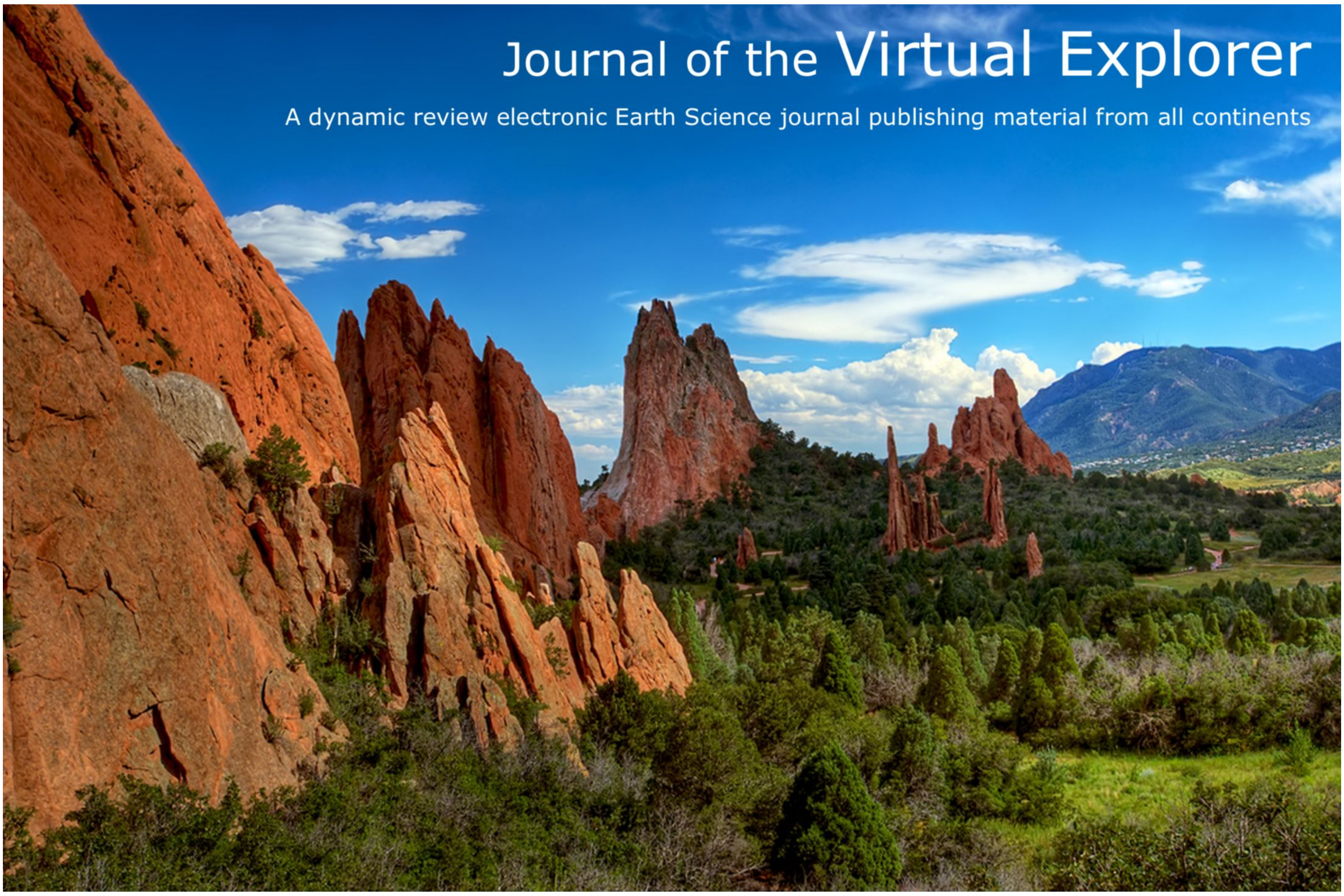

Proterozoic Eastern Ghats Belt, India – a witness of multiple orogenies and its lineage with ancient supercontinents

Subrata Karmakar, Sankar Bose, Kaushik Das, Somnath Dasgupta

Journal of the Virtual Explorer, Electronic Edition, ISSN 1441-8142, volume **32**, paper 3
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Abstract: The Eastern Ghats Belt of India exposes a deep crustal section that witnessed multiple events of deformation, magmatism and metamorphism throughout the Proterozoic eon. Structural and petrological styles show variations in both, space and time. Available petrological data suggest that the deep crustal section of this belt was subjected to extreme thermal perturbation causing high temperature (HT) to ultrahigh temperature (UHT) metamorphism over an extended geographical area, the nature of which again varied in time and space. It is now understood that the 1000km long edifice of the Eastern Ghats Belt evolved in a phase-wise manner due to recurrent crust-building activities surrounding cratonic India. Consequently, it is possible to correlate these events with global-scale orogenies that united India with east Antarctica and Australia in different time and space coordinates. This prompts us to a hypothesis that history of such a mountain belt can actually reflect the evolution of Precambrian supercontinents, namely Columbia, Rodinia and Gondwana. We review the present state-of-the-art, but also point out that more rigorous investigation in future may add a quantitative flavor to this.

Citation: Karmakar, S., Bose, S., Das, K., Dasgupta, S. 2009. Proterozoic Eastern Ghats Belt, India – a witness of multiple orogenies and its lineage with ancient supercontinents. In: (Eds.) Talat Ahmad, Francis Hirsch, and Punya Charusiri, *Journal of the Virtual Explorer*, volume **32**, paper 3, doi: 10.3809/jvirtex.2009.00254

Introduction

The Eastern Ghats Belt (EGB) of India exposes a deep crustal section in the form of a 1000 km long edifice along the eastern coastline of India. Consisting of a lithologic ensemble of diverse chemistry, it has long been recognized as a mobile belt that sutured cratonic blocks of India with their transcontinental counterparts in the Precambrian time. Preliminary isotopic signatures from variedly disposed high-grade paragneissic and orthogneissic rocks led early researchers to believe that the entire mountain belt arose during a major orogeny in the Archean time. This idea was drastically changed when precise geochronological data identified no Archean metamorphic signatures in EGB. Petrological and structural data available from studies spanning the last three decades identified this belt as polymetamorphic and polydeformed (summarized in Dasgupta and Sengupta, 2003; Mukhopadhay and Basak, 2009). Geochronological data, on the other hand, clearly show that the entire crustal architecture of EGB was framed during mountain building activities in the Proterozoic eon (Dobmeier and Raith, 2003 and references therein).

