneous and Metamorphic Petrology. Prentice Hall, New Jersey, 498p.

Powell, C.McA., Li, Z.X., Mcellhinny, M.W., Meert, J.G. and Park, J.K. (1994). Palaeomagnetic constraints on the timing of the Neoproterozoic breakup of Rodinia and the Cambrian formation of Gondwana. Geology, vol. **22**, pp. 889–892.

Ramakrishnan, M., Nanda, J.K. and Augustine, P.F. (1998). Geological evolution of the Proterozoic Eastern Ghats Mobile Belt. Geol. Surv. India Spl. Publ., vol. **44**, pp. 1–21.

Ramakrishnan, M. and Vaidyanadhan, R. (2008). *Geology of India,* vol. **1**. Geological Society India, Bangalore, 556p.

Raman, P.K. and Murthy, V.N. (1997). Geology of Andhra Pradesh. Geological Society of India, Bangalore, 245p.

Rao, A.T., Kamineni, D.C., Arima, M. and Yoshida, M. (1995). Mineral chemistry and metamorphic P-T conditions of a new occurrence of sapphirine granulites near Madhuravada in the Eastern Ghats, India. In: Yoshida, M., Santosh, M. and Rao, A.T. (eds.), *India as a Fragment of East Gondwana*. Gondwana Res. Group Mem., vol. **2**, Gondwana, pp. 109–121.

Rickers, K., Mezger, K. and Raith, M.M. (2001). Evolution of the continental crust in the Proterozoic Eastern Ghats Belt, India and new constraints for Rodinia reconstruction: implications from Sm—Nd, Rb—Sr and Pb—Pb isotopes. Precambrian Res., vol. **112**, pp. 183–212.

Rogers, J.J.W. (1996). History of 3 billion years old continents. J. Geol., vol. **104**, pp. 91–107.

Sarkar, A., Bhanumathi, L. and Balasubramanyan, M.N. (1981). Petrology, geochemistry, and geochronology of the Chilka Lake igneous complex, Orissa State, India. Lithos, vol. **14**, pp. 93–111.

Sarkar, A., Pati, U.C., Panda, P.K., Patra, P.C., Kundu, H.K. and Ghosh, S. (1998). Late-Archaean charnockitic rocks from the northern marginal zones of the Eastern Ghats Belt: a geochronological study (Abstract). International Seminar on *Precambrian Crust in Eastern and Central India,* held in October 29–30, Bhubaneswar.

Sarkar, A. and Paul, D.K. (1998). Geochronology of the Eastern Ghats Precambrian Mobile Belt—a review. Geol. Surv. India Spl. Publ., vol. **44**, pp. 51–86.

Sen, S.K., Bhattacharya, S. and Acharyya, A. (1995). A multi-stage pressure-temperature record in the Chilka Lake granulites: the epitome of metamorphic evolution in the Eastern Ghats, India. J. Metam. Geol., vol. **13**, pp. 287–298.

Sengupta, P., Dasgupta, S., Bhattacharya, P.K., Fukoka, M., Chakraborti, S. and Bhowmik, S. (1990). Petrotectonic imprints in the sapphirine granulites from Anantagiri, Eastern Ghats Mobile Belt, India. J. Petrol., vol. **31**, pp. 971–996.

Sengupta, P., Dasgupta, S., Raith, M., Bhui, U.K. and Ehl, J. (1999). Ultra-high temperature metamorphism of metapelitic granulites from Kondapalle, Eastern Ghats Belt: implications for the Indo-Antarctic correlation. J. Petrol., vol. **40**, pp. 1065–1087.

Sharma, R.S. and Pandit, M.K. (2003). Evolution of early continental crust. Curr. Sci., vol. **84**(8), pp. 995–1001.

Shaw, R.K. and Arima, M. (1996). High-temperature metamorphic imprint from calc-granulites of Rayagada, Eastern Ghats, India: implications of isobaric cooling path. Contrib Mineral Petrol, vol. **126**, pp. 169–180.

Shaw, R.K., Arima, M., Kagami, H., Fanning, C.M., Shiraishi, K. and Motoyoshi, Y. (1997). Proterozoic events in the Eastern Ghats granulite belt, India: evidence from Rb—Sr, Sm—Nd systematics and SHRIMP dating. J. Geol., vol. **105**, pp. 645–656.

Simmat, R. (2003). Indentifizierung hochgradig metamorpher Provinzen des Eastern Ghats Belt in Indien anhand EMS-Studie von Monazit-Altersmustern. Ph.D. thesis, University of Bonn, Germany.

Subba Rao, T.V., Bhaskar Rao, Y.J., Sivaraman, T.V. and Gopalan, K. (1989). Rb—Sr age and petrology of Elchuru alkaline complex: implication to alkaline magmatism in the Eastern Ghats Mobile Belt. Mem. Geol. Soc. India, vol. **15**, pp. 207–223.

Subramanyan, C. (1978). On the relation of gravity anomalies to geotctonics of Precambrian terrains of south Indian shield. J. Geol. Soc. India, vol. **19**, pp. 241–263.

Torsvik, T.H., Carter, L.M., Ashwal, L.D., Bhusan, S.K., Pandit, M.K. and Jamtveit, B. (2001). Rodinia refined or obscured: palaeomgnetism of the Malani igneous suite (NW India). Precambrian Res., vol. **108**, pp. 319–333.

Upadhyay, D. (2008). Alkaline magmatism along the southeastern margin of the Indian shield: Implications for regional geodynamics and constraints on craton-Eastern Ghats Belt suturing. Precambrian Res., vol. **162**, pp. 59–62.

Upadhyay, D., Raith, M.M., Mezger, K., Bhattacharya, A. and Kinny, P.D. (2006b). Mesoproterozoic rifting and Pan-African continental collision in SE India: evidence from the Khariar alkaline complex. Contrib Mineral Petrol, vol. **151**, pp. 434–456.

Upadhyay, D., Raith, M.M., Mezger, K. and Hammerschmidt, K. (2006a). Mesoproterozoic rift-related alkaline magmatism at Eluchuru, Prakasam alkaline complex, SE India. Lithos, vol. **89**, pp. 447–477.

Vinogradov, A., Tugarinov, A., Zhykov, C., Stapnikova, N., Bibikova, E. and Korre, K. (1964). *Geochronology of the Indian Precambrian*. Report 22nd International Geological Congress, Part 10, pp. 553–567.

Yoshida, M. (2007). Geochronological data evaluation: Implications for the Ptroterozoic tectonics of East Gondwana. Gondwana Res., vol. **12**, pp. 228–241.