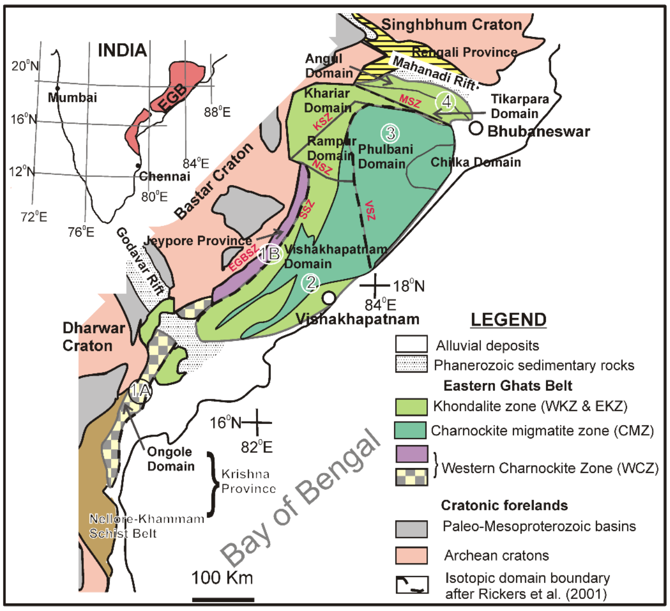
Crustal evolution during the Proterozoic eon is heralded by assembly and break-up of several supercontinents. These supercontinents formed, stabilized and eventually dispersed in response to crust-mantle coupling and decoupling (Condie, 2005). Although there is disparity in opinion about the history of early-formed supercontinents like Columbia (~1900-1400 Ma), considerable agreement exists for the much younger supercontinent Gondwana (~550-300 Ma). The supercontinent Rodinia (~1000-750 Ma) existed in-between and there has been considerable effort to model its evolution through time and space (reviewed in Li *et al.*, 2008). It is well established that global-scale orogenic activities played crucial roles in assembling each of these supercontinents under collisional and/or accretional tectonic settings. Traces of such activities are gathered from piecemeal evidenc from widely scattered areas in the present-day coordinates. Needless to say, compelling evidenceis pouring in day by day and strengthening the hypothesis of supercontinetal cycle.

EGB has long been identified as an important link in understanding the evolutionary history of the supercontinent Rodinia as petrological (Hoffman, 1991; Dalziel, 1991; Yoshida, 1995; Harley, 2003), and little reliable geochronological data has been found matching counterparts in east Antarctica (summarized in Dasgupta and Sengupta, 2003; Dobmeier and Raith, 2003). It is also exciting to find evidence of orogenic activities in EGB whose timeframe lies beyond Rodinia. With the arrival of new petrological, structural and most importantly, precise geochronological data, there is a need to re-look at this ancient mountain belt. We felt excited about the possibility of locating crustal segments belonging to extinct supercontinents within an apparently single geomorphological entity. With a continuous inflow of more precise data on deformation, magmatism and metamorphism in different continental blocks, it is possible to frame and correlate the events with higher resolution. However, at this point of time,there is also a need to review the existing database and understand the future demand of deep crustal studies.

Crustal source of EGB

The unique feature of EGB is that the entire belt is composed of high-grade granulites with minor lower grade rocks. The high-grade granulites consist of supracrustal rocks and intrusives of diverse chemistry. In an attempt to frame a lithological map, Ramakrishnan *et al.* (1998) introduced a four-fold longitudinal subdivision viz. Western Charnockite Zone (WCZ), Western Khondalite Zone (WKZ), Central Migmatite Zone (CMZ) and Eastern Khondalite Zone (EKZ). Additionally, their work invoked the existence of a Transition Zone (TZ) separating EGB from the adjacent Bastar Craton (Fig. 1). Despite being a pioneering effort, later petrological and isotopic data do not exactly comply with this scheme and reveal a more complex scenario. Rickers *et al.* (2001) carried out Nd-mapping over a large part of the EGB and based on Sm-Nd, Rb-Sr and ^{207}Pb-^{206}Pb isotopic data, subdivided EGB into four crustal domains whose boundaries do not match with those of Ramakrishnan *et al.* (1998). Domain 1 broadly coincides with WCZ and is subdivided into 1A and 1B based on positions with respect to the Godavari Rift (Fig. 1). Domain 1A is situated at the southern end of Godavari Rift and is characterized by homogeneous Nd-model ages for the paragneisses (2.8-2.6 Ga) and orthogneisses (2.5-2.3 Ga). Domain 1B is situated in the north of Godavari Rift and is characterized by older crustal protolith (3.9-3.2 Ga age for orthogneisses). Domain 2 consists of CMZ and EKZ and shows very complex isotopic characters. Metasediments have Nd-model age of 2.5-2.1 Ga, while the orthogneisses have a wide Nd-model age spanning 3.2-1.8 Ga. Earlier, Sengupta *et al.* (1999) had pointed out the differences in the history of petrological evolution of granulites occurring to the north and south of the Godavari rift. Domain 3 is situated north of Domain 2 and shows fairly homogeneous Nd-model age (2.2-1.8 Ga for both metasediments and orthogneisses). This domain has more juvenile addition compared to the others. Domain 4 is situated at the extreme northern part with Nd-model age of 3.2 Ga for the orthogneisses and 2.8-2.2 Ga for the metasediments. The essence of this subdivision of EGB is that the protolith history of all the four crustal domains is contrasting. The sources of the sediments deposited on a basement (of unknown age) are the adjoining Archean cratons, while small but variable quantities of juvenile material was added during Proterozoic-age orogenies. Dobmeier and Raith (2003) conceptualized EGB into four crustal provinces (instead of four domains) based on isotopic data of Rickers *et al.* (2001) combining with available petrological, structural and other geochronological data. Accordingly, the Jeypore Province and the Krishna Province, equivalent to Domains 1B and 1A of Rickers *et al.* (2001) respectively, are excluded from the sensu-stricto Eastern Ghats Province. The latter (combining Domains 2 and 3) consists of several domains with slightly contrasting protolith histories, all of which share a strong tectonothermal history in the Neoproterozoic time (~1000-500 Ma). The fourth one, the Rengali Province representing the Domain 4 has crustal antiquity similar to the adjoining Singhbhum Craton and available petrological data also allow its exclusion from the Eastern Ghats Province. According to them, therefore, only the Eastern Ghats Province bears the unique tag of representing a mobile belt, while the status of the other three provinces remains uncertain. It is not clear from the available data whether evidenc of an earlier orogeny are concealed within the belt which might have wider implication in crustal evolution. Several studies (*e.g.* Gupta, 2004) questioned the validity of such a classification, owing to the fact that different criteria were used to subdivide the EGB. Complexities do exist in crustal provenance (metamorphic and intrusive ages, P-T paths and structural styles) that pose serious problems. One important aspect of this kind of domainal or provincial classification of EGB is the nature of the mutual boundaries. Several workers (Chetty, 2001; Chetty *et al.*, 2003; Biswal and Sahoo, 1998) identified mega-lineaments in EGB from satellite imagery data albeit with limited ground checks. These lineaments broadly follow the river courses along the domain/province boundaries. Limited structural data (*e.g.* Chetty *et al.*, 2003) suggest such lineaments as ductile shear zones. However, lack of detailed structural, petrological and, most importantly, geochronological data do not allow one to test the nature of such domain/province boundaries.

Figure 1. Domainal divisions of Eastern Ghats Belt



Domainal divisions of Eastern Ghats Belt, India and adjacent crustal terrains (modified after Dobmeir and Raith (2003)). Encircled numbers represent the isotopic domains following Rickers *et al.*, (2001). Lithological divisions of EGB are based on Ramakrishnan *et al.* (1998). Crustal provinces and domain names of EGB are after Dobmeir and Raith (2003). EGBSZ- Eastern Ghats Boundary Shear Zone, SSZ - Sileru Shear Zone, VSV - Vamsadhara Shear Zone, NSZ - Nagavalli Shear Zone, KSV - Koraput-Sonapur Shear Zone, MSZ - Mahanadi Shear Zone.

Magmatic events

The evolutionary history of the EGB is punctuated with magmatic activities associated with tectonometamorphic events. Magmatic rocks of diverse chemistry are present all throughout the EGB. A large mafic-ultramafic complex is found to intrude the metapelitic granulites in Kondapalle in the southern EGB (Ongole Domain of Krishna Province). The complex consists of a gabbro-norite-pyroxenite-anorthosite suite of rocks which is presently metamorphosed to granulite grade (Leelanandam, 1990, 1997; Sengupta *et al.*, 1999). Geochemical signatures suggest that the complex was formed at deep-crustal level (9-10 kbar) from high-Mg basalt in an arc-related setting (Leelanandam and Vijaya Kumar, 2007). Emplacement of this magma caused ultrahigh temperature (UHT) regional contact metamorphism of the surrounding crust (Sengupta *et al.*, 1999). Emplacement age of this mafic complex is unknown, but must be older than ~1.72 Ga. The latter is the emplacement age of the enderbitic magma that intrudes the mafic complex at Kondapalle (Kovach *et al.*, 2001). A similar mafic-ultramafic complex was emplaced at Chimakurthy (Ongole domain) in further south of EGB. This too caused contact metamorphism of the surrounding crust, but the depth of emplacement was much shallower (~6 kbar) (Dasgupta *et al.*, 1997). From the northern part of EGB near Rayagada (Vishakhapatnam Domain), Shaw *et al.* (1997) determined the crystallization age of mafic magma (now mafic granulite) as ~1.45 Ga based on Sm-Nd data. Excepting this occurrence, the innumerable pockets of mafic granulite disseminated in the entire stretch of EGB remain largely undated, although such data may prove to be extremely important in understanding the geodynamic milieu for mafic magmatism. Voluminous amounts of enderbite/charnockite magma were emplaced in the entire stretch of EGB. Of particular mention is the linear stretch of western margin of EGB (Jeypore Province) where this forms a major mappable lithounit. Available petrological data show that this magma was emplaced broadly synchronous with the fabric forming deformation event (M2-D2) and metamorphosed to granulite grade (reviewed in Dasgupta and Sengupta, 2003 and Dobmeier and Raith, 2003). Although such magma is regarded as a member of calc-alkaline rock suite generated at Andean-type active continental margin setting (Dobmeier and Raith, 2003), its geochemical and geochronological attributes are not explored in detail. Such information would be essential in order to understand the paleotectonic setting under which such magmatism took place. Scattered geochronological data suggest the earliest age of enderbite emplacement in the southern part of EGB (Ongole Domain) is ~1.72-1.70 Ga (Kovach *et al.*, 2001). A second generation of charnockite/enderbite magma intrudes the gneissic enderbite at ~1.60 Ga (Mezger and Cosca, 1999). Porphyritic granitoids, some of which contain orthopyroxene were emplaced in different parts of EGB (Eastern Ghats Province, in general) broadly in the time span of ~1000-950 Ma (Grew and Manton, 1986; Paul *et al.*, 1990; Shaw *et al.*, 1997; Aftalion *et al.*, 1988; Kovach *et al.*, 1998). This phase of granitoid magmatism was associated with Grenvillian-age metamorphism of the EGB (as discussed later).

Anorthosite complexes of variable size are found as scattered bodies in different parts of EGB (particularly in Eastern Ghats Province). These anorthosite bodies represent mantle pulses presumably concomitant with major tectonometamorphic activities (Leelanandam, 1990; Maji *et al.*, 1997; Bhattacharya *et al.*, 1998; Krause *et al.*, 2001; Dobmeier, 2006). Available geochronological data suggest emplacement age of ~1000-900 Ma for these anorthosite bodies (references as above). Only one amongst these, the Chilka Lake Anorthosite, has some conflicting ages. Its previous emplacement age of ~792 Ma (Krause *et al.*, 2001) has recently been re-estimated as ~983 Ma (Chatterjee *et al.*, 2008). The Pangidi Anorthosite in the southern EGB has a much older emplacement age of ~1700 Ma (Dharma Rao *et al.*, 2004). It is interesting to note that these emplacement ages in different provinces/domains of EGB have strong resemblances with timing of granulite-grade metamorphism (as discussed in the following section). It is argued that the anorthosite magma was emplaced in thinned crust during differentiation of high-Al basic magma. However, there is hardly any clue whether this anorthosite has any consanguinity with more widely distributed mafic granulites.

Series of alkaline rocks occur along the western boundary of the EGB with the surrounding Bastar, Singhbhum and Dharwar cratons (Upadhyay, 2008 and references therein). Notably, most of the alkaline plutons follow the strike of two major mega-lineaments *i.e.* Sileru Shear Zone and Eastern Ghats Boundary Shear Zone (Dobmeier and Raith, 2003) or Terrain Boundary Shear Zone (Biswal *et al.*, 2007). Important members of these rock suites include syenite, nepheline syenite, hornblende syenite, monzosyenite and quartz syenite. Almost all of the alkaline complexes are metamorphosed to granulite-grade, while the sheared counterparts show amphibolite-grade of metamorphism. Such rocks are believed to have formed by fractionation of basanitic magma produced by partial melting of enriched subcontinental mantle source with variable degree of crustal contamination (Vijaya Kumar *et al.*, 2007; Upadhyay, 2008). In a recent study, Upadhyay (2008) argued that the alkaline magma was emplaced in a rift-related tectonic setting at the cratonic margin, which was earlier conceived by others

(Leelanandam, 1998; Leelanandam *et al.*, 2006). All these rocks were emplaced in the time span of ~1500-1300 Ma during break-up of the supercontinent Columbia (Upadhyay, 2008).

Metamorphic signatures

Multiple cycles of metamorphism are hallmarks of the EGB where at least two events occurred under granulite facies conditions. Considerable amount of petrological data have accumulated from studies in different parts of EGB over the last three decades (summarized in Dasgupta and Sengupta, 2003; Mukhopadhyay and Basak, 2009 and references therein). The apparently contrasting P-T data and conflicting nature of P-T paths can now be treated with domainal or provincial basis. It is now realized that crustal provinces/domains with contrasting evolutionary histories are likely to show such variability and one needs to understand the story in a fragmental way before being able to visualize the entire story in a collative manner.

The earliest event of granulite-grade metamorphism in EGB is reported from the Jeypore Province (or domain 1B of Rickers *et al.*, 2001) where the enderbitic gneiss with protolith age of ~3.90-3.00 Ga (Nd-model age) shows metamorphism at ~2.80 Ga (U-Pb zircon age after Kovach *et al.*, 2001). The nature of metamorphism, deformational pattern and field relations of this unit are not clear. No subsequent metamorphic imprints are identified from this province, which is partly caused by paucity of data. If we accept the fact that the Jeypore Province has antiquity beyond any known tectonothermal event in rest of the EGB, we are left with no alternative but to exclude this from the EGB. Moreover, since the southern tip of this province is conjectural (as discussed by Dobmeier and Raith, 2003); the apparent signatures of Grenvillian (~1.1-1.0 Ga) and Pan African (~500 Ma) events on Kunavaram Alkaline Complex can not be ascribed to that of Jeypore Province with certainty.

In the southern part of the EGB (Ongole domain or domain 1A of Rickers *et al.*, 2001), an early event of UHT metamorphism has been documented from enclaves of metasedimentary rocks within mafic magma (Sengupta *et al.*, 1999). UHT metamorphism has been interpreted as the fallout of regional-scale contact metamorphism of the mafic magma, now represented by mafic granulite. Peak temperature of metamorphism exceeded 1000°C at deep crustal conditions (9-10 kbar pressure). The resultant P-T path is a heating-cooling one and the post-UHT condition is marked by prolonged isobaric cooling and hydration. Timing of UHT metamorphism is not well-constrained so far, but it should be older than ~1.72 Ga emplacement age of enderbitic gneiss. Bose *et al.* (2008) identified a zircon SHRIMP U-Pb concordia age of ~1.76 Ga, which is the most likely timing of UHT metamorphism *vis-à-vis* emplacement age of basic magma in the basement of EGB. Evidence of metamorphic reworking is not prominent in this rock, yet zircon and monazite grains from different rock-types of the Ongole domain show a prominent growth at ~1.65-1.60 Ga (Simmat and Raith, 2008; Upadhyay *et al.*, 2009). Since this broadly coincides with emplacement of a pegmatoidal enderbite (Mezger and Cosca, 1999), it may be viewed at least as a thermal imprint. A somewhat similar heating-cooling type P-T path was also deduced from further south (Dasgupta *et al.*, 1997) which implies that the early UHT metamorphism in the Ongole domain was chiefly thermal in nature. The lower pressure (~6 kbar) of metamorphism in the latter suggest magma emplacement at much shallower level. Rocks of this domain did not undergo any granulite-grade reworking after ~1.60 Ga, but ^{40}Ar-^{39}Ar data from hornblende suggest weak amphibolite grade reworking during the Grenvillian (~1.1 Ga) orogeny. It is reasonable to postulate that the Ongole domain was far from the Grenvillian orogenic front and was mostly cratonized during ~1.60 Ga.

Considerable petrological data are available from the Eastern Ghats Province (combining Domains 2 and 3 of Rickers *et al.*, 2001). Although two isotopic domains of Rickers *et al.* (2001) are grouped under a single Province (Eastern Ghats Province of Dobmeier and Raith, 2003), careful inspection identifies several problems with this line of argument. The metamorphic history of the Domain 2 was initiated by a high-T/low-P progressive metamorphism and deformation that eventually led to UHT (~1000°C) peak (M_1-D_1) under deep-crustal conditions (8-9 kbar). This was followed by isobaric cooling. This entire process followed a single orogenic cycle when the lower crust evolved following a counter-clockwise P-T path (reviewed in Dasgupta and Sengupta, 2003). A second granulite-grade metamorphism and associated deformation (M_2-D_2) strongly reworked the deep-crustal granulites and exhumed them to mid-crustal level as evident from decompression-dominated retrogressive segment (Dasgupta and Sengupta, 2003; Dobmeier and Raith, 2003 and references therein). M_3 is weak amphibolite-grade overprint and mostly localized along ductile shear zones. Thermal imprint associated with this is manifested by emplacement of pegmatite crosscutting the M_2-D_2 foliation. The timeframes for this three-fold metamorphic cycle are more or less constrained from available data. The timing of M1 UHT metamorphism is a long-drawn controversy as it was previously constrained to be ~1100 Ma (Jarick, 1999) based on zircon common Pb method. Texturally-constrained monazite studies later portray a much wider timeframe (~1250-1100 Ma) (Simmat and Raith, 2008). This is still problematic since a time span in the tune of ~150 m.y. is too large for a specific tectonothermal event. Careful study using monazite and/or zircon grains by in-situ methods would probably resolve the issue. The timing of M_2 overprinting is ~950-900 Ma as all available geochronological studies seem to converge to this window (Grew and Manton, 1986; Shaw *et al.*, 1997; Mezger and Cosca, 1999). U-Pb zircon ages using LA-ICPMS (Upadhyay *et al.*, 2009) and SHRIMP methods (Bose *et al.*, 2008) also confirm this scenario. The timing of M_3 metamorphism and associated pegmatite emplacement is constrained to be ~550-500 Ma (Kovach *et al.*, 1997; Mezger and Cosca, 1999).

Metamorphic history of the granulites occurring in northern domains of Eastern Ghats Province (Phulbani, Angul and Chilka domains) is somewhat different from that in Domain 2 to the south. All the three domains are characterized by ~950 Ma high-grade granulite event (Dobmeier and Raith, 2003; Simmat and Raith, 2008). The most discernable metamorphic signature of the Chilka Domain is the decompression-dominated P-T path. In Chilka Lake area, Sen *et al.* (1995) documented stepwise decompression and cooling related retrograde path, the interpretation of which was later refuted by later work (Dasgupta and Sengupta, 2003). Nevertheless, an early decompression-dominated P-T trajectory is strikingly different from cooling-dominated one from that in the Domain 2. Geochronological data do not furnish any unique answer to this. Although monazite dating identified ages in the time frame of ~1250-950 Ma (*e.g.* Simmat and Raith, 2008), a more pronounced cluster of metamorphic ages is found in the time window of ~800-500 Ma (Simmat and Raith, 2008 and references therein). This is vindicated by more precise zircon U-Pb ages (Bose *et al.*, 2008; Upadhyay *et al.*, 2009). Moreover, the so-called “protracted” tectonothermal history of the Chilka Domain needs to be clarified as it is difficult to assume a single orogeny persisting over 300 Ma. Apart from regional-scale metamorphism, the Chilka Domain also witnessed contact metamorphism due to the emplacement of anorthosite magma. In the southern fringe of the anorthosite body, the enclosing metasediments underwent UHT metamorphism (~1000°C) at mid-crustal (6-7 kbar) level (Raith *et al.*, 2007; Sengupta *et al.*, 2008). Timing of this event is problematic as controversy over the emplacement age of the anorthosite still persists. The newly computed zircon ID-TIMS and monazite age (~983 Ma by Chatterjee *et al.*, 2008) contrasts the earlier age of ~792 Ma (Krause *et al.*, 2001; Dobmeier and Simmat, 2002). This again requires a proper reappraisal. The preponderance of Pan-African age granulite metamorphism in this domain certainly is a key feature and its implication will be explored later in the discussion section. The tectonothermal imprints in the time frame of ~800-500 Ma are characteristically absent in the Angul Domain whose metamorphic history is least known.

Rengali Province is situated at the northern extremity of EGB close to its contact with the Singhbhum Craton. This fault-bounded terrain has petrological, structural and geochronological signatures transitional between EGB and Singhbhum Craton. An early event of granite emplacement at ~2.80 Ga is the first tangible magmatic event in this terrain. Metamorphic signatures are of amphibolite to weakly granulite grade and scattered geochronological data suggest two thermal events at ~800-700 Ma and ~500 Ma respectively (reviewed in Dobmeier and Raith, 2003). This distribution of metamorphic ages is surprisingly similar to that of the Chilka Domain of the Eastern Ghats Province.

Spatial and temporal variations of the tectonothermal imprints

The nature of thermal and tectonic events identified in different crustal domains of the EGB depicts a time-specific segmented course of evolution. It is realized for some time now that the present configuration of EGB is a collage of crustal domains each having its own characteristic history. A critical look at the events in each domain through the time window may actually help us to visualize the evolutionary history in a holistic way.

Protolith isotopic characters of the Ongole domain suggest that the sediments were supplied to an unknown basement from the adjoining Dharwar Craton. The first major tectonothermal activity here occurred at ~1.76 Ga when the supracrustal rocks underwent UHT metamorphism due to emplacement of voluminous mafic magma in a continental arc type tectonic setting (Leelanandam and Vijaya Kumar, 2007). The sedimentary basin must have developed between ~2.60 Ga (youngest Nd-model age for the sediments) and ~1.76 Ga (metamorphic age), but could not be refined further since no systematic provenance study is carried out in this domain. A second pervasive imprint of metamorphism took place at ~1.60 Ga which coincides with the emplacement of pegmatoidal enderbite. The exact nature of this particular metamorphic overprint is not clear from available data, but it might have caused partial melting as reported recently by Upadhyay *et al.* (2009). It is still difficult to visualize how an UHT-metamorphosed lower crust underwent partial melting unless it was retrogressed by deep crustal shearing or transported to upper level by exhumation or erosion. It should also be noted that no decompression-related retrogressive metamorphism is discernable in UHT-metamorphosed lower crust of the Ongole Domain. There is no unique answer to this problem and it can only be resolved with sound petrological and structural data. For the time being, we simply assign the ~1.60 Ga event as a thermal imprint. In the mean time, the Ongole Domain witnessed intrusion of enderbitic gneiss at ~1.72-1.70 Ga. Lack of geochemical data on this rock suite prevents one from inferring a suitable tectonic setting, but an Andean-type active continental margin setting is one possibility (Dobmeier and Raith, 2003). This domain did not witness any further high-grade events although weaker event of ~1.10 Ga must have left its impression (Mezger and Cosca, 1999). This is consistent with the idea that the Ongole Domain became cratonized with the adjoining Dharwar Craton at ~1.60 Ga. This cratonization process incorporated thermal activity manifested by granitoid emplacement at ~1.60 Ga in the adjacent Vinjamuru Domain (Dobmeier *et al.*, 2006). During this entire sojourn, the Eastern Ghats Province did not exist in its entirety. However, presence of zircon within the UHT-metamorphosed paragneisses of the Domain 2 of the Eastern Ghats Belt with concordant inherited ages in the range ~1.76-1.70 Ga (Bose *et al.*, 2008) produces an interesting idea that such sediments were sourced from the Ongole Domain or its equivalents. Although the sediments have a Nd-model ages of ~2.5 - 2.1 Ga, the strong presence of ~1.76-1.70 Ga age in the zircon inherited domain may also suggest the age of the basement which has been postulated to be thoroughly reworked by later UHT event (Dobmeier and Raith, 2003).

Alkaline rocks were emplaced along the western margin and prominent shear zones of Krishna and Jeypore Provinces of EGB in the time span of ~1.5 – 1.3 Ga. This signifies onset of rifting in the already cratonized part of EGB (Upadhyay, 2008). No metamorphic signature of this period is seen in any rock of EGB. Emplacement of mafic magma at ~1450 Ma in the Vishakhapatnam Domain (Shaw *et al.*, 1997) is the only thermal activity in Eastern Ghats Province. However, the geochemical affinity of such mafic magma is not known.

A flurry of activity took place in the Eastern Ghats Province during the time segment of ~1250-900 Ma. These include UHT-metamorphic event (~1250-1100 Ma?) in an uncharacterized geodynamic setting. The overall counter clock-wise P-T trajectory of this event can be explained by extensional setting. The major problem with this kind of tectonic modeling is how to account for the anomalous heat supply which is a pre-requisite for UHT metamorphism. Recently, Brown (2006) argued that similar UHT metamorphism under low-P high-T prograde stage can be possible in a back arc setting. To establish such affinity we are severely short of documentary evidences. This UHT metamorphism was succeeded by emplacement of porphyritic granitoids (charnockite to granite in composition) at ~1000-950 Ma. A second granulite-grade metamorphism occurred in the time span of ~950-900 Ma when the deep crustal section was exhumed. This event was accompanied by pervasive deformation including deep-crustal shearing (Das *et al.*, submitted). Imprint of this very event is recorded in rocks of Angul, Phulbani and Chilka Domains as well. Metasediments of the Vishakhapatnam Domain did not undergo any younger tectonothermal event of granulite grade, although weak amphibolite-grade reworking at ~550-500 Ma is noted in localized shear zones (as reviewed in Dobmeier and Raith, 2003).

Chilka Domain in the northern part of EGB is notable in three aspects. Firstly, it has a metamorphic history different from that of the adjacent Vishakhapatnam Domain. Secondly, an important event of contact metamorphism took place in the sediments due to emplacement of anorthosite massif at ~983 Ma. Thirdly, and most importantly, the Neoproterozoic metamorphic history in the time span of ~800-500 Ma is unique for this domain in the

EGB. Metasediments of this domain have Nd-model age of ~2.2-1.8 Ga. This domain is bounded by Nagavalli - Vamshadhara Shear Zone (NVSZ) in the south and west and Mahanadi Shear Zone (MSZ) in the north. Restriction of Neoproterozoic age only in this shear-zoned bound block poses a possibility whether this domain represents an exotic block or its younger history is controlled by local factors. Some have argued that the ~800 Ma strong imprint is caused by anorthosite emplacement (Dobmeier and Raith, 2003; Upadhyay *et al.*, 2009). There are two problems with this logic. Firstly, ID-TIMS data of zircon from the anorthosite give an upper intercept age of ~983 Ma for crystallization which, if correct,means that the ~800 Ma age has nothing to do with the anorthosite emplacement. Secondly, this ~800 Ma event is very pervasive and recorded in metasediments occurring quite far from the anorthosite massif (Dobmeier and Simmat, 2002; Bose *et al.*, 2008). It is inconceivable that such enormous heat budget can be provided by the anorthosite magma alone. The preponderance of Pan-African (~550-500 Ma) ages in Chilka Block renders its proximity to the Pan-African front.

Discussion

Geochronological data correlated with specific magmatic and metamorphic imprints as described in the previous section allow us to visualize the evolution of the EGB in large canvass of ~1250 m.y. (~1.76-0.50 Ga), summarized in Table 1. It follows that the present configuration is a result of crustal growth in a phase-wise manner during this time span (Fig.2). We are excluding the ~2.8 Ga granulite metamorphism in Jeypore Province at this stage in the absence of compelling petrological and structural data.

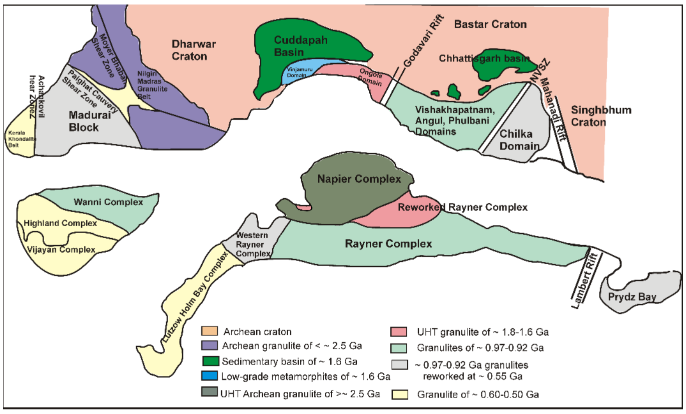
Table 1. Global geological events during Paleo-Neoproterozoic supercontinental cycles vis-à-vis events in EGB, India (Compiled from Zhao et al, 2004, Li et. al., 2008 and references therein, events in EGB are referred in accordance with the text).

Major Global Geological Events	Continents	Time Period
Earth's existing continents began to collide and finally coalesced into a pre-Rodinian supercontinent named "Columbia" evident from matching patterns of two pairs of rifts in the Columbia River region of western North America and Eastern India. Global scale collisional orogens were recorded e.g. Trans-Hudson Orogens in N. America, Nagssugtoqidian Orogen in Greenland, Kola-Karelia, Volhyn-Central Russian and Pachelma Orogens in E. Europe, Transamazonian and Eburnean Orogens in S. America and W. Africa, Capricorn Orogeny in Australia, Creek Orogen in N. Australia, Central Indian Tectonic Zone in India and Trans-North China Orogen in N. China.	Pre-Rodinian Supercontinent "Columbia"	2.1- 1.8 Ga
Growth of supercontinent Columbia		
1. Accretionary zone along the western margin of the Amazonia craton.	South America	1.8-1.3 Ga
2. An accretionery magmatic belt is extensively exposed as inliers surrounding the southern and eastern margins of the North Australian Craton and the eastern margin of the Gawler Craton, represented by the Arunta, Mt. Isa, Georgetown, Coen and Broken Hill Inliers.	Australia	1.8-1.5 Ga
3. An accretionery magmatic zone, called the Xiong'er belt (Group), extends along the southern margin of the North China Craton.	China	1.5-1.3 Ga
4.Granulite-grade metamorphism and magmatism in connection with probable accretionary orogeny in Krishna Province, EGB (Bose *et al.*, 2008; Upadhyay *et al.*, 2009), Banded Gneissic Complex, Aravalli (Buick *et al.*, 2006; Sarkar *et al.*, 1989), metamorphism and emplacement of felsic gneiss along the Napier-Rayner	India	1.76-1.6 Ga

Major Global Geological Events	Continents	Time Period
province boundary in E. Antarctica (Kelly *et al.*, 2002), granulite-grade metamorphism in Bhopalpatnam granulite belt (Santosh *et al.*, 2004) and Shillong Plateau Gneissic Complex (Chatterjee *et al.*, 2007).		
Fragmentation and final break-up of Supercontinent Columbia		
One of the most characteristic features of Mesoproterozoic geology is widespread continental rifting and anorogenic magmatism presumably due to mantle plume diapirism and asthenospheric upwelling. Continental rifting in Western Laurentia (1.6-1.2 Ga), Siberia (1.6-1.3 Ga), Northern China (1.8-1.4 Ga); Anorogenic magmatism in Baltica, Ural Mountains, Ukriane and Peninsular India (1.6-1.2 Ga), widespread alkaline ultrabasic rocks, represented by kimberlites, lamproites and carbonatites in West Africa, South Africa, India, South America and Western Australia (1.4-1.2 Ga). Major episode of plate-wide extension and rifting was marked by the intrusion of many mafic dike swarms and associated basaltic extrusions in North America Greenland, Baltica, north China, South America, East Antarctica, Western Australia and Central South Australia. Emplacement of alkaline rocks along the western margin of EGB and concomitant boundary shear zone (Biswal *et al.*, 2001; Upadhyay *et al.*, 2006).		
Formation of supercontinent Rodinia (ca. 1100 – 900 Ma)		
Collision of Yangtze craton with Laurentia at southern Cathaysia when Laurentia, Siberia, North China, Cathaysia (part of present day South China) and possibly Rio de la Plata were already together. King island, Tasmania, and the South Tasman Rise were close to the collision of Yangtze and Laurentia. Amalgamation of Australian craton and East Antarctica part of the Mawson craton occurred.	Growth of Rodinia	1100 Ma
Formation of Rodinia		
Kalahari collided with southern Laurentia and Continued collision of the Yangtze craton with western Laurentia. Development of convergent margins between most continents where oceanic lithosphere were consumed between them during assembly of supercontinent Rodinia.		1050 Ma
All continents assembled to be joined with Laurentia except India, Australia–East Antarctica and Tarim. The Yangtze craton was still suturing to Cathaysia part of Laurentia. The transpressional movement between Greater India and Western Australia advanced.		1000 Ma
All major continental blocks aggregated to form supercontinent Rodinia.		900 Ma
Orogenic events during this period:		
1) Arc volcanics and ophiolite obduction in the eastern Sibao Orogen of South China	South China	920–880 Ma
2) Arc volcanics along the northern margin of the Yangtze craton	Yangtze craton	950–900 Ma
3) High-grade metamorphic events in both the Eastern Ghats Belt of India and the corresponding Rayner Province in East Antarctica	India and East Antarctica	990–900 Ma
4) The Corn Creek Orogeny sometime	Northwestern Laurentia	between 1033 Ma and 750 Ma

Major Global Geological Events	Continents	Time Period
5) Southern Capricorn Orogen	West Australian craton	900 Ma
6) King Leopold Orogen	North Australian craton	900 Ma
Break-up of Rodinia		
Superplume events and continental rifting:		
Beginning of Rodinia break-up is represented by first sign of a Rodinia superplume, a small number of 870–850 Ma intrusions such as those in South China and Africa. Ca. 845 Ma and 870 Ma bimodal intrusions are reported from the Scandinavian Caledonides and the Scottish promontory of Laurentia.		ca. 860 – 570 Ma
Magmatism like mafic dyke swarms, intra-continental mafic–ultramafic intrusions, and felsic intrusions (resulting from crustal melt or magma differentiation) is commonly found in the polar end of Rodinia only, including Australia, South China, Tarim, India, Kalahari, and the Arabian–Nubian terranes. Felsic magmatism and metamorphism in Chilka domain of EGB (Simmat and Raith, 2008; Upadhyay *et al.*, 2008; Bose *et al.*, 2008) and anorthosite (?) magmatism (Dobmeir and Simmat, 2002). Ca. 800 Ma felsic magmatism (Shaw *et al.*, 1997) is reported from domain boundary shear zone (NVSZ, Fig. 1).		825 Ma
Origin of Gondwanaland		600–530 Ma
The Rodinia supercontinent fragmented around Laurentia with continental pieces that was moving away from Laurentia and colliding to form Gondwanaland. West Gondwana was largely together by ca. 600 Ma. By ca. 550 Ma India moved closer to its Gondwanaland position along the western margin of Australia along the Pinjarra Orogen. Kalahari started to collide with Congo and Rio de la Plata, thus closing the Neoproterozoic Adamastor Ocean between them. North China separated from Laurentia–Siberia after ca. 650 Ma was drifted toward Australia at that time. Final thrusting of EGB with Bastar craton on west and Singbhum craton on north ~550 Ma, granulite-grade metamorphism in Chilka domain of EGB (Bose *et al.*, 2008), Rengali province (Dobmeir and Raith, 2003).		
Finally Gondwanaland amalgamated by ca. 540–530 Ma.		
Major orogenic events during this period		
The Malagasy Orogeny in the East African Orogen		
India tied up to Australia–East Antarctica along the Pinjarra Orogen.		

Figure 2. Supercontinental cycles in India-Antarctica sector



Correlation of events related to supercontinental cycles in India-Antarctica sector during Precambrian time (modified after Harley, 2003). Chronology of events are followed after Harley (2003) and references cited in the present study. Domains and abbreviations are as the appear in figure 1.

The earliest high-grade metamorphism under UHT condition in the Krishna Province (Ongole Domain) occurred at ~1.76 Ga and it was soon followed by magmatism during ~1.72 - 1.70 Ga. Documentation of these events in the EGB has important consequences for the growth history of the supercontinent Columbia (*ca.* 2.1-1.8 Ga) (Rogers and Santosh, 2002; Zhao *et al.*, 2002, 2004). Columbia is postulated to have undergone long-lived subduction-related growth via accretion at key continental margins for nearly 500 Ma. This history is shared by major accretionary belts surrounding cratonic blocks of Laurentia, Antarctica, South Africa and Australia. Traces of tectonothermal activity of similar age are recorded from the Aravalli Craton of northwestern India, where granulite-grade metamorphism and emplacement of orthopyroxene-bearing TTG suite of rocks took place at ~1.72 Ga (Sarkar *et al.*, 1989; Buick *et al.*, 2006). It is likely that the ~1.76 - 1.70 Ga growth history of Columbia encompassed the southern part of EGB.

The ~1.60 Ga tectonothermal event in southern EGB (Ongole Domain) is often correlated with the juxtaposition of Napier Complex of east Antarctica with Eastern Dharwar Craton (Harley, 2003; Dobmeier and Raith, 2003; Upadhyay *et al.*, 2009). Identification of similar ~1.60 Ga tectonothermal imprints from other mobile belts surrounding cratonic blocks of India (Shillong Plateau Gneissic Complex by Chatterjee *et al.*, 2007; Bhopalpatnam Granulite Belt by Santosh *et al.*, 2004) are also encouraging. In a different viewpoint, this event was responsible for suturing the cratonic blocks of northern and southern India through the Central Indian Tectonic Zone (CITZ). Combining all the evidenc, we may postulate that the geographical span of this event was a result of the (more far-fetched) assembly of cratonic blocks of India and east Antarctica. The ~1.76 – 1.60 Ga history of the EGB thus can be correlated with the growth of the supercontinent Columbia.

Alkaline rock complexes of the EGB were intruded during ~1.50 – 1.30 Ma (Upadhyay, 2008 and references therein) and metamorphosed by Grenvillian and Pan-African events (Upadhyay *et al.*, 2006). These rocks are interpreted to form in rift-related tectonic setting during break up of Columbia (Upadhyay, 2008). Evidence of rift-related magmatism is widespread along the margins and interior of Columbia (Zhao *et al.*, 2004 and references therein). However, regional structural analysis suggests development of a fold-thrust belt at the north-western part of EGB (Biswal *et al.*, 2001) with concomitant formation of terrain boundary shear zone and synkinematic alkali magmatism at *ca.* 1400 Ma (Biswal *et al.*, 2001; Upadhyay, 2008). The tectonic framework is inconclusive as the geochemical affinity of these alkaline suites indicates extension related magmatism (Upadhyay *et al.*, 2006).

The UHT metamorphism in the Eastern Ghats Province (~1.25-1.10 Ga?) was followed by a separate pervasive granulite grade metamorphism and associated deformation during ~950-900 Ma. This latter part of the history has a strong resemblance to the evolutionary history of Rayner Complex of east Antarctica (Kelly *et al.*, 2002; Harley, 2003 and references therein). This led most of the researchers to conceive that the Eastern Ghats-Rayner belt amalgamated Indian and Antarctic cratons during the assembly of the next supercontinent Rodinia (Veevers, 2009 and references therein). Absence of younger pervasive granulite-grade events in this composite belt demonstrates that it was cratonized with India during ~900 Ma.

Strong presence of ~800-700 Ma tectonothermal activities in the granulites of Chilka Domain and lower grade rocks of Rengali Province is diagnostic. Thermal activities during this time frame are documented from Aravalli Craton (Malani Igneous Suite, Torsvik *et al.*, 2001), Cauvery Shear zone (Bhaskar Rao *et al.*, 1996), parts of Prydz Bay (Kelsey *et al.*, 2008; Wang *et al.*, 2008), Western Rayner Complex (Shiraishi *et al.*, 2008), south China (Zhao *et al.*, 2002) and Leeuwin Complex

(Collins, 2003). In all these occurrences, this broad time frame witnessed the disintegration of Rodinia. Magmatic and metamorphic signatures in most of such occurrences show rift-related setting (reviewed in Li *et al.*, 2008) for which little analogous data exists in the EGB (~800 Ma granite emplacement in the Rayagada by Shaw *et al.*, 1997).

The ~550-500 Ma granulite-grade events in the Chilka Domain and amphibolite-grade events in the Rengali Province trace the Pan-African signatures in the EGB. Available geochronological data suggest that the Pan-African front swap through the northern part of the EGB. This event left its strong presence in south India, Madagascar, east Africa, Sri Lanka, east Antarctica, Australia and south America (Li *et al.*, 2008 and references therein). It caused the final docking of India with east Antarctica and Australia during the assembly of the third supercontinent Gondwana. The present configuration of the EGB was finally achieved when its northern segment was thrust over the Singhbhum Craton with a westward vergence (Dobmeier and Raith, 2003). Discrete segments of EGB thus recorded three time-punctuated courses of development (Fig. 2). The amazing fact is, all these events and their interkinematic gaps coincided with the assembly and demise of three extinct supercontinents.

Acknowledgement

SB and KD acknowledge the Department of Science & Technology, Government of India for funding a research project (ESS/16/251/2005). SK acknowledges the CAS of the Department of Geological Sciences, Jadavpur University and SDG is thankful for the support obtained through J.C. Bose Fellowship from the Department of Science & Technology, Government of India. We thank Prof. Talat Ahmad for inviting us to write this review.

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